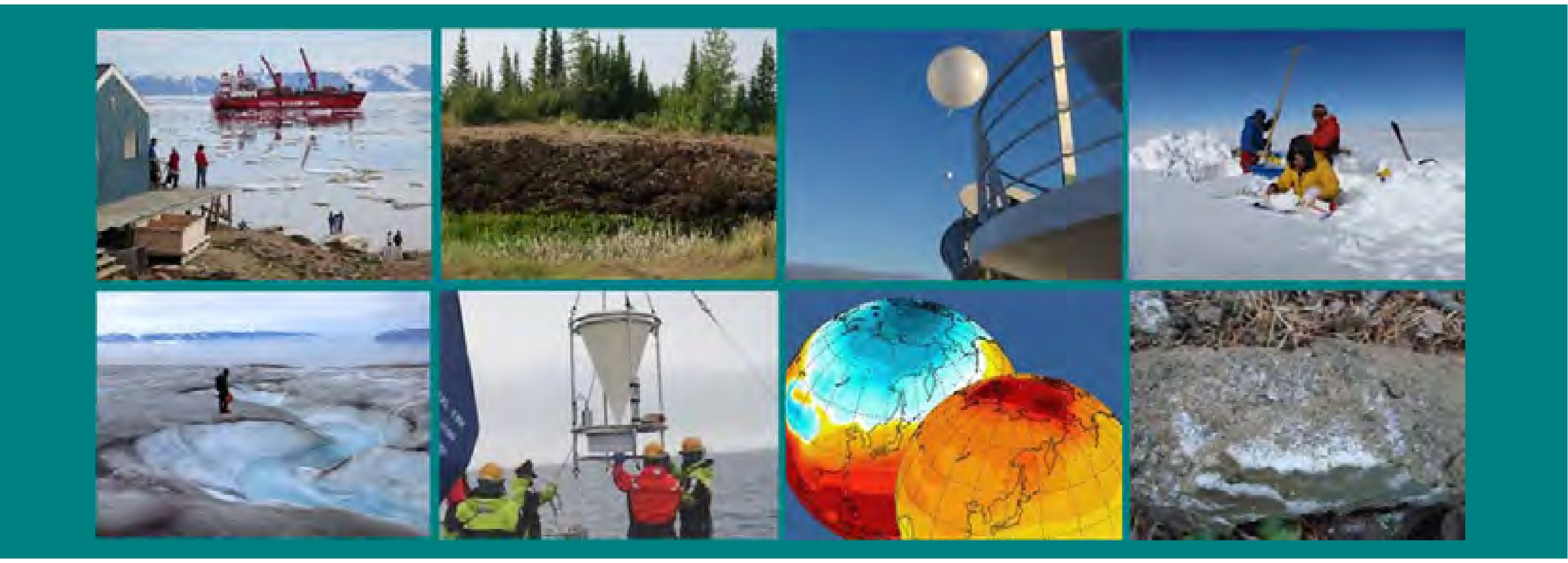
Long-term Plan
for Arctic Environmental Research

Japan Consortium for Arctic Environmental Research



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Preface

The JCAR was founded in May of 2011 and has as many as 384 supporting members as of August 2014. Behind the birth of the JCAR was the idea of persons involved in Arctic research to develop previous efforts for Japanese research in the Arctic in a new form. Up to now, many Japanese researchers have visited Arctic. However, although their individual research abilities are high, results from Japan are often not well remarked in the international movements. As these researchers travel to the Arctic as a small group and short timealone, they recognize that continuity from past observations, knowledge of the trends of other researchers, cooperation frameworks, and arrangement are the weak points of Japanese research. For activities like these, the research is inevitably temporary, and the vision or realization of long-term observations becomes impossible. The founding of JCAR is expected to improve the exchange information on activities conducted by every researcher, to have future directions, and to obtain partners for potential cooperative research. The importance of establishing a long-term vision of Japanese Arctic environmental research within that kind of activity was considered and recommended in a midterm report (August, 2010) after discussion at the 2010 meeting of the Arctic Research Working Group of the Ministry of Education, Culture, Sports, Science and Technology.

In the fall of 2011, the same year that JCAR was founded, the GRENE Arctic Climate Change Research Project started. In the following year, 2012, the minimum sea ice extent of the Arctic Ocean in the summer was recorded. The surface area of snow fall in spring was also a record low, and it was observed that extent of the melt of Greenland ice sheets expanded to almost the entire ice sheet surface. In March 2013, Japan's "Basic Plan on Ocean Policy" was renewed and attention also focused on the Arctic. In addition, Japanese Master Plan of Large Research Projects regarding the Arctic were submitted to the ScienceCouncil of Japan. In May 2013, Japan's participation in the Arctic Council as an observer country was recognized. The activities of the Arctic Council extend through many fields including international relations, environmental issues, and regional administration, but the base of decisions and those activities comes from information obtained through scientific activities. Regarding the quickly changing Arctic environment and research involving it, chances are increasing to prepare domestic research activities and appeals for international cooperation. It is important to understand the domestic situation in order to answer these problems.

The long-term plan began moving from consideration to implementation in 2013, under the firm commitment of JCAR's first-term representative, Tetsuo Ohata. The activities of the working group (WG), which was organized to carry out the implementation, undertook the editing work and how to proceed with the work. Along with three general workshops, discussion sessions were held in consideration of each field and research foundations shared among fields. In the beginning, there was a concern about inconveniences, such as the length of time needed to write up the long-term plan, or research ideas being made public. However, over 140 people cooperated with writing up the "Long-term Plan for Arctic Environmental Research." Activities for creating this plan progressed with support from the JCAR office and through discussion with many researchers involved with the Arctic, from Motoyoshi Ikeda, representative of the WG, as well as authors of the plan, those involved with peer review and proponents of this work. The writing of this long-term plan in Japan can be considered as the start of new research in the Arctic and an achievement for the system of Arctic researchers. We would like to show our deep appreciation for those who were involved in creation of this long-term plan.

For this plan, we considered tasks to be worked on over the next ten to twenty years. Many themes from each field were included. The authors did not just emphasize their own interests and activities, but took a wide perspective and included important fields and objectives Japanese researchers should work on. Many of the themes dealt with there do not end in Japan, but are ideas at a high level of completion which can be proposed internationally.

Changes in nature in the Arctic are happening at a rapid pace. The demands of a changing Arctic environment, as well as expectations and responsibilities of researchers, are increasing. Phenomena in the Arctic Circle are complex. Researchers are now expected to look at their own positions relative to the whole, to engage in cooperative research across fields, and for researchers of a particular field to learn from content of other fields. This "Long-term Plan for Arctic Environmental Research" allows researchers in the Japanese Arctic environment to show the challenges and directions of their own fields as well as to explore relations and movements in other fields. This provides an opportunity to deepen discussions of Arctic research, and the number of people participating in such research is expected to increase.

Japan Consortium for Arctic Environmental Research,
Chari of steering committee
Hiroyuki Enomoto

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Figure 1: A map of Arctic region displaying the main geographical names which appear in the long term plan. The original map can be downloaded from the JCAR website.

Chapter 1: The purposes of the long-term plan report

In this plan, Arctic environment specialists aim to present research direction for the resolution of environmental issues to citizens concerned with environmental problems and researchers in various fields. The primary concern on the environment is global warming. In particular, it is said that the Arctic is experiencing warming more than twice as quickly as the global mean warming, and dramatic changes in snow and ice covers which have been observed are drawing our attention. It is accepted that despite global warming, some areas sometimes undergo cooling. This is due to atmospheric circulation variability where air temperature may go up and down from year to year with certain spatial patterns, while global warming has a time scale in the range of several decades to centuries. Therefore, after experiencing unusually cold winters, it is understandable that some doubt the existence of global warming and question which direction Japan will take.

Let us move onto the map (Figure 1). By studying the Arctic, it has become apparent that during summer, open water areas exist which were covered by sea ice in a whole year until some years ago. The region off the Siberian coast already experiences only seasonal ice cover. The future projections indicate that seasonal ice cover will expand across the entire Arctic Ocean around the middle of this century, although some models suggest this will be rather sooner at ten years from now. Whilst simulation models are necessary for future projections, some may question their reliability. An even more difficult question is when the Arctic Sea Route will become substantially available.

The distribution of vegetation, which is mainly controlled by climate, will increase under gradual warming in the middle and high latitude areas. As soil moisture is crucial, vegetation is dependent on precipitation and the length of snow cover. There are concerns that forest ecosystems are not easily transferable and hence may not be able to follow climate change. When anthropogenic influences such as deforestation and development are included, changes in the biodiversity and biota become difficult to estimate. Human beings keep an issue to preserve biodiversity, which provides the foundation of terrestrial ecosystem services [1] and determines the level of response to environmental change. Terrestrial vegetation supports wild animals, which are subsequently hunted for food by indigenous people in the Arctic area. Their traditional culture provided many treasures to global citizens. The situation is similar for the marine ecosystem where changes in marine biodiversity and biota are crucial to the ecosystem services which support residents around the oceans. Both agriculture and fisheries are influenced by the climate, however, there is one significant difference: i.e., agriculture can be managed to some extent by maintaining water resources and choice of crop species, whereas the fishery is dependent on the more complex natural environment, with issues regarding food chains and conflict among different species.

It should be noted how glaciers, ice sheets and permafrost are changing, which are unique features in the Arctic. The rapid degradation of the Greenland ice sheet during this century is well known, because it is crucial to future sea level rise. Shrinkage of mountain glaciers varies from place to place, but the global decrease rate is monitored only at certain degree. In contrast, the permafrost is more challenging to monitor, as it also has an environmental impact when its thawing affects vegetation and river flows, as well as the release of greenhouse gases from decomposing carbon-containing compounds. The recent increase in Siberian river discharges is attributable to an increase in precipitation, and possibly thaws permafrost along the rivers.

In light of the factors mentioned above, paleoenvironmental research uses analysis of past climate changes recorded in strata and ice sheets to verify simulation models for future predictions. An interesting, broader view includes the timing of the development of the semi-closed Arctic Basin, and its consequences on climate in the Arctic Ocean and coastal areas. The impact of the upper atmosphere on the stratosphere and troposphere, in accordance with variable solar activities, is another example. Not limiting to natural sciences, wider attention should be directed toward the humanities and social sciences: e.g., how to develop collaborative relationship between the indigenous residents and recent immigrants. We would expect readers to understand these concerns when reading through this report, and generate ideas for resolving them.

Chapter 2: The background and particulars of this report

The long-term plan was proposed in the Basic Policy Terms of the on-going GRENE Arctic Climate Change Research Program[2] and moreover in the prospectus and agreement of JCAR[3]. Up to now, no long-term plan has focused on Arctic environmental research in our country, hence, it is important to present analyses of the current status and future direction to be taken. It is no exaggeration to say that the fact that this long-term plan has been developed by JCAR has confirmed its existence. This plan reflects the hopes of the next generation of researchers, encouraging forward progress toward common goals by working together.

It is sensible to select enhanced warming and biodiversity as the two foci of Arctic environmental research, since international programs are already in place to establish the current status, make future projections, and provide proposals for management. The advantage of JCAR is that it consists of various disciplines, which will enlighten each other. Therefore, the plan is organized around the core subjects, which should be tackled in

[1] Ecosystem services: Benefits that human being receives from ecosystems: i.e., main ones are food, mental and cultural benefits, and also mitigation of climate and water environment, extending further to oxygen supply and carbon dioxide absorption.

[2] GRENE Arctic Climate Change Research Project: project funded for 5 years starting in FY2011 by the Ministry of Education, Culture, Sports, Science and Technology-Japan (MEXT) within the framework of the GRENE (Green Network of Excellence) Program.

[3] JCAR: Japan Consortium for Arctic Environmental Research, a nationwide network-based organization for promoting arctic environmental research.

collaboration. Although environmental research has previously been carried out in the Arctic, global warming and biodiversity have not been directly focused on. Therefore, this research may not only enhance the activities of JCAR as a community, but also provide important, new information on global warming and biodiversity. Furthermore, this report includes guidelines to develop research infrastructure, construction of a platform for the research and capacity building.

This long-term report is being presented to researchers who are not involved in Arctic research, to policy makers who are not specialized in sciences, and to citizens generally concerned with environmental issues. We were actually able to document the thoughts and wishes of Arctic researchers, as well as to exchange information between us so that we may learn from each other's activities in various fields, in the process of compiling this report. These results provide an important step forward in advancing future research.

Contents of this report

Several themes have been chosen for each of the four objectives set here, starting with the changes and variations in the states to date, alongside a review of the research progress. We describe each theme, identifying gaps in the current understanding, and then suggest necessary research paths and systems for the next 10 to 20 years. The report is structured so that readers who are not familiar with science and researchers who are not involved in Arctic research, initially read the introduction about social concerns and then progress further into more specialized information with the deeper insights.

The four objectives are as follows. The first one, which is the background for formation of JCAR, is research on "Understanding of the abrupt-complex phenomenon and elucidation of the mechanisms and impacts associated with global warming enhanced in the Arctic, along with improvement of their future prediction". In this objective, seven themes have been selected such as amplification of warming in the Arctic. The second one, research to elucidate "Biodiversity in land and ocean, and also the effects of anthropogenic environmental change on ecosystem, not limited to global warming" is divided into terrestrial and marine themes. The third one covers "Broad and important research on the Arctic environment and its fundamental information" and includes three themes such as the geospace environment surrounding the earth. The fourth objective covers three categories of methods related to the previous themes, "Monitoring, modeling and integration of the two, enabling breakthroughs in environmental research".

Many of the environmental changes considered for these objectives contain complicated interactions among the atmosphere, ocean, cryosphere, land surface, geochemical cycle, and ecosystem. Hence, this approach activates inter-disciplinary research. In turn, this encourages a deeper understanding of each discipline and leads to exploration of unexplained phenomena. The forth objective encourages breakthrough research from the development of innovative methods of observation and modeling, not confined within the improvement of techniques.

This English version has been prepared in order to disseminate information from us to the international community. A main purpose is for the Arctic research community in Japan to present its research direction in terms of academic progress. As related discussions were initiated by ICARPⅢ in 2014, we should not miss the opportunity to use this material to provide input to the discussions from the Arctic environmental research group in Japan.

Chapter 3: Changes in the Arctic environment to date and in the near future

Let us consider the scientific questions for the academic experts as to how the Arctic environment has changed over time and will continue to change during this century. We also introduce progress in research, including the current direction, which has already been addressed. First, multi-disciplinary issues are described in association with the objectives of this long-term plan. Most of these issues are receiving attention from the ongoing GRENE program.

The various factors that cause warming over the global enhanced in the Arctic and are in turn affected by the phenomenon, are shown in Figure 2, where the warming is the pivotal point. For example, sea ice reduction and shortened and reduced snow cover occur as a result of global warming, and then contribute to a reduction in albedo (reflectance of solar radiation), making feedback to the Arctic amplification of the warming. Water vapor increases as a result of the air temperature rise, and hence, clouds and aerosols (air containing fine particles) increase. The effects of clouds are dependent on the season, while they increase the downward longwave radiation except for summer, contributing to warming at the earth surface. A future research topic will be to project quantitatively how much more rapidly the Arctic will warm up in comparison to the global average.

Greenhouse gases absorb longwave radiation from the earth's surface, causing the troposphere to warm up. In contrast, the stratosphere and upper atmosphere have been reported their cooling down. When temperature changes differ between the low- and high-latitudes, and between the lower troposphere and the upper atmosphere, various suggestions have been made regarding the feedback to the low-latitude atmosphere: e.g., how the jet stream around the Arctic changes, and whether meanders tend to grow more or not in the jet stream.

Global warming pushes the northern limit of forests northward, while permafrost tends to retreat, resulting in reduction of soil moisture and subsequent forest degradation in some areas. Once the warming affects atmospheric circulation through snow cover and the hydrologic cycle, feedback to the land surface should be considered, and hence, permafrost degradation and northward expansion of forests will vary by region. As a result of these changes, thawing permafrost may release greenhouse gases, while the growing forests will absorb carbon dioxide. Since soil moisture depends on precipitation, it is challenging to predict how vegetation will change. Improved prediction of ice sheet melting promote the correspondence of social infrastructure by estimating sea level rise, such as storm surges and lowland flooding.

The warming also affects the oceans. Cooling becomes

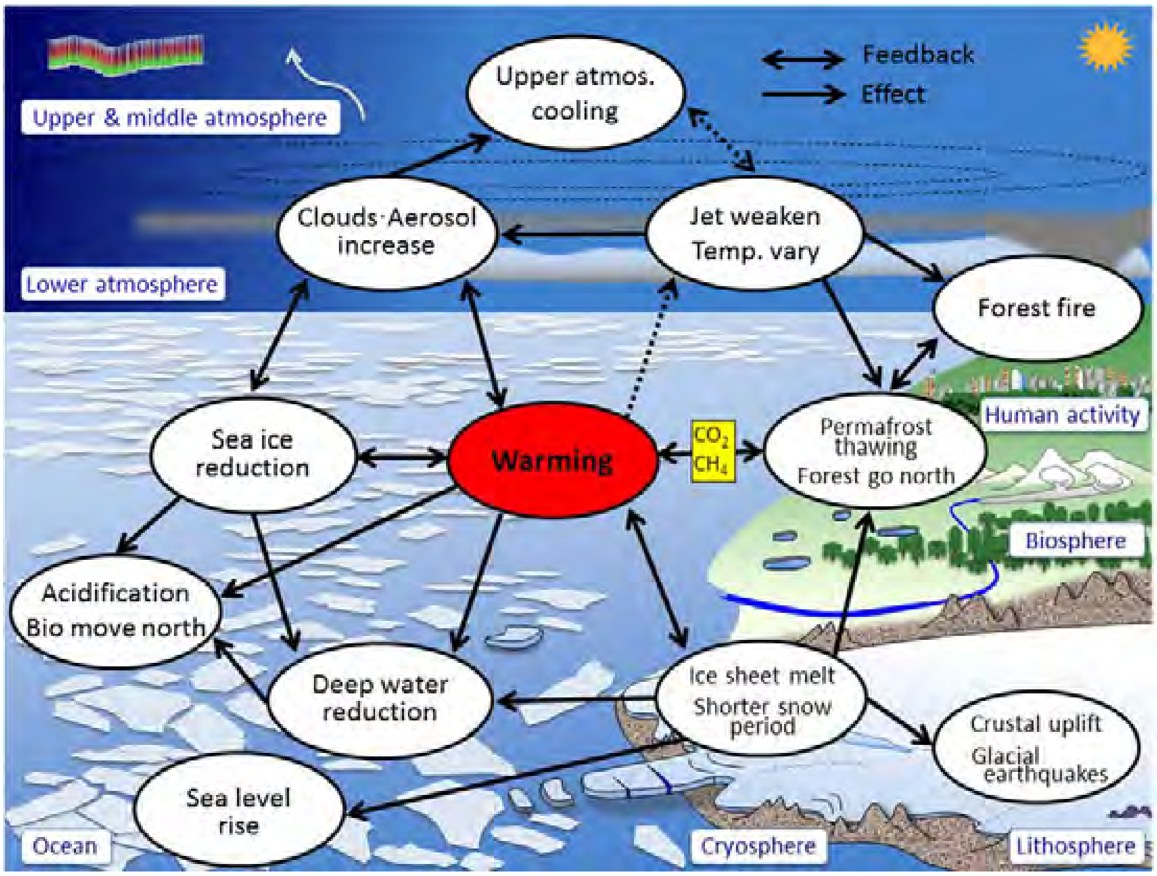

Figure 2: Crucial changes in the atmosphere, land, cryosphere and ocean, in response to current climate change, along with the effects (one way) and feedback (two ways). Note that while only major changes and interactions are displayed, other variations may exist. The solid arrows denote confirmed interactions, and the dotted ones denote more hypothetical ones. Also, the interactions between clouds and global warming can work both ways: e.g., the presented feedback is important in seasons other than summer, although clouds shield solar radiation and reduce sea ice melting in summer. In addition, forest fires occur without global warming, but are becoming more frequent.

weaker over the Greenland Sea, meaning that deep water formation under convection is reduced. Therefore, the driving force of the global conveyor belt[4] is weakened, or the deep water is reduced within the belt, resulting in a reduction of nutrient upwelling. In the Arctic Ocean and the surrounding seas, deep convection becomes weaker, impacting marine ecosystems. However, detailed investigations are necessary to judge the effects of changing conditions on both migratory species and the opposite ones. Acidification occurring primarily in the Arctic Ocean will have a large impact on the ecosystem. The partial pressure of carbon dioxide is determined by ocean temperature, inorganic carbon compound concentration and alkalinity, and increases under the global warming, although some unclear elements prevent prediction of the absorption of carbon dioxide in the ocean.

In order to retrieve useful information from the environmental variability of the past to enable predictions for the future, research activities have been focused on ice cores and marine bottom sediments, as well as exchanging knowledge with various other fields. A majority of this long-term plan is based on natural science, however, we also describe the social impacts of environmental change, and propose methods to respond to changing conditions with cooperation of the residents who rely on the Arctic area for their livelihood.

Next, we consider the on-going changes for individual elements of the Arctic environment and explore some academic questions. Around the atmosphere, increases in both longwave radiation from the sea surface and sensible and latent heat[5] fluxes due to sea ice reduction, will produce a significant change in the Arctic region. We need to improve the reliability of future prediction for the transition from stratus to stratocumulus by eliminating

[4] Global conveyor belt: mainly driven by the North Atlantic Deep Water, but also involves other important driving mechanisms. In the Atlantic, the Pacific and the Indian oceans, heating and cooling work on the sea surface; salinity is reduced by precipitation and river inflow, and increased by evaporation. As a result, ocean circulation is induced along the meridional (north-south) plane, and hence, the North Atlantic Deep Water near the ocean floor in the North Atlantic flows southward in the Atlantic, eastward in the Southern Ocean, and northward in the Pacific, and then, rises to the surface layer in the North Pacific. It then goes through the Indian Ocean and returns to the Atlantic. This circulation pattern is called the Global Conveyor Belt.

[5] Sensible heat and latent heat: the cold and dry atmosphere takes heat from the ocean. Sensible heat flux is caused by a difference in temperature between the atmosphere and the ocean. Latent heat flux is induced by evaporation, and then, water vapor returns to the liquid phase and releases heat to the atmosphere.

under- and over-estimation of cloud formation in a numerical model. Although increasing greenhouse gases modify the radiation balance, aerosols form cloud nuclei and enhance the cloud formation significantly in the Arctic, therefore we need to identify more appropriate processes. Atmospheric circulation patterns are modified by sea ice reduction and snow cover changes with spatial variability: e.g., the East Asian winter monsoon is modulated, giving anomalous weather around Japan. One of the necessary, but recently developing research topics, cover interactions of the Arctic area with interannual variability in the atmospheric circulation in the equatorial to mid-latitude areas.

As global warming occurs near the earth surface, the upper atmosphere becomes cooler. Monitoring the cooling provides us with an estimate of the global warming progress. The ozone layer, in the Arctic in addition to Antarctic, has been monitored, which highlights the need for continuous observations with regard to global warming. Since it has been suggested that solar activities affect the lower atmosphere, we should attempt to quantify the effects. Space plasma radiates along the magnetic field lines toward the polar region, producing various phenomena in the upper atmosphere such as aurora. Monitoring them from the ground helps us to examine the space plasma environment crucial to the safe and secure operation of satellites.

Let us consider the terrestrial cryosphere. As for ice sheets and glaciers, which melt and contribute to a rising sea level, we will investigate the dynamics and the energy/mass balance at the surface. Using observational data and modeling, we will be able to track the mass balance. Although the period of snow cover has been shortened over the high-latitude regions, snow depth and precipitation vary greatly in time and space. Therefore, the appropriate method is to combine continuous observations at stationary points and coverage with satellite data, where the northward shift and deterioration of forest zone are also monitored. It is examined quantitatively how much ice albedo is reduced by microbial effects, along with the effects of vegetation variability. We can easily imagine warming around the active layer in the upper part of permafrost, while the albedo and heat conduction are dependent on snow depth in early winter and will influence the loss near the southern edge. The net precipitation, which is precipitation minus evaporation, is thought to increase in time and contribute to river discharge into the Arctic Ocean. We should consider a complete picture of the hydrological cycle, by combining water vapor transport from the sea surface and mid-latitudes.

The terrestrial geochemical cycle remains as an uncertain component in identifying the global carbon fluxes. In the Arctic area, huge amount of organic matter in permafrost emits carbon dioxide and methane under global warming and large-scale forest fires. In addition to carbon, nutrients and trace metals also flow out to the ocean through rivers and due to coastal erosion, subsequently influencing the primary productivity of marine ecosystems. Contributions to monitoring of the environment are expected in Siberia, Alaska, Canada and Nordic countries.

Terrestrial vegetation supports wild animals, provides ecosystem services for human beings, and also has the capacity of feedback to climate change. It is well known that increased productivity of vegetation fixes more carbon dioxide, although the level of fixation is dependent on the abundance of nutrients. The other functions include reduction of albedo with the northward expansion of the forest zone, contribution to hydrologic cycle by soil moisture absorption and evapo-transpiration, and also arrangement of iron compounds for the marine ecosystem. Since reduced biodiversity yields vulnerability in environmental change, we should focus on exploring the biodiversity in the high latitude areas relatively behind mid- and low-latitudes.

Sea ice cover in the Arctic has noticeably reduced due to air temperature rise and ocean warming. Perennial sea ice has reduced all over the Arctic, shifting to a seasonal feature, which has happened most notably over the Siberian shelves. An increased flow of the warming Pacific Water into the Arctic Ocean is driving sea ice reduction. Based on historical records, our specialists should monitor oceanographic variability in the Pacific sector so that they may explore various components of sea ice and the processes. The inflow from the Atlantic region into the intermediate layer of the Arctic Ocean receives less brine rejection due to less ice formation in the Barents Sea, and hence, mixes with the Arctic surface water more easily. Thus, there is a need to investigate the processes associated with the seawater influx through the Barents Sea. Once we attempt a trial experiment to predict sea ice cover and movement with the navigability of the Arctic Sea Route in the near future, we will focus on a system to use satellite data and to develop numerical models.

Ocean geochemical cycles and the marine ecosystem will change, interacting closely with each other. Expansion of the seasonal ice-covered area tends to enhance the productivity, although it does not necessarily increase, for example, when circulation of nutrients is weakened under the freshened surface layer. The species that have lived in the adjacent seas continue to invade the Arctic Ocean, with the distinct possibility that the biota will be largely transformed. For the Arctic Ocean, which is under strong influences of river water spreading on the wide continental shelves, the research focuses on material exchange between the shelves and the basin, and the resultant responses of the ecosystem. As such, it is necessary to trace the effects of land-origin materials. In order to monitor the progress of ocean acidification, we should keep track the areas with under-saturated with calcium carbonate in the bottom layer of the shelf region and the surface layer of the basin. Our knowledge of the food-web and material fluxes from zooplankton to fish and birds is limited to early summer only, and hence, we have to build a platform to collect information during the other seasons.

Let us consider the phenomena over time scales longer than several hundred years. Paleoenvironmental data provide information on the interactions between temperature variability and geochemical cycles. Since the paleoclimate information is applicable to current environmental changes, the key issue is to develop and operate a research system under collaboration with various academic disciplines. Within the solid earth field, we focus on the effects of marine hydrothermal activities and seafloor geodetic on climate change through ocean circulation. As for the issues on the Greenland ice sheet, we propose to research the retreat of the grounding line under the ice sheet due to the sea level rise, and the response of the ice sheet to its own rapid melting, with a view of potential future problems.

As for the final issue, the social impacts of Arctic environmental change are described. In this plan, we list operation of the Arctic Sea Route, information transfer on earthquake and tsunami, impacts of terrestrial ecosystem changes, increasing forest fires, and changes in and maintenance of marine products. These aspects should not be considered just as information transfer to the Arctic residents, but be pursued in cooperation with them, as an understanding between the residents and the research community, and also on the basis of respect for other entire human beings.

Chapter 4: History of Arctic Environmental Research

International efforts focusing scientific studies on the Arctic were a response to the first International Polar Year (IPY; 1882 - 1883) in the late 19th century. Twelve countries participated in the IPY and 14 observatories were opened in the Arctic. In IPY, the main observations were meteorology, geomagnetism, and the aurora. Japan voluntarily participated in the IPY, with the advice of foreign experts, while the Ministry of Agriculture and Commerce Geological Survey and the Navy Hydrographic Bureau started the geomagnetic observation. Complete oceanographic observations in the Arctic began with the Fram Expedition led by Nansen ten years later (1893-1896). It was still a time of global exploration, when each country was in competition to explore the Arctic Sea Route, discover unexplored land, and reach the North Pole.

Based on the success of the IPY, the second International Polar Year (IPY2; 1932 - 1933) was conducted 50 years later; 44 countries attended, including Japan for the first time. Japan did not have territorial waters in the Arctic, therefore they started geomagnetic observations at Sakhalin close to the Arctic, and the meteorological observations at the summit of Mt. Fuji, which has a climate that is similar to the Arctic. The major challenges of IPY2 were to observe the ionosphere in relation to "radio waves forecast" for long-distance shortwave communication. Japan also participated in this international project by establishing the observatory.

After World War II, the Arctic became the stage of the Cold War for the United States and the Soviet Union. The Arctic Ocean was surveyed by nuclear submarines, sea ice and ice islands were used as drifting stations, and resource exploration and cold region research engineering of the Greenland ice sheet and permafrost (which has strong implications for the military including the resource exploration) were performed.

Japanese scientists began to conduct research activities in the Arctic, from the late 1950s. The study of ice cores in the Greenland ice sheet by Ukichiro Nakaya (Hokkaido University), and meteorological and glaciological research on the ice islands called ALIS2 and T3 of the Arctic Ocean by researchers were all carried out as participations of the United States project. From the late 1960s, tracking observations of ice nuclei from over Japan to Alaska by Nagoya University, permafrost research in Siberia and Alaska and glacier survey in Alaska by Hokkaido University were performed by Japanese research groups. This was during the Cold War era and research observations in the Arctic were restricted. In particular, the door to the Arctic was closed and access to data was limited in the Soviet Union.

A major turning point in the Arctic research was in 1987 when General Secretary Gorbachev of the Soviet Union gave his speech at Murmansk. He called for a release of the Northern Sea Route and the promotion of scientific research in the Arctic. A momentum of international cooperation in the Arctic research grew in response to this, and in August 1990, Arctic countries met in Resolute, Canada, and installed the International Arctic Science Committee (IASC). The first meeting of the IASC Council was held in Oslo in January 1991, where membership examination of non-Arctic countries was carried out, and the six applicant countries, including Japan, were accepted.

This was also a turning point for Arctic research by Japan. In 1990, the Arctic Environment Research Center was established by the National Institute of Polar Research (NIPR). In 1991, along with the cooperation of the Norwegian Polar Institute, a research station was also set-up in Ny-Alesund, Spitsbergen, Svalbard, which started observing atmosphere, snow and ice, ocean, terrestrial ecology and upper atmosphere physics.

In addition, in 1990, the Japan Marine Science and Technology Center (JAMSTEC; currently, Marine-Earth Science and Technology Organization) in collaboration with Woods Hole Oceanographic Institution, used the oceanographic vessel of the University of Alaska and automatic sea ice observing station to perform marine observations of the Arctic Ocean.

NIPR conducted observations of greenhouse gases at Ny-Alesund station, biological observations in the polynya (non-freezing open waters), ice core drilling on the Greenland ice sheet, the joint observation of the atmosphere by aircraft with the Alfred Wegener Institute for Polar and Marine Research of Germany, further aircraft observation of greenhouse gases, aerosols and clouds up to Svalbard across the Arctic Ocean from Japan, and carbon cycle study of tundra vegetation at Ellesmere Island in Canada and Svalbard. In contrast, JAMSTEC commended Arctic Ocean observations using the oceanographic research ship "Mirai" from 1998, with 10 voyages between 1998 and 2013 contributing to the international Arctic Ocean observation. From 1997, Nagoya University began water and energy cycle research in Siberia over snow cover on frozen ground, by installing the observation points such as Yakutsk and Tiksi, which also corresponded to WCRP[6] / GEWEX[7] research programs. Since 2001, the research project had been conducted by JAMSTEC, Hokkaido University, Nagoya University, and Research Institute for Humanity and Nature, and the research area has expanded around the Lena River basin.

In addition, from 1991, the National Institute for Environmental Studies (NIES), has continued sustainable observation of greenhouse gases in Siberia using the observation towers and aircrafts. Hokkaido University also began studying permafrost in Siberia and Alaska in

[6] WCRP: World Climate Research Program
[7] GEWEX: Global Energy and Water Cycle Experiment; in 2013 and later, Global Energy and Water Exchanges Project

the 1980s; Kitami Institute of Technology and Hokkaido University carried out glacier observation of Siberia in the 2000s, and the Forestry and Forest Products Research Institute has been completing a forest survey of Taiga band. Tohoku University and NIES have also continued observation of greenhouse gases by commercial airliner over Siberia. Furthermore, since 1999, JAXA (Japan Aerospace Exploration Agency) and JAMSTEC began joint research on the Arctic Research with the University of Alaska.

Observational research of the Arctic region by Japan had been carried out by group-based research, by institutions and projects, depending on the decentralized form; however, we recognize that domestic cooperation was essential to promote research, and consequently began Arctic research activities by constituting a committee by volunteers from 2006. To show our support, from 2008, the International Symposium on Arctic Research, which occurs every two years, and the Arctic session from 2008 at the Japan Geoscience Union General Assembly.

International research gained momentum around 2000 following sea ice decline in the Arctic Ocean. Between 2007 and 2008, on the 50th anniversary of the International Geophysical Year (IGY), with ICSU[8] and WMO[9] as the core, IPY2007-2008 for the Arctic and Antarctic was carried out with promotion of research activities on observation and data archiving. In order to strongly encourage research, expansion of the organization was discussed in the IASC, and the number of working groups increased since 2011. This gave Japanese researchers the opportunity to become more involved in IASC activities.

In 2011, the Ministry of Education, Culture, Sports, Science and Technology took up the "Arctic Climate Change" as a part of Green Network of Excellence (GRENE) program. Focusing on the "Rapid Change of the Arctic Climate System and its Global Influences", a five-year plan known as the GRENE Arctic Climate Change Project commenced. The GRENE Arctic project has the NIPR as a representative body and participating institution of JAMSTEC. It is a large-scale project with nearly 300 participating scientists participating from 36 universities and research institutes across the country.

JCAR was established in May 2011, as a part of the GRENE Arctic project. In addition to long-term planning on Arctic environmental research, JCAR has discussed the infrastructure of research and observation, promoted international cooperation and coordination, and development of human resources.

Regarding the sea routes across the Arctic Ocean, two main routes have been recognized since the era of great shipping in the 15th century: i.e., Northeast Passage is the route along Siberian coast between Europe and the Pacific, and Northwest Passage is the route along Canadian coast between the Atlantic and the Pacific. The Northeast Passage is now also called the Northern Sea Route, which is governed by Russia. In this report, we use Arctic Sea Route and also Arctic Shipping Route as the entire routes crossing the Arctic Ocean, including Transpolar Sea Route through the middle of the Arctic Ocean.

[8] ICSU: The International Council of Science
[9] WMO: The World Meteorological Organization

Chapter 5: Elucidation of abrupt environmental change in the Arctic associated with the on-going global warming

Global warming is the primary environmental change in this century, significantly impacting human society and ecosystems, causing great social concern. This is why we describe the themes in relation to global warming. The key processes are discussed, with the aim of clarifying feedback among the various elements of the Arctic environment. Feedback from ecosystem changes to global warming is also focused on.

Theme 1: Arctic amplification of global warming

Abstract

In the Arctic, several elements in the atmosphere, ocean, cryosphere, land surface and ecosystems are interwoven in a complex with various feedback effects, resulting in a more rapid temperature rise than in other regions. This particular phenomenon is known as "Arctic warming amplification". However, our understanding of the quantitative contribution from the individual elements and physical processes is still insufficient. Therefore, using the following five questions, we proposed a long - term research strategy for the current and future situation.

Q1: How does horizontal and vertical heat transport from lower to upper atmospheric layers affect Arctic warming amplification?

Q2: Is the role of terrestrial snow cover, permafrost, vegetation and ice sheet important?

Q3: To what extent does the role of sea ice albedo and heat accumulation in the ocean vary seasonally?

Q4: Is it possible to quantify the role of clouds and aerosols?

Q5: Why is Arctic warming amplification occurring, and how uncertain are the predictions? How are radiative forcing and feedback processes changing in the Arctic?

In the context of atmospheric circulation, Q1 was discussed by dividing the role of the effects of heat transport from the mid - latitudes and the role of the upper atmosphere, how the horizontal and vertical heat transport in the lower layer to the upper layer of the atmosphere would affect the Arctic temperature amplification. Q2 is related to terrestrial snow cover, permafrost, vegetation and the ice sheet. We considered the effects of snow cover, permafrost, and ice sheet changes with water circulation changes, and the effects of soil and vegetation alterations on the atmosphere. Q3 considered the role of sea ice albedo and heat accumulation in the ocean with seasonal fluctuations on the Arctic amplification. Q4 discussed the quantitative role of clouds and aerosols, considered to be extremely uncertain in Arctic warming amplification. Finally, as an overall summary, we questioned why Arctic warming amplification is occurring, how uncertain the predictions are, and what are the changes to the feedback processes and radiative forcing in the Arctic. We discussed the quantitative evaluation of the current state of research and the challenges. Through each question, we studied from the standpoint of process observation, long - term monitoring, process models and climate modeling.

Efforts for more than 10 years have focused on energy transport in the Arctic region, and continue to examine the interaction between elements from upper atmosphere to clouds, aerosols, snow cover, sea ice and ocean middle layer. In order to develop and use Earth System Models, not only is the cooperation of modelers in various fields required, but the planned acquisition of data for model validation is also needed. As a contribution from our country, we must work with the agency to continue sensor development and launch satellites in order to develop satellite observations from the sea ice to the upper atmosphere. In situ observations of the ocean are key to our contribution and should be repeated systematically.

Introduction

Climate change currently occurring in the Arctic directly or indirectly affects the natural environment and economic activities, not only of the region itself but also of areas further afield. These changes are resulting from global warming, in turn resulting from an increase in greenhouse gases; however, in comparison to lower latitudes, the temperature rise in the Arctic is high and subject to the amplification effect (Arctic warming amplification). However, the mechanism of global warming amplification in the Arctic is not simple, involving complex intertwining of various elements in the atmosphere, ocean, snow and cryosphere, land surface, and ecosystems; as a result, we can only observe the results of interactions between these components.

Figure 3 shows the direction of affect and feedback effects between each component in the Arctic. Our current knowledge of the size of each arrow is not very accurate, and also includes levels of "hypothesis". When "global warming" occurs in the center, this produces a reduction in sea ice and snow, increased melting of ice, changes in atmospheric circulation, and changes in clouds and aerosols; the high albedo snow and ice surface is consequently replaced by a relatively dark land and sea surface, and further heating of the near-surface (warming) occurs. In addition, melting of permafrost leads to emissions of further greenhouse gases. Furthermore, reduction of sea ice and expansion of open water leads to the supply of water vapor from the ocean into the atmosphere and increases cloud cover, which then further melts sea ice. It has been deduced from observation studies and numerical models that, as a result of these various feedback effects, warming in the Arctic is amplified; however, our understanding of the quantitative contribution of individual elements and of the physical processes occurring is still insufficient.

In order to accurately evaluate the environmental change effects of global warming and resulting impacts on human society and to then take appropriate measures with urgency, there is a strong need to understand phenomena occurring between the elements shown in Figure 3. This section discusses questions related to typical components, such as the atmosphere, ocean and terrestrial elements,

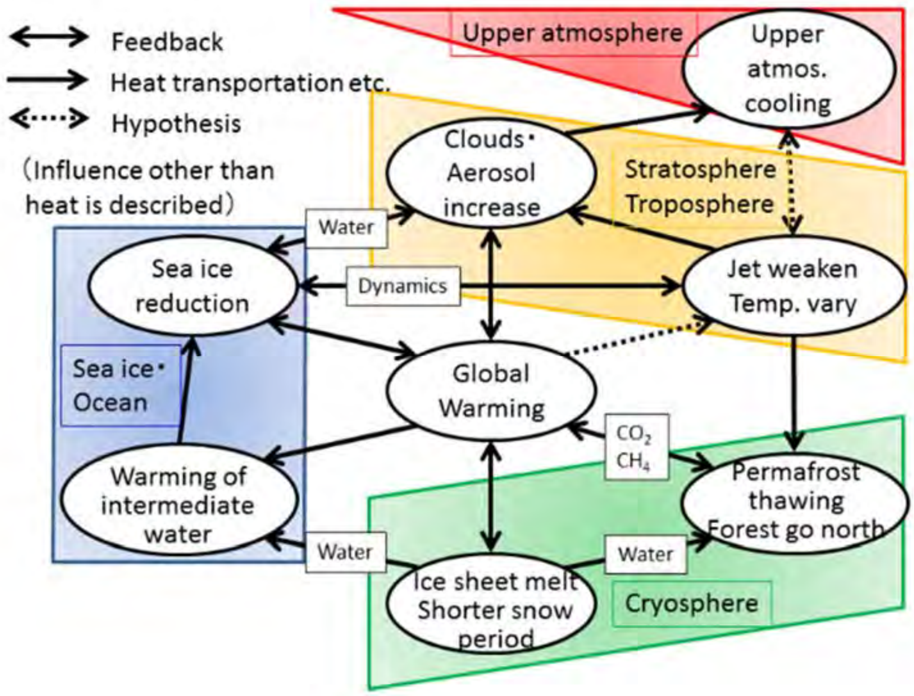

Figure 3: Potential feedback effects between each element in the Arctic

heat transport in the atmosphere, water circulation on land and in ice sheet, vegetation changes, and sea ice and ocean. We then address feedback processes between clouds and aerosols that are subject to high uncertainty, and discuss why Arctic warming amplification is occurring. We also analyze the current situation and identify a long-term research strategy.

Q1: How does horizontal and vertical heat transport from lower to upper atmospheric layers affect Arctic warming amplification?

a. The influence of heat transport from mid-latitudes

(1) The current state of research

Among the various effects of global warming are several changes occurring in the Arctic. Based on available continuous data obtained by satellite data over these past 30 years, we know that the sea ice area in the Arctic Ocean has greatly reduced in extent, as has the snow cover area; moreover, across a large area of the Arctic Circle, surface air, soil, and water temperatures are also exhibiting a warming trend. In addition, a variety of other changes are ongoing; examples include the release of methane (a greenhouse gas) due to melting of permafrost over Arctic land, increases in the flow of rivers discharging into the Arctic Ocean, melting of the Greenland ice sheet, shrinking of glaciers and ice caps, reduction of snow cover area and of its duration, reduction of the amount of ozone in the stratosphere over the Arctic, and increased occurrence of ocean acidification due to an increase in atmospheric carbon dioxide. Arctic climate change might, in reality, be proceeding faster than predicted by many climate models reported in the Intergovernmental Panel on Climate Change (IPCC) report.

As in the case of Arctic warming amplification, various factors of influence have been identified, including the ice-albedo feedback14 resulting from a decrease in sea ice area, changes in albedo due to black carbon, and an increase in poleward energy transport (Graversen et al., 2008, etc.). In the case of the latter, Oort (1971) showed seasonal variation using rawinsonde data, and Trenberth and Stepaniak (2003) used re-analysis data sets to show seasonal variations in and inter-annual variability of energy transport; the authors then estimated the individual contributions of dry static energy, latent heat, and kinetic energy in stationary and transient components. Hwang et al. (2011) used multiple model results of three-dimensional coupled climate models from the inter-comparison project CMIP3 to demonstrate that poleward energy transport in the Arctic decreased, due to the temperature rise in polar regions. At present, there are few studies directly dealing with energy transport (heat transport) and these cannot be said to be sufficiently linked to studies that describe the current state of the Arctic.

(2) Future research

In order to understand why warming is enhanced in the Arctic, and in order to clarify the relationships with mechanisms that underlie global climate change, it is necessary to understand, not only separate processes, but also the workings of the entire Arctic climate system, including by focusing on the role of atmospheric energy transport within this system. It is therefore important to conceptualize the Arctic atmosphere as one ‘Box’, analyzing how heat, water vapor, and substances are exchanged between the Arctic and mid-latitudes, and how atmospheric dynamics are involved. At the same time, it is essential to identify and understand feedback processes, such as those causing strong global warming. In particular, there is a need for further comprehensive research on three aspects: (1) heat, water vapor, and substance exchange between the Arctic and mid-latitudes, (2) several feedback processes, and (3) vertical coupling of the mesosphere, the stratosphere, and the troposphere including its boundary layer in the Arctic.

The key to understanding processes causing abrupt Arctic climate changes is considered to lie in spatial and temporal features of variation and change. It is well known that various changes have occurred, including a decrease in the area of sea ice and a rise in surface air temperature, especially in the 1990s. Furthermore, the fact that rapid surface temperature rise was occurring in this cold region of the Northern Hemisphere during the first half of the 20th century (in the 1920s and 1940s), in addition to global warming, suggests that there must be an inherent process causing abrupt climate changes; this is representative of the ice-albedo feedback mechanism of sea ice. Warming in the Arctic also tends to have a spatially non-uniform pattern, and especially during the first half of the 20th century, there was clear warming in the Eurasian sector. In comparison to other areas of the Arctic Ocean, seasonal-to-inter-annual variability in the extent of sea ice (from the Barents Sea to the East Siberian coast) is large; in particular, the Barents and Kara Seas have the highest levels of heat exchange between atmosphere and ocean in the Northern Hemisphere.

The Atlantic sector of the Arctic is functioning as an active area for heat and water exchange between mid-latitudes and polar regions, both in the atmosphere and in the oceans. Variations are strongly controlled by changes in atmospheric circulation, represented by the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO). On the other hand, sea ice variations in the Barents and Kara Seas, through heat exchanges between the atmosphere and oceans, could result in intensification of the winter monsoon in the Far East via the remote response of the atmosphere. Based on such insights, it is important to quantitatively estimate horizontal and vertical heat transport in the Arctic Atlantic-Eurasian sector, in order to understand Arctic warming amplification. Also, given such rapid climate change in the region and its spatial non-uniformity, it is necessary to consider the potential contribution to horizontal and vertical heat transport of radiative forcing and feedback mechanisms associated with aerosol-cloud processes. It is therefore important to comprehensively evaluate these aspects from the viewpoint of climate change in the Arctic.

b. What is the role of the upper atmosphere?

(1) The current state of research

Cooling occurs in the middle and upper atmosphere, while warming (due to an increase in carbon dioxide) is dominant in the lower atmosphere. Since atmospheric density is low in the middle and upper atmosphere, this change has been known to appear more pronounced. Based on cooling of the mesosphere due to an increase in carbon dioxide concentrations, water vapor, and methane in the vicinity of the mesopause, a recent increase has been reported in the occurrence rate of noctilucent clouds generated in summer in the polar mesopause. In addition, noctilucent clouds have also been observed in mid-latitudes, where they had not been seen in the past. From long-term observations of atmospheric density using orbital data from low-orbit satellites, there appears to have been a rapid decrease in atmospheric density in the upper atmosphere due to air shrinkage caused by cooling of middle and upper atmospheres. Thus, quantitatively understanding cooling in the middle and upper atmospheres can lead to accurate understanding of warming in the lower atmosphere. Recognizing the role of the upper atmosphere as a mirror of the lower atmosphere environment, there is a strong interest in reviewing more information concerning medium-term and long-term changes in the mesosphere and upper atmosphere. However, the absolute amount of available data available for mid-term and long-term change is insufficient, both in terms of observations of noctilucent clouds and in terms of observations of the density of the upper atmosphere. These discussions are also subject to many uncertainties.

It has been recognized that planetary waves of tropospheric origin propagate into the stratosphere, changing stratospheric general circulation, and finally affecting tropospheric general circulation (e.g., Baldwin and Dunkerton, 1999). In the mesosphere and thermosphere, various atmospheric waves of tropospheric origin contribute significantly to the formation of the zonal-mean zonal wind and to meridional circulation. However, it is not well understood whether atmospheric general circulation in the mesosphere and thermosphere is caused by various waves of tropospheric origin, or, on the contrary, by effects of the atmospheric vertical coupling process on the troposphere. Due to global warming, atmospheric circulation in the troposphere is known to be subject to large modulations, and as a result, there is speculation that atmospheric waves propagating vertically into the middle and upper atmosphere are also modulated. With respect to the modulation of atmospheric waves of tropospheric origin due to global warming, at present little is known regarding whether the zonal-mean zonal wind and meridional circulation in the middle atmosphere are affected. There is also uncertainty about whether this change could potentially affect the troposphere.

Ozone variations in the stratosphere are closely related to the activity of stratospheric planetary waves. However, stratospheric planetary waves are believed to change significantly as a result of global warming. In addition, it is very difficult to predict the photochemical reaction process of ozone destruction from winter to spring, since it is closely related to associated concentration changes in minor atmospheric constituents and to temperature in the lower stratosphere. For example, in the spring of 2011, the ozone hole also occurred in the Arctic, but it is not clear whether this phenomenon is due to cooling of the stratosphere with increasing carbon dioxide concentrations, and it is not known whether the occurrence rate of the ozone hole will increase in future (e.g., Manney et al., 2011).

(2) Future research

In the case of the Arctic, it is important to further develop global observation networks of the upper and middle atmospheres and satellite observations. In addition, multilateral comparisons with observations from mid-latitudes and from the Antarctic will contribute to a better overall understanding. To more quantitatively reveal the influence of cooling of the middle-upper atmosphere, it is essential to conduct numerical simulations using atmospheric general circulation models. It is also important to further improve the accuracy of atmospheric general circulation models, including of middle and upper atmospheres. In particular, to examine the effects of the middle-upper atmosphere on the lower atmosphere, it is very effective to simulate various runs while changing the top of advanced numerical models, enabling comparative analysis. Moreover, to accurately predict ozone depletion caused by global warming, it is necessary to use precise chemical climate models that include photochemical reaction processes.

Note) See Q4 of theme 5, Q2 and Q3 of them.

Q2: Is the role of terrestrial snow cover, permafrost, vegetation, and ice sheets important?

a. Changes in snow cover, permafrost, and ice sheets with water circulation changes

(1) Current state of research

With regard to feedback processes of snow and ice on land, permafrost, and ice sheets, and their relationship with Arctic amplification of global warming, it is necessary to first understand the features of each element efforts are presently underway to understand tracking of change processes, and to understand impacts using model reconstructions. Analysis and model calculations have been carried out to understand the promotion of spring melting by the albedo feedback of snow and ice, and relating to heat transfer to the surface and atmosphere; these are based on continuous and wide-scale information obtained from multi-point observation and satellite data for heat balance analysis of snow cover. However, there are many uncertainties concerning start of melting and the movement of melting water relative to the water cycle. There is a need to understand basic processes, such as the transfer of heat conduction and movement of melting water, through observations, expansion, and maintenance of monitoring points.

In the high latitudes of the northern hemisphere, it has been reported that snow cover area in spring has decreased (Derkson and Brown, 2012). However, since winter precipitation itself has not declined, early spring snowmelt and discharge are expected. The albedo feedback of snow cover occurs in spring with the increase in solar radiation, and spring snowmelt is also important for water circulation. From April onwards, the melting area of the northern hemisphere high latitudes extends rapidly northward to higher latitudes. Satellites are able to observe the progression of melting and albedo reduction, which occurs due to an increase in moisture content and snow grain size. In June, when solar radiation is at its maximum, snow cover over the land almost disappears, and the stage of ice-albedo feedback moves to the sea ice area of the Arctic Ocean. During this same period, on land there is infiltration of snowmelt water underground and runoff into rivers, while soil temperature also begins to rise. Reduction in spring snow cover in recent years is expected to cause modulation of the start and end of snow seasonal cycles, with a shift in the influence of the timing of albedo.

Melting of permafrost in the permafrost area has not yet occurred, even if an increase in soil temperature has been observed. Not only do summer temperatures in the active layer of surface permafrost cause seasonal melting, but snow in winter also suppresses ground surface cooling, affecting the increase in soil moisture content promoted by spring snowmelt. There is a need to observe permafrost melting promoted by winter temperature conditions and snow cover. Gravity observations of the satellite GRACE have indicated mass reduction in Arctic land, with estimates of reductions in ice sheet, glaciers, and ice caps, and changes in meltwater outflow from the permafrost.

In the Greenland Ice Sheet, melting of the entire surface was observed in the summer of 2012. The snow melting zone and the melting pond of the ice sheet surface expanded, and microorganisms bred on the surface; both of these lowered the albedo of the surface, facilitating melting. Not only have increases in hemispheric specific temperature, warm air flow, and synoptic weather around the ice sheet been reported, but also the promotion by melting of processes such as heating by atmospheric radiation due to increased water vapor. The impact of forest fires has also been detected in a decrease in reflectance due to impurities in the ice sheet surface. Water temperature rise in surrounding waters is believed to increase the instability of the end unit of the ice sheet and to accelerate glacial retreat. On the other hand, melting water from the ice sheet is also expected to influence ocean circulation, and there have been attempts to jointly study ice sheet and the ocean to detect such effects.

(2) Future research

Satellite observation is an important information source for albedo feedback of snow and ice, enabling observations over a wide area. It is expected to be possible to acquire observation data to confirm snowfall, snow cover period, and albedo changes, all of which are important in the analysis of ice-albedo feedback. Highly accurate satellite technologies are being developed to understand snow cover and melt regions. However, there is a need to check accuracy and to improve measurements of snow water equivalent (see theme A) in each region and during each time period.

For the snow forecast model, it is desirable to first improve the prediction accuracy of precipitation / snowfall, then to reduce the uncertainty of snow melting predictions. Although the observation area of the Precipitation Observation Mission satellite GPM is limited to south of 65 °N, when combined with ground observations of snowfall and its strength in this observation area (such as in Fairbanks and Yakutsk), it is expected to produce the basic information necessary to model snowfall prediction. In addition, the upper reaches of the basins of large rivers discharging into the Arctic Ocean are included in the observation area of the GPM. However, since the estimation error of snowfall by satellites is large, calibration by local observations will also be important in future.

With regard to permafrost melting involved in the water cycle and monitoring of river flow (flooding), there is a need to develop long-term observation systems. Since it takes time for data storage, it would be ideal to initiate observations in a typical region at an earlier stage. Long-term observations of these snow and frozen ground environments will depend on Arctic countries and on international observation network activities; examples include the installation of bases and the promotion of intensive observations in a typical region as international alliance activities.

When observing impurities, microorganisms, and the particle sizes that produce snow surface albedo changes, research into past changes can be validated by analysis of multi-point samples and by analysis of snow pits and cores. There is a need for development of high accuracy analytical methods and enhancement of monitoring systems Although regional and time variations in the distribution of impurities are expected, modeling studies are needed for transport and deposition processes.

In the Greenland Ice Sheet, melting water flows into the bottom of the ice sheet through Moulin, etc. Dynamic instability increases by acceleration of basal sliding of the ice sheet, with the likelihood of acceleration of ice sheet mass loss. Retention and re-freezing of melt water also affects ocean circulation and freezing of surrounding waters. In future, it will be useful to quantitatively understand melting and discharge from the ice sheet floor, and to examine the relationship between atmosphere, ice sheet, and ocean.

b. Influence of soil and vegetation on the atmosphere

(1) Current state of research and problems

In general, plant distribution is determined by external environmental conditions, such as temperature, precipitation, solar radiation, and carbon dioxide concentrations in the atmosphere. Temperature, in particular, is the most dominant factor in the Arctic. Boreal forests are located in the relatively warm low latitudes, while tundra vegetation is formed in relatively cold high latitudes. Geological evidence indicates that past distribution of vegetation was different from the present-day, reflecting differences between past and present climates. It is important to quantify the change in vegetation distribution considered to have occurred in association with the global warming that is currently in progress.

In the most recent 20 years, a trend of increasing vegetation in northern hemisphere high latitudes has been detected from satellite observations (Tucker et al., 2001). Although their spatial scales are different, increased vegetation in the Arctic has been detected by comparing scenic photography from the past 50 years with the current situation, which is considered to constitute a response to warming A mechanism that amplifies Arctic warming has been indicated by model simulation, with increased vegetation promoting the reduction of albedo and increasing the absorption of solar irradiance. Furthermore, because the Arctic is also covered with snow, albedo reduction by vegetation promotes early snowmelt in spring and further non-linear warming amplification can occur (O'ishi and Abe-Ouchi, 2011). Emission of organic carbon into the atmosphere by melting of the frozen soil layer due to warming (see Q2a of theme 1 and theme 3) further indirectly amplifies global warming. It is therefore important to quantify vegetation change in the Arctic.

However, there are still uncertainties regarding future vegetation change and warming amplification in the Arctic. This is because ground stations are limited and it is difficult to verify whether model processes can simulate real vegetation changes in the Arctic. Similarly, it is difficult to estimate vegetation change and organic carbon release resulting from permafrost melting.

(2) Future research

There is increasing qualitative clarity concerning individual processes related to vegetation change and their impact on climate in the Arctic. Over the time scale of the next 20 years, vegetation change trends observed so far are expected to become more pronounced. There are specific knowledge needs for anticipating change over this period, particularly relating to more long-term quantification of estimated vegetation change, and related future contributions to polar amplification; this requires continuance of existing monitoring, more close cooperation regimes for ground-based observation, satellite observations, and model research. The need for cooperation across these research areas has been discussed for more than ten years, and such cooperation has been advanced through the steady efforts of scientists. However, such problems cannot be expected to be addressed through revolutionary improvements, and the simplest method to reach this goal is to continue similar efforts in future. If we can have inter-comparison and verification of data obtained with the three research methods - ground-based observations, satellite observations, and modeling - with model data assimilation using satellite data, maintenance of observation points across a wide-area, and data integration, this will contribute to improved future predictive abilities of models. The latter would in turn enable reproduction of the northward expansion of the forest zone and of melting of tundra and changes in related wetlands, and estimation with high precision of forest distribution over several hundred years. Attempts at this kind of cooperation have already begun, and further future development is expected.

Q3: To what extent does the role of sea ice albedo and heat accumulation in the ocean vary seasonally?

It is to be expected that the Arctic has warmed in response to increases in global warming. The reason for the high temperature rise (in comparison with other regions) is ice-albedo feedback. With reference to Figure 4, we interpret the effect of the process related to the ocean, and present a direction for possible quantification.

a. Current status of research

(1) Quantitative determination of the role of ice albedo[10] and surface ocean (see theme 2)

A phenomenon has been deduced from the past, in which albedo of sea ice is higher than that of sea water; solar radiation is hence absorbed more by the ocean due to declining sea ice cover (Perovich et al., 2007). However, this feedback is directly limited in summer, with part of

[10] ice-albedo feedback: Based on the fact that the albedo of snow and ice surfaces is much higher than that of vegetation and soil surfaces, positive feedback that cools (or warms) increases (or decreases) snow and ice surfaces, then albedo increases (or decreases), with solar radiation that is absorbed by the ground surface reduced (or increased) and further progression of cooling (or warming).

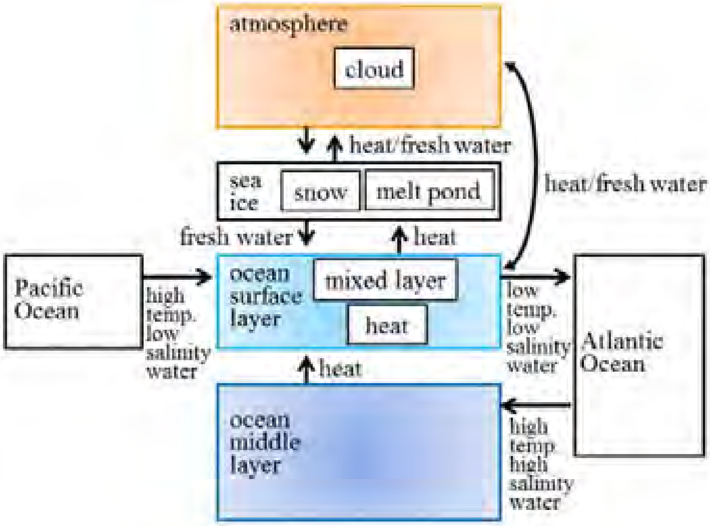

Figure 4: Potential feedback effects between each element in the Arctic

the accumulated heat transported downward by vertical mixing in autumn, and released from the open water to the atmosphere. Understanding the rate at which accumulated heat passes the winter is important. In addition, key points may be whether negative heat accumulation decreases with respect to the previous year with a reduction in the volume of sea ice, and whether open water increases during the next summer. It is also necessary to quantify heat accumulation in the atmosphere, and it is essential to understand difficult-to-observe changes in the ocean middle layer and in sea ice thickness.

Autumn precipitation may increase as a result of water vapor emitted from the increased open water area. Because snow cover will increase albedo, but will reduce heat conduction through sea ice; it is necessary to quantify the thermal effect, taking into consideration deposition, melting, and re-freezing of snow. The effects of summer melt ponds on albedo and heat conduction rely on satellite data estimates, even though depth is also important.

When sea ice is reduced in extent, seasonal variations in the melting-freezing of sea ice also increase. As shown in SHEBA[11], although in many waters, low salinity water produced by melting remains in the surface layer, at the margin of the sea ice area and in some areas where upwelling occurs due to the terrain (such as on the continental shelf), the effect of downward movement of summer heat by vertical mixing increases; and hence, this must also be taken into consideration.

(2) Role of interaction with the atmosphere (see theme 2)

A decrease in sea ice enhances heat transfer from the ocean to the atmosphere by promoting synoptic-scale atmospheric disturbances and cloud formation. At the same time, due to downward longwave radiation from clouds, the atmosphere supplies heat to sea ice and to the ocean. This interaction constitutes positive feedback. It is necessary to ensure that this is actually occurring, as well as to attempt quantitative estimation. On the basis of such results, it is important to produce estimates, as the Arctic amplification effect is the result of a coupled system of atmosphere, sea ice, and oceans.

(3) Role of inflow from adjacent waters (see theme 5)

High temperature seawater flows in from the Pacific Ocean through the Bering Strait in summer, and has played a large thermal role in reducing the extent of sea ice. As a result, it leads to ice-albedo feedback. Moreover, the amount of heat storage in the layer deeper than the winter mixed layer is biennial, and has the effect of melting sea ice in spring and summer. If the influx of Pacific water is increased by global warming, this process applies to Arctic amplification. In particular, since inflow is affected by an atmospheric fluctuation pattern (dipole mode), whether the pattern is amplified by warming would be key to estimating Arctic amplification.

(4) Elucidation and understanding of the role of processes, including in the middle-deep layer (see theme 5)

Sea water of high temperature and high salinity that flows from the Atlantic circulates in the middle layer of the Arctic Ocean and returns to the Atlantic Ocean. Thermal effects decrease when this water is fully affected by freezing in the Barents Sea, although it can be easily mixed with the shallow layer of the Arctic Ocean if this is not frozen. The rejected salt amount is reduced due to reduced freezing and vertical mixing may hence be locally activated, also increasing heat transfer to the surface from Atlantic water. When this process is significant, Atlantic water circulation may be transformed in the system, to be considered a mechanism for horizontal transport of heat to the surface of the Arctic.

Until now and notwithstanding mixing, only weak water movement reaches the deep layer from the surface. On the other hand, when sea ice is reduced to increase non-uniformity of the horizontal direction, vertical mixing and water movement may partially occur. In this case, the effect of heat storage in the deep layer continues at a scale of 100 years.

[11] SHEBA: Surface Heat Budget of the Arctic Ocean. Arctic Ocean surface heat balance observation project that was operated mainly in the Arctic Ocean (including the atmosphere) through United States funding in the 1990s. Ice observation sites were accompanied by a Canadian icebreaker for a period of one year.

b. Future research

For surfaces where sea ice is decreasing, it is essential to monitor inter-annual variability of sea ice thickness and heat exchange with the atmosphere and middle layer. For the middle layer, long-term monitoring of the movement and diffusion of Pacific and Atlantic water is important, as also of mixing that extends to deeper layers. In particular, in order to see changes in middle and deep water velocity patterns, the use of chemical tracers may also be considered. Satellite observation is useful for capturing (with high accuracy) important melt ponds, as also the state of the sea, and changes in cloud height.

Also, by using data assimilation and energy analysis, we attempt to identify key processes for interactions between surface and middle layers and between middle and deep layers of the Arctic Ocean.

Q4: Is it possible to quantify the role of clouds and aerosols?

a. Importance and current status of research

Aerosols and clouds play an extremely important role in the Arctic climate. There is as yet inadequately advanced understanding of complex interactions, since, in previous studies, observation was found to be insufficient and only a qualitative understanding of individual processes could be obtained. It is necessary to examine interactions between various fields, such as the relationship with mid and low latitudes, differences between both polar regions, and problems within polar regions. Clouds play a role in climate formation through the radiative effect (Curry et al., 1996). Cloud cover acts to cool the ground surface by reducing solar radiation and also acts to heat the ground surface by increasing longwave radiation from the atmosphere. The actions of both are opposed but since the season without sunlight is longer at the poles, and since polar regions are covered with snow, the latter is dominant over the former. Cloud cover has a feedback effect that causes warming amplification by downward longwave radiation. As for the direct effect of aerosols through radiation, the cooling effect by scattering of aerosols does not contribute greatly in the atmosphere over the snow surface; however, the heating effect produced by absorption of aerosols such as black carbon (black carbon aerosol) appears to be amplified. Aerosols have a variety of effects. These include climate impacts due to an indirect effect on clouds by acting as cloud nuclei, through effects on cloud formation and ice nuclei, and by contributing to changes in snow and ice surface albedo. A quantitative understanding of these impacts is therefore required.

In the Arctic, because of the uncertainty of cloud occurrence, the impact of the latter is immeasurable. There have been no precise observations of the vertical structure of clouds. In the Arctic, clouds are also important in terms of their relationship with sea ice. The presence of cloud cover affects the growth and melting of sea ice. Similarly, the presence or absence of sea ice affects the state and occurrence of cloud cover, reflecting the interaction of clouds and sea ice. Cloud feedback is one of the most uncertain processes in the polar climate model. With regard to aerosols that act as cloud nuclei, there is a need for integrated understanding that takes into account different scales of polar change; examples include generation and transport processes due to natural-anthropogenic origins, light absorption processes, and cloud condensation processes. For example, it is important to evaluate distribution forms, transport processes, and wet deposition processes of black carbon, and to evaluate the contribution of black carbon to climate change, not only directly to the atmosphere, but also due to interactions with the ocean, snow, and ice. Observational studies on the role of clouds and aerosols are therefore urgently required. In order to define the radiative effect of clouds, the cloud phase must be made clear. This refers to, for example, the kinds of particles clouds are made of, the amount of ice particles and water droplets, the size distribution, vertical profile, generation, growth, and scavenging processes of aerosols, and moisture absorption characteristics. In the Arctic, mixed phase clouds, where ice particles and water droplets coexist, are often said to be seen. Together with the discussion of cloud phase, it is important to explain the presence of these clouds and cloud cover. From what is known so far on the basis of satellite observations, spring and summer cloud cover appears to have increased.

b. Future research

Conventionally, ground-based observations of clouds have been conducted visually, and it would be better to replace this observation method with remote sensing devices. It is also desirable to understand the macroscopic distribution and microphysical properties of clouds through long-term quantified measurements. The cloud radar installed at the Ny-Alesund Station, Svalbard is an important means of cloud observation in the Arctic, and this is expected to be utilized through international cooperation. In addition, even with satellite observations, application of conventional passive observations of visible and infrared spectra to the polar cryosphere involves difficulties. It is necessary to establish new observation techniques to be used in combination with active and passive observation; these include active observation through new lidar and cloud radar technologies, and validation of direct observations by aircraft and tethered balloons. One example is the expected use of the EarthCARE satellite[12], to be launched in 2016 by the Japan Aerospace Exploration Agency (JAXA) in cooperation with the European Space Agency (ESA). It is important to reflect these results in the accuracy of repeatability of clouds in climate models.

Changes in cloud cover due to the recent decline in sea ice have been noted. Satellite observations have in fact shown that the quantity of clouds is increasing along with this reduction in sea ice (Liu et al., 2012), indicating positive feedback such that cloud cover is increased by evaporation from open water, with further reduction in sea ice then occurring as a result of downward longwave radiation from the cloud, which will enhance cloud formation through further evaporation from open water. It is therefore important to understand interactions of cloud-radiation and sea ice (sea surface) to predict climate change in the Arctic. A climate model is absolutely essential for integrated understanding of climate change

[12] EarthCARE satellite: Earth Cloud, Aerosol and Radiation Experiment. See Research infrastructure (satellite). Satellite equipped with cloud radar, lidar, radiometer, and image sensors for measuring the vertical distribution and radiative effects of clouds and aerosols.

resulting from changes in these aerosols and clouds. Although progress to date has allowed the development of climate models that explicitly[13] represent the interaction of aerosols and water clouds, ice clouds are abundant in polar regions, and in the case of all current major climate models in the world, the representation of aerosol interactions with ice nuclei is still insufficient. In future, we should strive to better address aerosol ice crystal interactions in climate models when drawing on newly-obtained observation data. As a prerequisite, it is necessary to quantitatively reproduce the distribution of dust and black carbon (having the potential to become ice nuclei) in polar regions. From this point of view, rather than the Gaussian lattice grid model, the size of which is very different in polar regions as compared to low and middle latitudes, would also be advisable to use the global homogeneous grid model (see theme B).

Q5: Why is Arctic warming amplification occurring, and how uncertain are predictions? How are radiative forcing and feedback processes changing in the Arctic?

a. The importance of research

To understand and predict climate change in the Arctic, it will be key to understand how radiative forcing will change through anthropogenic emissions of carbon dioxide and release of aerosols, and how feedback effects amplifying or suppressing warming by the climate system responding to it will function and / or change. As can be seen in Q1–Q4, with regard to the mechanism of Arctic warming amplification, the contributions of various processes have been noted. For a thorough understanding, it is important to systematically and quantitatively examine individual contributions and interactions between these processes.

b. Current status of research

There are radiative forcing and feedback processes that have not been considered or fully quantified in previous research. For example, light-absorbing aerosols can be cited as a typical example of radiative forcing having large uncertainty. When light absorbing aerosols, such as black carbon, are deposited on snow and ice surfaces, albedo reduction occurs, and positive feedback effects produce an increase in snow surface temperature, accelerating snow and ice melting. The amount of albedo reduction depends first on the concentration of light absorbing aerosols, but with the same aerosol concentration, albedo reduction increases with larger snow particle size. From the Greenland ice core analysis, black carbon concentrations after the industrial revolution have been restored, it is known that the peak was recorded during the first half of the 20th century, then dropping to the level of the 1800s. Growth of snow grain size and expansion of the ablation area due to warming produce albedo reductions that are due to light-absorbing aerosols and snow and ice microorganisms, with this accelerating positive feedback.

The effects of changes in vegetation distribution and of atmospheric variability higher than the stratosphere have not yet been sufficiently taken into account in climate models, particularly with respect to future prediction (see Q1–Q2). Cloud feedback mechanisms of the Arctic are also subject to very large uncertainty (see Q4). These interactions are evidently not well understood.

In climate model experiments, the contribution to Arctic warming amplification of individual physical processes has been systematically examined. Relatively simple analysis has been performed, based on the energy balance of the multi-model, and on detailed analysis of a small number of models (Yoshimori et al., 2014). As a result, the feedback process of the Arctic has been shown to have strong seasonality; solar radiation energy that is absorbed by the ocean surface through the albedo feedback resulting from the decline in sea ice in summer is released from autumn to winter. Arctic warming is also amplified by the greenhouse effect of low clouds. Thus, factors that have been indicated as being important are the ocean heat absorption process, the inversion layer and stability of the lower troposphere which determines the air-sea heat exchange, and response characteristics of low level clouds. However, such research is based on model experimental results under ideal scenarios, and direct comparisons with observational data have not been made.

It is possible to reduce the uncertainty of warming predictions using a method to identify the relationship between positive and negative aspects of the reproducibility of current climates in the multi-model and variations in future predictions. It is also possible to constrain the future prediction range based on observational data. Well-known examples include the use of current seasonal changes, based on the magnitude of the observed spring albedo feedback, to estimate the size of the albedo feedback of the Arctic land in future (Hall and Qu, 2006). Similarly, to evaluate the reliability and future predictions of climate models, there is a method utilizing Arctic warming amplification that actually occurred in the far past. This is discussed in Q2 and 3 of theme 6.

c. Future research

Climate predictions and sensitivity experiments have already been initiated, with an Earth system model that incorporates the "snow albedo physical model"; the albedo varies as a function of light-absorbing aerosol concentrations and snow grain size. An example can be provided from numerical experiments of the spring subarctic using the Earth system model, incorporating a physical model of the transport and deposition process of light-absorbing aerosols and snow albedo. With regard to the lowering effect of ground surface solar radiation due to carbon aerosols in the atmosphere, darkening (dimming) has been estimated to be smaller than the snow albedo reduction effect by aerosol deposition. It will be necessary to promote such model development in future. In addition, it is also necessary to model albedo reduction effects of snow and ice microorganisms through field observation, estimating feedback; these aspects are not currently being taken into account.

There are still challenges in terms of basic improvements in reproducibility of numerical models, for example relating to seasonal changes in sea ice and clouds

[13] In the field of modeling, "explicitly" is often used to refer to writing down a process (time change of variables) directly and explicitly in the model equation.

in polar regions. Energy balance estimation and quantification of cloud effects at the ground surface remain challenging, and it is essential to conduct evaluation through cooperative observation and modeling. In addition, and as mentioned in Q3, other important factors include sea ice reduction and synoptic-scale disturbances of the atmosphere, understanding of cloud formation processes, and quantification of their contribution. Including the effect of decrease in sea ice and the effects of heat and water transport changes from low latitudes, it is important to investigate the cause of cloud changes.

To understand actual Arctic warming amplification, it is considered effective to identify the contributions of individual processes not only through climate model experiments, but also by assimilating observational data. In addition, the long-term development of sophisticated coupled models that are data assimilated is important, as is their application to Arctic warming amplification research. In addition, it is important to conjoin day-to-day phenomena and their quantified relative contributions (for example, the role of cloud formation by synoptic-scale disturbances and cloud radiation effects in Arctic warming amplification), and to understand the series of physical processes involved in system response. To understand underlying individual elements, the role of continued long-term observation data remains critical.

Changes in vegetation patterns, mineral dust release related with vegetation change, and other factors such as the effect of light absorbing aerosols are not uncommon, and change will continue to be significant in future. In order to introduce elements or processes that have never been significantly taken into account, and to reduce the uncertainty of response characteristics by using observed data, it is essential to develop, refine, and use the Earth system model.

Although Earth system models are mainly referred to in theme B, these models will fulfill a central role in future prediction. As mentioned in theme 6, to constrain the climate system response using past Arctic warming amplification, a valid Earth system model contains all elements that can be considered. Also, as described in Q1, to consider the effect of the upper layer of the stratosphere, it is also necessary to consider sufficient resolution and higher top for models in the stratosphere. It is indispensable to comprehensively verify air-sea coupled energy balance processes, from the upper and lower layer atmosphere to cloud radiation, and from sea ice to ocean stratification, without relying on data assimilation. The establishment of an independent Earth system model that overcomes the current permanent bias is likewise critical.

Theme 2: Mechanisms and Influence of Sea Ice Decline

Abstract

Recent rapid sea ice decline in the Arctic Ocean has increased social concerns on the possibility of the entire disappearance of Arctic sea ice in summer. This change is closely related to the development of a new commercial sea route and cold winters in Japan. It has therefore become an important issue, not only for research scientists, but also for social and economic communities. Theme 2 contains four questions listed below. First, mechanical factors on sea ice motion (Q1) and thermal factors on sea ice growth /melting (Q2) are described to explore mechanisms of sea ice reduction. Then, influences of sea ice retreat on atmospheric (Q3) and ocean (Q4) systems are discussed.

Q1: Do changes in wind pattern and sea ice fluidity promote sea ice reduction?
Q2: How does sea ice thermal reduction proceed?
Q3: How does sea ice reduction influence cloud and cyclones?
Q4: How does sea ice reduction influence the ocean fields?

Since the variation in Arctic sea ice is closely related to changes in wind pattern and sea ice fluidity, we should persistently examine the atmospheric pressure patterns most likely to exist under the future climate and efficiency of momentum transfer among air, sea ice and underlying ocean. It is problematic to attribute the sea ice decline mechanisms only to either motion/melting of sea ice or atmosphere/ocean warming. We should quantitatively examine various interactions such as the impact of ocean currents and weather conditions on heat balance at the ocean surface.

International cooperation is essential for academic research on the Arctic Ocean environment, especially using field observations, which is too challenging to be adequately conducted by only one country. The Japanese research group has obtained many achievements from ship-based field campaigns in the Pacific side of Arctic Ocean. To continue our international contribution in the Pacific Arctic region, comprehensive year-long (including freezing period) measurements are big challenges to fill in blank data. Over recent years, several non-Western countries have already built their own icebreakers. Now we need further efforts to maintain and strengthen the scientific contribution of Japan. Satellite remote sensing represented by the microwave radiometer can play a leading role in Arctic environmental research by Japan in the distance from the Arctic. The improvement of numerical models is expected to provide more quantitative information on air-sea ice-ocean interactions and water mass transport across the multiple basins. The findings obtained by such efforts will result in the understanding of not only physical oceanographic properties but also polar marine ecosystems.

Over the next decades, we aim to clarify and quantify the processes on ocean heat transport covering ocean interior from bottom of sea ice to intermediate water layers and on air-sea ice-ocean interactions related to cloud and cyclones. With regard to the characteristics of sea ice itself, the detailed processes of melt pond formation and collision among sea ice floes should be analyzed. For these analyses, operations of an icebreaker and all weather-type satellite microwave sensors are essential. We should also develop next-generation sea ice-ocean models explicitly resolving individual ice floe and dense water plumes so that reliable information can be provided for vessels sailing through the Arctic Sea Route.

Introduction

"Sea ice" is generated by freezing of seawater and is essentially different from "icebergs", whose source is snowfall over land. Until several decades ago, most areas of the Arctic Ocean were covered with sea ice throughout the year. Recent observations revealed that the "seasonal ice zone" (i.e., the area where sea ice disappears entirely in summer) was expanding (Figure 5). In 2012, for example, the minimum sea ice extent in summer was just

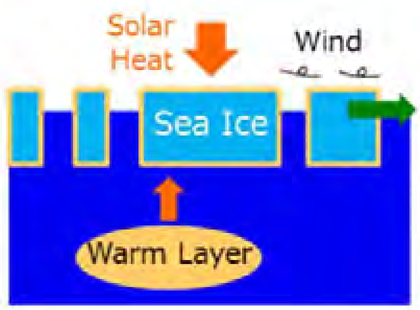

Figure 5: (left) Arctic sea ice distribution provided by IARC-JAXA Information System. In 2012, the extent of summer sea ice (purple) was just 20% of the winter value (white).
(top) Schematic image of sea ice variations. Sea ice forms from sea water cooled to its freezing point and melts due to solar and ocean heat. Due to wind, most sea ice is exported toward the North Atlantic.

20% of the preceding winter value. This summer value corresponded to about half of the average in the 1990s. There is thus certainly a temporal transition from multi-year ice zones to seasonal ice zones underway. The forthcoming ice-free period will attract social communities and has been predicted using various methods. Previous studies indicated that Arctic sea ice would disappear entirely in summers of the 2020–2040s (Overland and Wang, 2013). CMIP5 produced a wide range of simulated results. It should be noted that the assumed social and economic scenarios are also subject to substantial uncertainties (see also Theme B).

For safe sailing through the Arctic Sea Route (Russian Northeast Passage and Canadian Northwest Passage), it is necessary to accurately predict sea ice conditions within these passages using a combination of short-term (several days) and medium-term (several months) predictions, and to provide available information for vessels. It is important to clarify mechanisms of sea ice reduction rapidly occurring in the Arctic Ocean and to construct a sea ice prediction system based on obtained findings. Based on the prolongation of the open water period, the influence of cyclone and wave activities may become a concern. Accurate forecasts of weather and sea conditions are thus required. The unusually cold winter weather that has recently appeared in the mid-latitude zone (including in Japan) is considered to be a consequence of Arctic sea ice reduction. It has been suggested that sea ice conditions in the Barents Sea influence the winter climate in Japan. Arctic sea ice changes are thus becoming a hot topic, not only for the natural sciences, but also for social and economic communities.

Q1: Do changes in wind pattern and sea ice fluidity promote sea ice reduction?

Sea ice motion is controlled by wind forcing and internal stress (collision among sea ice floes). Export of sea ice from the Arctic Ocean toward the North Atlantic increased in the early 1990s, following wind pattern changes associated with the Arctic Oscillation (Theme 5). In the late 2000s, the dipole pattern of sea level pressure (SLP) (high SLP in the Canadian Arctic and low SLP in the Siberian Arctic) enhanced sea ice export. It is interesting that cyclonic (anti-cyclonic) wind anomalies in the central Arctic promote sea ice export toward the North Atlantic in winter (summer). Under non-uniform wind fields and in coastal regions, the collision of sea ice floes prevents sea ice motion. Recent weakening of sea ice due to its thinning has increased sea ice fluidity in the wide area of the Arctic Ocean (Rampal et al., 2011). Correspondingly, ocean current and ocean heat transport under sea ice cover have also been intensified (see Q2 for the relationship between ocean heat and sea ice decline). The sensitivity of sea ice motion to wind forcing has been quantified using an index such as wind factor (i.e., ratio of sea ice velocity to wind speed). To understand dynamic factors of sea ice reduction, for example, it is important to evaluate how the momentum transfer between air, sea ice, and ocean depends on sea ice thickness and shape.

Sea ice accumulation toward the northern coasts of the Canadian Arctic Archipelago occurs due to the Transpolar Drift stream and generates multi-year ice regions. In this situation, sea ice persists even in summer, and sea ice response to wind forcing is slow. However, sea ice thinning allows sea ice to flow easily. The "residence time" of sea ice from its thermal production in the Arctic Ocean to export toward the subarctic seas will eventually be shortened. This change results in reduction of multi-year ice (i.e., positive feedback). In situ data for sea level pressure and sea ice drift velocity widely obtained by the IABP enabled monitoring of the relationship between wind and sea ice motion. However, the setting of such sea ice buoys has become difficult due to the increase in vulnerable sea ice packs. Alternative methods should be conceived of to maintain the same amount of data acquisition as in the past. The Japanese research community should also participate in in situ sea ice measurements and should clarify dynamic processes with satellite remote sensing and numerical modeling. We already have the ground work in place. A sea ice model is a powerful tool for analyzing spatial and quantitative variability. When the horizontal resolution increases to the same scale of the individual sea ice floe, the formulation of sea ice dynamics should be revaluated. An additional possible approach is to estimate drag coefficients between air, sea ice, and ocean using data assimilation methods.

Over the next decades, we aim to 1) estimate dominant patterns of sea level pressure under future climate scenarios, 2) perform real-time extensive monitoring of momentum transfer among air, sea ice, and ocean, and 3) predict sea ice, taking temporal changes in sea ice motion into account, on timescales ranging from several days to decades.

Q2: How does sea ice thermal reduction proceed?

A significant part of the long-term declining trend in Arctic sea ice is owed to thermal factors, such as increased summer melting and decreased winter freezing of sea ice. Recent reports indicate that snowfall decreased in the Eurasian continent and increased over the Arctic sea ice, because of the northward shift of winter storm tracks in the high-latitude region of the Northern Hemisphere. Accumulation of snow, which has low thermal conductivity and high surface albedo, restricts both winter freezing and summer melting of sea ice. The sensitivity of sea ice growth to changes in the start period of snowfall and snow depth is very topical. Melt ponds, with their low albedo, promote sea ice melting. Even if the relationship between sea ice characteristics and heat/momentum transfer among air, sea ice, and ocean has been studied for a long time, quantification is difficult due to its complexity (see Theme 1 for efforts using climate model).

Arctic warming is accompanied by enhanced moisture and heat transport from mid-latitudes. We should predict and verify future changes in Arctic snowfall, which is considered to have increased (see Theme 4 for freshwater cycles). The inflow of warm water masses is listed as an ocean heat source for Arctic sea ice reduction (Figure 6). The Pacific-origin water entering from the Bering Strait becomes warmer due to solar heat absorption over the Chukchi shelf and intrudes into the subsurface layers of the Canada Basin. A significant part of the transported ocean heat probably affects sea ice freezing/melting in

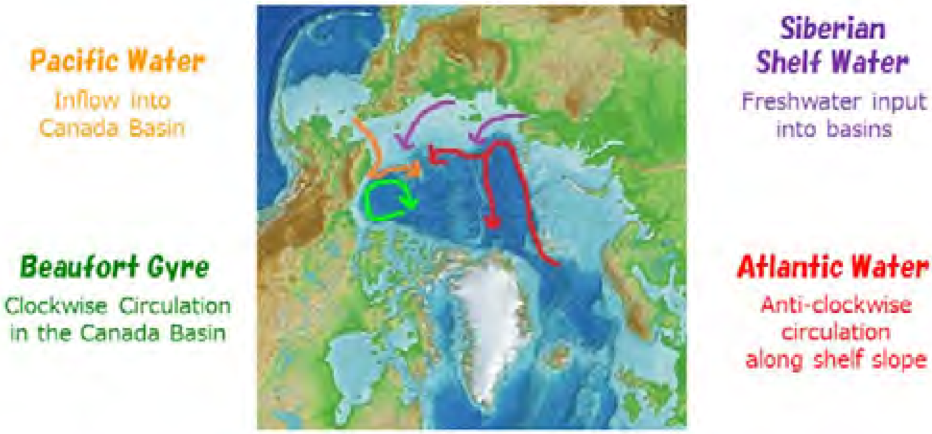

Figure 6: Major Arctic Ocean current.

subsequent years. The Atlantic-origin water flowing into the Fram Strait and the Barents Sea is closely related to ocean heat content and sea ice distribution in the Eurasian Basin. Atlantic water flows in the wide area of the Arctic basins on the decadal timescale. In the Canada Basin, the Atlantic water layer is centered at a depth of approximately 400 m, so that it plays a minor role in western Arctic sea ice.

Thermal sea ice variations are attributed not only to characteristics of sea ice floes and global-scale atmospheric/ocean warming but also to local feedback systems. Sea ice-ocean albedo feedback provides an example of important thermodynamic processes (Figure 7). Solar heat absorption into the open water fraction exposed in sea ice zones for some reason promotes lateral and bottom melting of sea ice or reduces freezing, eventually causing further sea ice decrease.

Ocean surface warming in the marginal ice zone activates cyclone generation and the inflow of warm air masses into the sea ice area. Cyclonic wind causes divergence of sea ice drift and corresponding expansion of open water fractions. Such a cyclone-sea ice feedback process is important. Open water expansion promotes the development of inertial motion and internal waves. Strenuous sea ice motion generates turbulent mixing and vertical heat transport in the underlying ocean layers. In the Pacific Arctic region, there are two warm subsurface layers whose heat source is solar heat input and Pacific summer water, respectively. We can therefore propose another feedback system where ocean heat released due to turbulent mixing contributes to sea ice decrease with enhancement of net sea ice melting. In addition, the upwelling of Atlantic-origin warm water is considered to be a heat source in the coastal region of the Beaufort Sea.

These thermodynamic processes include multiple interactions. The spatial distribution of ocean heat content

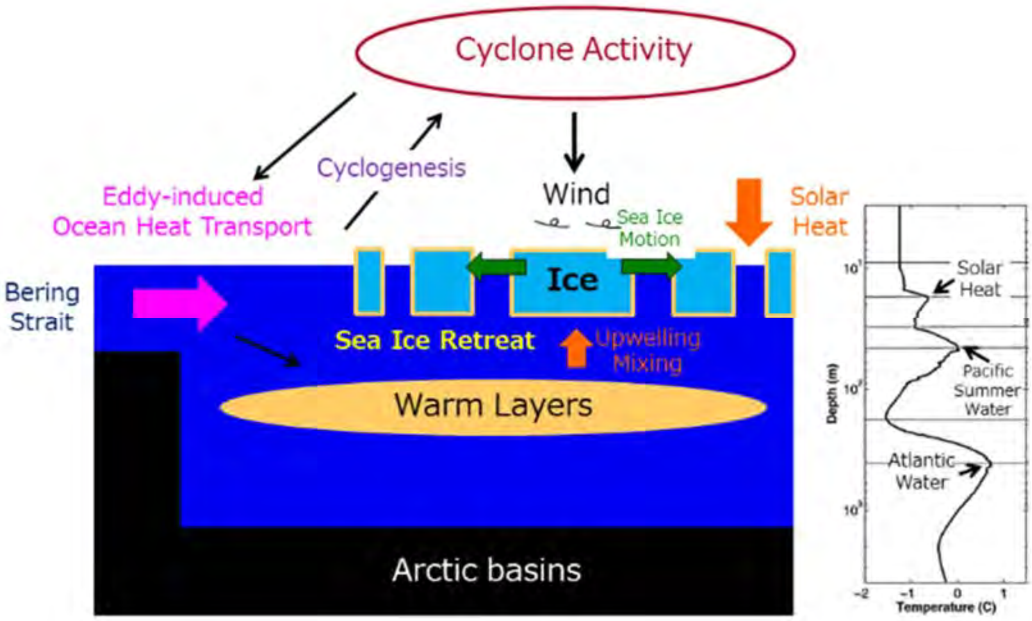

Figure 7: Examples of Arctic feedback processes between air, sea ice, and ocean. There are three temperature maximum layers with different heat sources in the Canada Basin. These ocean heat sources influence sea ice via various processes. The figure on the right shows the vertical temperature profile observed in the Canada Basin (Jackson et al., 2010).

derived from solar heat input and warm water intrusion varies inter-annually (Jackson et al., 2010). To understand the complicated system of sea ice decline, it is necessary to simultaneously and quantitatively capture variations in the heat balance between air, sea ice, and ocean. Satellite data analysis is also useful to widely explore sea ice area, where ship-based measurements are localized.

Q3: How does sea ice reduction influence cloud and cyclones?

Exposed open water is a heat source for the atmosphere over the sea ice area. It was recently reported that well-known stratus clouds were changing to a stratocumulus structure due to upward heat input from the ocean surface during the Arctic summer. Intensified air convection is a key process. Whereas increase in cloud bottom altitude reduces downward longwave radiation, poleward moisture transport accompanied by Arctic warming has an opposite effect. The cloud effect on heat budgets at the air-ocean boundary is thus subject to substantial uncertainty. On the other hand, the reduction in cloud fraction, which is caused by a structural shift from stratus to stratocumulus, potentially increases solar heat input into the ocean surface. However, an original factor for cloud structure change is upward turbulent heat fluxes with ocean surface cooling. The variation in net heat budget should be evaluated using cloud-resolving models, for example. It has been noted that the trend in cloud fraction differs among in situ and satellite and reanalysis datasets, and depends on spatial/temporal scales.

A recent study revealed that such change in cloud structure was related to cyclone activities (Inoue and Hori, 2011). For example, cyclones rapidly develop in the marginal ice zone, where the horizontal temperature gradient across sea ice and ocean surfaces is large. This extra-tropical cyclone-type structure transports the southern warm air mass to the north, and cold air masses from the sea ice zone to the south. The weather front passage remains characteristic, with a cloud-precipitation system as well as winter cloud bands observed in the Japan Sea. This hence indicates that the ocean heat accumulated in summer is efficiently released to the atmosphere during autumn and winter. This type of ocean heat release is a contributor to polar amplification in winter.

The increase in cloud fraction from autumn to winter was shown by radiosonde data of the Soviet Union. At present, vertical cloud structure data is obtained by satellite remote sensing, such as CALIPSO and CloudSat. However, wintertime cloud measurements are still difficult and a lot of uncertainties remain. The northward shift of storm tracks enhance precipitation and snowfall over Arctic sea ice and eventually influence sea ice growth. Since atmospheric-ocean reanalysis data (such as NCEP-CFSR) has recently been made available, analyses of coupled systems could take place in future. The impact of Arctic sea ice decline on the climate around Japan is described in Theme 5.

Q4: How does sea ice reduction influence the ocean fields?

Sea ice works as a buffer of motion, heat, and freshwater between atmosphere and ocean. The response of sea ice to wind is larger than the ocean surface, so sea ice motion can intensify ocean currents. On the other hand, ocean currents are weakened in areas where sea ice packs collide with each other. Wind-driven sea ice motion and ocean surface currents depend on shape and drift direction of each ice floe. The momentum transfer from atmosphere to ocean causes vertical mixing in the ocean surface layer and upward ocean heat transport to the sea ice bottom. Detailed investigation of such mechanical processes is an important sea ice-related analysis.

The quantification of heat and freshwater exchanges due to sea ice growth/melting becomes more important in the Arctic Ocean, where seasonal ice zones are expanding. The inputs of freshwater and solar heat after sea ice melting intensify ocean surface stratification and restrict vertical mixing. On the other hand, open water expansion accompanied by summer ice reduction favors winter sea ice freezing and formation of dense water, which is eventually located at 100–500 m depths within Arctic basins. As a result, intermediate layers would be occupied by colder and higher-oxygen water masses. Dissolved oxygen is closely related to biogeochemical cycles and marine ecosystems (see also Themes 3 and 9).

The intensified anti-cyclonic Beaufort Gyre is an example of the combined effect of motion, heat, and freshwater inputs associated with recent sea ice decline (McPhee, 2013). In the southern boundary of the Beaufort Gyre, mesoscale eddies with diameters of dozens of kilometers are generated from horizontal velocity shear between the basin-side westward current and the shelf-side eastward current. Such eddy activities induce shelf-basin water exchange. Local monitoring and high-resolution numerical modeling are required to estimate eddy-induced water transport.

Ocean vertical mixing is categorized into convective mixing due to dense water sinking and turbulent mixing due to internal waves. The early-winter turbulent mixing can change the start period of sea ice freezing via ocean heat release. The frequency and strength of internal waves are controlled by the vertical profile of water density (i.e., stratification). The investigation of seasonal and inter-annual variability provides useful information for evaluation of sea ice reduction. Constituting a mysterious phenomenon, several-meter thin layers with uniform temperature and salinity extending over 1000 km scales have been observed at depths of 200-300 m. Double diffusion is considered to be a possible formation mechanism. Their spreading process, detailed distribution, and appearance frequency include many uncertainties. The detection of relationships between microphysics and sea ice reduction would contribute to progress in physical oceanography.

Under present climate conditions, Arctic Ocean circulation is controlled by density gradients between low-salinity Pacific-origin water, high-salinity Atlantic water, and fresh riverine water. If increases in Pacific water salinity and decreases in Atlantic water salinity occur in each upstream region, the mixed water mass would be formed by enhanced vertical convection. To explicitly reproduce such vertical mixing, horizontal model resolution has to be less than 1 km. Because of limited computational resources, we should now verify convection schemes and focus on individual processes. From the viewpoint of future prediction, it is meaningful to explore the possibility of thermally-driven ocean circulation under global warming.

These physical oceanographic changes are closely related to biogeochemical cycles and marine ecosystems in the Arctic Ocean. The extension of river water, sea ice meltwater, and shelf-origin water pathways accelerates biogeochemical cycles via enhanced biological productivity. After sea ice melting, air-sea gas exchange is promoted by vertical mixing, but is restricted by freshwater input. Gas emissions accompanying sea ice freezing have also been reported. It is still unknown whether the Arctic Ocean shifts toward the region of being a CO_2 source or sink. In Japan, there have been interdisciplinary collaborations in studies of the Okhotsk Sea through marine physics, chemistry, and biology. By utilizing ship-based measurements, satellite remote sensing, and numerical modeling, we should detect key processes of biogeochemical cycles both from physical aspects (e.g., shelf-basin exchange, eddy, and upwelling) and from biogeochemical aspects (e.g., organic matter supply from river, coastal erosion, and sea bottom permafrost melting). Readers can refer to details of biogeochemical processes in Themes 3 and 9.

Decadal strategy in Japan

a. International programs and collaboration

IASC recognized that international collaboration is indispensable for Arctic Ocean research, in particular for field observation. Non-Western countries such as China, Korea, and South Africa have already established their own icebreakers for Arctic research. We should devise strategies to maintain and ensure the Japanese scientific contribution. The main target regions of Arctic coastal countries with their own icebreakers are territorial waters and exclusive economic zones. It is hence important that Japan leads scientific research from its neutral position as a non-coastal country. Japan's sophisticated skills in satellite remote sensing and modeling are now being recognized worldwide. We have active field, satellite, and modeling researchers. The trinity framework and the center of excellence would produce pioneering achievements.

Major international Arctic Ocean projects are summarized in Figure 8. The first year-long observation of heat budgets between air, sea ice, and ocean was SHEBA in the late 1990s. Since there is no other example of such long-term measurement specializing in heat budgets, the SHEBA products are frequently cited, even after more than 15 years. During the 2000s, CASES, BGEP, and DBO were conducted in the Pacific Arctic region, and NPEO, ASOF focused on the Atlantic side. JAMSTEC, Hokkaido University, TUMSAT, and NIPR participated in these various projects. As IASC programs, MOSAiC and AODS are scheduled to take place within the next decade. Japanese research communities are also expected to plan and implement field activities. Japan presently plays a leading role in simultaneous radiosonde observations referred to as ARCROSE. In satellite remote sensing frameworks, many polar researchers are engaged in the GCOM-W mission operated by JAXA. The obtained sea ice data are utilized worldwide so that the continuous operation of microwave sensors is an international responsibility. Modeling studies themselves do not always require international cooperation. However, the AOMIP started in the 2000s and has provided valuable resources to detect common biases and improvement points for Arctic Ocean models. Recently, a few Japanese researchers attended the successor FAMOS annual meetings. As a forum for human interactions, ART is committed to interdisciplinary collaboration among young scientists. We should take advantage of these international frameworks, which produce many opportunities for new cooperation.

b. Satellite remote sensing

Satellite measurement is very useful for monitoring the Arctic sea ice area, where ship-based expedition is difficult. Among a variety of satellite sensors, all-weather type microwave sensors enable daily global mapping and have played a central role in sea ice research for several decades. The main sensor is AMSR2, developed in Japan. The AMSR2 has four times higher spatial resolution than the U.S. SSM/I and enhanced data utility. The AMSR series is indispensable for monitoring and research of sea ice and its continuous operation is an international responsibility. Considering the period of AMSR2's durability, the succeeding sensor should be launched by 2020/21. The development of higher-resolution sensors is also important for ice-edge monitoring and for analyses of fine-scale sea ice variations.

The estimation of sea ice thickness is necessary to evaluate sea ice volume and growth/melting rate. There are some satellite algorithms for estimating sea ice thickness from sea ice surface conditions; however, their accuracy is still insufficient, especially in the multi-year ice zone. To obtain data that is independent of sea ice type, direct measurement of sea ice surface height is practical. NASA and ESA are operating ICESat with a laser sensor and CyroSat with a radar sensor, respectively. These altitude sensors provide information on the surface height of the ocean, in addition to sea ice. The spatial distribution and strength of ocean circulation calculated from sea surface height are closely related to ocean heat transport. Altitude data is therefore important to clarify mechanisms of sea ice variations and to predict corresponding future climate. Since the accuracy, resolution, and frequency of current sensors are unsatisfactory, further sensor development and operation of multiple small satellites should be discussed.

Visible/infrared sensors (e.g., MODIS and LANDSAT) and synthetic aperture radars (e.g., PALSAR and RadarSat) are also valuable. In spite of the state-of-the-art development, operation, and analysis of satellite products, these data have not been popularized in the Japanese Arctic research community. Well-established data archiving for easy access is an effective way to extend the range of satellite users. Satellite remote sensing and its application to Arctic environmental research can be one of Japan's leading roles, given the country's geographical location away from the Arctic region. More extensive utilization of present sensors, development of new sensors,

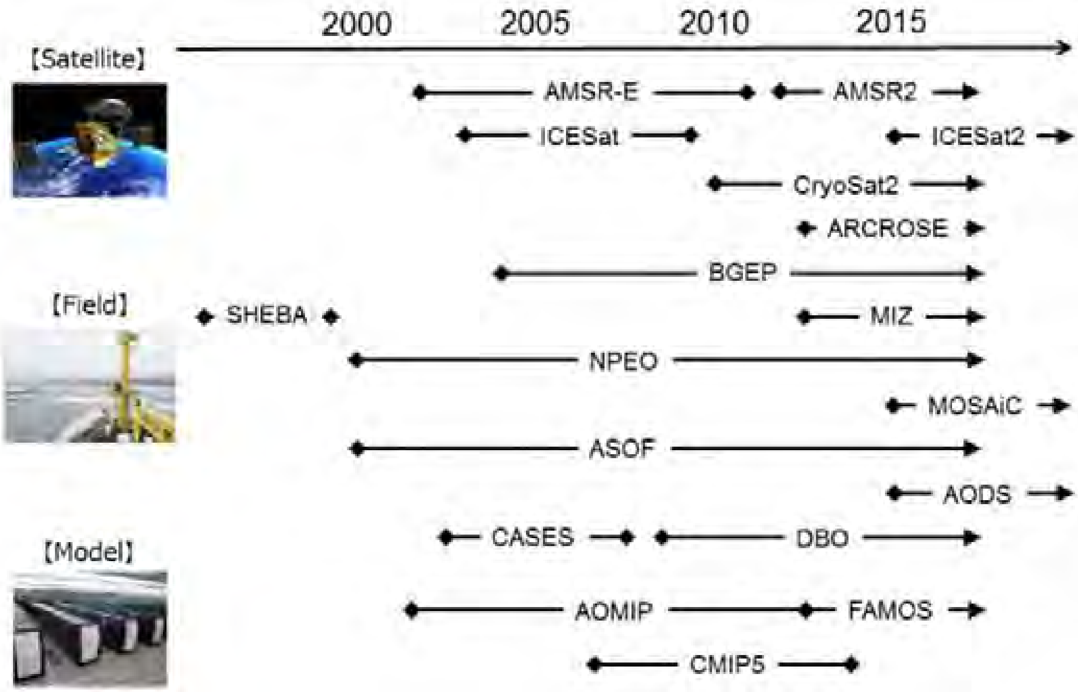

Figure 8: Major international projects on Arctic Oceanography. Right arrows mean that the end period has yet to be determined.

expansion of human resources, and organization of research institutes should be promoted.

c. Field observation

Japanese research communities have adequate achievements in terms of ship-based observations in the Pacific Arctic region. Unfortunately, the field campaign operated by Japan has been confined to outside the marginal ice zone. To ensure a continuous international contribution, our biggest challenge is to fill data blanks through year-long observation in Arctic sea ice zones. From the viewpoint of heat budget analysis, it is important to propose a new standard, following SHEBA. To advance Arctic oceanographic research in Japan, additional facilities for in situ measurements in sea ice zones (e.g., through icebreakers and unmanned stations) should be installed (see icebreaker conception in Chapter 9).

IPS mooring sensors play an active role in time series observation of sea ice. Data accumulation in the spatial direction is enabled by AUV and ice-class profiling floats. If the estimation of sea ice thickness from ADCP becomes practical, a dramatic increase in amounts of data is expected. In situ measurements at the spatial scale of individual ice floes contributes to refinement of sea ice models. On the other hand, an important task for continuous implementation systems is to foster human resources with know-how through international cooperation. Having a grasp of cloud and precipitation systems and snow processes over sea ice is also important to clarify sea ice variation mechanisms. An ice mass balance buoy is a robust tool for capturing seasonal transitions in snow depth on sea ice but the number of buoys is insufficient to allow for discussion of spatial patterns. Other snow depth data is available from the NCEP-CFSR reanalysis products. We should proceed with data validation. In addition to meteorological radar observations, SHEBA-like intensive field campaigns are also ideal for capturing temporal variations in snow depth and sea ice thickness. During the NSIDC Operation IceBridge mission connecting the ICESat and ICESat-2 periods, electromagnetic instruments loaded on helicopter were sometimes used to measure springtime snow depth and sea ice thickness in the Pacific Arctic region.

In Japan, the JAMSTEC R/V Mirai has worked on atmosphere and ocean observation in the sea ice reduction zone for more than 10 years. The radiosonde, in particular, is a unique item. The automatic release equipment enables very frequent operation even with a small group. In 2013, two weeks of fixed-point observations were conducted by the Mirai cruise for the first time. Pan-Arctic simultaneous radiosonde measurements were achieved in cooperation with land operational stations in Ny-Alesund, Alert, and Eureka. Since the importance of this mission and foresight were expressed beforehand during the IASC atmosphere working group meeting, international cooperation from Germany and Canada could be ensured. The U.S. and Russia are also developing an interest in these activities. This mission, named ARCROSE, is now being developed in terms of novel studies covering Arctic weather forecasts and the assessment of Arctic impacts on mid-latitudes. The aim of ARCROSE is consistent with PPP. It is noteworthy that this project started in Japan and is recognized as a MOSAiC pilot study scheduled for 2018 and 2019.

d. Numerical modeling

Skills in predicting recent rapid decline and thickness distribution changes in sea ice in climate model experiments under global warming scenarios are not yet adequate. Model biases are attributed to various factors, as referred to in Theme B. In this section, we describe points for model improvement to study Arctic oceanographic processes.

Most sea ice models have been developed following Semtner-type thermodynamics and Hibler-type dynamics. In the thermodynamic part, accurate expression of sea ice albedo, considering snow depth and melt ponds, is key. It is preferable to reproduce temporal changes in albedo differing between multi-year and seasonal ice zones. Although some models explicitly formulate the melt pond property itself, the choice of direct calculation of melt pond or indirect representation as an albedo change (i.e., parameterization) would depend on availability of validation data and computational costs. In the dynamics part, present schemes do not sufficiently include local mechanics with ice floe scales lower than 10 km. Sea ice rheology on internal stress was originally developed for medium-resolution models with their horizontal grid size of dozens of kilometers. The applicability of similar formulations to higher-resolution (grid of several kilometers) models should be verified. Further sea ice reduction in the Arctic Ocean is considered to enhance wave-ice interaction, where wind-driven ocean wave breaks pack ice into small floes. The variable coefficients of air-ice and ice-ocean drag (e.g., depending on sea ice thickness and melt pond conditions) would improve momentum transfer between air, sea ice, and ocean.

The ocean model component should also be improved. For example, medium-resolution models barely reproduce the intrusion of dense shelf water into basin interiors. In the Arctic Ocean, eddy-scale phenomena (which are generally finer than those in mid-latitude regions) and complex sea bottom topography control not only shelf-break currents but also basin-scale ocean circulation. Horizontal model resolution should therefore be of an order of 1 km for accurate simulation of pan-Arctic hydrographic fields. Hardware restrictions will probably be overcome through next-generation high-performance computers. In the coming stage, model configuration and experimental design should be rechecked. Mesoscale eddies, internal waves, and deep convection are important processes for inclusive solution of Arctic Ocean environments. Convective mixing, with its horizontal scale of 100 m, cannot be explicitly resolved even using high-end supercomputers. Following achievement of high-resolution experiments, additional approaches would be necessary for better modeling performance of dense water plumes and mixing processes. The reformation of convection schemes based on idealized model experiments should be factored into the choices.

In atmospheric modeling efforts, regional weather forecast models such as WRF should be established to examine meteorological variations reflecting air-ice-ocean interactions in marginal ice zones. These model improvements require data accumulation not only from field campaigns but also through satellite remote sensing. Japanese management and analysis of satellite products is highly valued. In addition to the above-mentioned process studies, reanalysis data used as atmospheric boundary conditions for sea ice-ocean models and validation methods for model performance should also be refined (see also Themes B and C).

Summary

The Japanese research community has had numerous achievements through field investigations in the Pacific Arctic region, where sea ice declined rapidly in the 2000s and where most sea ice disappears in summer. The R/V Mirai Arctic cruise led both atmospheric and ocean observation in the Chukchi continental shelf and the Canada Basin area for about 15 years. In particular, there has been the deployment of mooring buoys to estimate horizontal heat transport of Pacific-origin water, as well as turbulence measurements to address vertical ocean heat transfer. In addition, processes in the atmospheric boundary layer, such as ocean surface cooling, cyclone generation, and changes in cloud bottom altitude, have been clarified. In recent years, the T/S Oshoro-maru of Hokkaido University sometimes entered the northern Bering Sea and the Chukchi shelf to obtain high-latitude oceanographic data. We thus have an international reputation for ship-based observation in the Pacific Arctic region.

The Pacific Arctic region is a good example of a seasonal ice zone. We therefore plan for this region to be a priority area of comprehensive study. Whereas the Canadian, Chinese, and Korean icebreakers regularly transect the central Arctic basins, the U.S. has started to focus on marginal ice zones in the Beaufort Sea. Additionally, ICESCAPE is a breakthrough project, through which massive under-ice blooms of phytoplankton were discovered. These campaigns also provide a reference point for our future activities. Even though we could own an original icebreaker, wintertime cruises are severely restricted by weather conditions. We could therefore produce international contributions through a combination of short-term spot sampling in winter and year-long mooring (i.e., focusing on warm water intrusion under sea ice).

Numerical modeling is a useful tool for pan-Arctic mapping of oceanographic structures, but still has various weaknesses, such as model bias and high computational cost. We should now try to quantify ocean heat impact on sea ice, intrusion of dense shelf water into basin interiors, and cloud/cyclone formation. The global thermohaline circulation originating from the bipolar regions involves multiple phenomena scales (e.g., turbulent mixing, deep convection, eddy transport, and basin-scale oceanic currents). The interaction between individual multi-scale processes should also be addressed using high-resolution Arctic Ocean models for a unified understanding.

There have been many process studies, focusing on individual contributions of atmosphere and ocean to Arctic sea ice variation. The interaction between the three systems is also an important theme for clarification. For example, it has been suggested that the frequency of eddy generation and corresponding ocean heat transport depend on surface wind patterns in the western Arctic. On the other hand, ocean heat may alter atmospheric circulation fields via sea ice retreat. Such feedback processes will become important issues to be examined in future studies. For seasonal forecast of sea ice distribution, assumptions of characteristic wind patterns or of ensemble ice-ocean experiments using varied wind-forcing data are sometimes necessary. Quantifying how sea ice and ocean changes affect atmospheric condition would increase the accuracy of seasonal forecasts. Development of regional Arctic climate models is another approach to address the above-mentioned analyses (see also Theme B). This effort has already started in the Naval Postgraduate School, U.S., and further improvements to reproduce various phenomena scales are expected. We now have advanced model development techniques, powerful supercomputing systems, and individual model components for atmosphere, ocean, land, and ice sheets. The time to discuss better coupling methods is now approaching.

Close collaboration in field and modeling studies is strategically important to advance polar research. Benefits would result, not only from direct comparison of results, but also through approaches using data assimilation. In the tropical and mid-latitude ocean, data assimilation is widely recognized as a general research tool, taking full advantage of Argo buoy data. Unfortunately, the target variables assimilated in the Arctic Ocean are confined to satellite-based sea ice concentrations and mooring-based ocean velocity over a part of the continental shelf, because both available data amounts under sea ice cover and model performance are still insufficient.

However, over the next decades, we should look ahead to an innovative style of Arctic research with data assimilation, because we expect to have an enhanced observational network using automatic equipment and improved model performance. The data assimilation system itself has a common specification across the world ocean. In the polar ocean, a strategy for obtaining under-ice in situ data is important. For example, if we develop next-generation profilers that automatically move under sea ice in winter and lift up to the ocean surface in summer, the assimilated product would be practical research infrastructure for a variety of space-time scales as well as a high-accuracy one in the mid-latitude ocean. In addition, data assimilation is regarded as a useful tool to estimate optimal values of model parameters and to construct more realistic initial conditions for forecast experiments. It is desirable to develop short-term prediction systems, similar to JCOPE and JADE, and to inform commercial vessels sailing the Arctic Sea Route of weather, sea ice, and ocean conditions. These efforts would further contribute to social and economic communities. A detailed discussion of data assimilation is provided in Theme C.

Theme 3: Biogeochemical cycle and ecosystem changes

Abstract

Biogeochemical cycle across the atmosphere, land, and ocean is closely related to greenhouse gas dynamics such as CO_2 and methane, aerosols that affect cloud formation and solar radiation, and nutrients that sustain marine ecosystems. In the Arctic regions, sea ice, ice sheets, snow cover, and permafrost play a major role in biogeochemistry and complicate the processes further. Here, we highlight the following four questions that describe important aspects of changing biogeochemistry, which is the other side of the same coin with the perspective of environmental changes.

Q1: How are concentrations of greenhouse gases and aerosols in the atmosphere changing?

Q2: How are biogeochemical cycles that relate to terrestrial ecosystems changing?

Q3: What is needed for quantitative elucidation of the geochemical material transport from land to sea?

Q4: How are biogeochemical cycles that relate to marine ecosystems changing?

As for the atmosphere, since observational data are currently very poor in Siberia, deployment of new observation sites to implement year-round observations of atmospheric trace gases is important in Siberia. The use of satellite data and aerosol observation over the ocean using marine vessels on a regular basis are also necessary. For terrestrial ecosystems, the implementation of long-term study sites that allow centennial-scale continuous data acquisition of vegetation change such as species composition and structure change is important. Also, satellite observations that record signals of vegetation change, development of vegetation dynamics models that perform reliable predictions on long-term ecosystem changes, and understanding the geographical distribution and its accumulation and decomposition mechanisms of soil organic carbon (SOC) are crucial for the scientific progress. For the geochemical transport from land to ocean, we need to develop an extensive observation network around rivers and coastal areas in the Arctic to monitor fluxes of pollutants, carbon, nutrients, and trace metals etc. that are released by coastal/soil erosion and thawing of ice sheet and permafrost. For marine ecosystems, obtaining the observation data with no spatial and seasonal gap is important. For example, it is necessary to obtain the data by ice camps and year-round observation by sediment trap and mooring system to understand the seasonal variation of biogeochemistry and ecosystems. Furthermore, by comparing and integrating these data with the numerical models and incubating/feeding experiments, it is possible to evaluate quantitatively the relationship between biogeochemical cycle and ecosystem along with the effects of ocean acidification.

Introduction

It is almost certain that the increase of CO_2 in the atmosphere is the main cause of the global warming experienced in recent years, and this problem has attracted worldwide interest. While CO_2 has continued to be released into the atmosphere by human activities, it is also a fact that the concentration of CO_2 in the atmosphere has been moderated in some part by land and ocean absorption. In reference to the AR5 of IPCC (IPCC 2013a), about 40% of the CO_2 released into the atmosphere by burning of fossil fuels etc. has been absorbed by the land, and another 20% by the oceans, each year. From this, it is clear that, in order to understand the dynamics of CO_2 in the atmosphere, it is necessary to study the carbon cycle in the atmosphere, on land, and in the ocean. Figure 9 is a schematic diagram of the biogeochemical cycle in the Arctic region. In this region, a unique feature not extensively seen in other regions plays a significant role: snow, land ice, and sea ice. In addition, climate change is anticipated to be particularly strong in subarctic and Arctic terrestrial areas (Figure10; IPCC 2013b). Grasping accurately the impact of climate change on subarctic and Arctic terrestrial ecosystems (hereinafter, referred to as Arctic terrestrial ecosystems: ATEs) is crucial for understanding the feedback affecting climate through biogeochemistry.

In the Arctic regions, the primary production (i.e., photosynthesis) of boreal forests and marine phytoplankton is one of the major factors governing CO_2 concentration in the atmosphere, and it also has a large role in the global carbon cycle. Understanding carbon dynamics quantitatively, and its impact on ecosystems in the Arctic region, is very important for predicting the future global climate. The Arctic is unusually significant in this, because the warming there is particularly remarkable.

CO_2 is not the only factor related to the climate change. Methane emissions that may be increased by thawing of permafrost due to global warming, and the release of methane from the subsea permafrost of the Arctic Ocean could also have a significant impact on the climate. Furthermore, aerosols such as black carbon [14] (BC,

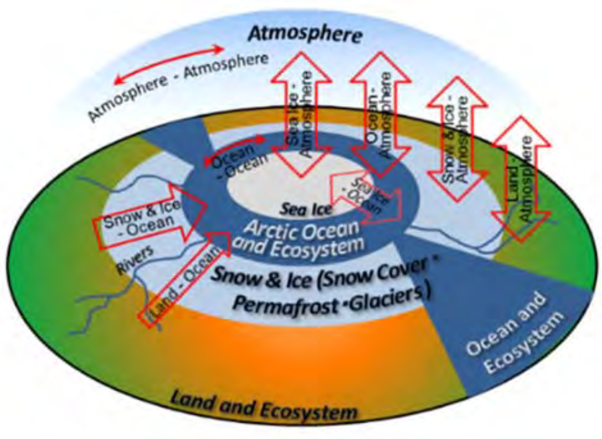

Figure 9: Schematics of the biogeochemical cycle in the Arctic.

[14] Black carbon (BC): Black carbon (BC) is the strongly light-absorbing component of fine particulate matter present in the atmosphere, containing graphite-like micro-crystalline structures.

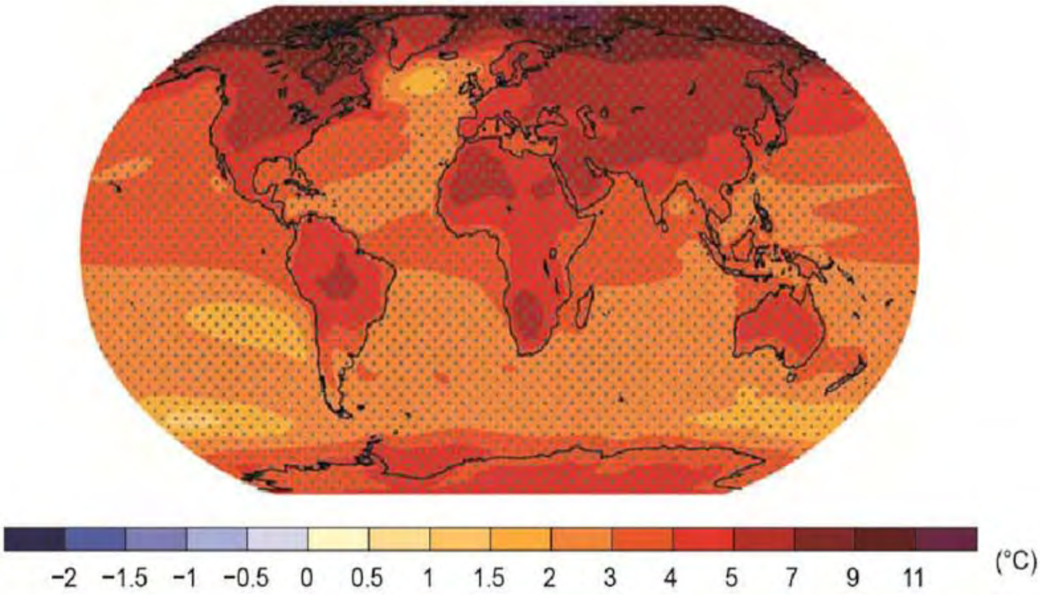

Figure 10: Prediction of global warming summarized by IPCC(scenario RCP8.5). It expresses how many degrees Celsius the average temperature of 2081 to 2100 is expected to rises from the average temperature of 1986 to 2005. Warming in the vicinity of the North Pole has been particularly intense. The cause is regarded as albedo feedback caused by reduction in the extent of snow and sea ice with warming. (IPCC, 2013b, Figure SPM.8. Maps of CMIP5 multi-model mean results for the scenarios RCP2.6 and RCP8.5 in 2081–2100; (a) annual mean surface temperature change)

emitted by frequent burning of biomass in the subarctic zone) produces cloud condensation nuclei that change the radiation process of the atmosphere and of snow surfaces, thereby changing the climate. Substances of terrestrial origin that enter the ocean from rivers and coasts, and substances transported by air that fall on the sea surface, are major factors in the function of marine ecosystems.

Since the behavior of individual parts of the land-atmosphere-ocean system is a strong determinant for the climate and the environment, it will be important in the long-term to clarify the dynamics of climate change and ecosystem roles. This could be achieved using modeling studies, in addition to field studies and satellite observation.

Q1: How are the concentrations of greenhouse gases and aerosols in the atmosphere changing?

a. The importance of this topic and current conditions

Trace components in the atmosphere (greenhouse gases, short-lived gases [15], and aerosols) have a significant influence on climate change through atmospheric budgets, as indicated in the schematic diagram of Figure 11. The Arctic region is composed of the sea-ice area, which accounts for most of the Arctic Ocean, the marine area, which has a large amount of biological production, and the land area, where very large permafrost areas and forest regions occur. These three areas play roles of both source and sink for atmospheric trace components. To clarify the circulation process and trends of atmospheric trace components, a number of countries, including Japan, have continued long-term observations, for instance, in Ny-Ålesund (Svalbard Islands), Barrow (Alaska), and Alert (Canada). In recent years in the Arctic, changes that are considered as effects of climate change, for example, a sudden reduction in the area of summer sea ice, have been observed. It is certain that such sudden environmental changes have a significant impact on the distribution and concentration of atmospheric trace components. To understand changes in the distribution of these components, and the influence of environmental changes, progress in observational studies is needed. This is essential if we are to prepare responses to environmental changes that may occur, and to accumulate knowledge of changes in biogeochemical processes in the atmosphere.

Expansion of the regions in which seasonal sea-ice and open water occur, relative to past conditions, is believed to enhance CO_2, exchange processes, to release short-lived (less than one day to several weeks) gases such as aerosol precursors[16] (e.g., DMS: dimethyl sulfide) to the atmosphere, and to increase the number of airborne particles of sea-salt. Knowing the distribution of CO_2 exchange in the ocean, and its seasonal change, is very important in understanding atmospheric carbon cycling.

[15] Short-lived gas: Is a gas with high reactivity and short chemical life, less than one day to several weeks, in the atmosphere (e.g., O_3, NO_y, SO_2, volatile organic matter).

[16] Aerosol precursor: It exists as gas in the atmosphere and can become an aerosol particle after conversion into a low vapor-pressure ingredient through an oxidation reaction in vapor phase, and condensation onto an existing particle, and can be converted into an aerosol-particle ingredient after condensation onto an existing particle and chemical reaction there.

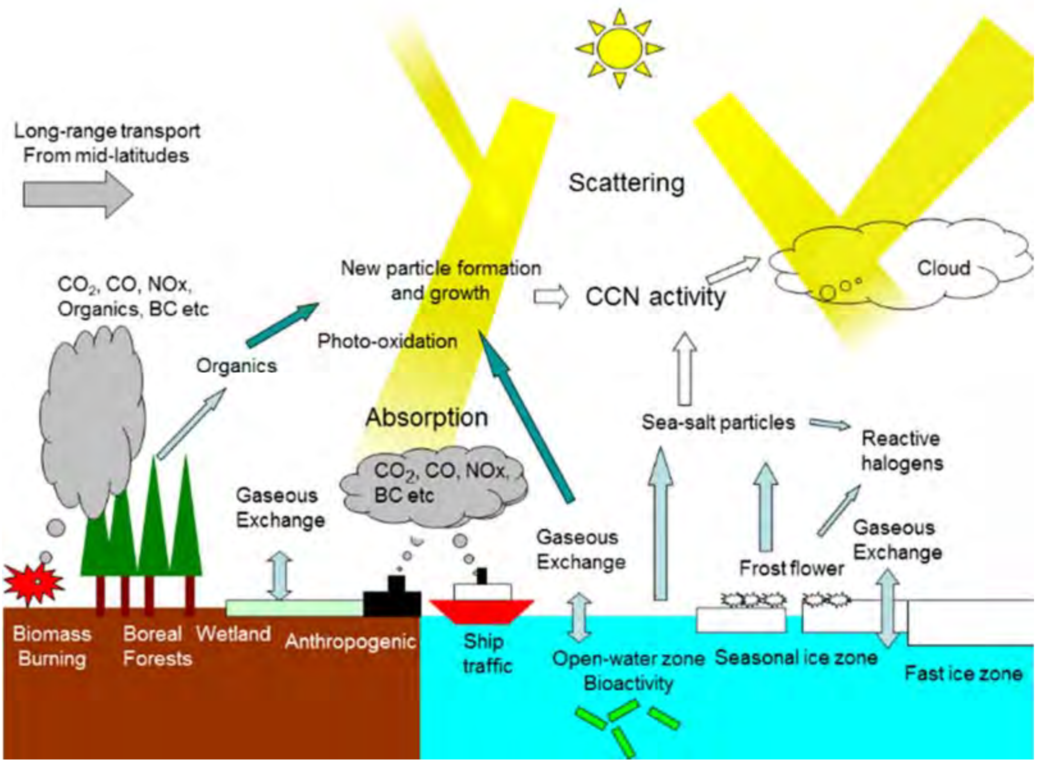

Figure 11: Schematic of biogeochemical cycling with focus on the atmosphere

In addition, expansion of open water is a factor in increasing aerosol concentrations because the release of aerosol precursors and sea-salt particles is promoted by the greater water surface accessible to the wind. The increase in the aerosol concentration increases the number of cloud condensation nuclei[17] and can influence radiative forcing indirectly by its effects on cloud processes[18] (Lubin and Vogelmann, 2010). Increased sea-salt particles in the atmosphere promote effective removal of acidic gases of artificial origin (such as SO_x and NO_y) by heterogeneous reactions on aerosol particles and deposition processes.

This is closely related to the atmospheric cycling of some short-lived gases. In addition, frost flowers[19] that form on seasonal sea ice (winter-spring) become a source of sea-salt particles. There is a possibility that sea-salt particle emission from seasonal sea ice changes the aerosol distribution in the Arctic from winter to spring. The heterogeneous reactions on frost flowers, and the release of highly reactive halogen species into the atmosphere by sea-salt particles, are closely related to atmospheric chemical processes (e.g., oxidation of short-lived gases, O_3 depletion, Hg removal) that occur in the presence of solar radiation (particularly during polar sunrise).

In terrestrial areas, changes in soil and vegetation could cause changes in emission of the greenhouse gases from wet areas, in emission of short-lived gases (volatile organic compounds: VOC) from forests, and in wildfire patterns. Thus far, observations of greenhouse gases and associated gaseous compounds in the Arctic region, suggest that inter-annual and seasonal changes are related to emissions from fossil fuel consumption, deforestation, biomass burning, and wetlands (Morimoto et al., 2010). Biomass burning, in particular, does not only causes release of greenhouse gases but is also an important source of light-absorbing aerosols (e.g., BC and BrC - brown carbon[20]). These greatly affect the albedo of snow and ice surfaces when deposited on them. Furthermore, we should include impacts from the expansion of human activities expected during extended periods of Arctic warming (e.g., use of Arctic shipping routes and exploitation of resources in the region). This could be addressed by future studies on the concentrations of atmospheric trace components (e.g., CO, CO_2, NO_x, and BC), their spatial distributions, and their impact on climate change. The contribution of long-range transport of anthropogenic substances from outside the Arctic Circle has also been pointed out, based on long-term observations of greenhouse gases and aerosols (Quinn et al., 2007; Morimoto et al., 2010). Basic scientific knowledge of the circulation of trace components in the Arctic atmosphere, and their influence, has been obtained from past energetic studies, but there remains significant uncertainty and many unexplained

[17] Cloud condensation nuclei (CCN): Particles that provide targets for condensation of atmospheric water vapor, for formation of cloud particles.

[18] Aerosol and cloud formation and their influence on climate: Vapor condenses on aerosol particles in the atmosphere and they become cloud particles, and a cloud is formed. The increase (decrease) in density of aerosols brings increase (decrease) in cloud particle density and decrease (increase) in cloud particle diameter. This greatly changes the lifetime and optical characteristics of a cloud. These conditions are closely related to emissions, and may greatly affect climate change

[19] Frost flower: At low temperature, ice crystals form on the surface of sea ice as it freezes. The salinity of frost flowers is very high since brine (concentrated seawater) on the sea ice coats them. By the chemical reactions that occur on the frost flowers, and due to fragmentation caused by strong winds, highly reactive components and sea-salt particles are released into the atmosphere.

[20] Brown carbon (BrC): This is a particulate organic compound with light absorption characteristics. It is released to the atmosphere by combustion.

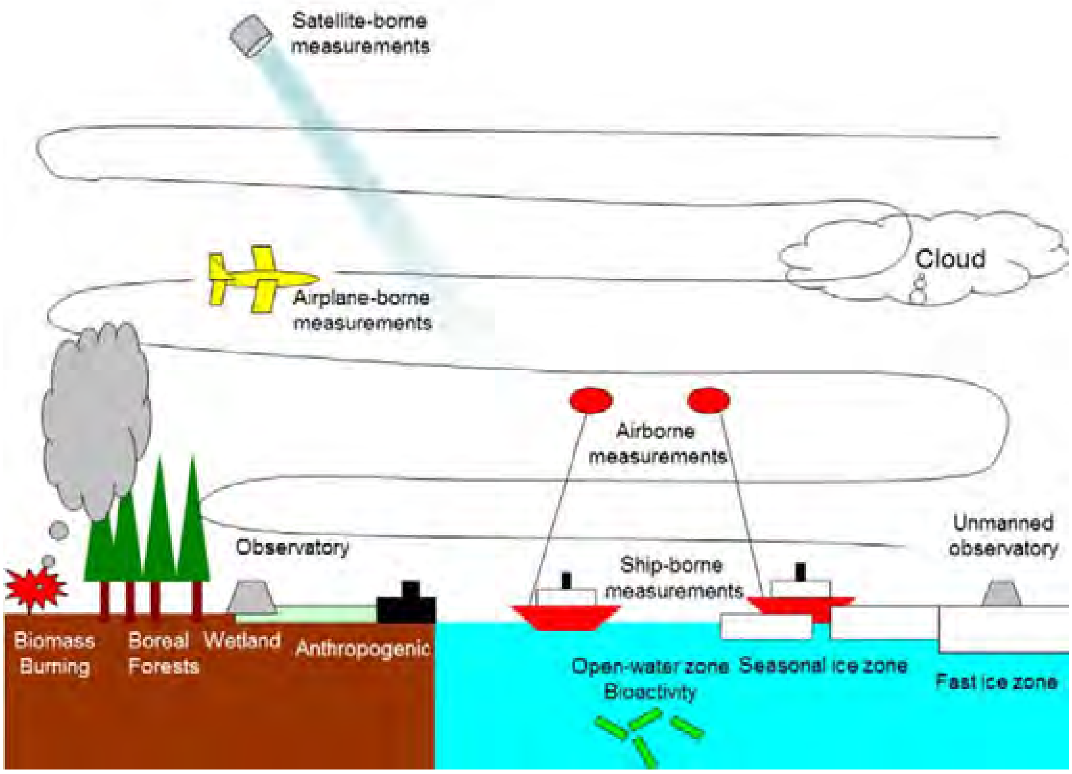

Figure 12: Conceptual picture of platforms from which to observe the biogeochemical cycle with focus on the atmosphere

points about interactions of atmospheric trace components, and the overall mechanism.

b. Future studies

In order to understand the dynamics of greenhouse gases, short-lived gases, aerosols, and their influence on climate change in the Arctic atmosphere, long-term and precise observation of spatiotemporal patterns is important. See Figure 12 for an outline of mainly atmospheric observations about biogeochemistry. Since the target regions cover a wide area, within which are sea-ice, open ocean, land, and atmosphere, it is important that the research community of Japan become the center from which we expand the observation of atmospheric trace components, aerosols, their isotopic ratios, and clouds, using ground-based observations, ships, aircraft, other flying objects, and satellites suitable for the subjects and regions to be observed.

For ground-based observations, in order to have new data be comparable with past data, current observations should be continued in cooperation with research institutes both domestic and abroad. In Siberia, where observed data are significantly poor, the observatories should be new, and year-round observation of atmospheric trace components should be implemented. In oceanic areas, because understanding the distribution of atmospheric trace components in open water and sea-ice areas is essential, observations of aerosols and short-lived gases should be executed regularly utilizing research vessels and icebreakers. Since the use of research vessels in the Arctic Ocean has often been carried out on open water during the summer, observations in sea-ice areas, in winter using icebreakers, and year-round at unmanned weather and aerosol observation bases on the sea ice are also necessary. Furthermore, in order to understand the distributions of atmospheric trace components (in particular, short-lived gases and aerosols), it is important to regularly conduct intensive observation that makes full use of aircraft, and other flying objects, to capture their vertical distribution from the ground to the upper troposphere, and their horizontal distribution over areas of land, open water, and sea ice. Moreover, because there are many constraints on spatial observation by research vessels and airplanes, an overall grasp of the spatial structure of greenhouse gases, short-lived gases, aerosols, and clouds by satellite observations should also be performed. From these observations, (1) the spatiotemporal distribution of atmospheric trace components, (2) distributions of the emission, absorption, and deposition amounts, (3) their seasonal changes, and (4) the inter-annual changes of gases and aerosols from the sea and land surfaces may be clarified with high resolution and high accuracy. Based on the results obtained by making full use of atmospheric composition and transport models, we should be able to elucidate the mechanisms of interaction among the oceanic, terrestrial, and atmospheric cycles of atmospheric trace components (greenhouse gases, short-lived gases, and aerosols) in the Arctic. As a result, we should aim to predict climate change with greater accuracy.

Q2: How are biogeochemical cycles relate to terrestrial ecosystems changing?

a. Importance of this topic and current conditions

Changes in temperature and precipitation have strong impacts on ATEs. For vegetation, changes in photosynthesis, respiration, biomass, and vegetation type occur. In addition, the fertilization effect [21] from increasing CO_2 concentration in the atmosphere has large impacts on ecosystems, and it is believed that the global average of photosynthesis will increase by 10–30% from a 2-fold increase in the CO_2 concentration by the latter half of the 20th century. In conjunction with this, it is estimated that land, acting as a carbon sink, might absorb approximately 40% of annual carbon released to the atmosphere artificially by combustion of fossil fuels etc. (IPCC, 2013a). For these reasons, it is important to estimate as accurately as possible the contribution of the Arctic ecosystem to these carbon budgets. Since ATEs are likely to be significant sources of CO_2 and methane, precise understanding of these dynamics is an urgent issue.

The interaction of climate and ATEs is not always in only one direction (i.e., climate to ATE). There is also influence from ATEs to climate, and this is the basis of a complex interaction[22] (Figure 13). Therefore, in order to understand the variation of terrestrial ecosystems and biogeochemistry, the impact on climate exerted by ATEs through biogeochemical cycling and physical processes at the land surface, must be considered. However, current understanding of Arctic terrestrial ecosystems is incomplete. By promoting scientific understanding from the perspective of system science, quantitative understanding of feedback with high uncertainty, such as impacts on vegetation dynamics due to global warming, and impacts on climate via albedo and carbon dynamics due to vegetation changes, should be studied further. Most of the carbon stored in ATEs is present near the ground surface in the form of SOC. For this reason, dramatic changes in SOC due to variation in soil temperature and moisture caused by global warming is expected. Because of reports that the amount of carbon stored in peat lands may be reduced by up to 80% due to a relatively mild temperature rise of 4 ºC by the end of the century (Ise et al., 2008), exact understanding of SOC dynamics is an important issue. In particular, considering permafrost melting, there is a possibility that dramatic changes may occur. Of particular concern is the possibility that current zones of permafrost will become wetlands due to global warming, and that the melted areas will become major sources of methane. Moreover, since the burning of biomass emits a large quantity of CO_2 in a short time, it is estimated that its influence on climate is significant. However, because it also causes related changes in evapotranspiration, surface albedo, and vegetation, as well as generating aerosols that become cloud condensation nuclei, quantitative prediction of its effects is unsatisfactory at present.

Field observation is important to understand the biogeochemical cycling of ATEs, but field data are limited because access is difficult in large parts of this area. Thus, it will be necessary to carry out local observations

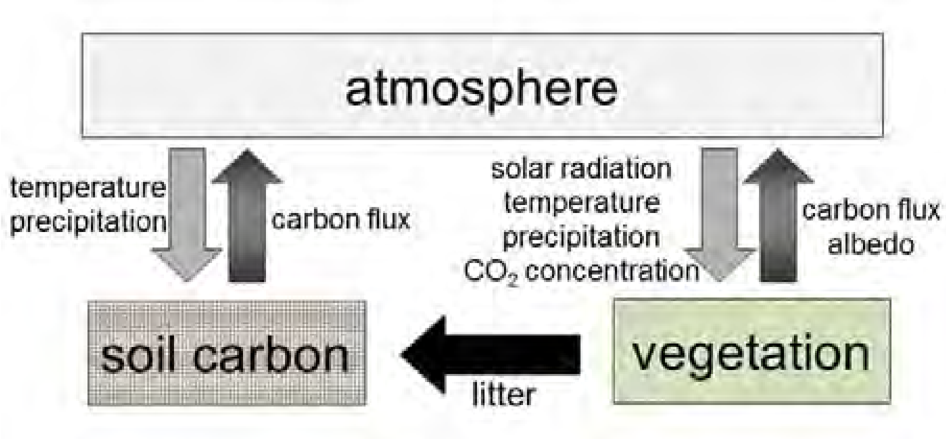

Figure 13: Terrestrial ecosystem and climate influence each other with strong interaction. The development, validation, and application of a simulation model that is able to bundle elements and processes and connect them in complicated ways, is urgently needed to project how these actions change in a scenario of climate change.

[21] Fertilization effect: The phenomenon that the photosynthetic efficiency of plants (which use CO_2 as a carbon source) rises as the concentration of atmospheric CO_2 rises. Because absorption of atmospheric CO_2 is increased by the fertilization effect, it has a function as a negative feedback to suppress a climate change. However, quantitative evaluation of the fertilization effect has not advanced much, and its range (5–30% of the artificial CO_2 discharge) is so wide that uncertainty is great. The results of future studies are much needed and awaited.

[22] Various feedback mechanisms to hide behind in terrestrial carbon cycling: CO_2 and methane are greenhouse-effect gases causing climate change, and both include carbon. They circulate through terrestrial ecosystems and the atmosphere via the physiological functions of organisms. The physiological activity of living organisms reflects the shifting environmental conditions caused by climate change, and in this way, change in carbon cycling causes feedback to climate change. This feedback is various: some acts as positive feedback to accelerate warming, and others as negative feedback to suppress warming. Regarding positive feedback, increased microbial activity due to rising soil temperature promotes more rapid decomposition of soil organic carbon, and can lead to greater rates of release of additional CO_2 into the atmosphere. Regarding negative feedback, climate warming increases the amount of photosynthesis and plant biomass, thus increasing the amount of atmospheric CO_2 fixed in the plants and soil of the land surface. In order to make accurate projections into the future, it is necessary to be clear about each of these conflicting feedback elements, and to model them.

continuously to acquire valuable data for the future, and also to utilize better techniques, such as remote sensing, for spatial observation and capture ecosystem changes over this wide area. The development of simulation models able to reproduce current ecological conditions and processes is indispensable. These are essential to understand interactions between environmental changes (e.g., climate change), and the biogeochemistry of terrestrial ecosystems, and to contribute rational predictions of future climate. However, development of an integrated model advances only slowly because there are many elements that should be included, and the feedback between them is extremely complicated.

b. Future studies

The research topics needed for ATEs are too numerous to mention. For this reason, here we list a few that contribute directly to understanding biogeochemistry at global scale, and which should be clarified from a long-term perspective.

From the fact that plant biomass functions as a carbon pool in global carbon cycling, it follows that we must understand its variation and dynamics. We should set up long-term plots of land to acquire continuous data on a century scale, about plant species and community structure. Included should be clarification of signals of changes in vegetation that are observable by satellite. Furthermore, it will be necessary to perform a reliable prediction about long-term changes in vegetation using a vegetation dynamics model. This will lead to quantitative understanding of the role of terrestrial ecosystems in the global carbon cycle. As a specific method of field observation, proactive use of non-contact observation technology (e.g., leaf area index measurement using fisheye lenses, basal area measurement using the prism method) in order to efficiently and strategically cover the vast Arctic terrestrial area, is also important.

Specifically, SOC functions as the largest carbon pool in ATEs, and the importance of grasping its distribution, and understanding the mechanisms by which it is accumulated and decomposed, is noteworthy. Since the thickness of organic soil, in which SOC is mainly accumulated, changes due to the increase and decrease of SOC, the physical condition of the soil changes as well. This means that carbon cycling, as well as energy and moisture dynamics, must be modeled at the same time. Therefore, we should promote the fusion of models of biogeochemistry and physical qualities of soils from a medium- to long-term perspective. Integration of ecological studies and land surface physics research is important, but it has not seen much cooperation currently due to differences in these academic disciplines. Moreover, physical understanding of the soil, based on observation and prediction by models is important for grasping the dynamics of methane generation.

By constructing a model that integrates biogeochemistry and soil physics, it would become possible to explicitly predict changes in the depth of the permafrost (more specifically, the thickness of the active layer) due to climate change, and to show how the microbial activity of each layer of soil, affects the dynamics of methane and CO_2. In addition, we could then contribute to the elucidation of water cycling and the flow of elements that accompany it from land to ocean. Quantitative understanding of the biogeochemical processes of terrestrial ecosystems, and projections into the future, might be accomplished with the construction of a unified model for land areas (see Q3 for the details).

Remote sensing by satellite, as well as simulation, will be a powerful tool for understanding ATEs and making predictions. Recently, there has been progress in the estimation of plant biomass and photosynthesis due to advances in remote sensing technology (Suzuki et al., 2013). In this way, studies to grasp carbon cycling over wide areas, based on field observation should be developed. Remote sensing can also be utilized for observation of large and critical events, such as biomass burning.

It may be said that the application of data assimilation technology is a key to the next ten years for connecting field observations to predictive models. We need to develop objective and integrative statistical technology able to utilize the accumulated field and remote sensing data, and to improve simulation models. In particular, by the application of the 4-D data assimilation technique, using such as the ensemble Kalman filter, there is great potential to revolutionize the objective model improvement by field observation and remote sensing observation. These data assimilation techniques are already used in atmospheric and ocean science, but their application to terrestrial ecosystem research hardly exists. Thus, it is also important to train proficient researchers in statistics theory and computer science.

Gathering Japanese study communities, and focusing on collaboration with international projects and networks, is indispensable for achieving these future aims. For example, consider ILTER[23] (long-term observation plan) and FLUXNET or GEO GFOI[24] (observation of the CO_2 exchange between the earth surface and the atmosphere). It is necessary to unify researchers, and promote the use of the data which study groups have individually acquired and managed in a traditional manner, and to fix the system by developing an All Japan Model. The change in biogeochemistry being reported for ATEs is of great interest for the IPCC reports and we should positively carry out the model inter-comparison with a group of overseas research institutions (such as NASA, GISS, and the Hadley Centre) to perform Earth-system modeling.

Q3: What is needed to quantify material transport from land to sea?

a. Importance of this topic and current conditions

Terrestrial materials are supplied to the ocean mainly by river or coastal erosion. Arctic rivers transport a large amount of freshwater and carbon, equivalent to 10% of the global river flux, into the Arctic Ocean. Therefore, the Arctic Ocean is the key for understanding material transport from land to the global ocean. Since deepening of active layers, melting of ice sheets, increase in river flow, and acceleration of coastal erosion, all increase with global warming, the input of terrestrial materials to the Arctic Ocean is expected to increase. Furthermore, it is expected that the spatiotemporal extent of the impact of

23 ILTER: International Long Term Ecological Research
24 GEO GFOI: Group on Earth Observation - Global Forest Observations Initiative

terrestrial materials will expand when the area of the seasonal ice zone increases. The release of organic carbon stored in permafrost attracts attention in particular, but its feedback to the climate largely depends on whether the carbon settles in coastal sediment or is re-mineralized and released to the atmosphere as greenhouse gases (i.e., CO_2 and methane). In addition, ocean acidification caused by increased absorption of anthropogenic CO_2 is particularly serious in the Arctic Ocean. Since the addition of terrestrial carbon is expected to promote ocean acidification, this may have a serious impact on Arctic Ocean ecosystems (Theme 9).

Generally, inputs of nutrients, trace metals, and dissolved organic matter from land are factors that can directly affect the productivity of marine ecosystems. In addition, dissolved and/or suspended terrestrial materials can limit primary production by decreasing light penetration of the water column. However, the contribution of terrestrial materials to the biological productivity of the Arctic Ocean has been considered small. In recent years, new observations revealed seasonal and spatial variations in concentrations of terrestrial materials in the major Arctic rivers. The quantity and quality (e.g., inorganic / organic, biodegradable / recalcitrant) of these materials are expected to change with global warming. The fate of terrestrial materials should also be affected by environment changes in coastal areas, such as decreased summer sea-ice cover and increased water temperature. Therefore, the importance of terrestrial materials in Arctic marine ecosystems is now getting more attention.

Data concerning the flux of carbon, nutrients, and other materials of the rivers of North America, and the main rivers of Siberia, as well as data about their seasonal/inter-annual changes, are provided by USGS and the Arctic-GRO project (e.g., Holms et al., 2012). However, the quantitative understanding of coastal erosion, soil erosion, ice sheet melting, and materials derived from medium and small rivers and groundwater in Siberia, is very incomplete. With global warming, it is certain that inputs of particles and organic matter to the ocean will increase due to coastal erosion and ice-sheet melting. For rivers, the contribution of groundwater will increase with thawing of the permafrost, and concentrations of major ions, phosphate, and silicic acid would be expected to increase. On the other hand, it is unknown whether the flux of dissolved inorganic nitrogen and organic matter will increase or decrease as a whole, because of large spatial variability (Frey and McClelland, 2009). The changes in the quality and quantity of terrestrial materials that might be caused by changes in vegetation, and by human activities such as agriculture, are also unknown. In addition, inflows of heavy metals and other pollutants to the ocean from the land are likely to increase.

The distribution of river water in the Arctic Ocean has been studied using chemical tracers or satellite observation of colored dissolved organic carbon. However, for most terrestrial materials, processes such as removal and redistribution in river mouths and coastal regions are not well quantified. Therefore, their fate in the ocean, and impacts to ocean ecosystem and biogeochemical cycles, are not well known.

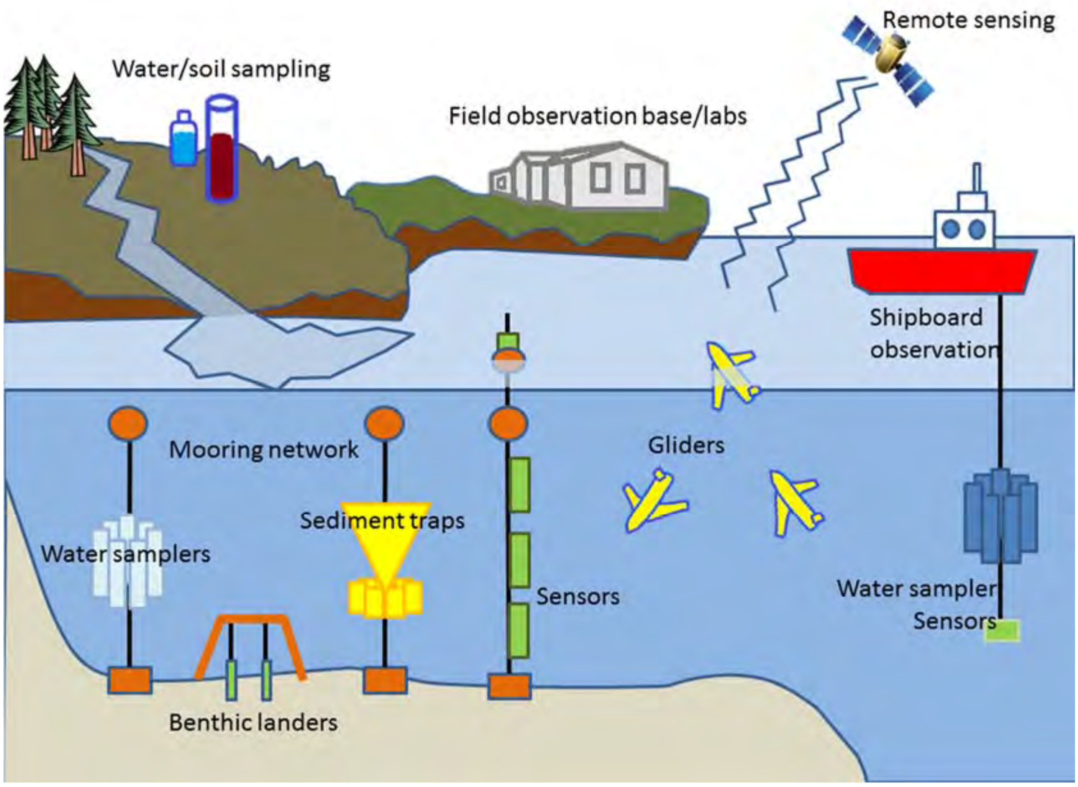

Figure 14: Schematic diagram of observations about transportation of matters of terrestrial origin from land to sea

b. Future studies

In order to monitor changes in the flux of terrestrial materials such as nutrients, carbon, and trace metals, and their influences on ocean ecosystems, it is necessary to set up and maintain an integrated observation network that covers river, estuary, and coastal areas (Figure 14). Since the inflow of these materials and the cycling processes in the ocean are being changed by global warming, it is desirable to start long-term (more than 10 years) monitoring immediately. For this, international collaboration is essential and Japan has a history of collaborative observations on land in Siberia and North America, as well in the Arctic Ocean. Integration and development of these observations with new stations and equipment, within an observation network, will fill the science gap and develop studies in the frontier that links the land to the ocean.

On land, it is important to monitor material concentrations and their seasonal and long-term variability in rivers, including small ones, using sensors or periodical water sampling. Combining these data with hydrological observations on land (Theme 4), will enable quantitative understanding of processes that determine material flux from land to the ocean. In addition, incubation experiments on soil and water are necessary for the interpretation of observations, and for development of predictive models to project future changes in material flux, with changes in temperature or soil moisture. Furthermore, detailed chemical analysis of soil and water samples may provide new tracers of terrestrial materials useful for understanding their distribution in the ocean.

For materials coming from coastal erosion and ice-sheet melting, it is necessary to grasp the distribution, scale, and frequency of the supply to the ocean, using observations from land and vessel.

Although modification, removal, and redistribution processes in estuaries and other coastal areas are keys for understanding or prediction of the influence of terrestrial materials on the ocean, their quantitative understanding is still poor. Therefore, it is recommended that some coastal regions be chosen for focused monitoring of changes in biogeochemical cycling of terrestrial materials. In order to understand seasonal and inter-annual variations in the distribution of terrestrial materials, photochemical processes, biological uptake, and the effects of physical environment on these, it is necessary to carry out comprehensive observations using small vessels and mooring systems, or seafloor observation platforms with sensors and automated water samplers.

For mooring observation in shallow waters, there can be problems of biofouling and damage by sea ice. Overcoming these challenges will enable detailed and quantitative understanding of the influence of terrestrial materials on biological production, ocean acidification, and the removal and mineralization of terrestrial carbon.

Terrestrial materials may eventually flow out from the Arctic Ocean into the North Atlantic Ocean and thereby affect biogeochemistry and biological production more extensively. Therefore, there is need for large-scale, spatial coverage in observations of oceans and seas adjacent to the Arctic Ocean. In addition to shipboard observation, remote sensing of colored organic matter distribution, under-ice observations from moorings, and use of autonomous underwater gliders equipped with sensors and water samplers, will enable 3-D mapping of terrestrial materials in the ocean. The use of newly developed tracers for terrestrial matter is expected to expand our knowledge about their fate in the ocean.

Furthermore, it is also very important to develop and improve numerical models for land-ocean biogeochemistry based on these observations and experiments, in order to predict future changes in the flux of terrestrial materials and their impacts on marine ecosystems in the Arctic and other global oceans.

Q4: How are biogeochemical cycles that relate to marine ecosystems changing?

a. Importance of this topic and current conditions

Recently, due to warming and the rapid decrease of sea ice in the Arctic Ocean, the quantitative evaluation of how biogeochemistry and ecosystems change, and how much influence greenhouse gases such as CO_2 and methane have on the exchange between atmosphere and ocean, have become important issues for understanding the climate system, not only of the Arctic, but also globally. In Figure 15, we show a schematic of changes in the biogeochemical cycles and ecosystems of the Arctic Ocean in a scenario of global warming and decrease of sea ice. It is estimated that currently, the Arctic Ocean absorbs 66–199 × 10^{12} gC from CO_2 each year, the equivalent of 5–14% of the global CO_2 budget (Bates and Mathis, 2009). From this, it can be said that the Arctic Ocean has a significant influence on global carbon cycling. However, since this estimate is based on data that are biased to summer conditions and cover a limited area of the sea, providing reliable estimates requires that we clarify variation by season, and by differences in regions (marginal seas and central basins), of CO_2 exchange between atmosphere and ocean. In addition, it is important to understand comprehensively the physical, chemical, and biological processes that affect absorption and release of CO_2. These include such as increasing sea surface temperature, freshening (dilution) of seawater, and ocean acidification, as well as changing primary productivity (CO_2 uptake) and phytoplankton assembladges. Also, see Section 2 regarding exchange of other greenhouse gases and aerosols between atmosphere and ocean, and their impacts on climate change. Note that the methane released from the Siberian shelf seas alone (8×10^{12} gC a year; Shakhova et al., 2010) was equal to that of all other world oceans combined, and this amount would be expected to increase with the ongoing thawing of subsea permafrost.

Primary production that affects atmosphere-ocean CO_2 exchange is an important factor in the function of marine ecosystems. Due to recent decreases in sea ice coverage in the Arctic Ocean, insolation into the water column increased, and this may increase primary productivity. However, melting of sea ice enhances ocean stratification and the growing surface layer of freshwater deepens the nutricline[25], resulting in decreased nutrient supply from deeper water. This could actually reduce primary productivity. In regions where upward movement of nutrients are inhibited, eddies may play an important role

[25] Nutricline: The layer in which the nutrient concentration sharply increases with depth in the water column.

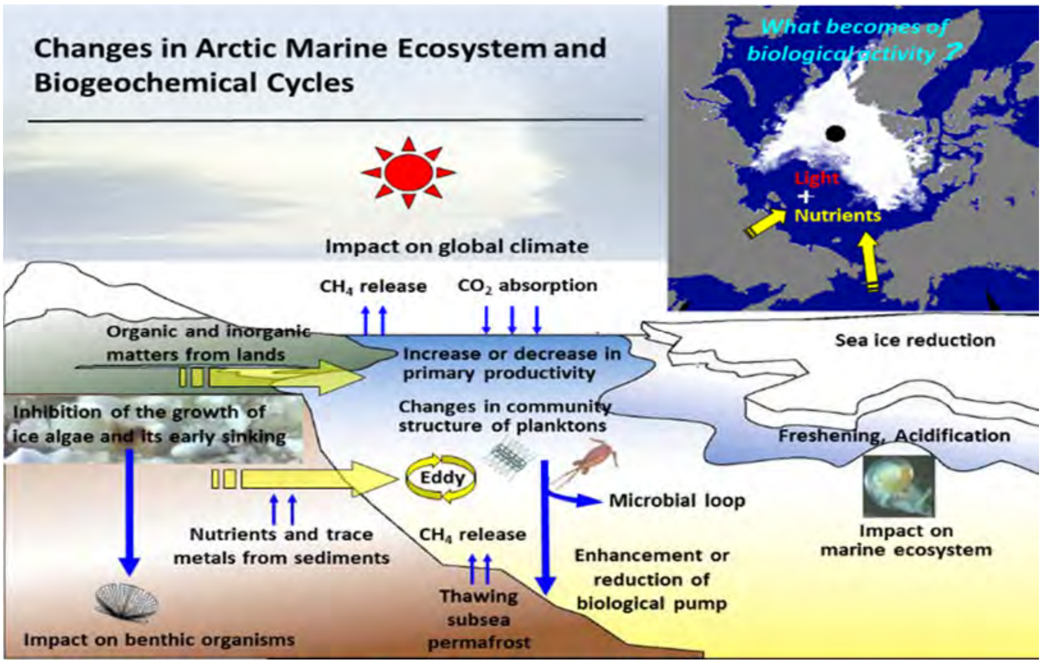

Figure 15: Biogeochemical cycles and ecosystem changes in the Arctic Ocean with warming and decease in sea ice. The figure at the top right corner was compiled based on F. Fetterer and C. Fowler. 2006, updated 2009. National Ice Center Arctic Sea Ice Charts and Climatologies in Gridded Format (http://dx.doi.org/10.7265/N5X34VDB).

in lateral nutrient supplies and primary production. Furthermore, the loss of sea ice and a general increase in the frequency and intensity of cyclones in the Arctic may cause episodic nutrient supplies, resulting in periodic increases in primary productivity (bloom)[26]. On the other hand, the decrease in sea ice and brighter seawater column may restrain the increase of microalgae[27] that are adapted to darker places, for example, algae in the brine[28] of sea ice and phytoplankton under the sea ice. Moreover, the rapid melting of sea ice may release ice algae to deeper layers, thereby impacting benthic communities.

It is presumed that 20–50% of carbon fixed by primary production in the Arctic Ocean flows into the food chain called the microbial loop as dissolved organic matter, as it does in other seas (Kirchman et al. 2009). In addition, the Arctic Ocean requires attention to the following combination of mechanisms supplying organic matter:

1) Inflow of a large amount of dissolved organic matter from rivers,
2) Addition of organic matter from melting ice, and
3) Infusion of organic matter inflow from marginal seas with high productivity.

About the latter in particular, water of Pacific origin that has passed over the Chukchi Sea shelf, a region of high primary productivity, supplies organic matter to the Canada Basin, thereby maintaining a layer of high bacterial productivity on the Alaskan side of the Arctic (Uchimiya et al., 2013). However, little is known about the Siberian side, where a large amount of terrestrial organic matter is supplied. In addition, many questions remain unanswered regarding the influence of increasing water temperature on the dynamics of bacteria and other microbes in the Arctic Ocean.

For marine ecosystems, another important issue is ocean acidification. In the Arctic Ocean, when the sea-ice cover that previously prevented absorption of CO_2 decreased, acidification proceeded rapidly (Yamamoto-Kawai et al., 2009). As acidification has progressed, some marine areas are already able to dissolve calcium carbonate, and the areas in which this condition exists will inevitably expand in the future. There is concern that plankton and benthic organisms that have shells of calcium carbonate may be damaged, and that higher trophic levels may be affected via food chains. In another case, on the bottom of the shelf under the Chukchi and East Siberian Seas, the seawater is acidified by CO_2 produced from the decomposition of organic matter. Because the supply of terrestrial organic matter is expected to increase, acidification of the bottom layer could increase even more, and would be expected to influence benthic organisms.

Bottoms of continental shelves, such as in the Chukchi and East Siberian seas, are important sites for study of the cycling of nitrogen and trace elements. Denitrification[29] occurs at the bottom of the shelf, and nitrogen is less abundant in water of Pacific origin flowing into the Arctic Ocean, than is incoming water of Atlantic origin. Therefore, the primary production of the sector of the

[26] Bloom: A phenomenon of explosive growth of phytoplankton caused by the combination of excessive nutrients, plentiful sunlight and suitable temperature.
[27] Ice Algae: The alga that thrives and spreads on the bottom or inside of sea ice.
[28] Brine: Water of very high salinity and high density. In the ocean, it is formed by the rejection of salt from water freezing to form sea ice. The accumulation of rejected salt creates brine that is increasingly resistant to freezing. When released into the water column, its high density causes it to sink to the bottom, unless mixed.
[29] Denitrification: In oceans, the phenomenon in which mainly nitrate nitrogen NO_3^- is reduced to form nitrogen gas (N_2) or nitrogen oxide (N_2O) by the function of bacteria in sea-bottom sediment, and then released to the atmosphere in gaseous form.

Arctic Ocean most influenced by the Pacific Ocean is limited mainly by nitrogen. On the other hand, when sea ice forms over the continental shelf in winter, iron that is essential to primary production is packed and concentrated in the sea ice, and is transferred with the sea ice. In addition, iron derived from sediment on the continental shelf becomes abundant in the dense shelf water (DSW) [30] made by brine rejection during the formation of sea ice, and is transferred to the continental shelf slope with DSW. Trace elements may also be carried to the Arctic Ocean by aerosols. It is thought that the cycling of nitrogen and trace elements changes with environmental variation, and that this is a key factor controlling future primary production in the Pacific-influenced sector of the Arctic Ocean.

b. Future studies

It is necessary to acquire observation data that have no regional or seasonal biases in order to clarify the cycling of carbon, nitrogen, and trace elements, as well as the changes related to them, in the Arctic Ocean. This will also contribute to understanding of the roles of the pan-Arctic region in the global climate system. For this, there is need for observations carried out by multiple vessels, with international collaboration, to acquire the desired data over broad areas. It is expected that mesoscale observation will be able to resolve ocean eddies, but, because time is limited, it is necessary to focus on the target areas now using satellite observation and numerical models. Until now, Japan, the United States, Canada, Russia, China, and Korea have contributed to the Distributed Biological Observatory [31] and carried out repeated observations in the Chukchi Sea using multiple ships. Japan and Canada jointly observed a wide area of the Canada Basin, and have also contributed to the research results described previously.

There are still data blanks, particularly on the Siberian side of the Arctic Ocean, within the Russian EEZ, where the most dramatic biogeochemical changes in the world occur. In addition, data are insufficient in the region of the Canadian Archipelago where thick ice prevents in-vessel observation. Furthermore, it is necessary to acquire data that are not provided by summer ship observations, by observation from winter ice camps, and by long-term observation using sediment traps[32] and mooring systems[33]. It is also necessary to evaluate quantitatively the relationship between ecosystems and ocean acidification, by performing culture and breeding experiments, by numerical modeling, from comparison of data from ship observations, and by use of sediment trap and mooring systems. These research activities are expected to be in cooperation with projects such as RUSALCA [34] or AODS [35] in the future, and to be carried out with international collaboration. At the same time, it is important to show Japanese originality by analysis of many items that Japan is able to provide high-quality data, and that Japan leads by cooperation with satellite observation and study with models.

It is expected that new findings on biogeochemistry and ecosystems will be obtained by adopting new techniques, by pushing forward the development of chemical and biological sensors and observation platforms, and by advancement of satellite observation (refer to Theme 9 on the maintenance of the study base). Regarding the chemical and biological sensors, we will determine seasonal variation by attaching them to mooring systems, and by measuring the microstructure of chemical and biological properties (not able to be measured before) by attaching them to a CTD and turbulence meter. Then we should be able to discuss the origin and formation of new water masses. In addition, quantitative analysis of the cycles of nutrients (carbon, nitrogen, and trace elements) will be enabled by estimating their flux in conjunction with measurement by physical sensors. Chemical and biological observations, in open ocean and also on or under sea ice, may be enabled by sensors on profiling floats, on underwater gliders, on autonomous diving machines, and by mounting water sampling devices on them. A system that can observe the flux of nutrients, methane, and trace elements between the bottom sediment and the water just above the bottom, is also necessary for understanding the biogeochemistry of the continental shelf area, and for understanding shelf-basin interaction. Data from satellites, particularly about the distribution of chlorophyll-a (Chl-a), is indispensable to understanding the Arctic Ocean ecosystem. However, there are problems to be overcome, such as the loss of data due to cloud cover, overestimates of Chl-a caused by colored dissolved organic matter (CDOM) from rivers, and poor estimates of subsurface Chl-a maxima. If we are able to obtain time-series data over more extensive regions in the future, this will become a strong tool by which to answer the question of how biogeochemistry involved in ocean ecosystems in the pan-Arctic seas, changes.

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[30] Dense Shelf Water (DSW): Water of high salinity and high density (see Brine) formed at the time of sea ice formation during winter cooling on the continental shelf.

[31] Distributed Biological Observatory (DBO): US-led international project using multiple research vessels to understand marine environmental changes in the Chukchi Sea, Arctic Ocean < http://www.arctic.noaa.gov/dbo/index.html >.

[32] Sediment trap: A funnel-shaped sampling device used to gather settling particles in seawater.

[33] Mooring system: For research, an observation system anchored by heavy weights on the seabed, which floats in seawater, from which sensors are able to measure currents, water temperature, salinity, and other physical, chemical and biological characteristics.

[34] RUSALCA (Russian-American Long-term Census of the Arctic): US-Russian collaborative hydrographic experiments in the Chukchi and East Siberian seas <http://www.arctic.noaa.gov/aro/russian-american/>

[35] AODS (Arctic Ocean Drift Study): International project to scale-up observations and modeling studies to include the Arctic Ocean and sub-polar seas. This is an integrated effort involving a) ship-based cross hemisphere transit sampling; b) three in situ ice camps: one in the Eurasian Basin, one at the ice exit of the Fram Strait, and one in the Southern Beaufort sea ice gyre; and c) a Lagrangian autonomous ice-drift program designed to connect process studies from ‘a’ and ‘b’, and to extend observations to cover a full annual cycle.

Theme 4: Ice sheet / glaciers, permafrost, snowfall / snow cover and hydrological cycle

Abstract

Change to glaciers and ice sheets in the Arctic region affects the regional climate and hydrological cycle, and furthermore, has effects on the global-scale environment including sea level and albedo. Strong collaboration between in situ/ satellite observation and modeling is important in order to clarify the variation mechanism and to improve projections into the future. Moreover, understanding of phenomena such as interaction between calving glaciers and the oceans, and the influence of cryosphere biology and ice quakes also need to be advanced.

Change in the surface layer of permafrost (active layer) is strongly related to snow cover and soil moisture, in addition to warming in the area. When the active layer reaches the level of permafrost ice and melting proceeds, irreversible thermokarst occurs, and resulting in feedback to the climate system through ecological and hydrological processes. In order to clarify these changes, research schemes based on integration of existing permafrost-observation networks, observation of land-surface processes, and support of satellite data and modeling, will all be needed.

Snow cover in the northern hemisphere is decreasing, especially in spring. However, existing information on quantitative and qualitative conditions is insufficient. Integrated research schemes, consisting of combined in situ observation and satellite observation need to be developed. Specific objectives should include improvement of the accuracy of observations of winter precipitation, snow quality and impurities/biological components, as well as improvement of the snow-cover model.

Study of the hydrological cycle in the Arctic region, including land, atmosphere and ocean, is proceeding in each research field, but the current understanding of the interrelationship between the fields is inadequate. Continuation of land and satellite observations, and synthetic study done under collaboration of terrestrial, climate, hydrological, and ocean modeling is necessary. With more data and insights, may come chances to clarify the influences of frozen ground, snow cover, vegetation, rivers, and meteorological conditions on the hydrological processes in the pan-Arctic terrestrial region, and on the sea-ice formation and material cycle in the Arctic Ocean.

Q1: Will the change in ice sheet and glaciers accelerate?
Q2: How will the permafrost change interlink with climate change?
Q3: How is the snowfall and snow cover of the Arctic Region changing?
Q4: How will the hydrological processes in the Arctic change?

Q1: Will the change in ice sheet and glaciers accelerate?

a. Background of the research

(1) Mass change of the Greenland ice sheet and its mechanisms

Greenland holds 10% of the ice on Earth. The ice mass showed clear decrease after year 2000, and the loss of mass has been accelerating (through 2010). The rate of mass loss was 200 Gt a^{-1} from year 2000 to 2010, and this is equivalent to a sea-level rise of 6 mm annually (Shepherd et al., 2012). The change in mass occurs mainly due to the following processes.

(1) Accumulation due to snowfall
(2) Loss due to melting
(3) Ice loss at the terminus of the calving glacier (loss due to iceberg runoff and melting by the ocean)

From recent observation, the contribution of (2) seems to be predominant, but (3) seems to be increasing. On the other hand, (1) also seems to be increasing, but not enough to compensate the losses from (2) and (3).

(2) Mass change of glaciers/ice caps (GICs) and its mechanisms

The GICs in the Arctic are distributed widely in Canada, Greenland, Alaska, and the Russian and Svalbard Archipelagos. Their total mass is estimated to be 200 to 300 mm sea-level equivalent. This amount is smaller than the Greenland ice sheet, but due to the rapid change in these GICs, they are considered important for sea-level rise. In particular, changes from 2003 through 2009 in three regions (Arctic Canada, Greenland area, and Alaska) were especially large, and accounted for more than half of the world glacier mass loss during that period (Gardner et al., 2013). Changes in mass are determined mainly by the balance between snowfall and melting, and mass loss at the terminus comes in the form of calving. Since a number of calving glaciers exist in the Arctic, and they show relatively larger changes compared with non-calving glaciers, calving there contributes significantly to ice loss.

(3) Reconstruction of present ice sheet/glacier change by numerical model

Numerical models to simulate ice sheet/glacier are generally composed of various sub-models. The models are usually simplified depending on the objective of the

Photo 1: Calving glacier flowing from the Greenland Ice Sheet to the ocean (Photo: Shin Sugiyama)

study, the glaciers of interest, and the predominant processes involved. Although a high-resolution glacier-flow model using full Stokes equations became applicable due to the effort of Japanese scientists in recent years, numerical experiments covering extended periods, such as glacial-interglacial cycles, is still difficult. At the present stage, computationally less expensive models are made usable by assuming relatively simple approximations of ice dynamics. The most important uncertainties in the calculation of glacier flow, involve basal sliding and calving. Presently, empirical methods are used for these processes since observations are difficult.

(4) Influence of the growth of glacier microbes on ice sheets and glaciers

The albedo of snow and ice surfaces has decreased in the Arctic due to the activities of microbes, resulting in increased melting on ice sheets and glaciers. Photosynthetic microbes such as cyano-bacteria and green algae live on the glacier surface even in cold environments. The organic matter made by these microbes changes to dark humus, which along with mineral particles, soot, and microbial remains, may form cryoconite, a dark material that may concentrate on the surface of glaciers. When this dark cryoconite is plentiful, it lowers the albedo of the glacier surface (Takeuchi et al., 2001). Albedo lowering was studied in Asian mountains mainly by Japanese researchers, but it has been found, in the recent years, to be affecting the bare ice area of the Greenland ice sheet (Yallop et al., 2012).

(5) Increase of glacial earthquakes

Glacial earthquakes are seismic events accompanying glacial sliding, ice fractures, and calving from the Greenland ice sheet, especially at its periphery (Ekstrom et al., 2006). Since the frequency of glacial earthquakes has increased recently, and their occurrence shows seasonal variation, it is assumed to be associated with melt water flowing onto the bases of glaciers. This appears to lubricate and thus increase the speed of a sliding glacier, and consequently increase the rate of calving at its terminus. The frequency of glacial earthquakes peaked in 2005 and decreased afterwards, but is now increasing. This increase is more significant in the northwestern region of the ice sheet, according to measurements in which Japanese researchers are taking part.

b. Key Question: Will change in the ice sheet and glacier accelerate?

(1) Uncertainty in the mass loss of the ice sheet, glaciers and ice caps in the future

The future variation of the Greenland ice sheet is determined by the amount of snowfall, the amount of melting (snow and ice), and the amount of calving from calving glaciers. Melting is considered to be increasing due to the temperature rise in the Arctic and albedo lowering of snow and ice surfaces. On the other hand, the estimation of future snowfall, and the frontal ablation of calving glaciers, is not clearly understood. Snowfall might increase in response to the warming climate, and might exceed the mass loss from surface melting and calving. There is also a possibility that the on-going acceleration and recession of calving glaciers will end at some time in the future. Uncertainties related to ocean temperature and circulation also complicate evaluation of future changes in the mass of the ice sheet.

Under the present warming conditions in the Arctic, the mass of the GICs there is expected to decrease. Because the GICs respond more quickly to climate change than does the ice sheet, it is important to estimate its future rate of mass loss. It is not clear whether the previous rapid loss of mass continues at the calving glaciers, which are presently showing large changes. This is partly because the interaction of calving glaciers with the ocean is poorly integrated with knowledge of the ice sheet.

(2) Uncertainty of influence on sea-level change and effort for estimation

It was pointed out that GICs have a larger influence on sea-level change than do large ice sheets. Accurate estimation of the extent of GICs all over the world is difficult, but more and more reliable numbers are being reported, based on gravity measurements and elevation measurement by ICESat (Gardner et al., 2013). These results showed that the recent mass loss of GICs in the Arctic has had a relatively large influence on sea-level change. Ice mass loss is large particularly great in Arctic Canada, Alaska, and the Greenland coastal area, which accounts for a significant portion of global mass loss from GICs. Therefore, it is necessary to observe these changes at high resolution, and to be able to predict future changes. In recent years, glacier mass change has been calculated globally based on regional mass balance and parameterization of glacier area and volume.

The contribution of the Greenland ice sheet to sea-level rise is also increasing, as shown by satellite observations. There are projections of ice-sheet-mass loss using numerical models, such as those based on surface-mass-balance calculation (generally assuming fixed ice-sheet dimensions), and those coupled with ice-flow models. For example, the contribution of the Greenland ice sheet to SLR was estimated to be 2–13 cm from 1980 to 2099, by Yoshimori and Abe-Ouchi (2012). It is projected to be 16 cm by year 2100, by those of the Ice Sheet Inter-comparison Project (SeaRISE), using a warming scenario equivalent to RCP8.5.

(3) Interaction between the ice sheet and ocean/solid earth and influence on the acceleration of calving from glaciers

There is a need to understand the interaction between the ice sheet and the ocean, due to the strong acceleration and recession of the calving glaciers in Greenland. Recent observations on the Greenland coast suggested that a rise in ocean temperature is driving the change of calving glaciers. Furthermore, melt-water discharge from the ice-sheet changes ocean currents, and sediment and chemical inclusions in the melt-water affect the marine ecosystem. Key processes controlling change of calving glaciers include forcing from the ocean to the ice-sheet (e.g., melting of a glacier in the ocean at the calving front), and in turn, forcing from the ice-sheet to the ocean. These should become more significant if the ice-sheet mass continues to decrease.

Glacial earthquakes in Greenland were identified in the 21st century, but remain poorly understood. By better understanding this mechanism, the frequency and mode of glacier earthquakes might be used to study glacier dynamics. Further studies will enable us to find relationships between on-going climate change and temporal variation of glacier-earthquake frequency, and to provide new information related to other glaciological, meteorological and geophysical processes. By comparison and coordination of glacial earthquake data with climate modeling and paleo ice-sheet studies, the effect of climate change on the Greenland ice sheet may be assessed more accurately.

(4) Ecological change of ice sheets and glaciers and its influence on albedo and ice flow

Albedo decreases under the influence of red snow phenomena, caused by the occurrence of green algae. This enhances snow surface melting, not only in the ablation area of glaciers, but also in areas of accumulation and seasonal snow cover. Such albedo decrease due to snow microbes is not as well understood as for black carbon (soot) and mineral dusts, but microbes may also accelerate change of the Arctic ice sheet and glaciers. Therefore, there is a need to advance our quantitative understanding of the influence of environmental change, such as global warming, on the ecological conditions on glaciers, and specifically, their influence on the albedo of the snow surface.

c. Future ice sheet and glacier studies (direction, content and method)

(1) Quantification of the ice sheet and glacier changes, and understanding of the driving mechanisms, using in situ and satellite observations

Satellite measurements are the most effective method for monitoring both the Greenland ice sheet and the GICs there. Detailed measurements of surface elevation changes are possible using DEMs generated from stereographic visible-image pairs and SAR data, as well as satellite altimetry. Changes in the position and areal extent of each glacier terminus can be detected in satellite images. Furthermore, the speed of ice flow can be measured using the image correlation method or interferometry of SAR images (InSAR), and change in ice mass can be measured using satellite gravimetry. Technical development of satellite sensors in Japan has contributed to these satellite observations, and it is important to continuously develop sensors and improve data processing tools for future observations.

Field measurements remain important because of the high temporal and spatial resolution of in situ data. In fact, many measurements are possible only in the field (e.g., englacial and subglacial measurements and sampling). Furthermore, in situ data is important for calibration of satellite data and as input data for numerical models. More efficient and higher quality measurements are required for the northwestern part of Greenland, the Russian Arctic, and Alaska, where Japanese researchers worked actively and achieved progress, in the past.

(2) Improvement of the numerical modeling of the ice sheet and glaciers

Numerical modeling of glaciers requires adequate development and improvement of models according to the objectives of the study. Simplification and parameterization are essential to manage the number of glaciers needed to estimate the influence of the mass-change of Arctic glaciers on sea level. On the other hand, refinement of process models and higher-order assumptions are needed, in order to estimate glacier variations more accurately, and to understand the mechanisms causing abrupt changes of calving glaciers. Coordination between satellite-data analyses and field observations are indispensable for validation and improvement of numerical models. Bed geometry, surface mass balance, and flow velocity data are particularly important for further development of numerical models.

Numerical modeling is important for studies on the ice sheet as well. Adequate development and improvement of models is needed, that relates to the temporal and spatial scales under consideration. Key issues in the field of ice-sheet modeling include

(1) Calibration of models by comparison of modeled and observed, present-day ice-sheet geometry,
(2) Improvement of processes related to surface-mass balance,
(3) Improvement of basal hydrological processes and ice flow, and
(4) Coupling with Earth-system models, including ocean and solid land.

Observational data should be used effectively for the calibration of the models. It is also important to include adequate interaction between climate and the ice sheet, in order to reproduce global-scale climate and ice-sheet variations (Abe-Ouchi et al., 2013). Effort is needed to reproduce accurately changes in surface-mass balance, and interactions between calving glaciers and the ocean (e.g., melting of ice fronts in the ocean). For example, estimates of surface-mass balance could be improved by developing a regional meteorological model of Greenland, using observational data.

(3) Ecological change on the glacier and its influence on climatological components

Studies on the quantitative evaluation of the growth of microbes, and its effect on decreased albedo, are necessary to explain the accelerated melting of glaciers and snow cover by the activities of snow microbes. First, a microbial growth-process model should be developed based on the physical and chemical conditions of snow and ice surfaces. Next, the optical characteristics of microbial products should be measured and then included in a snow/ice albedo physical model, together with black carbon and dust. Such an albedo model could be used to compute accurately the heat balance at the surface of a glacier, and its mass budget. Along with such studies, long-term satellite observations on spectral reflectance, and in situ monitoring of microbe communities, are also needed to monitor temporal variations of surface albedo and microbial growth.

(4) Status and projections of the interaction between ocean and ice sheet

The importance of the interaction between the Greenland ice sheet and the ocean is recognized. However, more observations are needed on the Greenland coast to develop a system including both in situ and satellite observations. The physical properties of ocean water, ocean circulation, and sea-ice conditions in the fjords of the calving glaciers are especially important; because they are suspected of being the drivers of recent rapid variation of glaciers. Cooperation with polar oceanographers is crucial for installing mooring buoys, and for measurement and sampling by research vessels. Furthermore, more satellite observations and better numerical modeling of coastal ocean processes are needed as well.

The Greenland Ice Sheet monitoring Network; (GLISN), a long-term seismic monitoring program on the ice sheet, was organized by an international research group as a program for the post-IPY period. Japanese researchers had already established a seismological observation site (ICE-S) on the ice sheet in 2011, in cooperation with the earthquake observation network of the USA (IRIS) (Toyokuni et al., 2014). We will enhance glacier-earthquake-monitoring activity by integrating our data with those of the GLISN observation network. These data are used to position the origins of earthquakes within the ice sheet, and to describe related fault parameters, by the determination of accurate hypocenters and earthquake mechanisms. Herein is a unique opportunity to study the influence on global warming of glacier earthquakes and their mechanisms. New data sets and interdisciplinary viewpoints will be provided to study the response of the Greenland ice sheet to climate change.

Q2: How will the permafrost change interlink with climate change?

a. Background

(1) Permafrost change due to global warming

Permafrost is defined as soil or ground that remains below the freezing point for at least two consecutive years, and this condition exists on 20% of global land. In contrast, soil that freezes in winter and thaws completely in summer is called seasonal frozen ground, and this condition exists on 60% of global land. Temperature observations during recent decades indicate a general trend of warming permafrost. This warming (increased temperature) has been greater in severely cold regions with continuous permafrost zones at high latitudes. There are sites in the Russian and Canadian Arctic, where the increase has been more than 1 °C per decade. Strong temperature rise, and thawing of permafrost, is occurring at discontinuous and sporadic permafrost zones at their southern limits, and the boundary between continuous and discontinuous permafrost is tending to shift northward (Romanovsky et al., 2010).

(2) Deepening of the active layer

In permafrost zones, the surface soil layer that freezes in winter and thaws in summer is called the active layer. The active layer thickness (ALT) is approximately 0.5 and 1.5–3.0 m in the continuous and discontinuous permafrost zones, respectively, in Alaska, and 0.4 and 1.0–3.0 m in the tundra and taiga areas of the permafrost zone in Eastern Siberia. The ALT depends greatly on the summer air temperature (accumulated warmness), and snow depth in the winter. The long-term tendency of ALT differs among regions. For instance, it is getting shallower, despite rising air temperature, in North America. This reason is possibly due to intensified freezing caused by decreasing snow depth in winter, and drying of the soil in summer, which suppresses thawing (Park et al., 2013). On the other hand, the ALT is getting deeper due to warming and increased snow depth in Siberia (Park et al., 2013). The variation in ALT depends much on hydrological conditions, such as snow depth and soil moisture, as well as temperature variation.

Photo 2: Thawing of permafrost around the alas (thermokarst lake) near Yakutsk, Eastern Siberia (Photo: Yoshihiro Iijima)

(3) Active layer variation and hydrological / ecological change

Variation in the active layer induces change in ecological and hydrological processes. When ice-rich permafrost melts, and the melt-water is discharged, a form of land subsidence called thermokarst occurs. Subsequently, lowlands expand and extensive regions of thermokarst lakes are formed. The formation of thermokarst lakes is presently active in the continuous permafrost zone, while lowering of the groundwater level, with drying due to disappearance of the permafrost, is taking place in the discontinuous zone. Increased collapse of landforms facing rivers and coastal areas has been reported in the continuous permafrost zone of North America. This is caused by increased soil instability due to melting of ground ice (Jorgenson et al., 2006).

In Eastern Siberia, the ALT has deepened in the first decade of the 21st century (Iijima et al., 2010). This is mainly due to high winter snowfall and summer rain occurring continuously for several years. This has enhanced thawing of the surface layer, and kept a high level of soil moisture within the active layer. Subsequently, the ALT became deeper, and extensive death of larch trees occurred because of the greatly increased water content within the active layer (Ohta et al., 2014).

In the 2000s, the soil moisture level in East Siberia increased by ca. 10 mm per year, based on GRACE satellite data (terrestrial water storage estimated by gravity change measured by twin satellites, Ogawa et al., 2010). Thus, this inter-annual trend is likely due to increase in the number of thermokarst lakes, and of soil moisture within the active layer, in regions of boreal forest.

(4) Observation system for the active layer

The measurements of permafrost temperature and ALT are presently conducted in the pan-Arctic by the GTN-P (Global Terrestrial Network for Permafrost) and CALM (Circumpolar Active Layer Monitoring Network). However, the present pan-Arctic network is insufficient in terms of integrated observation sites that could supply data adequate for understanding comprehensive interactions between conditions affecting permafrost, climate, soil and vegetation.

b. Key question: How will permafrost change in conjunction with climate variation?

(1) What and how does active layer thickness change?

Earlier spring thaw, and later autumn freezing, effectively manifest variation in ALT under conditions of warming air temperature. The ALT is also affected by the timing of the disappearance of snow cover in spring, and by changes in soil moisture due to summer precipitation. An ice-enriched layer, ranging from several tens of cm to 1 m, is formed at the boundary between the active layer and the lower permafrost layer, because this zone provides physical conditions favorable for ice growth. This layer is called the transient layer, and may alternate from thawing to freezing over sub-decadal to centennial time-scales (Shur et al., 2005).

This transition layer exists between the active and permafrost (Yedoma) layers, and is typified by the presence of a large ice body (ice wedge). The thermokarst process involves melting of soil ice and subsequent subsidence, but tends to be delayed in places with a transient layer, since more latent heat energy is needed to thaw the ice wedge. However, after the entire transient layer is thawed, an irreversible process of melting permafrost will be manifested. Thus increasing heat conduction, due to changes in climate and environment, leads to abrupt deepening of the active layer. However, we do not have enough observational data yet to illustrate these degradation processes.

(2) Influence of the melting and deepening of the active layer

We should pay attention primarily to clarification of feedback processes induced by "warming of the permafrost" and "deepening of the active layer" as the permafrost portion of the environment changes. These appear to have occurred during the past one or two centuries, and see likely to continue through several tens of years into the future. Most environmental change (increased runoff, decline of boreal forest, and emission of methane gas from expanding lakes) that occurs in conjunction with the occurrence of thermokarst in the pan-Arctic region, will all be caused by "deepening of the active layer", and a great deal of observational knowledge has been accumulated. For example, near-surface permafrost has become 'talik' (a non-freezing layer throughout the year) due to deepening active layers in various areas of Siberia (Hiyama et al., 2013). Key research to clarify the influence of changes in permafrost on climate change should therefore, aim to understand the successive processes of permafrost in the larger eco-hydrological system. These would be expected to induce change in the distribution of water (areal and depth) and wetlands. Such a case was recently reported in Eastern Siberia; that is, extensive boreal forest mortality induced by deepening and wetting of the active layer, due to increased precipitation.

(3) Relation between change in the active layer and large-scale hydrological cycles

Variation in ALT changes the vertical profile of soil moisture, and thus changes the hydrological characteristics of the land surface. For example, regional hydrological cycles and ecological systems would be expected to be influenced by the drying of the surface layer due to deepening of the active layer. In fact, a substantial decrease in the area and number of lakes was apparent at the discontinuous and southern limit of permafrost zones. Recent climate change also induces different patterns of precipitation and evapotranspiration. This affects the terrestrial water balance through change in the thermal regime within the active layer. Since permafrost and the active layer, act as a buffer layer affecting soil moisture and ground water transfer, variation of the water balance at the land surface shows a certain time lag, in relation to the atmospheric water cycle. For example, gravity change data from the GRACE satellite showed an inter-annual anomaly of terrestrial water storage in the surface layer, with one-month temporal resolution and several hundred km spatial resolution. However, understanding the permafrost-hydrological process is hindered by a lack of the in situ observations needed to resolve the heterogeneity of the permafrost structure at river-basin scale.

c. Future study on surface variation of permafrost: Direction, content and method

(1) Understanding the evolution of the active layer and the thermokarst development process

Identification of the spatial distribution of soil moisture dynamics in the active layer, and ice content in the permafrost layer, is indispensable for discussion of the stability of change in the active layer, and thawing of the permafrost under conditions of Arctic warming. Measurement of soil temperature is basic practice for monitoring permafrost, but we should refine it to include measurement of the active layer, transient layer, and upper part of permafrost; and then add sites over an expanded area, to better depict the extent of thawing. Obviously, the moisture conditions in the active layer and ice content in the permafrost layer need to be measured as extensively as the soil temperature. Sample cores from the near-surface layer of the permafrost are also important for making clear the range and frequency of ALT variation in the past by glaciological analysis, stable isotope ratio and chronological analysis. Prompt implementation of in situ survey measurement of ground subsidence and morphological change are also needed.

(2) Understanding of the influence of active layer deepening on the surface environment, hydrological cycle, and climate change

Continuous observation at an integrated observation site (super-site), and refinement of land surface models based on those data, are needed in order to understand how changes in near-surface permafrost, and the active layer, affect the surface environment and how these changes feed back to the climate system via changes in the heat, water, and carbon balance. Satellite remote sensing and application of regional land surface models, are effective for understanding the related phenomena of extensive active layer deepening induced by forest fire, and climate change (wet and dry anomaly). Temporal and spatial variation of permafrost thawing, may be indirectly detected using satellite data obtained from microwave and optical sensors, to quantify devastation of vegetation from active layer deepening and thermokarst development. The latter affects variation in the area and number of thermokarst lakes. However, satellite sensors that could directly measure ALT do not presently exist. In the future, development of new satellite sensors and algorithms that could estimate the sub-surface temperature profile is needed, in conjunction with hydro-climatological study through the development of synthetic analysis methods to detect variation in ALT by applying numerical models, in situ measurements, and satellite observations.

(3) Establishment of an integrated system for observation of active layer variation

Measurement of permafrost temperature should follow the guidance of GTN-P instruction. In addition, we should make efforts to develop suitable instruments with durability and accuracy appropriate for cold, remote sites. There is need for a new network to cover key regions where thermokarst processes are active and urgent need for a standardized scheme for international observation. Simultaneous observation of meteorological, ecological, and hydrological elements intimately related to active layer variation needs to be established. Japan has taken a leading role in cooperative collaboration in Eastern Eurasia, as well as international collaboration in Alaska and the Canadian Arctic. These regions are possible areas for intensive research where Japanese research groups should contribute. Support of research by bilateral (or international) science agreements should be pushed forward for implementation of the above steps, to ease efforts to access and set up infrastructure in each country.

Q3. How is the snowfall and snow cover of the Arctic Region changing?

a. Background

(1) Snow cover of the pan-Arctic region

The area under spring snow cover in the northern hemisphere, has decreased substantially in the latter half of 21st century, especially after 1980. The extent of snow cover exhibits differences in inter-annual variation, depending on the month. Moreover, the degree of contraction (relative to previous coverage) is largest in spring and summer, and differs regionally (Brown and Mote, 2009). On the other hand, the extent of snow cover is generally decreasing, or showing no change, in the last 40 years in the southern hemisphere. The main cause of the decrease in snow cover is the rise in temperature. This is both decreasing the snowfall and shortening the period of snow cover, while increased precipitation is generally the cause for areas showing increased snow cover (Lemke et al., 2007).

(2) Observation accuracy of high latitude precipitation

The precipitation data lack reliability in the Arctic region due to low number of stations and low accuracy of observations. Clearly, improvements need to be made (Goodison et al., 1998). The satellite for the GPM Project was launched in February 2014, and estimation of precipitation is expected to improve for regions up to 65 degrees north. In particular, the data for southern Siberia and southern Alaska should be improved. A project called SPICE (Solid Precipitation InterComparison Experiment), of the WMO, was implemented to operate from 2013 to 2015, to clarify the present condition and to improve observation accuracy of snowfall and snow cover. The Japan Meteorological Agency (JMA), National Research Institute for Earth Science, Disaster Prevention (NIED), and National Institute of Polar Research (NIPR) are cooperating in this project, and have set up observation sites at Jyoestu City, Niigata Prefect, and at Rikubetsu City, Hokkaido.

Photo 3: Snow cover over which depth hoar layer developed at a forest site in Siberia (Photo: Yoshihiro Iijima)

On the Greenland Ice Sheet, surface elevation and ice mass is measurable using satellite, but snowfall is only measured by automatic equipment as a change of snow depth. Deductions of spatial and temporal variation of snowfall is done using a model.

b. Key question: How is the snowfall and snow cover changing?

(1) Temporal and spatial variation of the period of snow cover, snow depth and water equivalent

It is very clear that the duration of snow cover is shortening on the scale of the northern hemisphere. However, more, and more representative, stations are needed, since the variation of snow depth and snow-water equivalent differs regionally. Setting up ground-based observation sites, large-scale derivation from satellite observation data, and their integration with predictions of precipitation by models, are all needed. It is thought that the reliability of observations of snow-cover distribution and areas of ablation is high, but the reliability of snow-water equivalent is still low, in spite of the development of microwave satellite-observation methods. The derivation of the amounts of snow in forested areas remains an unresolved issue.

(2) Quantitative evaluation of snow impurity, snow texture, and microbes

Quantitative evaluation of snow impurity, snow texture, and microbes have only been undertaken at several sites, and only as case studies. There is a need to understand observations of these factors at an Arctic scale. Based on such necessity, research directed to derive snow impurity and grain size from satellite observations is being done, but more land-based calibration data need to be accumulated.

(3) Interaction between snow cover and changes in the albedo of soil, ecological systems, and the atmosphere

Winter precipitation is not decreasing, although a decrease of snow cover in spring is occurring. This means that snowmelt is intense in springtime. Furthermore, an increase in atmospheric water vapor due to sublimation from snow-covered areas is indicated (Sugiura and Ohata, 2008). As for the study on the interaction between snow cover and changes in the albedo of soil, ecological systems, and atmosphere, integrated in situ observation of precipitation, snow cover and land-surface processes is needed, along with integration of this new data with models.

c. Future study of snowfall and snow cover: Direction, content and method

(1) Observation and modeling of snowfall and snow cover

There is need to initiate high-accuracy measurement of precipitation (especially snowfall), along with the physical parameters of snow cover for the Arctic Ocean, tundra, boreal forest, glaciers, ice sheets, and ice caps. Then, this data should be combined with satellite data to develop a long-term data archive. There is also a need to develop calibration methods by which past data might also be included in the new data archive. Through these activities, it is possible to understand better past changes in precipitation and snow amount, to prepare boundary conditions, to calibrate climate models, to develop analysis algorithms for satellite data, and to create new satellite sensors suitable for snowfall and snow-cover observation. There is a need to combine the data from new precipitation satellites, such as GPM/DPR, and to improve methods for assimilating atmospheric data, in order to estimate global precipitation by satellite.

Hydrological components involving strong wind and forested areas could be measured by technical development of new observation instruments, and hydrological conditions of the winter cryosphere could be clarified through these efforts. As for snowfall, data over shorter intervals (intensity over hours and minutes) and automatic observation of snow particles are needed. There is need for increased number of automatic observation sites that use lasers for the measurement of snow depth. There is also need to proceed with study of interactions with the ecosystem through ground-based observation of the heterogeneity of snow distribution around vegetation, using interval cameras that have recently come into use.

Also needed is clarification of the interactions between vegetation, soil, snow cover, snowfall and atmosphere, using high-precision, multi-element data, and using these data for calibration of numerical models. As for numerical models, the most pressing need is to improve the snow-cover models, and combine them with meteorological, ocean, and soil models. There is a need to clarify the factors determining snow texture, and these need to be reflected in the snow cover model. Satellite use needs to be advanced, and standard products from snow parameters (i.e., water equivalent, canopy intercepted snow, snow texture, and impurities) should be prepared. As for ground-calibration data, improvement of the precision of estimates of snow-water equivalent, particularly in forested regions, is needed.

(2) Snow on sea ice

Snow on sea ice is a factor deeply related to the growth and melting of rapidly changing sea ice. There is need to understand the role of snow cover and the metamorphism of snow and ice, and to develop observation methods to determine large-scale snow cover. The snow on sea ice is important from the standpoint of apparent thickness, albedo, and thermal conductivity. The satellite observation method for snow on sea ice has not advanced much, and new methods are needed. The snow on sea ice influences the accuracy of observations of apparent sea-ice thickness, so there is need to establish methods for both in situ and satellite observations.

Q4 How will the hydrological processes in the Arctic change?

a. Background

In the Arctic terrestrial region, permafrost, snow and boreal forest play key roles in the hydrological cycle. Rivers in the Arctic are sources of freshwater, nutrients, and organic matter for the Arctic Ocean. An abrupt increase in river discharge harms local residents due to ice jams and summer floods, whereas it is a boon, due to nutrient transport, for people who live by farming or fishing aquatic or marine stocks. In addition, changes in the condition of river ice and permafrost, affect transportation and living conditions in this region. Therefore, changes in Arctic rivers have a large influence on the lives of residents.

Change in the river discharge induces changes in materials of freshwater and terrestrial origin, and also affects sea-ice formation, ocean circulation and material cycles in the Arctic Ocean. The change in discharge is effected by variations in precipitation associated with atmospheric circulation and various terrestrial hydrological processes within the river basin. The Arctic terrestrial region located between mid- and high-latitudes cannot be ignored in the climate system due to the atmospheric linkage between these latitudes. There is concern that changes in terrestrial hydrological processes will affect atmospheric circulation and weather over the region. This is because there is a possibility that changes in water and heat fluxes, and albedo, associated with terrestrial processes might affect temperature in the lower atmosphere. In this case, the contrast in meridional temperature, between the Arctic Ocean and the surrounding land area and also associated atmospheric circulation will be changed.

Photo 4: Lena River in Eastern Siberia: Freshwater gathering from major discharges into the Arctic Ocean (Photo: Yoshihiro Iijima)

b. Key Question: How will hydrological processes change in the pan-Arctic terrestrial region?

(1) Change in river discharge flowing into the Arctic Ocean and its cause

River discharge into the Arctic Ocean has increased in recent years. This is because river discharge from Siberia was large for several years in the latter half of 2000s, although the change in Northern America was small. The influence of dams, thawing permafrost and wildfire have been discussed as causes of the long-term change in river discharge, but the impact of all of these factors are considered to be small compared with the recent changes observed. River discharge is mainly governed by net precipitation, which is the difference between precipitation and evapotranspiration (Zhang et al., 2013). The variation of net precipitation is affected by moisture transport associated with synoptic-scale atmospheric circulation and cyclone activity over the region. In addition, terrestrial hydrological processes (e.g., transpiration from vegetation, change in soil moisture due to thawing permafrost) also affect river discharge. A recent study indicated a relationship between summer base flow and deepening of the active layer (Brusaert and Hiyama, 2012), and a review of the terrestrial hydrological process is important for future work.

Climate models project precipitation increases over high latitudes under conditions of global warming, and river discharge in the pan-Arctic region is also expected to increase over the long term. Therefore, if freshwater input into the Arctic Ocean increases in the future, so also will heat, nutrient and organic matter. A change in the terrestrial hydrological process has the potential to change the source of land-derived materials from the river itself (refer to Theme 3). However, there is large uncertainty in the projections of precipitation increase and regional distribution, and the survey of terrestrial processes at large spatial scales is still not sufficient. There is need to discuss future change, while clarifying the interrelations between terrestrial processes.

(2) Changes in hydrological processes in the pan-Arctic terrestrial region

In the 21st century, snow depth (increased only in East Siberia) has decreased over wide areas of the pan-Arctic region, and some effect on soil moisture and river runoff is expected. In fact, trends of increasing soil moisture over North America and Siberia were observed by the GRACE satellite (Landerer et al., 2010). In addition to the snow amount, variation in the duration of snow cover is also important. The snow duration tends to be shorter in recent years, due to the delay of snow accumulation in autumn, and the start of spring melting tends to start earlier, likely mediated by the recent rise in temperature. The ability of snow to provide insulation that impedes heat transfer between the atmosphere and soil affects soil temperature and soil freezing. This effect results in changes in soil moisture, phenology (seasonal changes in vegetation activity), radiation, and surface-heat flux. There are regional differences in the effects from disappearance of snow. The difference in early summer albedo associated with snow, affects the radiation balance in western Siberia, meanwhile summer snowmelt water affects the ratio of sensible and latent heat in eastern Siberia (Matsumura et al., 2010).

Under the condition of global warming, a large rise in temperature and increase in precipitation over the pan-Arctic terrestrial region, will induce shortening of snow duration, deepening of the active layer, and changes in the hydrological process that are expected to affect soil moisture, evapotranspiration and vegetation activity. The temperature rise will shorten the snow duration, and water vapor increase due to the warming has the potential to change evaporation, transpiration and sublimation in the dry continental inland of eastern Siberia. In fact, long-term increase of evapotranspiration was indicated by observation and model studies (Zhang et al., 2009). It is indicated that, in addition to snowmelt, sublimation is also important in the process diminishing snow in eastern Siberia (Suzuki et al., 2006). The precipitation increase will promote deepening of the active layer and increase of soil moisture. The above terrestrial processes indicate that snow ice is a key factor in this region, and not only the hydrological processes, but also various processes associated with heat balance, are important in the Arctic terrestrial region.

(3) Freshwater budget in the Arctic Ocean and hydrological cycle in the Arctic

Increase of freshwater from the surrounding land area strengthens salinity stratification at the ocean surface, and promotes sea-ice formation due to the low-salinity water layer at the ocean surface. The increase of freshwater supply will weaken deep-sea water formation on long-term timescales, since the freshwater into the Arctic Ocean flows out through the northern Atlantic. To reveal these processes, it is important to understand simultaneous changes in sea-ice formation and ocean circulation in the Arctic Ocean.

The amount of snow on the sea ice will increase under global warming, and this will strongly control the formation and melting of the sea ice. More direct input of freshwater as precipitation, due to rising temperature and expansion of the area of seasonal sea ice, results in low salinity at the surface of the ocean. However, there are few studies about snow on sea ice, and there is need to observe cloud, precipitation and snow-cover processes above the ocean and sea ice (Theme 2). Considering the above points, it is greatly needed to understand better the hydrological cycle, and to evaluate quantitatively the water budget of the entire Arctic region. This should specifically include the Arctic Ocean, pan-Arctic land area, Pacific Ocean, Atlantic Ocean and the atmosphere over these regions.

c. Future change in the hydrological cycle

(1) Enhancement of terrestrial observation sites for better understanding of hydrological processes

For integrated utilization of the observation results, it is needed to promote cooperation with those modeling. To do this, there is need to prepare input datasets (meteorological elements), parameters (information on vegetation and soil), and validation data (ground temperature, soil moisture, photosynthesis). In situ observations in eastern Siberia have mainly been conducted by researchers in Japan and Russia, and they have produced substantial results. However, the winter season has been an observational blank. To achieve year-round observation, there is need to set up and sustain a supersite at which variations of meteorological elements, heat/water/carbon flux, frozen ground and soil moisture, can all be measured. For that purpose, it is requested to establish a bi-lateral or multi-national cooperative structure, with a Japanese research institute responsible for the observations. In Siberia, the candidate sites are Sapasskaya Pad near Yakutsk, Elgeeii near Ust-Maya, and Ol'okminsk along the Volyui River. A domestic cooperative research structure is needed to develop a long-term dataset of combined in situ observation, objective analysis, and downscaling by regional models and satellites, for validation of the hydrological cycle and of extreme events.

(2) Observation of freshwater, organic matter, and heat transports from Arctic rivers, and development of the ocean model

In order to elucidate the relationship between terrestrial hydrological processes via Arctic rivers, and oceanic processes, there is need to set up observation sites in river basins with different hydrological characteristics for the measurement of the amount and timing of river discharge, and of materials of terrestrial origin (refer to Theme A). For projection into the future, there is need to reveal factors determining the timing, quality and the place of inputs of freshwater and materials from land into the Arctic Ocean. This might be accomplished by combining observations of precipitation, evapotranspiration, and soil moisture with modeling. The stable isotope of water provides an index appropriate for understanding the hydrological processes on various time and spatial scales, and its use is an effective method by which to reconstruct past hydrological cycles. Although the discharge data in the Arctic is limited in both period and sites, it is important to continue these observations, and to elucidate the variation of factors by means of water budget analysis, model research, and paleoclimate proxy-data analysis.

Ocean observation and ocean circulation models are effective for evaluating the influence of river discharge on the ocean. There is need to observe spatial and temporal changes in freshwater input and output using moorings and small vessels in coastal areas, and to examine the relationship between heat and materials of terrestrial origin, and sea-ice formation. To evaluate the influence of changes in terrestrial hydrological processes on the freshwater supply into the Arctic and Atlantic Oceans, the ocean circulation, material cycle and ocean ecosystem; it is needed to take account of not only the main rivers, but also freshwater and materials from small rivers, melted water from ice sheets and glaciers, and groundwater. There is also need to develop a sophisticated model that can reproduce realistic ocean circulation.

(3) Integrated understanding of ice sheets, glaciers, permafrost, snow, and the hydrological cycle

For understanding large-scale hydrological variation that cannot be covered by in situ observation, the use of satellite observation, terrestrial models, and objective analysis of data is effective.

Since evaluations of water and heat budgets in the

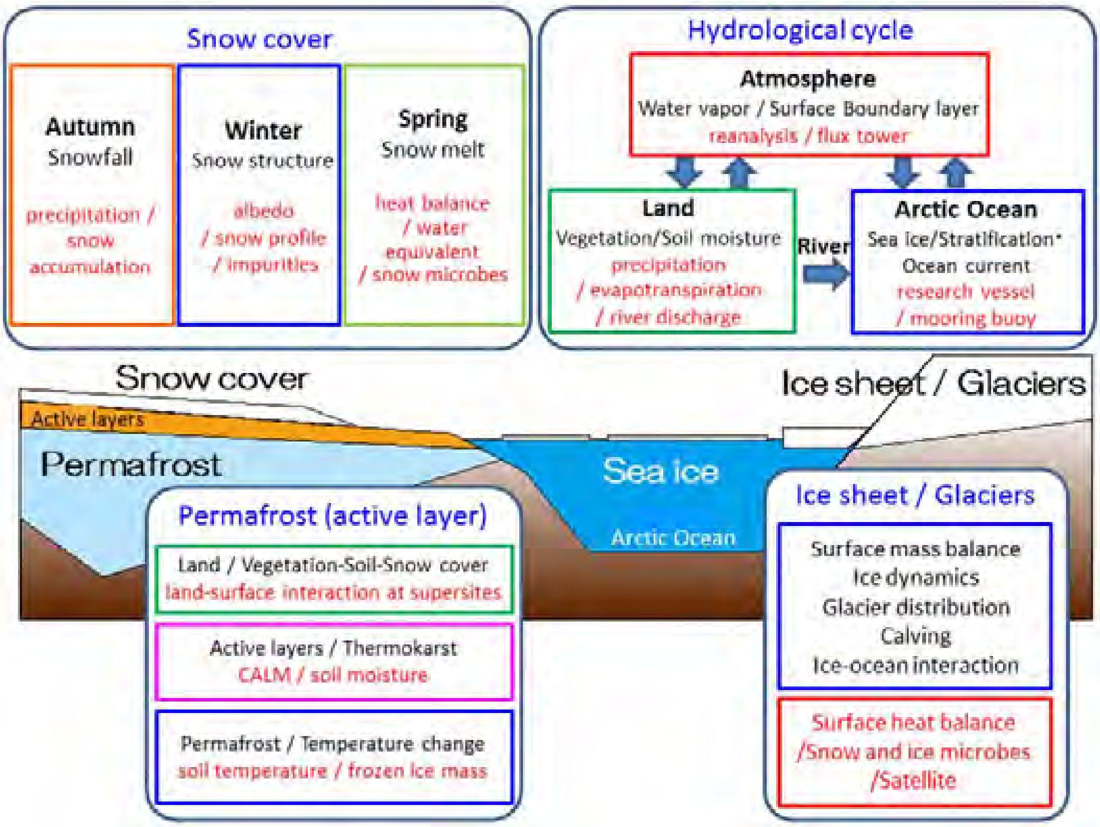


Figure 16: Schematic diagram of the research on ice sheet/glacier, permafrost and snowfall/snow cover variation and hydrological cycle. [Theme 4]

Arctic on spatial scales such as continents and river basins are insufficient, they are important research targets for learning about the Arctic terrestrial hydrological cycle. Recent satellite observations, such as terrestrial water storage from GRACE, snow water equivalent from AMSR2, the high frequency observation of precipitation from GPM/DPR, and high-resolution land-use classification (e.g., water body) from ALOS and ALOS2 are useful for understanding and elucidating large-scale hydrological processes, and for validating models. It is necessary to validate satellite products with in situ, ground-based observations, and this demands continuous in situ observation, especially in the Arctic terrestrial region, for which there is little ground data.

To understand realistic hydrological processes in the terrestrial model, adequate modeling of water infiltration and heat conductivity in terms of permafrost, improvement of snow cover, and snow-storm processes, are required. Moreover, on long-term timescales (decades or longer), a dynamic vegetation model is required, since changes in vegetation affect transpiration and soil conditions. Integrated in situ observation covering these components are needed for validation of the model (refer to Theme A).

Objective reanalysis data is important in climate-change research. Technical development of objective reanalysis has been important for Arctic climate research, for which in situ observation and expression by numerical models are restricted. While the present objective reanalysis includes atmosphere and ocean, there is need to develop techniques of data assimilation for a coupled atmosphere, ocean, and terrestrial climate system in consideration of terrestrial processes. This would be expected to provide a breakthrough for the study of the hydrological cycle in the Arctic.

Theme 5: Interactions between the Arctic and the entire earth

Abstract

In this theme, we discuss the interactions between the Arctic region and global-scale processes recognized by climate system research. In comparison with previous interests, greater attention is now given to Arctic-global interactions, exploring the potential significant effect of atmospheric and ocean circulations in the Arctic on the other regions. One of the examples actively discussed considers the impact of the sea ice decrease on the East Asian monsoon in winter, which may contribute to the improvement of seasonal prediction of abnormal weather. There are many suggestions from various points of view that the Arctic-global interactions may need to be explored well to facilitate our understanding of climate change over the time scale of several years to several tens of years, including global warming.

The elements composing the climate system are described first: i.e., the Arctic-global interactions in each of the tropospheric and stratospheric atmosphere, the ocean, land and the upper atmosphere. The central research of the troposphere and stratosphere covers dynamical processes of various teleconnection patterns related to the westerlies and polar vortex surrounding the Arctic, and also in the climate variability mode such as Pacific Decadal Oscillation. The results of these studies will give a basic understanding on the interactions between the atmosphere and the other systems (ocean, land and upper atmosphere), and also on the climate change expected to occur in this century.

The important research topics in the oceanographic field include water exchange between the Atlantic and the Pacific, deep water formation and the general circulation in the mid-latitudes, all of which require the arrangement of observational infrastructures such as a research vessel and high-resolution numerical models with model verification. In the terrestrial field, considerable attention has been paid to quantitative estimates of the effects of snow cover variability on energy and water balances over large areas, and also the effects of variability in biogeochemical cycles of soil, vegetation and permafrost, in the form of carbon flux and so on. The most active research until now was conducted by field observations and process modeling. However, further basic research is necessary to provide quantitative estimates of the effects of terrestrial processes on climate variability at large scales, including the establishment of an assessment method for the terrestrial processes. With regard to the upper atmosphere, the most important issues would be its variability in the mid- and low-latitudes caused by an energy injection into the polar region from the Sun through the near Earth space, the cooling associated with increasing greenhouse gases, and also the effects of the polar upper atmosphere on the lower atmosphere. A deeper understanding of the roles of the upper atmosphere on the climate system is expected by using ground-based observation networks, satellite observations with multiple sensors on a global scale, and numerical modeling with the inclusion of photochemistry.

Following these approaches, we describe the interactions among the systems introduced above, such as the atmosphere, being remained challenging issues continuously. The troposphere plays an important role in the interactions, due to its location among the others. It can interact with the upper side, the stratosphere and the upper atmosphere, as well as the lower side, the ocean and land. One of the examples referred to at the beginning of this theme was the effect of the sea ice decrease on the East Asian monsoon in winter, which could be led to the feedback from the atmosphere to sea ice.

The effects of the Arctic variability appear in the mid-latitude area, such as the Far East, where climate variability is significant. The research community in Japan is supposed to play a major role in this subject. In fact, the researchers in Japan have made a pronounced contribution to understanding the effects of Arctic sea ice on atmospheric circulation. We are expected to advance our knowledge of the Arctic climate system within the global climate system, on the basis of this research achievement. As a result, more sophisticated and accurate prediction will not be limited to the Arctic climate, but also possible for the global climate.

This theme is formed with the five key academic questions as follows:

Q1: Roles of the atmosphere: Is its variability intensified or weakened for example, the Arctic Oscillation?

Q2: Roles of the ocean: Is the water exchange between the Atlantic and the Pacific intensified? Is the deep water formation reduced? Is general circulation modified in the mid-latitudes?

Q3: Roles of land: How does the variability in vegetation and permafrost have effects on carbon flux and the geochemical cycle? How does the variability in snow cover and vegetation have effects on energy and water balances at large scales?

Q4: Roles of the polar upper atmosphere: What effects does the upper atmosphere in the

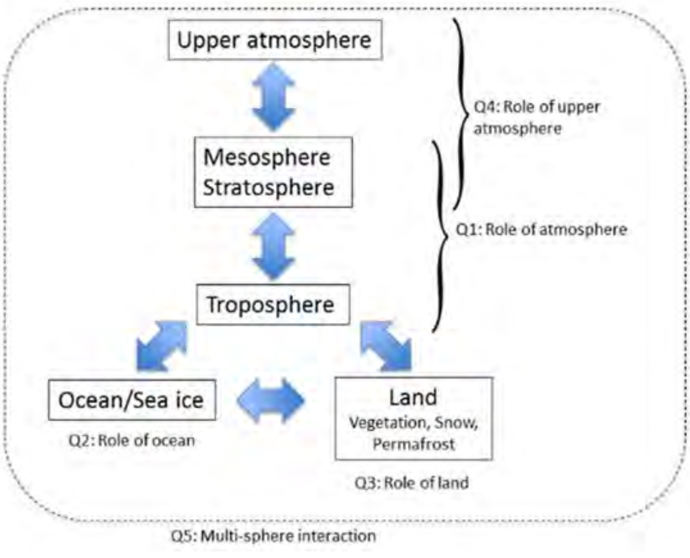


Figure 17: The interactions among the spheres: i.e., the atmosphere, the ocean, land and the upper atmosphere. The mesosphere is the layer defined to be part of the upper atmosphere and immediately above the stratosphere.

polar region have on the lower atmosphere and the whole region of the upper atmosphere?

Q5: Interactions among multiple spheres: Which one is the most influential on Arctic-global interactions, among the upper atmosphere, the atmosphere, snow and vegetation on land, or the ocean?

Introduction

In this theme, we discuss the interactions between the Arctic and other areas of the planet. In the field of climate variability and earth system science, significant attention has been paid to the effects of this topical area on the entire earth, for example through phenomena such as the El Niño Southern Oscillation (ENSO) and La Niña. However, as sea ice declines and as the Arctic environment has been changing rapidly in recent years, growing attention has been paid to the role of a cold source in the Arctic, and to its effects on mid- and low-latitude areas. In fact, several new research results have been published, mostly by research groups in Japan, on the interactions occurring between the Arctic and other areas in the atmosphere and other spheres; for example, sea ice reduction in the Arctic produces effects on the winter East Asian monsoon through atmospheric circulation. This type of research provides insights into extreme weather and climate variability, not only creating academic interest but also addressing social concerns; hence, there is expected to be further progress in this regard. In the following, the interactions between the Arctic and the entire earth are discussed with reference to the atmosphere (including the upper atmosphere), ocean, and land, through scientific questions, Q1–4, and their answers. Finally, in Q5, interactions, including between multiple spheres, are discussed. We hope the discussion here can help guide research by providing an overview of Arctic-global interactions.

Q1: <Roles of the atmosphere> Is its variability intensified or weakened for example, the Arctic Oscillation?

a. Importance and the present status of the research

A teleconnection pattern (or “teleconnections”) denotes particular patterns in atmospheric circulation variability at global scale and could be interpreted as variable modes in westerly and polar vortices around the Arctic. Various teleconnections have been reported, as described here, with these having close relationships with the occurrence of extreme weather. It has also been pointed out by some researchers that teleconnections play an important role in generating climate change over longer time scales of several years to several decades, given their close relationship with climate variability modes according to some researchers. For the past 15 years or so, greatest attention has been paid to the Arctic Oscillation (AO) or Northern Annular Mode (NAM). In addition, the North Atlantic Oscillation (NAO), the Pacific-North American pattern (PNA), and the Western Pacific pattern (WP) are often explored in connection with extreme weather and climate variability. Along the same lines, an emerging state-of-the-art research topic is dynamic connection (or coupling) between the troposphere and the stratosphere. It is quite revolutionary to state that the stratosphere is affected by the troposphere, while the reverse process is also considered to be important. In addition, research efforts are exploring how sea ice decline and snow cover changes produce atmospheric variability, such as in the East Asian monsoon in winter.

b. Future research

Patterns or climate variability modes (such as AO and WP), most of which have not yet been understood, have to be explained for more advanced understanding of atmospheric circulation characteristics and improved predictability. For example, we have no answer to the fundamental problem of the relationship with ocean temperature variability in tropical regions. In addition to these teleconnections, process studies are also important, such as those relating to the “Arctic cyclone”, Beaufort high pressure in summer, storm tracks over the Arctic Ocean, and sudden stratospheric warming frequency.

The dynamic effects of Arctic sea ice decline in the Barents Sea and in other seas on the winter East Asian monsoon and other atmospheric circulation patterns have attracted attention but are not yet well understood. The following are important topics. Sea ice decline has resulted in thermal condition changes near the sea surface, with horizontal scales relatively narrower than atmospheric circulation. Westerly winds are very weak in the lower troposphere of the polar and cold regions. Even though these conditions are not favorable for Rossby wave responses, why does sea ice decline produce large-scale atmospheric circulation? We still do not have an answer to this point. In addition, some basic aspects, such as potential vorticity distribution in the lower troposphere, have not been examined sufficiently, implying the possibility that our understanding does not account for the dynamic effects of sea ice on the atmosphere. Another crucial research topic is the change in effects of sea ice decline on atmospheric circulation variability (such as severe winters around Japan); we also need to understand how a change will proceed, if it does occur. A further attractive topic focuses on the extent to which atmospheric circulation in the Arctic affects extremely cold events in northern Eurasia, as well as its influence on severe 2014 winter in North America.

In addition to the effects of sea ice described above, we should pay more attention to, and can expect progress in research on, the effects of land surface change on atmospheric circulation. Topics include the effects of snow cover decrease in recent years and the future of climate in the Arctic and in low- and mid-latitude areas, as well as frequencies of heat waves and blocking high pressure.

We need to extend research on dynamic interactions between the troposphere and stratosphere. In research on the effects of the troposphere on the latter (not limited to the vertical propagation of Rossby waves), it is becoming clear that atmospheric circulation variability with equivalent barotropic structures also affects vertical propagation, even if this research is still in its infancy. One of the key aspects for dynamic interactions is "modulation of planetary Rossby waves", which may become important not only in Arctic research but also in considering the effects of ENSO on mid- and high-latitude areas, and intra-seasonal shifts in these effects (Fereday et al., 2008; Ineson and Scaife, 2009). On the other hand, it is important to also clarify the effects of the stratosphere on the troposphere. As the basis for this objective, clarification of Lagrangian flows in atmospheric circulation seems to be crucial, requiring theoretical advancement and model development so that flows may be described. In addition, we should extend research targets upwards beyond the stratosphere to the mesosphere and above it. Gravity waves play a central role in consideration of the mesosphere, and we need to research their activities and feedback between waves and mean states.

Researchers in Japan have made significant contributions to research on the effects of sea ice cover variability in the Arctic Ocean on atmospheric circulation variability. As in this case regarding the role of the troposphere-stratosphere in interactions between the Arctic and the entire earth, research results prepared by groups in Japan are the focus of attention from others. The research community in Japan is therefore expected to play a major role in Arctic research.

Q2: <Roles of the ocean> Is the water exchange between the Atlantic and the Pacific intensified? Is the deep water formation reduced? Is general circulation modified in the mid-latitudes?

a. Importance and the present status of the research

In interactions via the ocean between the Arctic and the entire earth, main components are the formation and circulation of North Atlantic Deep Water (NADW), and the Pacific-to-Atlantic route under mixing with various water masses in the Arctic Ocean. Furthermore, the ocean is not only influenced significantly by the atmosphere but must also provide feedback to the atmosphere through the sea surface. We discuss these factors, including a future hypothesis and a proposed research strategy.

(1) NADW formation in the Greenland Sea

Figure 18 schematically shows Arctic Ocean circulation. The circulation is described in the surface (0–200 m depth) and middle (200–700 m depth) layers as follows: low-salinity Pacific-origin water, including river water, stays near the sea surface in the Arctic surface mixed layer and beneath it. Circulation is driven mainly by the density distribution composed of surface water and high-salinity water in the middle layer, which flows in from the North Atlantic Ocean. This ocean circulation and wind-driven advection are the main elements determining sea ice distribution. Once the larger water mass formed in the Arctic Ocean flows out to the Atlantic, the NADW decreases in salinity, and its formation rate decreases in the Greenland Sea. This change occurs over a long time scale, as it has been detected in the Atlantic (Dickson et al., 2002) and is expected to spread gradually to the global ocean.

Let us consider the lower layer. The Norwegian Sea Deep Water, with its origin in the NADW, flows through the Fram Strait to the lower layer of the Nansen Basin and then to the Amundsen Basin, and controls water properties in the Arctic Ocean lower layer. However, based on geochemical tracer data, it has been suggested that this lower layer water receives the effects of the Pacific Water along with the Atlantic Water in the Arctic Ocean middle layer. The water mass flowing out from the Arctic Ocean lower layer is called the Upper Arctic Deep Water and replaces the Norwegian Sea Deep Water.

As global warming continues, sea ice and less saline water flow out of the Arctic Ocean, and the Greenland ice sheet melts faster; hence, the NADW becomes less saline, with less penetration to the deep layer. The NADW has been less saline for half a century, and if this trend continues, the overflow in the lower layer from the

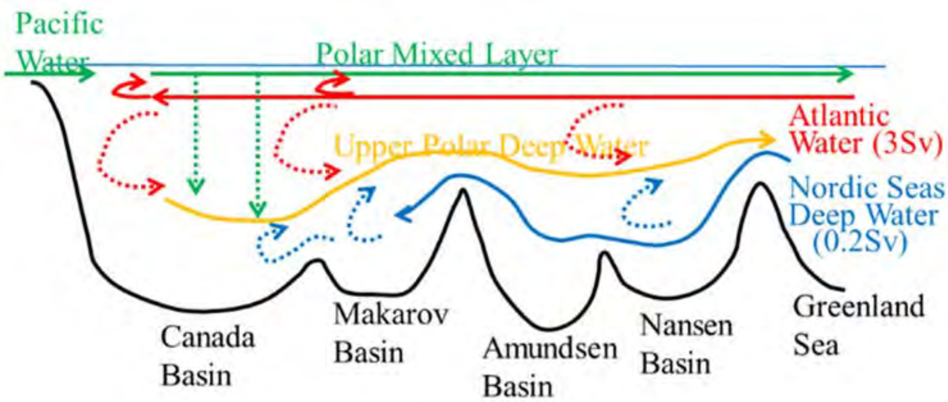


Figure 18: Ocean circulation in the Arctic Ocean on the vertical cross-section from the Bering Strait to the Fram Strait. The total ocean depth is about 4000m, and the Atlantic Water flow in red occupies the depth of 300~700m. The solid lines denote clear currents, and the dotted lines denote mixture of weak currents and mixing. The dotted lines have not been clarified well yet.

Greenland Sea to the Arctic Ocean will reduce in salinity and weaken (blue flow in Figure 18). It is then presumed that the flow from the Canada Basin to the Makarov Basin will become weaker (yellow line in Figure 18), with a direct effect, through an additional component toward the Arctic, on the middle and surface layers above it. Atlantic Water flowing into the middle layer (red line in Figure 18) and Pacific Water flowing into the upper layer (green line in Figure 18) tend to persist longer in the Arctic Ocean and could modify its density distribution and circulation. One of the hypotheses at decadal scale would be a more intense density contrast in upper and middle layers, intensifying Arctic-Atlantic water exchanges in upper and middle layers, and reducing the role of the lower layer in water exchange. Consequently, heat storage in the Arctic Ocean caused by Atlantic Water increases, mixing partly with the lower layer but also with the upper layer. As a result, the extent of sea ice might reduce; this encourages us to quantify its effects. As for global results, the NADW becomes less saline in the global ocean conveyor belt, intensifying mixing with water masses of southward flow in the Atlantic lying above it. It will hence be more difficult to identify characteristic water properties of the conveyor belt.

(2) Sea water passage from the Pacific to the Atlantic

The Bering Strait has a width of only 85 km, and permits the inflow of Pacific Water into the Arctic Ocean at an average flux rate of 0.8 Sv (1 Sv = 106 m3 s−1), about 3% of the Kuroshio transport, although it plays an important role in the climate system of the Arctic and the Atlantic. For example, it has been suggested that the Dansgaard-Oeschger cycle, representing rapid climate change during the last glacial period, occurred in association with the closure of a freshwater flux from the Pacific to the Arctic (Hu et al., 2012). Another report argues that the heat content in Pacific Water may be a main mechanism for the extreme decline in sea ice in the Pacific sector of the Arctic Ocean.

Pacific Water inflow has long-period variations caused by a dynamic sea surface height difference between the Pacific Ocean-Bering Sea and the Arctic Ocean-Atlantic Ocean (Steele and Ermold, 2007); this also results from short-period variations caused by a geostrophic adjustment to wind stress along the coastline in the Bering Strait. With regard to mechanisms of dynamic height variations, we list freshwater inflow to the North Atlantic due to the Greenland ice sheet melting and sea ice fluxes, freshwater storage variations in the individual oceans due to precipitation minus evaporation, heat storage variations in the oceans, and atmospheric circulation variations. Global warming retains both mechanisms, to increase and decrease inflow from the Pacific, and we hence need to pursue research projects of multi-disciplinary observation and modeling to comprehensively cover the atmosphere, sea ice, ocean, and land surface.

(3) Feedback to the Arctic through the atmospheric and ocean general circulations in the mid-latitudes

We note atmospheric circulation changes in the northern hemisphere and also feedback produced by their effects on ocean general circulation in the mid-latitudes. Several different views have been presented on changes in atmospheric variations (AO, PDO, PNA, etc.) over periods of several years to several decades as global warming proceeds. For example, some model predictions show that the AO will shift to positive, with a more intense polar vortex over the Arctic Ocean, and with a mild winter in the mid-latitudes, whereas analysis of observation data often indicates more frequent negative cases of the AO in the 21st century. In the case of phenomena with large natural fluctuations like the AO, we need to consider these carefully, combining modeling and observation data. We should keep in mind the possibility that ocean circulation varies in response to atmospheric circulation variations and carries seawater from the mid-latitude and subarctic areas to the Arctic Ocean.

Common features shown in global warming model inter-comparison are an atmospheric pressure fall over the Bering Sea and a rise in the Atlantic subpolar region during the second half of the 21st century (Chapman and Walsh, 2007). The fall over the Bering Sea leads to item (2) here. In the Atlantic, sea surface temperature lags behind the land surface, pushing air pressure up over the ocean. As a result, it is predicted that transport will increase in the Gulf Stream, and high temperature sea water will extend northward. However, if the atmosphere warms up significantly over the Arctic Ocean, an increase in Atlantic Water may not make a significant difference in the thermal effects of flow into the Arctic. High salinity Atlantic Water will approach the Fram Strait, maintaining the hypothesis that the salinity contrast will control water exchange between the Atlantic and the Arctic Ocean. This hypothesis provides insights into the research strategy.

b. Future research

In contrast to the hypotheses based on principles and prediction models discussed above, some different hypotheses may also be proposed; for example, Arctic Ocean circulation will change to temperature-driven circulation, under rapid water temperature rise. Considering that modeling research may advance not only by elaboration but also by verification of a hypothesis, we should boldly advance a new topic by keeping an objective view. When examining differences in responses to global warming between ocean and land, we need to use earth system models that appropriately represent the atmosphere and ocean, as well as vegetation and snow cover on land.

A research vessel is essential for monitoring circulation and water mass through field observations, even though we have never yet operated a research icebreaker in Japan. This barrier should be overcome. In addition, our pressing need is development of automatic lifting current meters and automatic driving water samplers. Furthermore, we need to use geochemical tracers for monitoring long-term variability.

With reference to circulation between the Arctic and Atlantic Oceans, with their middle and deep layers strongly affected by bottom topography, we require a research plan to develop and verify a high-resolution model. For model verification, we need analyses with a basis in the theory of underlying physical oceanography (for example, relating to vertical mode expansion of velocity profiles in a stratified ocean). The key element is verification using data.

Q3: <Roles of the land> How does the variability in vegetation and permafrost have effects on carbon flux and the geochemical cycle? How does the variability in snow cover and vegetation have effects on energy and water balances at large scales?

The effects of terrestrial processes, which apply to interactions between the Arctic and the entire earth, appear as changes in the carbon balance and in bio-geochemical cycles due to vegetation and soil (including permafrost); and they also relate to changes in energy and water balances due to snow cover and vegetation. It is noted that a bio-geochemical cycle is appropriate to replace a more general term, a material cycle, in the case of land processes. These changes produce variations in atmospheric circulation and in energy balances and the water cycle at large scales (Figure 19), in turn producing effects on other areas and on mid- and low-latitude regions. Quantitative explanation of these effects therefore requires assessment of land surface conditions at large scales, as well as identification of important processes for large-scale variations. However, the high level of heterogeneity of the land surface creates a bottleneck in applying the findings of physical parameter variability and interaction processes from field observations to large scales. This scale-up procedure should be challenged using a combination of approaches (Figure 20), such as (i) a process study at a plot scale (100 m or so) using intensified field observation data with vertical one-dimensional experiments using precise land surface process models, (ii) analyses of variations at regional scale using observation networks and satellite data, along with verification using multiple models at multi-locations, and (iii) examination of effects (including interactions) through sensitivity experiments using regional and global models.

a. Vegetation

(1) Importance and present status of research

Terrestrial vegetation has been attracting attention as a sink for anthropogenic carbon dioxide, through its influence on the global carbon balance and bio-geochemical cycles via absorption and emission of carbon dioxide. In the northern boreal regions, the annual cycle of vegetation activity is so large that it significantly contributes to seasonal variability of carbon dioxide concentrations in the global atmosphere. Through collection of satellite data to monitor the distribution of vegetation and variations in vegetation dynamics at large scale, a trend of increasing biomass over several recent decades has been noted in the Arctic Ocean coastal region of Alaska (Tape et al., 2000). Some global warming projections indicate that boreal forests will extend northward and increase biomass, while carbon storage, including the soil component, will reach a maximum around 2050, maintaining this amount thereafter. There is thus still large uncertainty with regard to quantitative estimation of this trend and its spatial distribution. We have not yet even clearly identified where such sinks exist.

It is well known that changes in vegetation affect energy and water balances through albedo changes. In particular, albedo reduction resulting from plant parts being exposed above snow cover can substantially affect the large-scale energy balance, even if quantitative evaluation of these effects is not yet sufficient. In addition, it has been reported that infrared radiation from plants modifies the radiation balance in the vicinity and that spatial variability in snow depth is produced by snow drift formation and melting by plants (e.g., Liston (2004)). As vegetation varies, the drag coefficient varies, with effects on atmospheric circulation. There has not been significant study of these effects of boreal forests on atmospheric variability modes in mid- and high-latitudes. With regard to latent and sensible heat fluxes within a stable boundary layer on the ground in cold regions, international research efforts have just started exploring relevant mechanisms, using field observations and numerical modeling; i.e., these efforts are expected to produce new results. The interactions between vegetation and the atmosphere should be explored from both perspectives, i.e., the effects of vegetation on atmospheric circulation, and the effects of cloud and precipitation changes on vegetation.

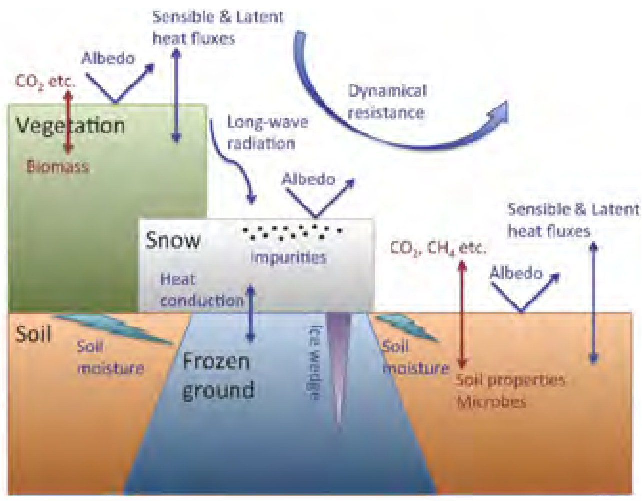


Figure 19: Interactions of the land-surface processes with the atmosphere

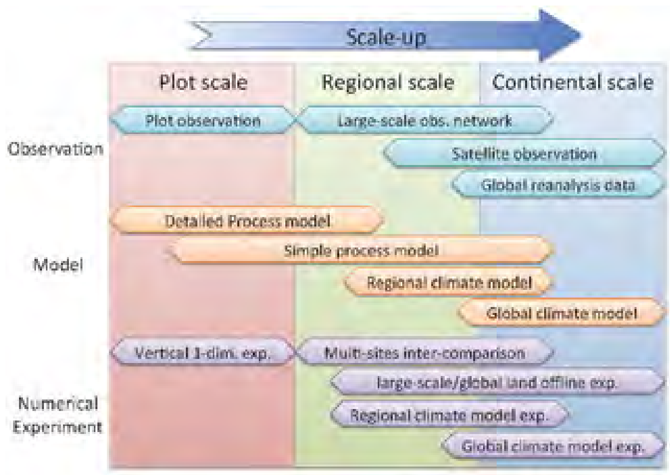


Figure 20: Scale-up of the land-surface processes

(2) Future research

Following process studies of vegetation dynamics through field observation and precise process modeling, it is now desirable to create observation networks over wide areas of the Arctic, cooperating with those present in Asia, Europe, and North America. Since the carbon balance and bio-geochemical cycles have a long response time because of long time-scale variability in structures and vegetation species, we need to construct long-term observation systems and networks to understand the roles of Arctic vegetation on global climate change (e.g., LTER - Long Term Ecological Research). By using the outcome of these process studies to clarify the effects of vegetation on the carbon balance and on bio-geochemical cycles over a wide area, we can extract and standardize processes for wide area assessment, validating them over this area with satellite data, and evaluating the effects of interactions using earth system models.

With regard to albedo effects on vegetation, it would be useful to quantify the dependence of albedo on interactions between vegetation and snow cover, using satellite data of global distribution of vegetation and land surface albedo accumulated over the last few decades. To explore the dynamic effects of vegetation on friction near the land surface and turbulence structures, we need to conduct fundamental research on the mechanisms of a stable boundary layer and of latent and sensible heat fluxes on the land surface. One useful method is Large Eddy Simulation, in which turbulence-induced transport is calculated directly (Beare et al., 2006).

b. Snow cover and permafrost

(1) Importance and present status of research

It has been shown by many studies that snow cover plays a central role in Arctic amplification of global warming through snow-albedo feedback, in addition to having effects on energy and water cycles in mid- and high-latitude areas, such as on monsoon systems (e.g., Groisman and Davies (2001)). Elucidation of snow cover processes has been achieved by field observation and process modeling, as in the case of vegetation. In addition, it is possible to capture long-term variations (including annual cycles) at large scales using accumulated satellite data (Brown et al., 2010); where the latter are also used for verification of global climate models. It is well known that snow albedo, which is the key parameter for climate impacts of snow cover, is affected by snow characteristics (such as snow grain size); and additional effects are also now attracting attention (for example, concentrations of impurities in snow cover, namely black carbon (BC), soil particles, and snow-ice microbes). These effects are now being explored by process studies based on comprehensive field observation of snow, radiation, energy, and water balances, along with quantitative estimates of land surface albedo at large scales using satellite data.

It is well known that snow cover has a large thermal insulation effect and reduces vertical heat fluxes. In recent studies, it has been suggested that the effect of snow insulation is such so as to lead to a slower increase in permafrost in winter under deeper snow cover, with deeper melting within the active layer in summer (Zhang, 2005). Process studies have been carried out for frozen ground with field observation and process models, as an ordinary approach. More attention is now being paid to large-scale effects on carbon balances and on interactions with ecosystems (e.g., deeper melting tends to enhance emission rates of greenhouse gases (GHG), such as carbon dioxide and methane, and to reduce soil moisture available for vegetation, depending on topography). If permafrost melts under global warming and turns into wetland, more methane could be emitted, with worrying potential for positive feedback to the global climate. However, changes in the hydrological environment and in the carbon balance (i.e., emission of carbon dioxide and methane) due to permafrost changes depend on various conditions, such as physical and chemical properties and soil microbial environments. There hence remains large uncertainty in quantitative estimates of these effects at large scales.

(2) Future research

To quantify the climate effects of snow cover and frozen ground at large scales, a core activity involves extending our understanding of processes at plot scale to behaviors at large scales. Satellite data are useful for capturing snow cover area, along with some estimates of grain sizes and wetness from microwave data. However, quantitative verification is necessary to reliably estimate snow properties, such as snow type, depth, and water-equivalent amounts, which are important to quantify the processes of snow variations. Soil moisture near the ground surface is key for terrestrial hydrology processes, and it would be useful to capture its large-scale distribution and variability. There have been many efforts to estimate soil moisture from microwave data, even though quantitative reliability still has to be improved (for example, by removing vegetation effects). A useful approach would be to carry out field observation over a wide area so that we may verify satellite data for physical snow properties (such as grain size and depth), and soil moisture. We will then be able to improve the reliability of satellite data and to elucidate large-scale characteristics and mechanisms of snow cover and surface soil moisture.

Variations in frozen ground and in the associated hydrological environment and GHG emission rate are sensitive to local ground surface conditions (such as vegetation and micro-topography, as well soil properties, moisture, ice wedge, and micro-organisms). Since soil conditions have high heterogeneity and are affected by vegetation, it is difficult to capture a large-scale overview of frozen soil with satellite data, except to estimate the frozen portion at the ground surface. Soil is also one of the major sources of uncertainty in the carbon balance, and it is challenging to compare bottom-up estimates derived through field observations with top-down estimates from atmospheric GHG variations. Various approaches are necessary to understand the effects of soil and frozen ground on the carbon balance and the hydrological environment; these include process studies, understanding of large-scale variations (including establishment of evaluation methods), and quantitative evaluation of uncertainty through sensitivity experiments, using models.

Q4: <Roles of the polar upper atmosphere> What effects does the upper atmosphere in the polar region have on the lower atmosphere and the whole region of the upper atmosphere?

a. The upper atmosphere variations in the mid- and low-latitudes due to energy injection into the polar region

(1) Importance and the present status of the research

Energy enters into the polar upper atmosphere due to particle precipitation and electromagnetic processes from near Earth space, or from the magnetosphere in association with aurora phenomena. In particular, it is well known that global thermospheric circulation and atmospheric waves are intensified or generated by strong Joule heating, which is caused by enhancements of the electric field and conductivity during periods of magnetic storms. Thus, energy input into the polar region is one of the causes generating upper atmospheric variations in mid- and low-latitudes. We are not yet able to quantitatively understand and forecast ionospheric variations.

(2) Future research

It is necessary to quantitatively evaluate the effects of the polar upper atmosphere on changes in the global upper atmosphere, by setting up a wide-area observation network and performing GCM simulations. As the world research community is making progress in multiple-satellite observations of the upper atmosphere, we should also adopt the same strategy in Japan. Please refer to Q4 in Theme 10.

b. Cooling in the upper atmosphere due to greenhouse gas increases

(1) Importance and present status of research

The mysterious noctilucent cloud has been noted in the polar mesosphere in summer since the Industrial Revolution. This cloud is considered to be a typical example of anthropogenic influences that appear in the upper atmosphere in the polar region.

We can recognize ongoing cooling in the upper atmosphere in response to global lower atmosphere warming due to an increase in carbon dioxide; this recognition comes from estimates of secular variations in upper thermosphere density using satellite orbit data, from more frequent noctilucent cloud observations in high and even in mid-latitudes, and also from some numerical simulations. It is not so simple to separate the global warming trend from other air temperature increases in the lower atmosphere, within which various fluctuation phenomena exist. Since atmospheric variations generated in the lower atmosphere propagate to the upper atmosphere with increasing amplitude, quantitative analysis of cooling in the upper atmosphere will lead us to understand warming in the lower atmosphere. It is desirable to examine upper atmospheric variability over medium and long ranges, on the basis of its role as a mirror of the lower atmospheric environment, even though not enough data have been accumulated for accurate estimates of medium and long-term variability. We have also noted another issue, namely discrepancies in estimates of secular variations in upper atmospheric density between satellite orbit data and GCM simulations.

(2) Future research

We need to re-examine historical data, such as reanalysis of satellite orbit data, and to perform calibration of the data set. It would be useful to capture faint signals of upper atmosphere cooling by improving the accuracies of observations and model simulations. It will be indispensable to maintain and further expand uninterrupted observations over a long period. Please refer to Q5 in Theme 10.

c. The effects of the upper atmosphere on the lower atmosphere

(1) Importance and present status of research

It is well known that nitric oxide (NO) is produced in the polar lower thermosphere and mesosphere in association with auroral phenomena and solar proton events. NO is transported downward and also towards the equator by eddy diffusion and thermospheric circulation. The transported NO causes ozone depletion in the upper stratosphere, although we do not yet have quantitative understanding of this (e.g., at which altitude it occurs and the extent to which it causes ozone depletion). The location of ozone decrease has not yet been properly estimated.

(2) Future research

It would be useful to quantitatively estimate the effects of NO, which is produced in association with auroral phenomena and solar proton events in the lower atmosphere, through simultaneous observations from the stratosphere to the thermosphere, and GCM simulations. To support this approach, we need to construct a ground-based global observation network and to observe minor constituents and dynamics in the upper atmosphere from satellites. An additional plan is to develop a precise photochemical model, which can be included in the upper atmosphere GCM, or which can be used in collaboration with numerical simulations. Please refer to Q3 of Theme 10.

Q5: <Interactions among multiple spheres> Which one is the most influential on Arctic-global interactions, among the upper atmosphere, the atmosphere, snow and vegetation on land, or the ocean?

In this section, we attempt to propose research directions for interactions across multiple spheres, namely the upper atmosphere, the mesosphere, the lower atmosphere (stratosphere and troposphere), the terrestrial area, and ocean-sea ice. In addition, we also pay attention to feedback mechanisms between the Arctic and other areas of the globe, the energy balance, and water transport processes.

a. Introduction: research topics to be proposed

Interactions between the troposphere and other spheres are important for understanding multiple sphere interactions, because the troposphere strongly interacts with the ocean, sea ice, and land on the lower boundary, and its circulation is also closely linked with the stratosphere and mesosphere through the upper boundary (Figure 17). The troposphere thus has more partners than other components. It is also true that some spheres interact with each other without the troposphere and have significant influence on the earth system (e.g., ocean circulation and terrestrial hydrological cycles). These questions have posed challenges in recent years and indicate various potential research topics, such as the ones introduced in Questions 1–4. Elucidation of those topics will deepen the understanding of variations in the climate system over time scales ranging from intra-seasonal to several years and decades, also contributing to improved accuracy of seasonal forecasts. These topics are considered to constitute important research challenges.

In recent studies, the effects of the lower boundary on the troposphere have attracted attention as a potential new research direction, as represented by atmospheric circulation variations induced by sea ice decline (refer to Q1 in Theme 5). This direction needs to be tackled from now on. In addition, by combining the opposite direction from the troposphere to the ocean and sea ice on the lower boundary (refer to Q2), we should come closer to describing interaction systems, such as between ocean-sea ice-atmosphere, and between land surface-atmosphere.

b. Interactions between the atmosphere and the ocean-sea ice on the lower boundary

An interesting research topic is elucidation of the process in the atmosphere that interacts with lower boundary components over an intra-seasonal time scale, contributing to improved accuracy of seasonal forecasts. In recent studies, much attention has been paid to the relationship between sea ice decline in the Barents Sea and the East Asian monsoon in winter (refer to Q1 of Theme 5). However, there are open questions about which is the key process of importance, whether a storm track (Inoue et al., 2012) or a stationary Rossby wave response, generating wavy westerlies (Honda et al., 2009). Studies of the effects of sea ice on the atmosphere in other regions have just commenced. It is desirable to also advance research about the effects on the atmosphere resulting from sea surface temperature anomalies in the ocean, and from snow cover distribution in terrestrial areas.

We consider climate variations over time scales of several years to decades to be an important research topic, because these have to be clarified for future projection of global warming. Interactions between the atmosphere and lower components (the ocean and land) play key roles in most of these climate variability modes, such as AO, NAO, PNA, PDO, and Atlantic Multi-decadal Oscillation (AMO), and constitute interesting research targets. These variations need to be understood in terms of interactions with ocean and land to elucidate whether these constitute natural variability or anthropogenic consequences. In particular, oscillatory variations should be reasonably reproduced in climate models, with verification against observation data; then, we could comfortably provide projections of future trends.

We should also study climate changes over longer time scales, including several decades and more, as relevant to global warming. More attention will be paid to ocean circulation variability induced by atmospheric variability, and also the reverse relationship (e.g., Chapman and Walsh (2007) cited for Q2)).

c. Interactions between the atmosphere and land on the lower boundary

Vegetation, snow cover, and permafrost interact with each other and vary on land, affecting climate variability over a wide area, through energy, water, and material exchanges between the ground surface and the atmosphere. Process elucidation of vegetation, snow cover, and permafrost has been carried out steadily on the basis of field observations and detailed process-oriented models. Quantitative estimates of variability over a wide area represent a step forward in efforts to assess impacts of global climate variability. Satellite data have been accumulated relating to certain physical quantities, such as vegetation distribution and snow-covered portions, and these have been used for quantitative estimates of wide-area variability. On the other hand, there is need for basic research into some physical parameters, such as soil moisture and ground conditions; there is also a related need for development of methods suitable for wide-area estimates. In principle, scaling up the roles of individual processes is necessary to acquire quantitative estimates over a wide area.

d. The interactions among the troposphere, the stratosphere, the mesosphere and the thermosphere

Research has just commenced on the dynamic coupling of the troposphere-stratosphere, and also on interactions between the mesosphere-thermosphere and the lower atmosphere. Important research topics to be pursued include coupling between the troposphere and the stratosphere, the activities of both Rossby waves and gravity waves along with their impacts on the basic state (refer to Q1), and also accurate estimates of the transport of atmospheric trace components (refer to Q4). As more results have emerged through observation data and GCM simulations of variability in the mesosphere-thermosphere due to stratospheric sudden warming, future advancement is expected regarding the physical mechanisms that generate vertically coupled variability through the stratosphere-mesosphere-thermosphere.

e. The role of water and material circulation associated with ocean outflows of land-origin substances

In addition to interactions between the atmosphere and other components, land-ocean interactions are also important foci of study, without the atmosphere. A concrete topic is explanation of the role of water and material circulation (mostly bio-geochemical cycles) caused by outflows to the ocean having their origin in land substances. These substances included in river flows have significant impacts on marine biological production, as described in Themes 3 and 9. Nutrients, as well as metal elements, are significant. In an ocean having enough nutrients but insufficient iron (such as the subpolar area of the North Pacific), even a small amount of iron moving through a river or the atmosphere serves to activate the marine ecosystem. Dissolved iron stays on land, with its form dependent on the hydrologic cycle and vegetation. Since a substantial quantity of dissolved organic matter forms complexes with iron in forests and surrounding rivers, a large amount of dissolved iron flows in rivers and is used by phytoplankton in the ocean. On the other hand, as a result of either the natural environment or human development, the iron which remains in a region without forests settles immediately as granular iron in the ocean and hence, is not utilized in the ecosystem. If precipitation decreases in mid-latitude areas due to climate change, iron compounds may change their forms, affecting the marine ecosystem.

f. Freshwater balance in the area affecting the Arctic

In Theme 4, the hydrological cycle is described with reference to the freshwater balance in the Arctic Ocean. In Theme 2, the coupled ice-ocean system in the surface layer of the Arctic Ocean is explained in detail. In Theme 1, along with the main focus on energy transport in the Arctic area, the associated hydrological cycle is also shown. In this theme, in conjunction with these efforts, we concentrate our efforts on exploring vapor transport in the high-latitude atmosphere so that we may estimate net precipitation (equal to gross precipitation minus evaporation) in the basin of the Arctic rivers. Thus, we also aim to elucidate freshwater fluxes between the Arctic Ocean and two other oceans, the Pacific and the Atlantic. Looking at areas connected to the Arctic, we examine net precipitation over the North Pacific and North Atlantic, in comparison with vapor transport in the atmosphere. In approaching these topics, we pay attention to inter-annual variations in atmospheric circulation patterns, with a basis in the outcomes for Q1. In association with examining and elucidating salt transport, including in subpolar-subtropical areas in the Pacific and Atlantic, we focus on mechanisms of the global ocean conveyor belt.

g. Research direction for this theme

Based on the above-mentioned discussion, we propose the following research strategy. A main framework is to explore fundamental behaviors of multi-sphere interactions, such as the coupled atmosphere-ocean system and the coupled atmosphere-terrestrial system. It would be difficult, without such exploration, to pursue quantification of meridional heat-water transport. Some projects, such as AOMIP, are capable of playing a major role in elucidation of these topics. Earth system models also play an important part, with individual element models verified against data, and with errors appropriately estimated using data assimilation methods. An important plan is to examine the effects of material circulation, which is influenced by atmospheric variability patterns, the hydrologic cycle as affected by the atmosphere, and even vegetation distribution, by including these components in earth system models.

Theme 6: Predicting future environmental conditions of the Arctic based on Paleoenvironmental records

Abstract

The effects and feedbacks resulting from warming of the Arctic region on ice sheet, sea-ice, permafrost, land vegetation and aerosols continue to receive attention (see Figure 21). However, by studying only the modern and recent past records, it is not possible to understand the entirety of the Arctic climate system which has time scales of variability over ten thousand years. During the past tens of millions of years, there have been periods when there were no continental ice sheets and atmospheric CO_2 concentrations were much higher than today, and when there were glacial-interglacial cycles in which Arctic temperature and ice sheets underwent large variations due to Earth's orbital cycles. By examining such records, it is possible to understand the Arctic climate system and test numerical models. Here, we list five questions for reconstructing Arctic paleoenvironment and for understanding its mechanisms by linking data and numerical modeling.

Q1: How different are the past Arctic amplifications from that of today, and what are their causes?

Q2: How did the Greenland and continental ice sheets change, and what caused them?

Q3: What were the environmental conditions of the Arctic Ocean, especially in terms of sea-ice and biological productivity?

Q4: How different were the terrestrial Arctic paleoenvironmental conditions from that of today, and how were they related with atmospheric composition and climate?

Q5: Were the natural variability on timescales from years to centuries in the Arctic different from today?

Research methods include collection and analyses of ice cores and marine sediment cores as well as geomorphological and geological surveys of land and sea-floor. Regarding the modeling, the approach is to develop a coupled Earth system model including climate, ice sheets, vegetation and solid Earth, and to conduct numerous, long numerical simulations. While it is particularly important to reconstruct and understand environmental conditions during previous warm periods, it is also important to investigate instability and variability of the climate system by studying abrupt climate changes which occurred repeatedly during glacial periods and deglaciations, and natural climate variations on timescales from years to centuries.

Introduction

The concentration of atmospheric CO_2 has varied significantly through time; for example, it was more than 800 ppm around 55 Ma (Table 1). The Earth's surface at the time was warmer than at present due to a stronger greenhouse effect, a higher sea-surface temperature in the Arctic Ocean (> 18 ºC) resulting in the growth of subtropical ferns. More recently, the CO_2 concentration in the Pliocene was greater than 330 ppm, during a time when extensive forests of huge trees occupied the Canadian Arctic Archipelago. During the penultimate interglacial (~125 ka) and the early Holocene (~10 ka), tundra in the Arctic region disappeared and taiga boreal forests spread around the coasts of the Arctic Ocean coasts because of the high summer insolation. On the other hand, during the repeated glacial periods, continental ice sheets grew over vast areas of the Arctic, and the Arctic Ocean was covered by ice shelf and sea ice. While the changes in CO_2 concentration and insolation are thought to have affected the climate globally, the magnitudes of the changes have been the greatest in the Arctic region.

Today, the Arctic is warming. Sea-ice, permafrost, and tundra vegetation, which are sensitive to temperature change, are extensive in the Arctic, and their roles in amplification of climate change have been receiving attention. In order to clarify these roles, it is important to reconstruct past Arctic environments and understand the relationships between environmental conditions and forcings, such as CO_2 concentration and insolation.

The objectives of paleoenvironmental studies are to reconstruct past climates and environments, and to clarify the mechanisms for changes in them. Researchers have analyzed samples from the sea floor, land, and ice sheets with various methods, assigned their ages, reconstructed environmental changes indirectly, and interpreted the geological records (see Box 1). Furthermore, numerical modeling (computer simulation) has a growing role in clarification of climate change mechanisms. Paleoenvironmental studies provide not only knowledge about past phenomena, but also the means for improving future predictions through assessment and advancement of climate models. In particular, it is not possible to reconstruct and understand the variations and mechanisms of environmental factors as ice sheets, vegetation, and carbon cycles, which involve long-term climate change over tens to thousands of years, only by study of the recent climate (recent ~100 years). Therefore, paleoenvironmental studies are important for climatic science to serve societal needs. Progress in such paleoenvironmental studies in the Arctic region has benefitted from Past Global Changes（PAGES）under the framework of the International Geosphere-Biosphere Program (IGBP), which was initiated in the 1990's. In Japan, large efforts have been made by the PAGES subcommittee under the Science Council of Japan, since the establishment of PAGES. Furthermore, Japanese communities and individuals have been participating in numerous international programs involving ice core drillings, Arctic Ocean drillings, and intercomparison of paleoclimate models.

Concerning the characteristics of climate change and climate sensitivity in the Arctic, investigations involving both paleoclimate data and modeling have been proceeding, and significant space is used for paleoclimate studies in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). In the past of ten million years, we can certainly locate many intervals that are clearly warmer than today, as well as events that can be utilized to verify climate models. In particular, it is important to extend our understanding of the past warm intervals for advancement of our understanding of Arctic

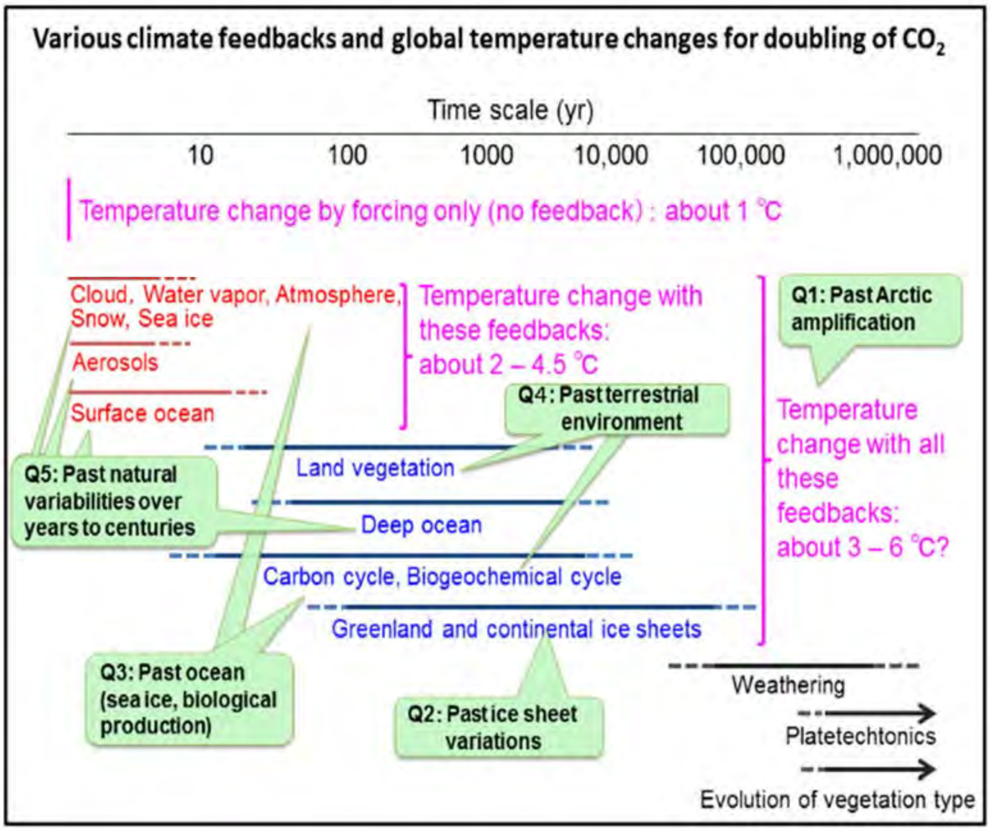


Figure 21: Climate feedbacks and resulting global temperature changes under doubling CO_2. The timescales of each climate component, as well as the relationship between the questions in the text and climate components, are also shown. [Theme 6]

warming, which may accelerate in the future, and its effects on the global climate (Table 1). For example, there have been periods when the concentration of atmospheric CO_2 was higher than today, and no continental ice sheets existed. There have also been interglacial periods, warmer parts of the glacial-interglacial cycles in which the Arctic temperature and ice sheets significantly fluctuated. Furthermore, ice sheet variations and abrupt climate changes during glacial and deglacial periods are also important because they may shed light on the future occurrence of instability in our climate system. There have also been unusually warm intervals during the past 1,000 years. Reconstructions of climate, greenhouse gases, solar and volcanic activities, as well as paleoclimate modeling on timescales from years to decades, have been conducted on this interval.

However, many tasks remain to be done to achieve quantitative, spatially dense reconstructions of paleoenvironments; and to achieve successful collaborations between paleoenvironmental reconstruction and modeling. Five questions of prime importance for Arctic paleoenvironmental studies follow; the present status and future tasks related to each one are summarized.

Table 1. Targets of the warm intervals in Arctic environmental reconstructions

Interval	Age	CO_2 concentration (ppm)	Insolation (with respect to today)	Northern Hemisphere high latitude air temperature (℃ higher than today)
Late Paleocene	55 Ma	800-2000	Equal to or higher	8-35
Pliocene warm period	3.5 Ma	330-380	Equal to or higher	11-16
Interglacial	400 ka, 125 ka	270-280	Higher	5
Early Holocene	10 ka	270	Higher	2
Medieval Warm Period	1 ka	280	Nearly equal	0-5

Q1: How different are the past Arctic amplifications from that of today, and what are the causes of these differences?

a. Importance of research and present status

When we examine the long-term evolution of climate during the past several tens of millions years, the following becomes clear. When CO_2 concentrations were high, air temperature and sea-surface temperatures were also high, and continental ice sheets emerged and expanded as CO_2 concentration decreased. As the Northern Hemisphere ice sheets expanded, glacial-interglacial cycles emerged in association with variations in summer insolation, and their amplitudes have increased. From available data, it is known that polar amplification occurred in all cases (Figure 22).

The Integrated Ocean Drilling Program (IODP) Arctic Coring Expedition (ACEX)[36], in which Japan participated in 2004, obtained paleoclimatic records of the past 55 Ma from Lomonosov Ridge in the vicinity of the North Pole (Moran et al., 2006). The analyses of sediments and organic compounds showed that the average sea-surface temperature of the Arctic Ocean was 18 ºC at 55 Ma, around the Paleocene-Eocene boundary, and reached 24 ºC when greenhouse gases were released over a short period during the maximum warm interval. At least five research groups, including a Japanese team, conducted comparisons between model results and data for the

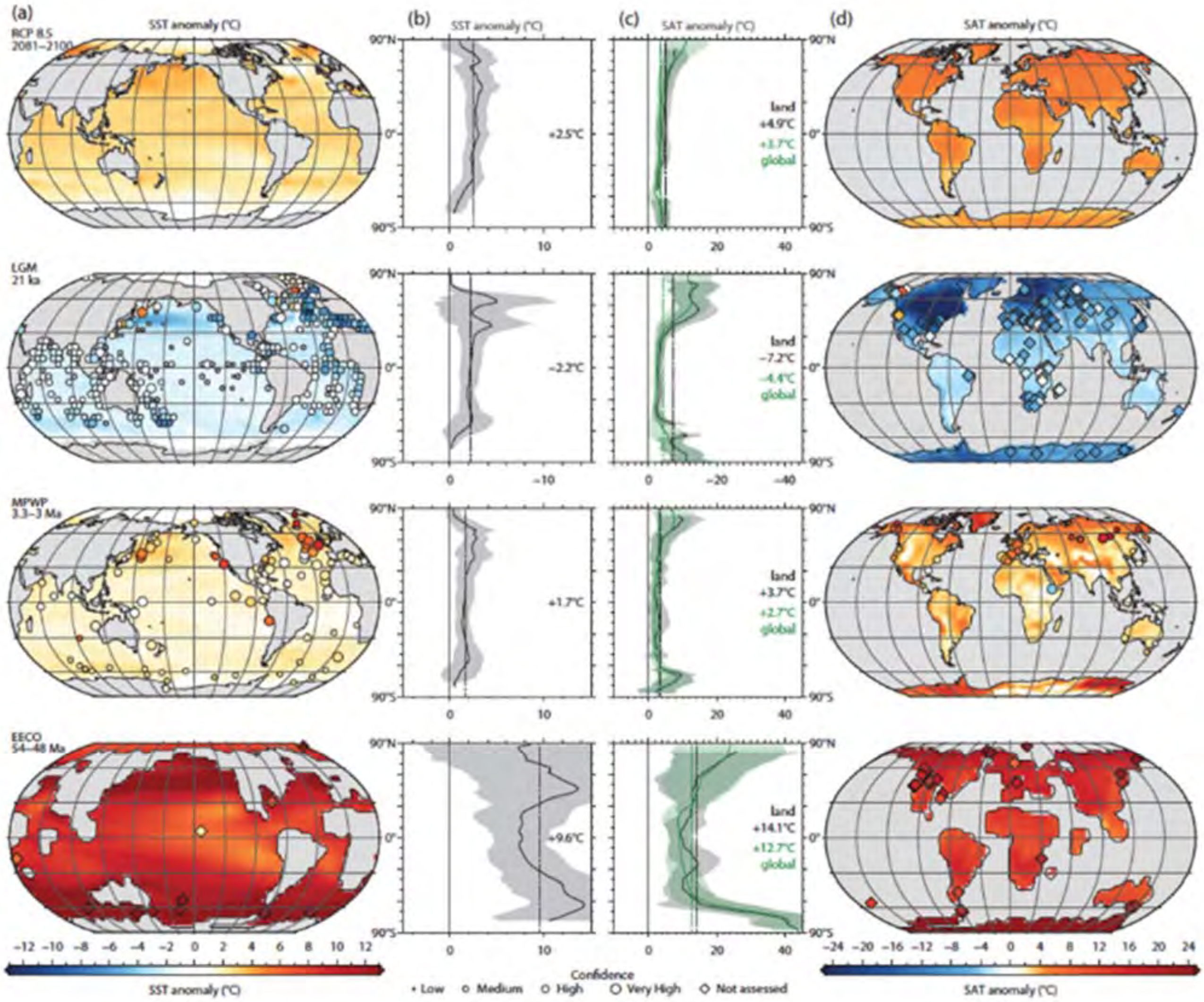


Figure 22: Data-model comparisons of surface air temperatures (SAT) and sea-surface temperatures (SST) for the Eocene, Pliocene, and the last glacial maximum (LGM) (Box 5.1, IPCC AR5), Figure: 1 Comparison of data and multi-model mean (MMM) simulations, for four periods, showing (a) Sea-surface temperature (SST) anomalies, (b) Zonally averaged SST anomalies, (c) Zonally averaged global (green) and land (grey) surface air temperature (SAT) anomalies, and (d) Land SAT anomalies. The time periods are 2081–2100 for the Representative Concentration Pathway (RCP) 8.5 (top row), Last Glacial Maximum (LGM, second row), mid-Pliocene Warm Period (MPWP, third row) and Early Eocene Climatic Optimum (EECO, bottom row).

[36] Climate sensitivity: The temperature changes that only take into account fast feedbacks, such as the changes in clouds and water vapor over the sea surface, which can be completed within several decades. Normally, the term is used for the changes in global terrestrial mean surface temperature for CO_2 doubling.

following two periods: ca. 50 Ma in the middle Eocene warm interval, and ca. 3.5 Ma in the middle Pliocene warm period. The results indicated that models overestimated air temperatures at low latitudes and underestimated at high latitudes, compared to the data. In particular, the discrepancy in the Polar Regions was due to problems in both data and models. Regarding the data, it has been pointed out that different regression curves from proxies to sea-surface temperatures must be employed according to the seasons. On the other hand, it is necessary to assess the validity of the radiation processes of clouds in Polar Regions, and of the heat-transport processes by the oceans. It is also necessary to assess consistency between the data and models of terrestrial vegetation.

During the interglacial periods of the glacial-interglacial cycles of the last one million years, Northern Hemisphere continental ice sheets disappeared (or significantly shrunk), except for the Greenland ice sheet. While the Earth experienced 10–20 m higher sea levels than today during some of the last five interglacials, CO_2 concentrations were roughly the same during all the interglacials (280±10 ppm) and the only difference in radiative forcing was from variation in the distribution of insolation, due to changes in orbital parameters. For example, the summer solstice insolation reached a maximum, which was approximately 10% greater than that of the maximum of the Holocene, at 126 ka during the the penultimate interglacial. Recent investigations showed evidence for high air temperatures, northward forest expansions, and sea levels 5–10 m higher than today (indicating smaller ice sheets in the Northern Hemisphere). In addition, evidence exists that the central Arctic Ocean was only seasonally covered by sea ice, suggesting higher summer air temperature than today. According to the estimations by the North Greenland Eemian Ice Drilling (NEEM) project, the state of the art international ice sheet drilling project in which Japan has participated in the ice core drilling and analyses, the mean annual air temperature in the northwestern Greenland interior was 8 ºC higher than today (NEEM project members, 2013). Concerning the penultimate interglacial, an international model-data comparison project (Paleoclimate Model Intercomparison Project, PMIP) was conducted with participation of 16 climate models including Japanese ones (Figure 10.9, IPCC AR5). Transient model experiments with time-varying insolation and atmospheric composition were also conducted using seven models. The results indicated that, while no statistically significant difference was seen between the data and models in sea-surface temperatures, statistically significant differences were found in the terrestrial air temperatures of December-February. This resulted in significantly lower values of the modeled mean annual air temperatures of terrestrial high latitudes, compared with reconstructions. The reasons for such discrepancies between the data and models may be due to insufficient expression of processes concerning clouds, sea ice, and land vegetation in the models. Another reason may be the neglect of effects from changes in the source-regions of water vapor with decreasing sea-ice cover, on the reconstructed air temperatures based on the isotopes of ice cores.

The Arctic region experienced a warm interval early in the Holocene (current interglacial), except for a part of North America, where continental ice sheets still existed. This can be attributed to greater summer insolation than today, which affected the cryosphere, including sea ice. The climate changes in the Northern Hemisphere during the past 2,000 years are characterized by the Medieval Warm Period of ca. 950–1250 AD and the Little Ice Age of ca. 1450–1850 AD. The changes in the Arctic region were significantly greater than those of the average Northern Hemisphere. Major radiative forcings such as greenhouse gases, solar radiation, and volcanism have been reconstructed with high temporal resolution for the last 2,000 years. It is possible to use those parameters as input data for transient experiments with general circulation models, and an international comparison project for paleoclimate models, in which Japan participated, was conducted. While the results of the climate models fall within the uncertainty range of reconstructions for Northern Hemisphere mean temperatures, the agreement between models, or between climate data and models, is poor when considering the Arctic region. In addition, because the uncertainties in radiative forcing and reconstructed data are large in the Arctic, it is at present difficult to constrain the climate sensitivity of the region firmly; hence, this remains a significant task for the future.

b. Future research

Progress has been made in reconstruction of past air temperatures and water temperatures by analyses of sediments and ice cores, as well as on simulations of past environments by climate models. However, these are still in various stages of development, for example, because of errors in the processes used to convert proxy data into temperatures, as well as neglect of the interactions between ice sheets and climate in the models. Furthermore, while studies about estimating climate sensitivity from paleoclimate information exist, few studies focused on the Arctic. In order to quantitatively reconstruct and analyze the causes of polar amplification and ice-sheet-driven sea-level change, it is necessary to provide collaborative interaction between proxy-data collections (e.g., greenhouse gases, aerosols, ice sheets, sea ice) and the Earth system modeling to simulate paleoenvironments.

Many tasks have been identified through the data-model comparisons. Data-related tasks involve obtaining and extensively analyzing samples (Arctic-sea sediment cores and Greenland ice cores) for intervals that currently have little data, while considering seasonal and climatic dependences of the regression curves for converting proxy data into temperatures. On the other hand, modeling-related tasks involve investigating elementary processes, such as radiative processes of polar clouds and aerosols, heat transport and stratification processes of ocean and sea ice, as well as the processes involving land vegetation and terrestrial/ice-sheet interfaces. Then, these updated processes will need to be incorporated in the climate models. It is necessary to continue improving both data and models, as well as comparing them for different ages.

For interpreting paleoclimatic data on the relationships between radiative forcings and climate, it is essential to consider feedbacks from the cryosphere (e.g., ice sheets) and land vegetation to air temperature. The responses of ice sheets and land vegetation to warming extend for centuries to millennia; thus, their influences on Arctic amplification and global temperature are similarly prolonged. This type of climate sensitivity (magnitude of temperature increase for a given increase in CO_2 concentration), including long-timescale feedback, is called “Earth System Climate Sensitivity (ESCS)” and it is greater than ordinary “climate sensitivity (86)” which only considers short-timescale feedback (Figure 21). According to investigations based on comparison of climate models with paleoclimate data, the ESCS can be up to twice as high as the ordinary climate sensitivity, and can vary depending on climatic conditions (PALEOSENSE Project Members, 2012). To quantitatively utilize long-term paleoclimate information in future studies, it is necessary to integrate climate modeling with whole-Earth-system and paleoclimate proxies. In particular, assessment of the performance of the models requires considerations of all uncertainties (e.g., in parameterizations and structures of models, as well as in boundary conditions). Therefore, it is essential to reconstruct accurately the boundary conditions, to conduct model experiments involving many different periods, and to secure resources for the extensive computations needed. It is necessary, for example, to obtain samples (e.g., ice cores, borehole temperatures, marine sediments, permafrost) representative of extensive geographic areas and long time-scales, to develop proxies and analytical methods, to acquire large paleoclimatic data sets of high resolution, and to interpret the data by proxy-data assimilation. In order to link the past and the present, it is also necessary to accumulate pan-Arctic paleoenvironmental sample archives covering the years after 2000 A.D.

Q2: How did the Greenland and continental ice sheets change, and what caused them? What are their relationships with, and contributions to, sea level?

a. Importance of the research and state of the art

(1) Mechanisms and prediction of ice-sheet variations

The fluctuation of ice sheets significantly affect the Earth’s environment by changes in sea level and in atmospheric/oceanic circulation (see Theme 4). The response of ice sheets to climate change exhibits hysteresis behavior with different “threshold” values for increases and decreases in temperature. When such threshold values are crossed, an ice sheet drastically changes its shape or volume. Numerical simulations of glacial-interglacial cycles have revealed that it is extremely important to elucidate different hysteresis structures for different ice sheets, in order to estimate their abrupt decay in response to warming (Abe-Ouchi et al., 2013). Furthermore, because the time scale of ice-sheet response is very long, there is concern that past climate changes may influence ice sheets for more than several hundred years into the future. In fact, members of SeaRISE, an international project for comparing ice-sheet models, have pointed out the possibility that consideration of ice-sheet histories over the last 130 ka can generate differences in the predicted change in ice volume in the next 100 years, by as much as 40% (Bindschadler et al., 2013).

In order to constrain future changes in ice sheets accurately, it is important to reduce the uncertainty of ice-sheet responses to external forcing. One way to achieve this is to clarify actual ice-sheet changes in the past, and their driving factors, thereby advancing their simulation by ice-sheet models. In particular, it is indispensable to estimate accurately the threshold values of climate and CO_2 concentration that cause ice sheets to collapse. To accomplish this, it is necessary to conduct numerical experiments, and to acquire data that can lead to better understanding of the hysteresis structures.

(2) Reconstruction of the past ice sheet distribution

It is possible to reconstruct the areal bounds of past ice-sheet expansions by identifying marginal positions and ages of the ice sheets from geomorphological and geological evidence (e.g., glacial erosional morphology), as well as from traces of past glaciers and ice sheets, left on land and the sea floor. For interglacials, when ice sheets were reduced, ice-sheet distribution can be reconstructed based on relationships between marine sediment cores and terrestrial geological distribution. For reconstructing the volume of ice sheets, a commonly employed method is inverse modeling using a glacial isostatic adjustment (GIA) model, with relative sea-level data as input (see Theme 11).

In the Arctic Ocean, there have been times in glacial periods when continental shelves were exposed due to drops in sea level and then covered by ice sheets. In such cases, evidence for past ice sheets exist as erosional furrows caused by icebergs, lined structures caused by glaciers, and depositional topography caused by ice-rafted matter dropped onto the sea floor of up to 1000-m water depth. While studies on the Lomonosov Ridge and Chukchi Sea have indicated the possibility of ice sheet expansion from continents to the central Arctic Ocean, as well as the presence of an ice sheet over the continental shelf of the East Siberian Sea, the evidence is still fragmentary. Progress is being made on simulation of the distribution of past ice sheets by climate-ice sheet models, and on linking them to understanding of the processes driving ice-sheet fluctuations.

(3) Past Greenland ice sheets

Investigations have been in progress concerning the relationships between the growth of the Greenland Ice Sheet, which began ca. 3 Ma, and CO_2 concentrations; as well as between the responses of the Northern Hemisphere ice sheets (North America, western Eurasia, and Greenland) to orbital parameters and CO_2 during the glacial-interglacial cycles. In particular, relatively abundant data are available for reconstructing ice-sheet volume and distributions, as well as climate conditions, during the penultimate interglacial at ~125 ka, with 5–10 m higher sea level than today, and the deglacial period from the last glacial maximum (LGM, 20 ka) to the present. Simulations by integrated climate-ice-sheet models have also been initiated.

According to ice-coring and analytical projects in which Japan participated, as well as the analyses of marine sediment cores collected from the south of Greenland, the air temperature in the LGM at the NEEM site (NE in Figure 23) was 8±4 ºC higher than today, with frequent surface melting. However, the estimated reduction of ice-sheet volume was only equivalent to less than ca. 2 m of sea level (NEEM community members, 2013). Simulated Greenland ice sheets show large differences among models (Figure 23), and sufficient data for evaluating model performance are lacking. On the other hand, analyses of ice cores suggested that, during the interglacial

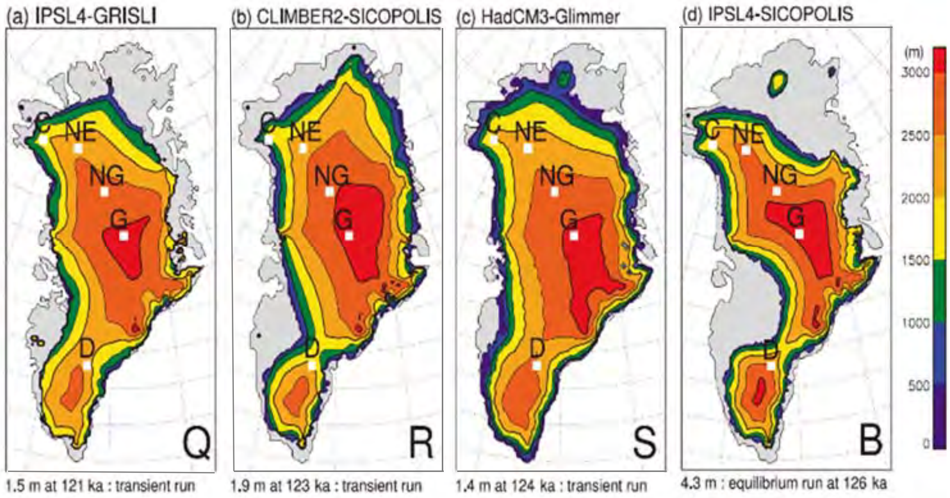


Figure 23: Distribution of Greenland Ice Sheet during the LGM, computed by state-of-the-art ice sheet models: IPCC AR5, Figure 5.16, Simulated GIS elevation at the Last Interglacial (LIG) in transient (Q, R, S), and constant-forcing experiments, (B)

of ca. 400 ka, sea level was 10–20 m higher that today. The Greenland ice sheet had retreated extensively and land vegetation was present despite weak summer insolation. The model simulations for this period have not been successful, and the factors driving the retreat of the ice sheet are unclear.

While the Greenland ice sheet extended to cover the continental shelves during the LGM, the evidence from sea floor surveys is limited to a part of southern Greenland, and the evidence from land is also fragmentary. It is suggested that existing data regarding the paleoshoreline height during the deglaciation period contain large errors, and consistent results involving data and models have not yet been obtained.

b. Future research

Following are the leading issues that need to be resolved by linking models and data:

- Understanding the mechanisms for the growth and decay of past Greenland ice sheet and the determination of their thresholds,
- Elucidation of the change to dominant 100 ka cycles of the Northern Hemisphere ice sheets at ca. 1 Ma,
- Finding out when, and due to what processes, did the ice sheets surrounding the Arctic Ocean exist,
- Finding out why the sea level during the interglacial of 400 ka was very high, and why the Greenland ice sheet retreated extensively,
- Achieving detailed model-reproduction of the Northern Hemisphere and Greenland ice sheets during glacial cycles and deglacial periods, and estimation of threshold values for the ice sheet changes, and
- Understanding and reproduction of the determining mechanisms for the occurrence, cycles and magnitudes of large-scale, iceberg-releasing events.

(1) Ice sheet-climate model

In order to solve the mystery of past ice sheets, it is necessary to reproduce their non-stationary responses to external forcing (e.g., insolation and greenhouse gases), by numerical simulations with integrated climate and icesheet models, and by evaluating the results by comparisons with field data. The important aspects for advancing the models are (1) interaction between ice sheets and oceans; (2) basal processes; (3) atmosphere/surface mass balance processes; (4) advancement of interactions between ice sheets and solid Earth; and (5) increase in the resolution of models. Furthermore, it is necessary to directly or indirectly integrates ice sheet models with other models, such as those pertaining to atmosphere, ocean, GIA, and land vegetation. A massive amount of computer resources and adequate infrastructure would be required to proceed with model experiments fully utilizing paleoclimate data.

(2) Reconstruction of ice sheet distribution based on terrestrial geomorphological investigations

Detailed investigations on the correspondence between marine sediments and land geology during the past interglacials are needed at many sites on continental shelves where ice sheets are thought to have existed (particularly Greenland). It is necessary to reconstruct, both extensively and in detail, the locations of ice sheet margins, ice-sheet basal environments, and uplifted beach morphologies by studying the traces of ice-sheet reduction on land. Recently, discussions have been made about past ice-sheet fluctuations based on satellite-observed temporal changes in the gravity field and on GIA modeling. For such studies, it is important to remove the signal from modern ice sheet fluctuations. To establish a GIA model with detailed seawater loading, it is indispensable to incorporate the effects of changes in the Earth's rotation on sea level changes, on the viscosity structure of the interior Earth, and on the close link between geodetic data and ice-sheet models.

Furthermore, to reconstruct long-term changes in ice-sheet margins and their retreat processes, it is important to survey the sea floor and analyze multi-beam topographic data obtained by icebreakers over the Siberian continental shelf and continental slope. In addition, in order to obtain the age of formation for glacial landforms, it is desirable to collect marine sediment cores and correlate stratigraphic horizons. These will bring new knowledge of the history of Northern Hemisphere ice sheets, which are currently unknown, and provide valuable data for testing paleoclimate models.

(3) Ice cores

To clarify the history of the Greenland ice sheet, deep drillings at selected sites and many shallow drillings over extensive areas, are both necessary. Particularly important research targets include the fast-flowing ice in northeast Greenland, continuous climate records from the penultimate interglacial to the present, and the onset age of ice sheet cover, as determined by analyses of the basal ice. Because Japan has been participating in international drilling projects, it is important to continue active participation into the future as well.

For precise temperature estimations of ice sheet and atmosphere, it is essential to interpret water-isotope signals accurately, which in turn requires consideration of variations of ice sheets and ice flows. At the same time, accurate reconstruction of the past ice sheet variations requires high-quality paleoenvironmental reconstruction, thus they depend on each other. An important target here is to find the most consistent reconstructions of both, by employing a data assimilation technique. For this reason, it is also desirable to conduct shallow and intermediate-depth drillings at many sites on the Greenland ice sheet, and on circum-Arctic ice caps and glaciers.

Q3: What were the environmental conditions of the Arctic Ocean, especially in terms of sea-ice and biological productivity?

a. State of the art of the research

In order to understand Arctic climate it is important to evaluate sea-ice albedo feedback, and thus, it is necessary to understand accurately, past sea-ice distributions. While scientists have evaluated the effects of past ice-sheet distributions on the past air circulation of the Northern Hemisphere using climate models, the effects of sea-ice have not been well addressed. This stems from the lack of detailed understanding of the past distribution of sea ice. It is therefore necessary to elucidate the sea-surface conditions that govern both winter and summer atmospheric circulations, by further refining sea-ice proxies, and by reconstructing sea-ice margins during both winter and summer, at many locations.

Reconstructions of past sea-ice distributions have been tried by employing proxies in marine sediments, such as ice rafted debris (IRD), grain size distribution, iron oxide particles, microfossils (diatoms, dinoflagellates, benthic foraminifers, silicoflagellates), biomarkers (in particular IP25), calcite oxygen isotopic ratios, inert gases, and mercury isotopic ratios. Information concerning sea-ice distribution in the Arctic Ocean, can also be provided by other proxies: coastal marine sediments, fossil driftwood, fossil whalebones, fossil shells, and wave-eroded topography. Moreover, indirect estimates of the extent of sea ice have also been conducted based on ice-core and land-vegetation records. As ice cores can be analyzed at high temporal resolution, various ice-core-based sea-ice proxies have been proposed (e.g., oxygen isotopic ratios of ice, sodium ion concentrations, methane sulphonic acid concentrations, and halogen concentrations).

The Integrated Ocean Drilling Program (IODP) Arctic Coring Expedition (ACEX) drilled the Arctic sea floor on the Lomonosov Ridge in 2004 and reported the evolutionary history of the sea-ice record for the past 55 Myr (Figure 24: Moran et al., 2006). Based on the appearance of the IRD, it became evident that the formation of sea-ice began around 47 Ma. Perennial sea-

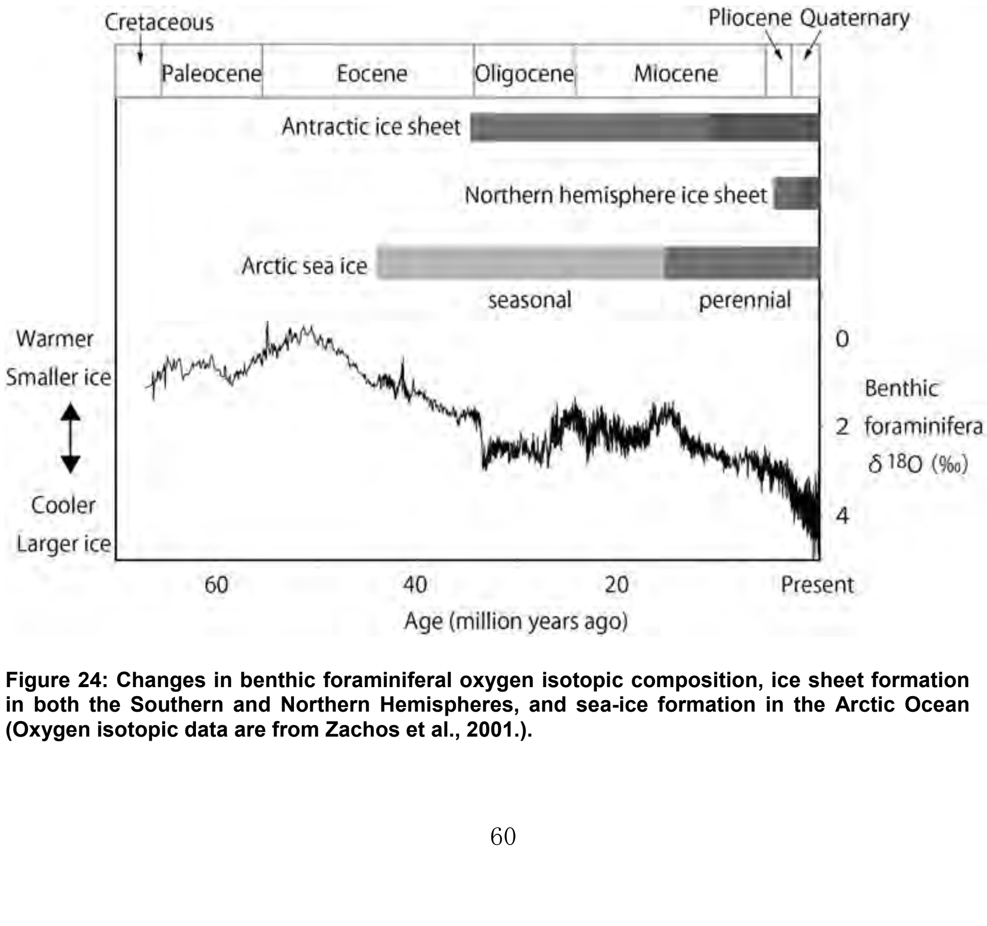


Figure 24: Changes in benthic foraminiferal oxygen isotopic composition, ice sheet formation in both the Southern and Northern Hemispheres, and sea-ice formation in the Arctic Ocean (Oxygen isotopic data are from Zachos et al., 2001.).

ice was formed 16-13 Ma. The extent of sea-ice increased with global cooling after 3 Ma in the North Pacific, North Atlantic, and Norwegian Sea. During the penultimate interglacial of 125 ka, planktonic foraminifers, which dwell in seasonal sea-ice areas, appeared in the central Arctic Ocean. The perennial sea-ice during the early Holocene is thought to be less than what we see today, based on the driftwood record of Greenland beaches, fossil bowhead wales on the coasts of the Canadian Archipelago, and IP25 in marine sediments of the Northwest Passage. On the other hand, sea-ice was shown to be abundant during the early Holocene in the Chukchi Sea, based on assemblage components of dinoflagellate cysts. Hence, it was suggested that expansions and retreats of sea-ice cover were not uniform within the Arctic Ocean.

The continental shelves of the Okhotsk and Bering Seas, which represent typical seasonal sea-ice regions, are among the regions with the world's greatest biological productivity. During the early to middle Holocene, in the Okhotsk and Bering Seas, coccolithophores were relatively abundant, and diatoms became dominant during the late Holocene. As such changes occurred, the efficiency of biological pump must also have changed dynamically. However, the factors controlling these changes have not yet been clarified.

The IODP ACEX 302 has played a major role in reconstructing sea-ice in the Arctic Ocean. The ACEX materialized as part of the IODP, which was primarily co-led by the US and Japan, and operated by the European consortium. In 2009, parts of the Bering Sea floor were drilled by Professor Kozo Takahashi of Kyushu University, and others, as part of the IODP. On the other hand, scientists of the US, Europe, and Japan have submitted new drilling proposals for the Arctic Ocean. None of these has yet been scheduled because of insufficient site information, the existence of which is a prerequisite for drilling. While paleoceanographic studies in the Arctic Ocean have primarily been advanced by the scientists of European and North American countries thus far, in recent years the Peoples Republic of China and South Korea have become active, employing ice breakers to pursue investigations of sea-floor topography, structural survey, and piston-coring of sediments. As for our own investigations in Japan, the R/V Mirai has been employed for sea-floor topography and sediment surveys during the decade since the year 2000. Since 2010, surveys employing the vessel I/B Araon have been carried out as a joint project between the scientists at the Korean Polar Research Institute and Hokkaido University. In order to pursue continuous paleoceanographic studies in the Arctic Ocean hereafter, it is indispensable for Japan to construct an icebreaker research vessel and make good use of it.

b. Future research

It is an urgent task to reconstruct sea-ice distributions during intervals warmer than today, in order to predict future sea-ice distributions in the Arctic Ocean. Specifically, we need to target the following intervals: the Medieval Warm Period (1 ka), the early Holocene (10 ka), the penultimate interglacial (125 kya), and the Pliocene (3.5 Ma) (Table 1).

In order to reconstruct past sea-ice distribution, we need to reconstruct the conditions favoring sea-ice formation by obtaining marine sediment cores, and by analyzing them in relation to sea-ice proxies. Regarding the Medieval Warm Period, the sea-ice conditions are understood only for the Norwegian Sea and Canadian Arctic Archipelago passages, but not for other regions; hence, a sea-ice distribution map cannot yet be drawn. We need to expand the records spatially. It is a good idea to select topographic low areas of marginal seas where sedimentation rates were high, to obtain sediment cores, and employ sea-ice proxies for the reconstruction of past sea-ice distribution.

The early Holocene is the most advanced interval of the four target-research time-periods. Sea-ice reconstructions employing dinoflagellate remains have been made in significantly extensive areas of the Arctic Ocean for that period (de Vernal et al., 2013). It is desirable to refine sea-ice reconstructions by employing proxies other than dinoflagellates. While sea-ice reconstructions have been made in the Norwegian Sea and Atlantic sector of Arctic Ocean for the LGM; today, it is not possible to compare different sites because of the lack of systematic investigations using common proxies. It would be desirable to obtain data employing common proxies more systematically. Furthermore, the number of existing cores is insufficient for fully understanding past distributions. Thus, we need to target continental-slope regions with high sedimentation rates, obtain marine sediment cores, determine ages, and obtain proxy records. For age determination, while core-to-core correlation is useful, it is important to systematically obtain many cores and analyze them in order to establish stratigraphy for each of the regions. Regarding the Pliocene, we only have information from the ACEX record, and other Pliocene records for which sections were coincidentally obtained. It is important to drill several hundred meters deep and obtain Pliocene sections where such Pliocene records likely exist: on the Lomonosov and Mendeleev Ridges. It is desirable to proceed with the drilling as part of the IODP, but before this can occur, it will be necessary to acquire topographic and seafloor structural data for the candidate drill sites, and to obtain preliminary results by analyzing piston cores.

While a number of sea-ice proxies are already used for past sea-ice distributions, developing new proxies, as well as refinement of the current proxies, remains important. It is warranted to clarify the sea surface conditions that govern winter and summer air circulation, by reconstructing winter and summer distributions of sea-ice margins at many stations.

Ice cores are natural archives recording sea-ice changes with high temporal resolution, and hence making the effective use of them in the future, highly desirable. We need to reinterpret existing proxy records, develop new proxies and apply them for sea-ice reconstructions. A possibility of reconstructing biological production using ice core records has also been pointed out, and progress in research on this approach is expected in the future.

The Arctic Ocean of the Pacific sector (e.g., Chuckchi Sea, East Siberian Sea, Laptev Sea) are regions where particle flux increased, due especially to sea-ice decline, during the 1900s to 2000s. For this reason, the Arctic Ocean of the Pacific sector constitutes a hotspot where biological production will likely increase as sea-ice declines drastically in the future. Studies in this region are expected to clarify the relationships between past climates and biological productivity, as well as material balance.

Furthermore, it is extremely indispensable to conduct numerical simulations for various intervals by employing the integrated global circlation models (atmosphere-ocean-sea ice, Theme B). It is also essential to establish agreement between the model results and paleoceanographic data (sea-ice and marine ecological system), thereby advancing our understanding of their determining processes. Conducting the necessary experiments for sea-ice and ecological systems requires vast computing resources. This is due to the need for detailed calculation of conditions in the both atmosphere and ocean simultaneously, and the achievements thus far are fragmentary. In order to make good predictive use of paleoclimate records, vigorous advances in paleoclimate simulation are required. This can only be achieved by greatly improving computational resources and related infrastructure.

Q4: How different were the terrestrial Arctic paleoenvironmental conditions from those of today, and how were they related to atmospheric composition and climate?

a. Importance of the research and state of the art

Past status and changes of land surface conditions, such as vegetation, may provide essential clues for reconstructing past climatic conditions and for improving the accuracy of climate models by providing boundary conditions and validation data. However, the terrestrial paleoenvironmental records available from the Arctic region are comparatively few, with respect to those from temperate and tropical regions. Except for analytical data from some lacustrine sediments, they have been confined to sporadic pollen records, remains of macro plants, lacustrine sediments, and fragmentary and qualitative information from glacial geomorphology. In recent years, however, possibilities have emerged in paleoenvironmental reconstructions employing temperature profiles of permafrost, isotopic analyses of Yedoma containing ice and organic matter (see Theme 12), and analyses of multiple proxies. While variations of permafrost are considered to provide positive feedback for climatic change, the extent of permafrost, the quantities of its constituting substances, and their rate of change are not well understood. This results in substantial uncertainty in climate-change predictions. Nevertheless, efforts have just begun in recognizing permafrost layers as archives of terrestrial environments, and in understanding the relationships between environmental changes related to frozen ground dynamics and climate change.

Because ice cores contain information on both the Arctic and global environments, they provide outstanding records for reconstructing the changes of substances originating from land (e.g., aerosols and greenhouse gases), which are important constraints for paleoclimate reconstruction of the Arctic region. In recent years, it has become increasingly possible to measure trace species such as metal isotopes of aerosols, black carbon, and organic aerosols. Furthermore, it has become possible to analyze methane and water-soluble aerosols, which have also been measured in conventional ways, at very high resolution, by continuous melting methods. Japan has been a leading country in the analyses of aerosols and gases.

In recent years, numerical simulation of terrestrial paleoenvironments has been carried out with global climate models involving physical and chemical feedbacks from changes in the distribution of vegetation. The results have been compiled by the Palaeoclimate Modelling Inter-comparison Project (PMIP). An example of the model simulation for the LGM is shown in Figure 25. Because the results of modeling cannot be directly compared with observational results, there are many regions where the distributions of past vegetation cannot be well established. In addition, there are other remaining problems such as "Green Sahara", which cannot be reproduced by current climate models (PMIP, Joussaume et al., 1999). However, the importance of changes in land vegetation in determining climate has been demonstrated quantitatively, for example by improving agreement between model and data averaged over large areas, by introducing land-vegetation feedback in a model (O'ishi and Abe-Ouchi, 2011). The terrestrial environments in the Arctic region must have drastically changed along with the global paleoclimatic changes such as the glacial-interglacial cycles, due to polar amplification. In order to investigate the Earth's climate, it is extremely important to accurately reconstruct the terrestrial paleoenvironment and understand its underlying mechanisms.

b. Future research

Regarding the research on reconstructing past land vegetation by modeling, it is necessary to make progress in verification of not only the equilibrium states of land vegetation, but also their changes over time. In order to achieve this, it is necessary to conduct long-integration experiments with variable orbital and volcanic forcings,

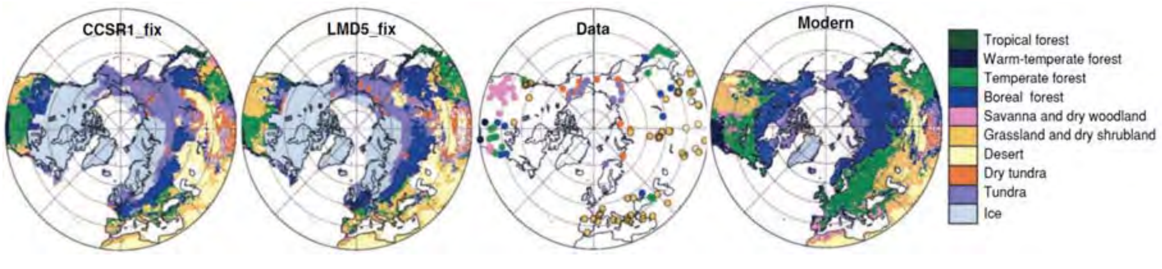


Figure 25: Examples of model simulations of the LGM and the present by dynamic land vegetation models (Harrison and Prentice, 2003). Three panels, starting from the left, show the ground cover types during the LGM, from a Japanese model, a French model and from paleoenvironmental data, respectively. The illustration on the far right shows the ground cover types of the present climate.

using Earth-system models involving not only coupled atmosphere and ocean, but also the cycles and feedback among elements such as carbon, nitrogen, phosphate and sulphate, which may limit the growth of vegetation. Among various terrestrial environmental factors, the distribution of vegetation, soil-water content, and surface wind speed most affect dust-source strength. It is thus expected that using dust data from ice cores, marine cores, and other archives, as constraints on the models should improve the reproducibility of these factors in climate modeling (Lambert et al., 2013). While the main provenance of dust is the dry regions of the low to middle latitudes, it is also important to investigate the strength of high latitude dust sources of the past and future, because of the high amplitude of their climate changes due to polar amplification. In addition, it is also necessary to integrate the processes concerning permafrost into Earth-system models.

It is particularly necessary to advance paleoenvironmental reconstruction of the permafrost in northeastern Siberia and Alaska, where little information is available from glaciers and ice sheets. For the studies of depositional layers of permafrost, glaciological methods are applied to Yedoma, and biomarkers are utilized for sediments. For example, environments from the late Pleistocene to the Holocene have been reconstructed based on age determination, and stable isotopic ratios, of water from underground ice (Meyer et al., 2010). This work has to be extended temporally and spatially. While paleoenvironmental reconstruction based on geomorphology (glacier-margin topography) for investigating permafrost has problems (e.g., coarse temporal resolution and low accuracy), it remains useful for adding constraints regarding geographical distributions of permafrost, and thus should be re-evaluated. The reconstructions of surface temperature history based on temperature profiles of permafrost (Pollack et al., 2003) are important in regions such as Siberia where paleoenvironmental data are sparse. It could also be possible to put constraints on the reconstructions of past surface temperature based on the depth of permafrost. Because most areas in permafrost regions cannot be accessed without employing helicopters and snowmachines, extensive logistical support is required for permafrost drillings and outcrop investigations.

Because the processes for methane formation and destruction are rather limited, they could be utilized as constraints on carbon cycles in a model. Improvements in simulations could be expected particularly in the distributions of swamps and vegetation in high latitudes, as well as for soil organic carbon, by employing methane concentrations (measured in ice cores) as constraining factors. On the other hand, the isotopic ratios of aerosols can be used as clues to understand provenance and transport processes. Sulfur isotopic ratios of sulfuric acid aerosols are valuable for provenance estimation because of the fact that the isotopic ratios vary depending on, for example, gypsum, volcanos, and marine biotas, and that the isotopic ratios of strontium and neodymium on dust (silica minerals) vary depending on the provenance continents and regions. In recent years, better isotopic data can be obtained with higher temporal resolution and accuracy than ever, attributable to improved analytical methods. Furthermore, it may be possible in the future to isolate and reconstruct aerosol histories of forest fires, soil aerosols, biogenic, and anthropogenic activities because many compounds in organic aerosols have limited provenances. It is also necessary to make progress in the area of multiple-proxy analyses, for example, by combining sulfur ion concentrations and sulfur isotopic ratios in ice cores, by acquiring the composition and carbon isotopic ratios of organic matter, and by estimating emission provenance of gases by isotopic analyses.

Q5: Were the natural variability on timescales from years to centuries in the Arctic different from today? What are the mechanisms?

a. State of the art of research

Today, Arctic Oscillation (AO) dominates the inter-annual variations of atmospheric circulation in the Arctic region (see Theme 5). The importance of other modes has also been pointed out for sea-ice transport, and for the entry of warm water masses into the Arctic Ocean from the Pacific (see Theme 1, Theme 2). While it is highly important to understand natural climate variability on timescales from years to centuries for predicting future climate, their statistical characteristics, and the mechanisms for their variability on long time-scales, are not well understood. One of the reasons for this shortcoming is the short interval over which instrumental data has been collected. Furthermore, it is complicated to characterize the cause of natural variability because the recent climate has been influenced by anthropogenic activities such as increase in greenhouse gases. Reconstructions and modeling of paleoclimate covering the past several thousand years, provide the means to overcome these problems and may lead to understanding natural variability, including climatic responses to solar activity and volcanic eruptions. The characterization of anthropogenic effects will be useful for prediction of future conditions, once natural variability can be taken into account.

While the AO is primarily an internal variability (mode) of atmospheric circulation with a time scale of ca. 10 days, long-term variability of years to several decades is also known. For example, a winter trend lasting several decades was seen near the end of the 20th century and a positive AO trend is seen in predictions for the 21st century. In order to investigate long-term characteristics of variability, several studies attempted reconstructions of such variability by employing proxy records from the past several centuries. While relatively many time-series data have been reconstructed for the North Atlantic Oscillation (NAO), which is specific to the North Atlantic Ocean, a limited number of reconstructions have been accomplished for the AO of the entire Arctic region.

Only coverage of the past 1000 years has been attempted in studies employing climate models. While this mainly stems from limited computer resources, there are other limitations. For example, there is great uncertainty regarding external forcings, such as solar activity and volcanic eruptions, which drive climate models. Earth-system models of intermediate complexity (EMIC, relatively simple climate models) were primarily employed for simulations at the time when the Fourth Assessment Report of Intergovernmental Panel on Climate Change (IPCC, AR4) was published in 2007.

Later, many results from the Atmosphere-Ocean General Circulation Model (AOGCM) were published in the Fifth Assessment Report (AR5) of the IPCC, and analyses of temporal and spatial variation patterns became possible by employing multiple models. Part of the background of such advancement, was that the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3), an international project, had established common forcing data and proposed experimental settings, and the PMIP3 was supported by the Coupled Model Intercomparison Project Phase 5 (CMIP5). Japanese AOGCMs also participated in experiments covering the past 1,000 years, then contributed and published the results to CMIP5/PMIP3 (Sueyoshi et al., 2013). In those studies employing a single model, the relationships between solar activity and the AO, and between volcanic eruptions and the AO or Pacific Decadal Oscillation (PDO), have been pointed out. As a result of these advances and activities, analyses of simulated climates using multiple models are being initiated.

It is well known that the changes in the Greenland air temperature are affected by the NAO. Moreover, in paleoclimatic studies, it has been reported that oxygen isotopic ratios of Greenland ice cores correspond well with the proxies of NAO. In addition, it was found by a research team led by Japanese scientists, that variations in Greenland air temperatures on decadal to century scales deviated from the average trend of the Northern Hemisphere. The proposed cause for this is modulations of NAO-like patterns driven by variations in solar activity (Kobashi et al., 2013).

b. Future research

Climatic parameters such as air temperature are affected by both global and regional climate changes; therefore, it is desirable to obtain proxies from many locations, with consideration of spatial patterns, in order to reconstruct regional climates (e.g., changes in atmospheric circulation). Thus far, collection of proxy data have mainly been limited to middle latitudes of the Northern Hemisphere, and insufficient data have been obtained from the Arctic region. It is thus important to participate actively in projects such as the Past Global Changes (PAGES) 2k consortium, which is focused on the past 2,000 years, and to construct data sets integrating multiple stations to cover the Arctic region.

The paleoclimatic and paleoenvironmental information that can be obtained from ice cores is extremely important in the Arctic region, where long-term instrumental data are lacking. In Greenland, in addition to deep ice-core studies for long-term climate reconstructions (such as for glacial-interglacial cycles), shallow ice-core studies are also conducted for environmental reconstructions over the past several hundred years. These have been led by researchers in the USA and Germany. Concerning the NAO and its effect, it is important to clarify regional patterns, and the causes of the decadal-scale NAO, by conducting new drillings and analyses of ice cores from sites in places such as Greenland, Canada, and the Svalard Islands.

On glaciers and ice caps in the circum-Arctic region (except in Greenland), several countries including Japan have conducted ice-core research in Arctic Canada, Arctic Russia, and the Svalard Islands during the 1990s and through the early 2000s. At present, there is a well-recognized and pressing need for reconstruction of the rapid climate change that has taken place in the 21st century, and considerable potential has been provided by new proxies, the analysis of which have recently become possible due to the advancement of analytical techniques (e.g., black carbon, trace metals, organic matter, and $\delta^{17}O$). All this makes it highly desirable to drill new samples on glaciers and ice caps in the circum-Arctic region. Several countries including Japan have sporadically conducted independent research on ice cores from high mountains (Kamchatka, Yukon and British Columbia in North America, Caucasus, Mongolia, and Altai). In the future, effective research strategies will require international cooperation aimed at integrated understanding of paleoclimatic data.

Oxygen isotopic ratios of ice cores, which have been widely used as a temperature proxy, are affected not only by regional temperature, but also by the transport routes of water vapor, and the temperatures of their specific source regions. As an alternative method for temperature reconstruction, physical methods based on isotopic ratios of argon and nitrogen have been developed (Kobashi et al., 2013 and references therein). It is important to apply this method to many cores, and therefore reconstruct patterns of regional climate variation. Similarly, it is necessary to reconstruct the variability of Arctic air temperatures and atmospheric circulation, and to advance interpretation, by employing oxygen-isotope-ratio data as constraints for data-assimilation techniques used with isotopic models (Yoshimura et al., 2014).

Significant factors limiting interpretation of model-results are large uncertainties in external forcings such as solar radiation and volcanic aerosols, which are input data for models. While multiple data sets are used in recent climate simulations, the model experiments are not necessarily carried out comprehensively due to limitations in computing resources. Improvements in the accuracy of external forcings are essential for reliable comparisons between simulated climatic responses and paleoclimatic reconstructions. Concerning volcanic forcing, data sets with significantly improved accuracy have been reported based on combined analyses of many Antarctic ice cores and Greenland NEEM cores (Sigl et al., 2014). Augmentation of the Greenland data is anticipated to provide better quantitative estimation of volcanic forcing. It has also been suggested that solar activity and volcanic eruptions affect climate in the troposphere through stratospheric responses, thus simulations using models with sufficient resolution in the stratosphere are needed. Furthermore, due to weak external forcing, many numerical experiments are needed for the past millennia, to extract statistically significant signals from the simulated climatic responses. It is also necessary to establish model infrastructures that will support parallel usage of high- and medium-resolution models with the same physical processes, for effective use of computational resources (see Theme B). Furthermore, the Atlantic meridional overturning circulation (AMOC) is considered to play major roles in decadal to century-scale climatic variations, which has attracted international research. Collaborative studies involving many AOGCM experiments and paleoclimatic data are needed, and it is essential to establish sufficient computing infrastructure.

Through the above-mentioned research, the paleoclimate research community is expected to clarify how and why the intensity and spatial patterns of past natural fluctuations are different from those of today.

Box 1 Development and interpretations of paleoenvironmental proxies and dating methods

Paleoclimatologists employ proxies (proxy indicators) to reconstruct past climates. Paleoclimate archives include ice cores, marine sediment cores, lacustrine sediment cores, stalagmites, loess deposits, coral annual rings, and tree annual rings. For example, the oxygen isotopic ratio of benthic foraminifers, the remains of which are found in marine sediments, is a proxy for terrestrial ice volume. Dating (age determination) methods of paleoclimate archives are also important, and they include counting of the annual varves of sediment cores, analyses of radionuclides (using half-life), and correlation with past variation in insolation (determined by astronomic calculations).

Although proxies play central roles in paleoclimate research, all proxy records entail calibration errors, and there are many proxies for which it is difficult to quantify the error. In the future, it is important that there be more cooperation among proxy and modeling studies, in order to improve the interpretation of proxies. Important tasks include (1) modern observation of proxy formation and preservation (e.g., isotopes of water vapor and rain, atmospheric composition, and aerosols), (2) method development of provenance estimation by aerosol isotopic ratios (e.g., sulfur and lead), (3) development of analytical methods for new chemical and gas composition and isotopic ratios, (4) high temporal resolution analyses of samples, and (5) development of dating methods. Some of the most important proxies are described below.

a. Paleoclimate proxies in ice cores

Stable isotopic ratios of oxygen in water ($\delta^{18}O$) are widely used. However, because $\delta^{18}O$ values are also affected by factors other than air temperatures (e.g., seasonal variation in snowfall), the isotopic records must be calibrated using other temperature reconstructions (e.g., borehole temperatures and gas isotopic records). In other words, accurate air temperature estimation by $\delta^{18}O$ requires consideration of the entire hydrological circulation system. In recent years, efforts have been made to estimate simultaneously the past temperatures of ice coring site, and water-vapor source using oxygen and hydrogen isotopic ratios (Uemura et al., 2012). In addition, the data assimilation technique is also promising. With this technique, temporal and spatial distributions of circulation fields in a GCM are corrected to match the computed isotopic ratios of precipitation with observational data (Yoshimura et al., 2014).

The aerosols in ice cores are present in various chemical phases (e.g., solid micro particles, liquid droplets). The chemical forms of water-soluble aerosols, which are proxies for the chemical environment of the atmosphere, are lost when subjected to the usual methods of ice core analyses, in which the samples are melted and the ion concentrations in the meltwater are measured. A new method, which directly analyzes aerosol particles by sublimating ice, has been developed in recent years (Iizuka et al., 2012), and it has begun to be applied to the Greenland NEEM ice core. Other new methods include measurements of the concentrations of heavy metals, organic carbon, and black carbon, and the reconstruction of aerosol provenance and transport pathways by isotopic analyses. Reconstructions of CH_4 and N_2O concentrations have been done directly via gas analyses of ice cores (NEEM community members, 2013) and their isotopes are also analyzed. Surface-temperature reconstructions and detection of surface melt are now possible based on nitrogen and noble gas concentrations and isotopes (Kobashi et al., 2013; NEEM community members, 2013).

Advances in these proxy studies will require multiphase research developments. These include development of isotope and transport models, observations of water vapor, rain, snow, and aerosols, as well as better understanding of preservation processes of various substances in ice, and better understanding of ice-core drilling and analyses at many sites. While ultra-high-resolution analyses of ice and gases with continuous ice-core melting systems are becoming practical in Japan, further developments are important in order to advance multiple-component analyses involving many ice cores.

b. Sea-ice proxies in marine sediments

There are well-utilized sea-ice proxies found in marine sediments: ice-rafted debris (IRD), iron oxide particles, microfossils (diatoms, dinoflagellates, benthic foraminifers, and silicoflagellates), biomarkers (in particular, IP25). IRD is deposit transported by sea-ice and icebergs. IRD can be fractionated using a 63 μm sieve because it contains particles > 63 μm. The weight of the IRD fraction can be measured to estimate the IRD mass. Iron oxide particles are widely distributed on the continental shelves of the Arctic Ocean and the chemical constituents found in them are characteristic of certain regions. Iron oxide particles can be extracted with a magnet, and the constituent elements of the particles are analyzed to estimate the provenance of sea-ice formation. Because sea-ice related phytoplankton and benthos, such as some diatoms (ice algae), dinoflagellates, and silicoflagellates, grows in the water and on the bottom surface of sea-ice and can be preserved in sediments in the regions of seasonal sea-ice and sea-ice margins, their microfossils can be used as indicators of seasonal sea-ice and/or sea-ice margins. Because benthic foraminifers also grow in the regions where sufficient organic matter is available, their fossils can indicate the disappearance of seasonal sea-ice. IP25 is a characteristic lipid specific to algae that dwell on the bottom surface of sea-ice; thus, regions with active sea-ice melt can be determined by its presence.

Theme 7: Effects of the Arctic environment on human society

Abstract

The five academic questions in this theme are as follows:

Q1: How do the impacts of climate change, including global warming, appear?

Q2: What apparent effects in the terrestrial environment change due to global warming?

Q3: What apparent effects in the marine environment change due to global warming?

Q4: How do the impact of solar activity and the Arctic upper atmosphere appear on the human societies?

Q5: How do the human societies in the Arctic respond to these impacts?

In the Arctic area, the natural environment is rapidly changing, for example, sea ice reduction, permafrost thawing, and changes in terrestrial vegetation and wild animals, caused by proceeding global warming along with development from the last century. As implied by the increasing interannual variability, unusual weather episodes that we have never experienced are likely to occur more probably. Fluctuations in climate and weather differ according to the region; therefore, the prior selection of suitable varieties is necessary for effective agricultural production. Vegetation and wild animals are seriously impacted by environmental change, including forest fires, which causes significant problems for residents with a livelihood in hunting. Disturbances caused by solar activities create communication failures in the polar region. As such, it is necessary to intend to preserve the environment and living conditions by taking measures and advantage to reduce the emission of greenhouse gases; for example, carbon credit.

As the sea ice retreats, seasonal ice cover basically expands in the Arctic Ocean. Since the Arctic Ocean is a semi-enclosed basin influenced by river water, the deep basin and bottom sediments, the variability in nutrient distribution is complicated. In addition, it is the first place in the world to suffer marine acidification. As for fishery resources suitable for the Arctic Ocean, we should be concerned with resource management, keeping in mind the serious impact on the residents who rely on fishing and hunting sea creatures. In order to safely operate the Arctic sea routes, effective prediction of sea ice conditions is essential. In addition to pollution associated with accidents such as groundings, livelihoods may be modified by shipping, therefore development should be conducted with consideration of the impact on residents.

By using examples from the alarm system in Japan for earthquakes and tsunami, we propose a method to cope with environmental problems that will be acceptable to residents with a livelihood in the Arctic. The important point is cooperation with indigenous peoples, who account for the majority of the population in the region, and not forcing them to accept the methods in the developed nations. We will present research on the impact on human societies and the countermeasures taken, including information on humanities and social sciences, and propose measures to be taken at each level of international relations, and the national and local governments. The basis of the long-term plan is to develop cooperation between the natural sciences and the humanities and social sciences across the Arctic area, which will extend beyond the existing environmental research community.

Introduction

In this long-term plan, our basis for discussing environmental changes that have occurred to date and that are predicted to occur this century is the natural science; i.e., the focus is on mechanisms and effects of global warming, and on the effects of other anthropogenic changes (including development) on ecosystems. The originality of Theme 7 is in describing research directions with regard to effects on human society and potential countermeasures, including through knowledge derived from the humanities and social sciences. While considering effects on livelihoods of local residents, we describe methods to reduce negative impacts and disasters occurring due to unusual weather, forest fires, permafrost thawing, changes in wild flora and fauna, and solar activities. As for the effects of Arctic environmental change on industrial activities, we list possible problems and solutions for operation of the Arctic sea route, and for future agriculture and fisheries under predicted climate change (Figure 26).Here, it is noted that both Arctic sea route and Arctic shipping route are used in this report with the common meaning. It is shown that cooperation with local residents is indispensable for effective transfer of information on ongoing and possible effects. In addition, we propose measures that can be taken at levels of international relations, and also national, and local governments.

Let us list predicted problems, with a focus on societal concerns. As climate changes, air temperature fluctuates and precipitation varies, with different tendencies in different regions. Agricultural production is sensitive to

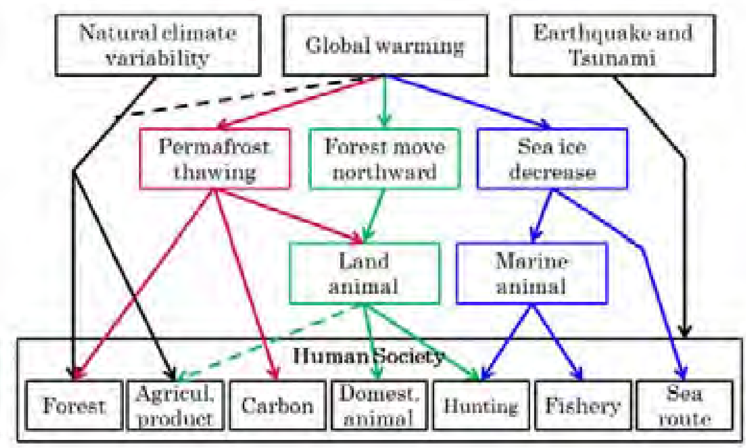


Figure 26: The impacts of the Arctic environmental changes on the human society

air temperature and water resources, and it is hence necessary to select varieties suitable for cultivation in advance. As inter-annual climate variability increases, in addition to specific trend changes, terrestrial vegetation will be seriously impacted, so as wild animals of the region; causing significant problems for residents with hunting-based livelihoods.

In the Arctic Ocean (including the Siberian Shelves and the Barents Sea) and its adjacent seas (the Bering Sea, Greenland Sea, etc.), there will be changes in the marine environment (such as in levels of nutrients in seawater) in response to sea ice decline. At present, seasonal ice cover is expanding in the Arctic Ocean, but given that the Arctic is a semi-enclosed basin, with a relatively large inflow of river water and that it is also subject to the effects of deep basin and bottom sediments, we need to keep in mind more complex changes. In addition, ocean acidification is going to be the most significant first in the cold seas. The fact that some fishery resources may be more suitable for a warming Arctic Ocean raises resource management concerns. There may be serious impacts on residents who rely on fisheries and marine mammal hunting. With reference to recent viewpoints in ecological conservation research, it appears that human activities not only induce environmental disturbances but also possibly contribute to maintenance of biodiversity. Some have pointed out that biodiversity and cultural diversity depend on each other.

Following the decline in sea ice, the Northern Sea Route between Asia and Europe is rapidly looking likely to become operational. For safe operation, effective predictions of sea ice conditions are essential. Should there be accidents resulting from, for example collision with icebergs and grounding, pollution will persist for long periods. The effects of the Arctic Sea Route (including the Northwest Passage on the Canadian side) are not limited to pollution, since livelihoods may also be modified by shipping. Development should therefore be conducted taking into account the various effects on residents. We propose a method for coping with environmental problems similar to the alarm system adopted in Japan for earthquakes and tsunamis, providing the indigenous peoples to accept resolutions proposed. Cooperation with indigenous peoples is important, but without forcing them to accept the methods in use in developed nations.

Q1: How do the impacts of climate change, including global warming, appear?

a. Unusual weather

(1) Present status of unusual weather

Global warming results in air temperature rise near the land surface, while it has also been shown to induce significant changes in seasonal weather cycles (See Theme 1). Maximum summer air temperatures have recorded large increases in many parts of the world, leading to human disasters such as heat stroke and damage to agriculture due to drought and high temperature failures. On the other hand, never-yet-observed cold waves are affecting some locations worldwide, resulting in major disasters in urban societies. Associated with amplification of seasonal cycles, various natural disasters occurring due to unusual weather have also increased around the world including large-scale torrential showers, floods, heavy snowfall, and frequent tornados.

(2) Impacts on society

An example of impacts on society arises from the heavy snow cover (30–80 cm) that occurred in February, 2014 over the Kanto region, where snowfall is usually minor. A heavy snow warning was issued and people experienced major disruption to their lives, for example with the collapse of housing and interruptions to the transportation system. This case constitutes a natural disaster due to snowfall variability exceeding the location-dependent threshold. In the same year, similar disasters caused by snow and ice occurred in the North American continent, resulting in devastating airline damage, even for airlines with advanced modernization. In the East Siberian interior, an increase in snowfall amount occurred due to wetting, and central Asia and Europe also suffered many disasters due to cold waves and heavy snow. With the recent warming trend, these disasters due to cooling and heavy snow have occurred more frequently in many parts of the world than they used to previously.

In most areas, global warming is occurring and is reducing snow and ice. Even in such cases, communities are still susceptible to disasters, given changes to the environment to which they have tried to be adapted. Taking the example of wheat, a main staple food globally, damage to winter wheat production is dependent on snow depth in North America, i.e., winter wheat in the ground withers with frost damage under conditions of lower snow cover, because snow acts as a good-quality insulation material. Under average conditions, benefits increase (decrease) by 300 million US dollars with a 1 cm deeper (shallower) snow cover (Steppuhn, 1981). In many cities, residents' daily lives and industries are supported by a water supply that is dependent on melting mountain snow and glaciers. Most glaciers have been reported to have shrunk under global warming conditions, creating serious concerns of water resource depletion in the near future, particularly for inland cities.

We have used the example of snowfall levels as an example here, but many other unusual weather conditions create human disasters, direct damage to agricultural/industrial production, and also damage to social infrastructure. Such weather conditions include, for example, heavy rain, drought, tornadoes, typhoon-hurricanes, and high tides.

(3) Future research direction

We need to scientifically predict global warming tendencies and climate variability, and to estimate the probability of disaster occurrences. In addition, we need to build a robust living foundation for coping with disasters. For this purpose, we should keep analyzing the history of mankind using reconstructions of the paleoenvironment as one method. During periods of repeated warming and cooling, historical turning points occurred mostly as a result of the impacts of unusual weather. The Ur kingdom of Ancient Mesopotamia, which prospered with control of water resources, declined due to warming and drying, becoming a ruin in the desert. The Vikings constructed settlements and camps in Greenland and northwest of Canada during the warm period of the medieval ages; however, they abandoned these territories

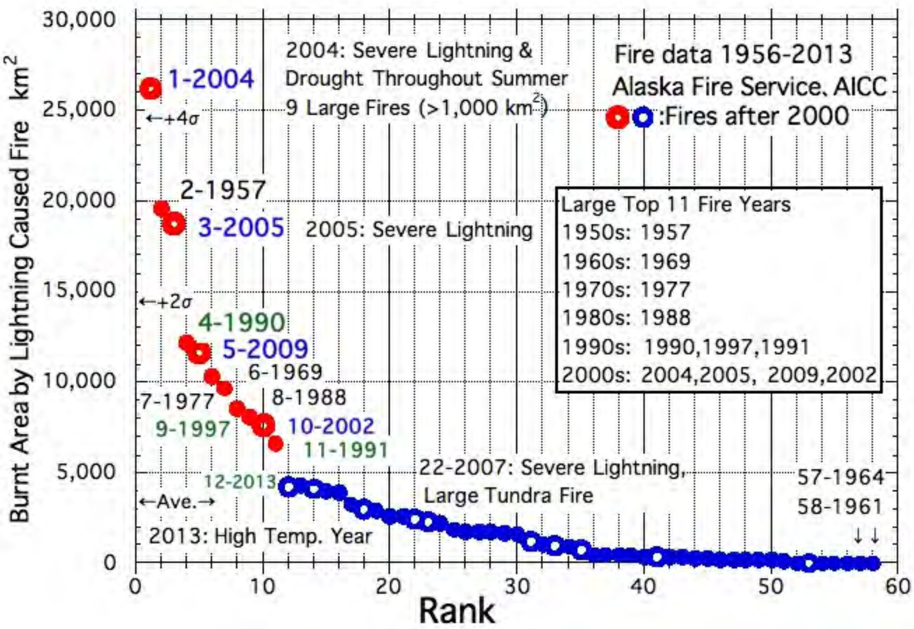


Figure 27: The areas burnt by forest fires caused by lightning since 1956 in Alaska in descending order

since they could not maintain trade due to the closure of trade routes by sea ice at the beginning of the Little Ice Age. These events tell us that civilizations have had the ability to respond to frequent minor climate variations, but could not deal with large changes that exceeded certain thresholds and resultant unusual weather, otherwise choosing to migrate to a different location. Although we do not subscribe to the hypothesis that the environment determines everything, we should take serious consideration of the fact that large environmental changes have been key players in history.

We expect detailed comparisons between historical events and analysis results of climate variability records developed in recent years, derived from ice cores and pollen. It is necessary to carry out quantitative studies by advancing research collaborations across academic disciplines, looking at how human activities were affected by, dealt with, or declined due to unusual weather (such as heavy rain or drought, high or low temperatures, heavy or light snowfall, etc.). Based on these studies, we will have a basis for examining social response capabilities with respect to future climate changes in the Arctic and its adjacent areas. The indigenous population living in the polar environment has, until now, conventional knowledge related to weather, with this having value in terms of intangible cultural heritage for humanity. We will document and record this knowledge and evaluate it from the viewpoint of the natural sciences, with the expectation that it may help identify possibilities for dealing with unusual weather in future.

b. Forest fire

(1) The present status and research of forest fire

The boreal forests (Taiga) are distributed over the northern parts of North America and Eurasia, accounting for about one third of the global forest area (about 10% of global land area) and 30–40% of the carbon stock on land. Forest fires act as a natural regeneration process and as the most significant factor of disturbance, having a close relationship with organic matter in the permafrost and on the forest floor. We can identify recent features of forest fires in Alaska from Figure 27, which lists forest fires caused by lightning in descending order of burnout areas. Large-scale fires, which exceed the burnout area of 6500 km^2, were observed eleven times in the past 58 years, about once a decade over the 1950s, 1960s, 1970s, and 1980s. Such fires then occurred three times in the 1990s and four times in the 2000s. The total burnout area of 46000 km^2 in 2004 and 2005 is close to 10% of the forest area in Alaska. In Siberia, human-made forest fires have increased following development and have also been enhanced by unusual weather events.

Through research on forest fires and vegetation in mid-Alaska, fire behaviors and vegetation variability were analyzed over the past ten thousand years. It has been suggested, from analysis associated with climate change, that recent intense fires exceeded the limit of burning, although fires may fit vegetation change well similar to the warm period of the medieval ages (MWP) (Kelly at al., 2013). However, we do not yet have an explanation for why the limit of burning was exceeded in both cases.

(2) Impacts on society

Large-scale forest fires, which have occurred frequently as a result of rapid climate variability in recent years, have effects not only on vegetation renewal, the carbon cycle, and permafrost areas, but also on the acceleration of global warming through emissions of carbon dioxide and methane. Furthermore, pyrocumulus formed from smoke has parasol effects, containing carbon particles similar to those emitted during a volcanic eruption, and these reduce the albedo of snow and ice surfaces. Thus, fires cause environmental problems on a global scale. For communities in the regions, research activities with a wide perspective are required to enable preparation for fires, mitigation of air pollution, assessment of fire impacts, information transmission to residents, and other such aspects.

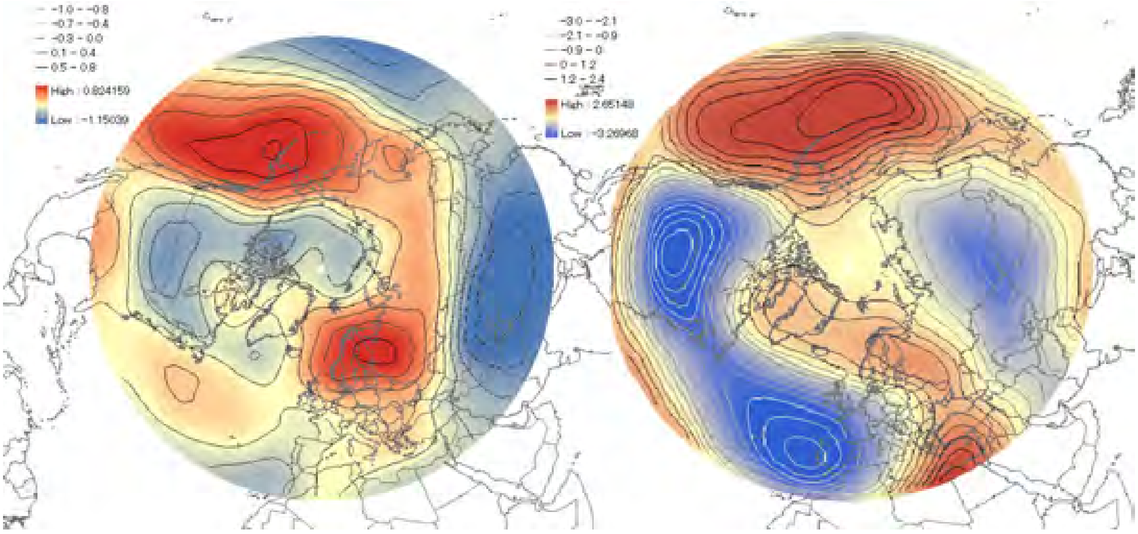


Figure 28: The averaged winter 500hPa geopotential height anomalies in the top five years of the frequent cold Arctic Outflow Events (left), and the third EOF associated with the same ECMWF geopotential height data (right)

(3) Future research direction

Recent studies suggest that strong easterly dry air winds from Canada are one of the causes of large-scale forest fires in Alaska. This weather pattern is related to variations in atmospheric circulation, i.e., the rapid decline in sea ice cover in the Arctic Ocean tends to reduce the temperature difference between the high and low latitudes and also to weaken the high latitude jet stream, by which the atmospheric pressure ridge develops over Alaska along with the Beaufort high pressure (see Theme 5). We should carry out more detailed analyses to understand forest fire mechanisms that are different from the response to vegetation change in the MWP. It is important to quantify accelerating effects on global warming by monitoring emissions of carbon dioxide and methane associated with forest fires.

If we can predict a large-scale fire at the same level of the sort that occurred in 2004 and 2005 (with a burnout area of about 20000 km^2), and manage the damage it induces, it will be possible to reduce emissions of carbon dioxide to one tenth, because fires other than the top eleven shown in Figure 27 have burnout areas of about 2000 km^2. We can mitigate air pollution emitted from large-scale fires by prescribed fires, which are deliberately started in areas with growing vegetation mass. These can be predicted with satellite images and using hot spot data. Although it is difficult to forecast an extreme event related with a blocking high pressure, we can identify the occurrence of the extreme event from wind directions. This type of information can be transmitted through the Alaska Interagency Coordination Center. We can obtain the results of the latest research, as collected by the Alaska Fire Science Consortium.

c. Agricultural production

(1) Atmospheric circulation variability

We expect that regions with potential for agricultural production will expand in the Arctic due to environmental changes, even though there are some concerns with respect to the effects of weather conditions. Weather conditions are highly dependent on atmospheric pressure distribution, analyzed through principal components as widely used in atmospheric science. The first mode of the empirical orthogonal function (EOF-1) with the largest amplitude is derived from pressure at 500 hPa (height about 5000m) over the northern hemisphere, representing

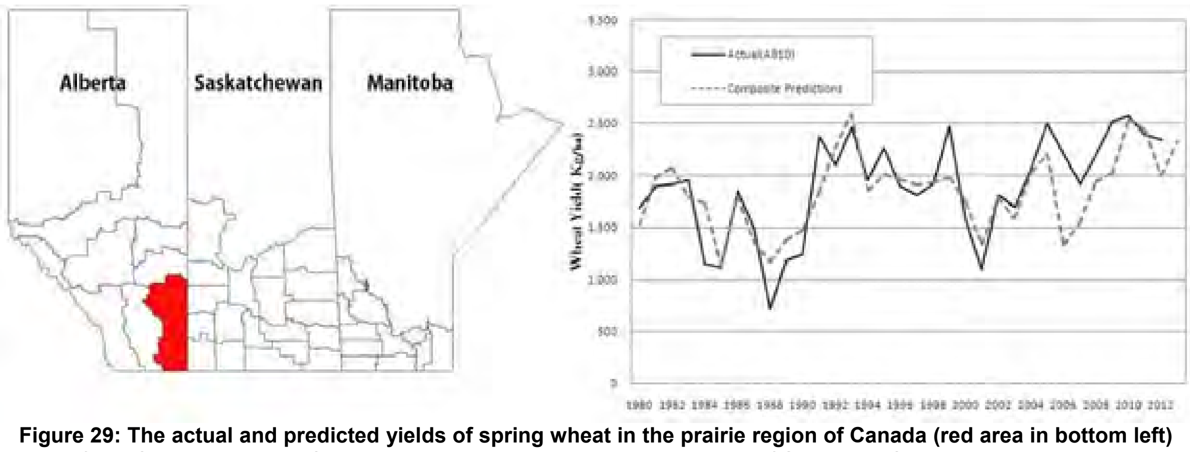


Figure 29: The actual and predicted yields of spring wheat in the prairie region of Canada (red area in bottom left) taken from Canadian Prairie Crop yield data (2012), Agricultural Division of Statistical Canada

the Arctic Oscillation (see Themes 1 and 5). This mode has been found to be related to unusual weather in various regions of the northern hemisphere (Tanaka, 2008). The two following modes are also derived in the order of larger amplitudes: EOF-2 as Dipole Mode (see Theme 5) and EOF-3.

If we look at the prairie region in Canada, we can examine the spring wheat yield in a unit of plant area, and the temperature and accumulated precipitation over the period from planting to harvest. Under the Arctic Outflow Event (AOE), cold and dry conditions are expected to appear in winter (Dec–Feb) along the west coast of Canada, resulting in a yield reduction during the following spring. The pressure anomaly at 500 hPa is averaged for the top five years, with many AOEs over 30 years (Figure 28), showing a pattern similar to EOF-3 and providing supporting evidence for the relationship between weather and spring wheat yield.

(2) Impacts on agricultural production

The predicted yield variability approaches actual yield if we include EOF-3 as an explanatory variable, in addition to air temperature, precipitation, and the previous year's yield (Figure 29). Since EOF-3 persists for a period, we could use it to select types of crops a few months prior to harvest.

In the Trans-Pacific Strategic Economic Partnership Agreement (TPP) currently under negotiation, there is increasing global safety awareness of and resistance to genetically modified (GM) foods; for this reason, there is growing demand for grains that are not genetically modified (non-GM). However, it has been pointed out that non-GM crops have reduced productivity and are also weaker under unusual weather conditions. The type of soybean used for fodder has been genetically modified to be resistant to weed killers, and it is hence difficult to select a non-GM kind.

(3) Future research direction

It is necessary to apply methods that have been established for the prairie region in Canada to other regions in the northern hemisphere, constructing a system to predict yield in advance of harvest by a few months. Cold region farming used in Hokkaido has been tested in the Amur district of the Russian Far East. We could contribute to the stability of agricultural production in the Arctic Area by experimentally supplying yield prediction information in the Amur district. According to the hearing of the 39th International Food and Beverage Exhibition (FOODEX Japan 2014) in March, 2014, higher yields of almonds were predicted between the autumn of 2013 and the spring of 2014 in Australia; however, yields in California were predicted to be lower. By referring to significant differences in agricultural production between northern and southern hemispheres, we can widen the scope and coverage of research.

Q2: What apparent effects in the terrestrial environment change due to global warming?

a. Permafrost thawing and carbon emission

(1) What happens due to permafrost thawing?

Permafrost thawing has been reported with confidence (see Theme 4 and 12), and emissions of methane and carbon dioxide have been confirmed (see Theme 3). However, it is not yet well known which greenhouse gases are emitted and to what extent. The running water from thawing permafrost tends to extend lakes, and we have measured methane fluxes to the atmosphere at spots on the soil surface of tundra and taiga. In some regions, thawing permafrost leads to an extreme increase in soil moisture, damaging forests and reducing the absorption of carbon dioxide. In cases when thawing permafrost induces desiccation, carbon dioxide must be emitted from the ground. Forest fires are remarkable sources of carbon dioxide. Continuous measurement of methane concentrations in the atmosphere has indicated an increase, and carbon dioxide emissions are estimated to cancel out half the absorption increase caused by activation of vegetation.

Methane may vaporize and be emitted not only from permafrost on the ground but also from methane hydrates in the frozen soil layer under the continental shelf seabed. There is still large uncertainty regarding the amount of methane in methane hydrates and the rate at which this will be released.

(2) Impacts on society

There is a physical impact of permafrost thawing on collapse of houses and damage to gas and oil pipelines. There are seemingly positive-sounding impacts in terms of farmable area expanding and the extension of the farming period. However, the ground might be submerged by melt water, and sometimes desiccation occurs; and for this reason, impacts may not necessarily be positive.

In cases when methane and carbon dioxide are emitted from the ground under the effects of thawing permafrost, reduction in emissions through a number of measures provides carbon credits; thus, this is one example of Reducing Emissions from Deforestation and Forest Degradation (REDD+). In Indonesia, integrated management of peatland (through the SATREPS Project) has been proposed, and doing something similar in the Arctic is therefore not necessarily unachievable. However, a quantitative estimate is required by monitoring emission rates in both cases, considering scenarios with and without reduction measures.

(3) Future research direction

The main research actions in relation to REDD+ are quantitative measurements of methane and carbon dioxide emissions, and proposed means to reduce these. We will propose technical development to suppress greenhouse gas emissions, by cancelling changes in the water environment caused by permafrost thawing. With regard to forest changes due to fires, if we can prevent forest fires that exceed the usual level, it would be possible to convert measures to the reduction of carbon emissions.

It may be possible to propose measures to reduce greenhouse gas emissions to society. However, even though we can propose one-way communication of scientific and engineering knowledge to residents, this would not be an adequate approach. Residents who are deprived of their livelihood might have to change their lifestyles. We should avoid forcing them to agree with proposals for carbon reduction by putting them in a situation where they have no other choice. If they have the choice to maintain their conventional livelihood by using carbon credits as a support, this would likely help to ensure residents' agreement. Even in this case, we should avoid forcing a proposal onto them, but rather, we need to take advantage of the knowledge of indigenous peoples, recognizing differences in value systems. There would thus be increased mutual support between indigenous residents and recent migrants. In terms of research activities in the humanities and social sciences, the required approach involves recording economic impacts and analyzing means of support through social policy theory.

b. Wild flora, wild fauna, and domestic animals

(1) Changes in wild flora, wild fauna and domestic animals

Global warming and associated changes in the hydrologic cycle (drying, wetting, and changes in snowfall and precipitation) lead to a reduction in the area of distribution of species adapted to cold conditions, conversely encouraging the northward and upward expansions of southern species. When considering direct and indirect interactions between various species (such as predation and competition), as well as a variety of feedback loops, complicated changes may be produced at the level of communities, ecosystems, and landscapes (see Q1 and Q2, in Theme 8). At present, vegetation changes that are thought to be caused by global warming, wild fires, and land use changes are occurring, and the direct and indirect effects of these changes are reflected in the behavior and ecology of individual species, as well as through changes in structures and functions (Post et al., 2013; see Q3, Box 4 and Box 5 in Theme 8).

(2) Impacts on society

Changes in behaviors, individual numbers, and distribution areas of wild animals and plants in the Arctic area increase the cost of indigenous residents' traditional hunting, fishing and gathering activities; and then, in some cases, their activities may become impossible. It is widely known that, due to separation of fast ice from the coast in the Arctic area, indigenous peoples have difficulty in continuing traditional marine mammal hunting and fishing practices. There are also remarkable effects of climate change on the hunting of wild animals on land. Specifically in the case of wild animals and domestic animals (cattle, horses, and livestock reindeer) that supply protein to inland regions, various problems are occurring, such as mass death due to ice storms and ice plate formation, predation due to predator increases (e.g., wolves), and also food competition with and kidnapping by wild reindeer. The social structures of northern indigenous residents, whose livelihoods have relied on nomadic reindeer herding, hunting, and fishing, are being transformed at an accelerated rate, from conventional life to urban life, under the double load of cost increases for hunting of wildlife and pasture of domesticated animals.

Social responses to these problems tend to be symptomatic treatments, such as mitigation of hunting regulations, acceleration of pest culling, implementation of high technology equipment, and providing economic aid for traditional lifestyles. As a result, problems of biodiversity conservation and sustainable use of resource animals will become more serious.

(3) Future research direction

Changes in the Arctic due to global warming are also influencing Japan, even though this has no territory in the Arctic; although Japan is also partly responsible for these changes. There are still few Japanese researchers participating in biological research in the Arctic, although there are many cases when we could act on our responsibility to the international community through technical cooperation and educational support for areas in which Japan excels. We need to carry out research in both ecology and management policy, on the basis of cooperation between Arctic countries and non-Arctic countries, as well as collaboration with researchers and policy makers in Arctic countries. In terms of concrete actions, we can propose monitoring of biodiversity using advanced technology, such as satellite transmitters, habitat evaluation using model simulations (see Q3 in Theme 8), and integrated management for the protection and utilization of wild flora and fauna (e.g., protected and hunting areas) by introducing the concept of adaptive management.

In addition, migratory birds and large mammals, such as reindeer, take on roles of connecting different regional ecosystems (biotopes) through materials and functions. Hence, fluctuations in the number of individuals and in the composition of species in the polar region influence ecosystems and society at resting and wintering sites far away, including in Japan. Collaborative research is hence particularly important to explore habitat states and functions of migratory animals, based on the construction of cooperative management systems across multiple nations.

Q3: What apparent effects in the marine environment change due to global warming?

a. Sea ice decline, marine product industry advance and ecosystem deterioration

(1) Effects of sea ice decline on marine ecosystem

There have been observations of changes in the biological pump, which plays an important role in biogeochemical cycles between the surface layer and the seabed zone in the open ocean, as well as of changes in the biomass and distribution of large fish (such as salmon) and of Arctic imports of warm species, including whales (see Theme 9). Research conducted from a bottom-up perspective is not sufficient for understanding the effects of a declining ice-covered area in summer on primary production and on community composition (i.e., diversity) of phytoplankton. On the other hand, research from a top-down perspective has not sufficiently analyzed effects of biomass increases of whales and of fish such as salmon.

(2) Impacts on society

The impacts on marine production industries vary between the Pacific and Atlantic sectors, depending on fishery characteristics. For example, Arctic cod is treated as a marine product and production variability in the Arctic has direct effects on the marine product industry in the Atlantic. It also has an indirect effect in the Pacific, even if here it is not treated as a marine product. However, for species other than Arctic cod to be key species, the effects of production and distribution of cod (such as pollock and Pacific cod) should be considered in terms of the supply of marine products to the import destination. We need to explore not only biological aspects but also complicated relationships, such as fishermen's behavior when considering economics aspects, and trends in the marine product industry under the influences of international relations.

(3) Future research direction

It is predicted that, as global warming proceeds, the distribution area of fish of the salmon genus will extend to the Arctic Ocean (see Theme 9). It is widely known that these fish carry a large quantity of marine-derived nutrients (MDN) to the terrestrial ecosystem (e.g., Kaeriyama et al., 2013; Koshino et al., 2013). Also, the MDN transport mechanism operated by these same fish is expected to occur in surrounding seas and in the terrestrial ecosystem affected by environmental change in the Arctic Ocean. Following the northward shift of marine production resources, their use is growing in the Arctic Ocean and in surrounding regions. We will analyze the globalization of the Arctic Ocean with respect to marine production resources, and evaluate comprehensively the effects of Arctic coastal communities on ecosystems and on social economy. We will collaborate with other disciplinary experts so that we may provide proposals for industries that affect marine production, such as the shipping and energy industries.

b. Sea ice decline, Arctic Sea Route, and marine pollution risk

(1) Sea ice decline and feasibility of the Arctic Sea Route

Through this century, seasonal ice coverage has been consistent on the Siberian side, even though the open water area varies each year (see Theme 2), which determines the operational period of the Northern Sea Route for cargo ship sailing. Thick multi-year sea ice still covers the Canadian side, and hence innovative methods are required to render the Northwest Passage operational. Although use of the Arctic Ocean as a route for cargo ships may seem realistic, more practical approaches are needed for operation, including through monitoring and predictions of the state of sea ice, understanding the operational impacts on hulls, and planning of effective operations. For these, interdisciplinary cooperation between the sciences, engineering, and economics is essential (Kitagawa et al., 2000; Yamaguchi, 2013).

Once the Arctic Sea Route is operational, the length of time and cost of transportation will be reduced, also allowing for reductions in greenhouse gas emissions. The first condition for operation is establishment of a sea ice prediction method. Some plans are making progress in understanding sea ice distribution, ice thicknesses, melting states in July and August, and initiation of formation in September and October. This achievement allows for building of a support system for navigation through ice floes, which includes safety indicators.

(2) Aspects to be resolved and impacts on society

In addition to navigable conditions, there are some other aspects to be resolved. Once sea ice retreats, waves become higher, and seawater spray freezes immediately, fixing to ships in a cold, rough sea. Under conditions of increased icing, even large vessels suffer from adverse impacts on navigation support equipment, such as radar. There are also a reduction in deck workability and hindrance to cargo handling systems. Small vessels such as fishing boats risk capsizing due to raised gravity centers. If prediction of sea ice movement fails, hulls may be damaged by extremely thick, ridged ice. In addition, drifting bergy bits and sea ice pieces increase due to global warming, presenting a greater risk of collision, particularly since such fragments are difficult to detect from a distance. Even if rescue operations are successful, ecosystems would be damaged by environmental pollution due to fuel spills, with resultant serious impacts on residents who rely on seafood.

Even though sea route operation is progressing steadily, associated problems could arise. Ports of call are necessary along the route. There may not be large numbers of vessels, but there will be impacts on the lifestyle of residents due to economic effects. Problems that have often been observed are likely to occur.

(3) Future research direction

We will build reliable predictions of various sea ice elements, to ensure safe navigation for economical purposes. Useful tools include short-term forecasts on a weekly basis for safety, as well as mid-term predictions at a monthly term, and long-term projections over annual to decadal time-frames for economic stability. We will carry out research on the mechanical impacts of contact with sea ice, and also on the effects of hull icing, accompanied by research into prevention technology. On the basis of the research outcomes, a navigation support system will be developed for judgment of capability and efficient use of the Arctic Sea Route. In addition to predicting icing amounts on new types of vessels, such as tankers and icebreakers, an integrated prediction model of hull icing will be constructed to ensure the safety of medium and small vessels, such as fishing boats. Actually, the latter are expected to increase given the search for rich marine resources in the Arctic Ocean. The model would also aim to eliminate dangers during dock work.

When selecting ports of call, it is important to explain the likelihood and environmental impacts of accidents to residents. However, consent would not be likely to be achieved with unilateral explanations based on scientific and engineering knowledge. Research based on humanities and social sciences is required in order to build a relationship of mutual understanding between resident groups having varying livelihoods, languages, and traditions. The result would enable mutual understanding between residents and developers. With regard to usage of routes, we need to proceed with a full economic geography assessment of global distribution systems. At the same time, an approach is required to explore the nature of governance in the Arctic Ocean on the basis of analyses of international laws and legal systems in relevant nations.

Q4: How do the impact of solar activity and the Arctic upper atmosphere appear on the human societies?

a. The effects of solar activities

Many physical phenomena in the upper atmosphere of the Earth are caused by variations in the solar wind, including the interplanetary magnetic field (IMF) and radiation, constituting energy flows from the sun. In particular, the solar wind and IMF originating from the sun interact with the Earth's magnetosphere, generating an influx of plasma and electromagnetic energy into polar areas. In the upper atmosphere, this causes large electric currents associated with the auroras, expansion and disturbance of the atmosphere, and environmental change in radio wave propagation. The galactic cosmic rays from outside the solar system, which vary depending on solar activities, have potential effects on Earth's climate by ionizing the atmosphere and increasing cloud formation. The disturbances triggered by the sun thus have significant impacts on the Earth's atmosphere, although we have not yet acquired an understanding of these physical processes and have difficulty in predicting the occurrence of these phenomena at this stage. Please see Theme 10 for reference.

b. Impacts on society

High energy particles accelerated by, for example, solar flares cause an air shower in the lower part of the stratosphere and the troposphere, generating a large amount of radiation (Figure 30). There may come a time when top level radiation exposure may reach the dose set as the annual management target for aircraft crew. Measures should therefore be considered to minimize health impacts on aircraft crew and passengers.

Geomagnetic variability, which is caused by interactions between the solar wind and the Earth's magnetic field, and also by aurora activities in the polar areas, creates geomagnetically induced currents (GIC) in power lines and pipelines. These currents result in failure of control systems and accelerate metal corrosion, thus having an impact on the key infrastructure of modern society. It is known that sudden changes in the magnetic field during March, 1989 induced electric currents on the ground; and the resultant electric currents exceeded the allowable limit in the substation transformer of the transmission line in Quebec, Canada, causing a blackout affecting six million people.

In recent years, we have been utilizing space via satellites and manned spacecraft; satellite positioning systems, such as GPS, are also widely distributed. We hence need to mitigate the impacts of the upper atmosphere on these applications. Use of satellite positioning by the aviation industry is currently promoted as international policy. Particularly in this case, where safety is a key priority, technical development is necessary to ensure safety when considering the properties of ionospheric disturbances. In systems for Long-Range Identification and Tracking of Ships (LRIT), used to determine vessel locations through satellite communications, the use of optical fiber networks is being studied in order to reduce the effects of variations in the sun and upper atmosphere.

c. Future research direction

As an element of important knowledge infrastructure projects supporting human society, we plan to continue with research that monitors the polar upper atmosphere, and research targeted at effective and reliable detection of ionospheric disturbances, in cooperation with the engineering field. In particular, it is necessary to aim for observation of the upper atmosphere by satellites, radars,

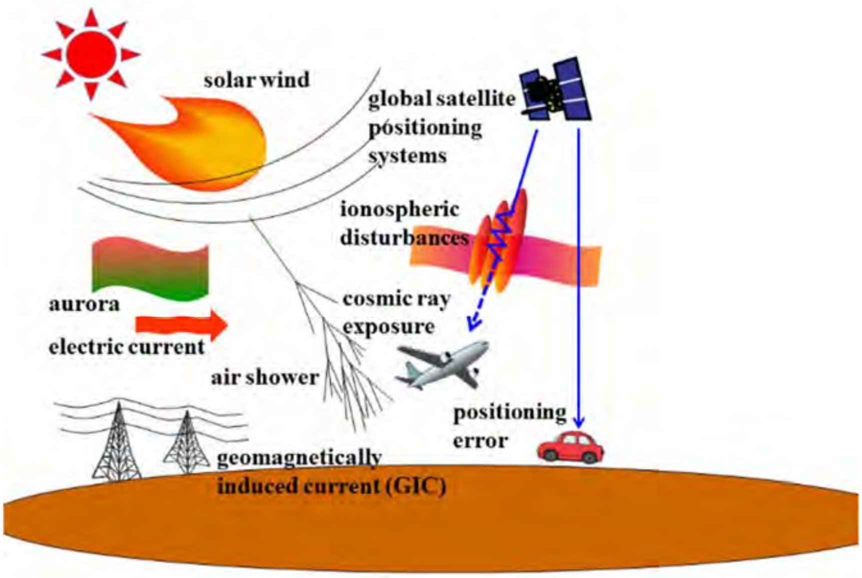


Figure 30: Examples of impacts on society due to solar activities partly modified from the figure in 'Present and Future of Society of Geomagnetism and Earth, Planetary and Space Sciences' (SGEPSS, January 2013)

spectroscopic equipment, and electromagnetic field measurement from the ground. In addition, we need model development to accurately predict the reach of solar energetic particles to Earth, as well as high-accuracy real-time simulations of coupled magnetosphere-ionosphere-thermosphere systems. Please see Chapter 3 of 'Present and Future of Society of Geomagnetism and Earth, Planetary and Space Sciences' (SGEPSS, January 2013).

Q5: How do the human societies in the Arctic respond to these impacts?

a. Emergency communications for earthquakes and tsunamis

(1) The present status of, and research regarding, earthquakes and tsunamis

Large earthquakes have occurred repeatedly in the southern part of the State of Alaska, where the Pacific Ocean plate is subducting. Tsunamis have followed the quakes, for example, following the Alaska earthquake that occurred on March 28, 1964, with a magnitude of 9.2. In 2002, the Denali earthquake (magnitude 7.9) occurred, having its epicenter within the active faults of interior Alaska (Tsuboi et al., 2003). There is no record of a huge tsunami along the coastline of the Arctic Ocean, although it is well known that an earthquake and associated tsunami could occur even in areas where this is not expected, as in the case of the East Japan earthquake in 2011. In recent years, the Greenland ice sheet has been melting, creating uplift in the mantle under Greenland, with distortion accumulated in the crust. There is hence the possibility that large earthquakes could occur within several centuries, along with tsunamis.

(2) Measures for mitigating earthquakes and tsunamis in Japan

A tsunami forecast system has been developed in Japan so that a tsunami warning may be emitted immediately after an earthquake, based on size and location for purposes of minimizing possible disasters in coastal regions. It is necessary to have high-precision seismic networks and to determine epicenters in order to issue a quick and accurate tsunami warning. It is also possible to apply the technology of this system to tsunami forecasts via existing seismic networks. Since it usually takes ten minutes or longer from an earthquake to arrival of a tsunami, depending on the location of the quake, it is possible to minimize impact by evacuation, once the warming is sent correctly using existing seismic observation systems.

(3) Proposal for residents in the Arctic area

For residents to begin evacuation following the issue of a tsunami warning, it is necessary to routinely ensure that residents are alert, building on evaluation of tsunami disasters. It is clear from the history of tsunami disasters in Japan that education is necessary to ensure that residents with little scientific background understand earthquakes and tsunamis. It is important to educate residents about the possibility of a tsunami following an earthquake, based on correct scientific knowledge, and to remind them routinely to flee immediately to high-altitude places should they feel tremors, or should a tsunami warning be issued, even without shaking.

Furthermore, it is also necessary to have methods of transmitting disaster information that are well accepted by residents. We should start by estimating tsunami height, selecting refuges, and establishing evacuation routes, in cooperation with local governments. The next step is to conduct evacuation drills with residents, making sure that evacuation is completed in a reasonable time. We need to conduct actual drills regularly so that residents are constantly aware of tsunami disasters. For this purpose, disaster researchers in Japan could utilize their own experiences.

b. Construction of sustainable systems in indigenous and urban societies

(1) Human societies in the Arctic

The foundation for understanding human history, Arctic nations, and human societies in the Arctic lies in the relationship between various indigenous peoples and the nations surrounding the Arctic Ocean (referred to as Arctic waters in the social sciences, i.e., Canada, Denmark (including Greenland and the Faroe Islands), Finland, Iceland, Norway, Russia, Sweden, and the United States).

The concept of borders between modern states became applicable in Arctic societies only after the early 20th century. Indigenous peoples, whose ancestors lived before nations dominated, are populations with a variety of languages, cultures, and races. Based on ethnographic studies of the early 20th century, we know that their economy was supported by hunting and gathering, fishing, reindeer herding, and hunting of marine mammals, while trade was actively carried out between regions.

From the perspective of nations, the Arctic was the land of buried resources. Russia and Canada advanced to the Arctic area to acquire fur resources, and the United States extended its activities into the Bering Sea for the whaling industry. The relationship with indigenous peoples evolved through wars, trade, and dependence, while the territorial domination of modern states was established through the adoption of a similar process in any region.

The Cold War and resource issues

Immigrants established resource development bases for animal and mineral resources, linked via networks. For indigenous communities, nations' settlement and national education policies began in earnest from 1950 (or so) onwards.

Since the middle of the 20th century, the Arctic has been a highly militarized space, as symbolized by US military bases in places such as Greenland and by the Soviet nuclear test site Novaya Zemlya. At the same time, the Arctic area has also been a space for scientific research. In contrast to the philosophy of the Antarctic Treaty reflecting the outcome of the International Geophysical Year (IGY) of 1957–58, the Arctic was affected by the Cold War, also in scientific fields. In this sense, during the 20th century, Arctic human society was subdivided into categories of indigenous peoples, immigrants, soldiers, and scientists.

Indigenous peoples and environmental issues

The states described above changed after the collapse of the Cold War. Mikhail Gorbachev, supreme leader of the Soviet Union, called for peaceful use of the Arctic in 1987. Finland then played a leading role in 1989 in gathering the eight Arctic nations to ensure environmental protection of the Arctic, leading to the formation of the Arctic Council (AC) in 1996. Within this space that had traditionally been governed exclusively on the basis of national sovereignty, an inter-governmental organization was thus formed to ensure the welfare of Arctic residents (including indigenous peoples), sustainable development, and environmental protection.

Although the Arctic Council's decisions are made by the eight member countries, it is important to guarantee participation of indigenous organizations as permanent participants. Indigenous peoples can be involved in consultation, not just as nationals of the member countries, but in positions similar to being nationals of indigenous organizations. This system follows the decision-making systems adopted by international organizations, such as the United Nations, in recent years.

In recent years, western Europe, east Asia, and India, among others, have developed significant economic interest in the Arctic area. These countries are participating in the Arctic Council as associate members or observers, together with NGOs. Arctic human society of the 21st century has thus started to be constituted of both conventionally-configured population members and new participants.

(2) Current status of research

Development and health problems

The humanities and social sciences have explored Arctic human society, with the main research challenge being the history and culture of indigenous peoples. One of the contemporary challenges is the impact of resource development. Analysis of the impact of oil and gas development in west Siberia on indigenous communities after the collapse of the Soviet Union reported negative impacts on indigenous communities. For example, regional priorities were ignored, grazing land was bisected by pipelines, the environment was degraded due to waste, and forced migration was induced. On the other hand, it has been reported that reindeer herding by indigenous peoples contributes to the food supply of the new developed area. It has been suggested that development and traditional occupation could possibly coexist. On the other hand, research is underway regarding damage to the health of indigenous communities that are dependent on mammals and fish in coastal regions, due to environmental pollutants from mid- and low latitudes entering and persisting in the Arctic Ocean.

Identity and indigenous movement

It was considered that cultural identity would suffer in the face of modernization, with increasing nationalization. However, as can be seen from the organization of indigenous movements, subjective ethnic and cultural symbolism is emphasized in the globalized world and facilitates to sense the idea of belonging as a response of political and economical dynamism. Particularly in recent years, indigenous concepts have become cross-regional and cross-ethnic, constituting an international political 'actor'. As seen in the formation of Kamuchadal in the Kamchatka Peninsula, the descendants of immigrants also conduct their own self-identification. Thus, the ethnicity of Arctic human society is dynamically evolving.

Effects of climate change

Does global warming have any positive or negative impacts on local communities that depend on natural resources? Through the results of research projects based on the fusion of humanities and sciences, promoted in recent years, the conventional wisdom (indigenous knowledge) of communities and its social role have been better understood. Analyses of resilience, i.e., capacity to absorb environmental change, have also been conducted. On the other hand, it has been noted that both urban and rural areas are subject to inundation and erosion damage because of sea level rise due to melting of the ice sheet and glaciers, and more flooding due to melting of snow and permafrost as well as wetter weather conditions. (Symon et al., 2005).

(3) Future research direction

Direction

We need to apply perspectives of traditional indigenous research to immigrants, to then establish Arctic humanities and social sciences via integration of conventional political and economic analyses performed for each nation. In addition, it is necessary to analyze Arctic human society from the perspective of east Asia, including Japan.

Contents

① Indigenous movement in Arctic Ocean governance

We analyze how indigenous movements are organized within regional governance mechanisms, such as the Arctic Council, and how they operate with respect to political claims, inter-organizational cooperation, and counter-national policy.

② Arctic multiculturalism and identity

The lives of immigrants and indigenous peoples engaged in resource development and tourism, among other sectors, have been intertwined via social, economic, and cultural aspects. For a better understanding of this point, we analyze cultural mixing phenomena and the process of restructuring identity.

③ Conventional knowledge as cultural heritage, and its development

Indigenous knowledge related to weather and ecology of indigenous peoples who have lived in the northern environment has developed through history over several thousand years; it is therefore of great worth as intangible cultural heritage of humankind. In addition to collecting and recording this knowledge, we provide applications to develop its value further for future generations, based on natural scientific evaluation.

④ Environmental changes due to global warming and Arctic natural disasters

Global warming is producing impacts, not only through sea ice decline, but also on forest areas, including permafrost. We therefore characterize disasters occurring in the Arctic and evaluate how local communities and cities could respond.

⑤ Environmental assessment analysis of coastal communities linked to Northern Sea Route development and fisheries resources development

The use of seas connecting the Arctic and low-latitude areas will tend to increase due to warming. We carry out overall evaluation of the impacts on ecosystems and socio-economics of Arctic coastal communities.

⑥ Social dynamics analysis of east Asia, Siberia and the Arctic Ocean

East Asian countries are committed to Arctic problems from the perspective of resource development and scientific observation, while China and Korea have also introduced immigrants and capital into east Siberia, territory that is contiguous with these countries. By considering these aspects in a comprehensive manner, we perform geopolitical and social-economic analyses of the connection between Arctic human societies and east Asia.

Methods

Construction of research network for Arctic humanities and social sciences

We will build media to promote mutual exchange and understanding across the humanities (with a focus on indigenous peoples), social sciences (with a focus on national issues), and natural sciences (with a focus on the human environment). In particular, based on knowledge related to indigenous concepts and related social reality, as studied in anthropology and law, we build models of Arctic human societies that can be shared with the research community, synthesizing individual analyses.

Chapter 6: Elucidation of Environmental changes concerning biodiversity

Ecosystems are affected by global warming and other various environmental changes caused by both natural and human factors. Here we describe the mechanisms in ecosystems and effects on that, and note current status and changes in biodiversity.

Theme 8: Effects on terrestrial ecosystems and biodiversity

Abstract

Arctic terrestrial ecosystems and its biodiversity are now exposed to significant changes due to strong impact of human activities such as global warming. Compared with other ecosystems of the world such as temperate and tropical, the expected environmental changes in the Arctic terrestrial regions are particularly strong (IPCC AR5), and we have to predict the future conditions by promoting research and organizing the knowledge about the effects of the environmental changes. Nevertheless, research on Arctic terrestrial ecosystems is significantly delayed, when compared with other ecosystems, and a strong emphasis on this topic is urgently needed. In Topic 8, Arctic terrestrial ecosystems, biodiversity that is an important component of the ecosystem, and impacts from changes in ecosystems and biodiversity on the climate change and regional communities are considered. Because Arctic terrestrial ecosystems are now facing serious changes that caused by human activities, such as agriculture and forestry and exotic species other than climate change, we have to highlight the importance of field observations and experiments, remote sensing, and simulation studies that integrate spot field observations and predict future ecosystem conditions in large scale. Studies and observations on biodiversity of the Arctic terrestrial regions are not progressed sufficiently due to the vastness of the region, but further expansion of the investigation, networking of the field studies, and studies on ecosystem and biodiversity under the environmental changes are required. Changes in the ecosystem will have strong impacts on animals such as mammals and birds. In addition, since the effect of the Arctic terrestrial ecosystems that accumulate large amounts of soil organic carbon in the vast wetlands on the global carbon cycle is large, it is essential to enhance both field and simulation studies that are essential to make appropriate predictions using explicit reproduction of ecosystem processes.

Here we have three study questions:

Q1: What environmental changes will occur in the Arctic terrestrial ecosystems due to anthropogenic factors?

Q2: How is the biodiversity affected?

Q3: What are the impacts on climate and animals due to the changes in the Arctic terrestrial ecosystems?

Introduction

Terrestrial ecosystems and their biological diversity are important elements of the earth system, and these are closely related to the productivity of agriculture and forestry at local scale, with significant impact on the global climate through carbon cycling. Terrestrial ecosystems are therefore very important and it is important to accurately understand their present conditions and prepare for the future, particularly because of the pronounced recent direct and indirect impacts of human activities. Humans affect many aspects of ecosystems and biodiversity in the Arctic terrestrial area (Figure 31). Direct influence involves impacts of human activities (such as land use change due to agriculture, forestry, hunting, and mining) in the Arctic area. Indirect impacts constitute environmental changes caused by climate change (such as temperature increase, precipitation change, snow/ice/permafrost melting, and wildfire). In this theme, in addition to the direct effects on Arctic human societies (cf. theme 7), we examine indirect influences on global human society through global climate and biogeochemistry (cf. theme 3). This is a very important and urgent concern for all, including us Japanese.

The description of this theme has been compiled on the basis of Questions. In Q1, we give an outline of impacts on Arctic terrestrial ecosystems affected by artificially-induced environmental changes. In Q2, we focus on biodiversity and discuss requirements for future studies and measurement. In Q3, we describe the impact of changes in terrestrial vegetation on animals, the

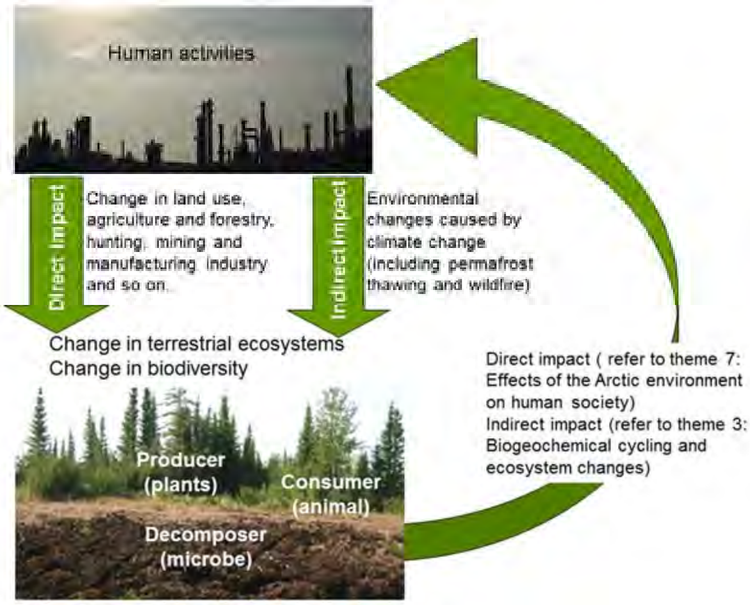


Figure 31: ATEs and biological diversity are closely related to human life and activity. This aspect is not only of relevance to people living in polar areas, but interacts with global human societies through climate change.

higher consumers in ecosystems, and feedback to climate from vegetation changes. This constitutes the output from this theme to the whole report.

Q1: What environmental changes will occur in Arctic terrestrial ecosystems due to anthropogenic factors?

a. Importance of this topic and current conditions

The terrestrial ecosystems of the Arctic and subarctic zones (hereafter referred to as Arctic terrestrial ecosystems: ATEs) have unique characteristics. Species in ATEs are unique due to severe environmental constraints (such as low temperatures, snow accumulation, and short growing seasons). Since seasonal changes in environmental conditions such as temperature are particularly intense, there are many animals that move seasonally and that use ATEs temporarily. The necessary information to scientifically understand ATEs varies, because these are comprised of two very different ecosystems: boreal forests (taiga) and tundra (with no tall trees). Because, given their specific nature, ATEs are sensitive to even slight environmental changes, and because climate change is expected to become particularly intense in this area, we should expect the promotion of intense research. Knowledge of ATEs should be used for environmental conservation.

Artificial environmental change, including global warming, has strong impacts on ATEs that are expected to be exacerbated in future. There are various factors of artificial environmental change; here, we discuss a representative selection, considering the severity of impact and present state of scientific knowledge. First, climate changes resulting from greenhouse gas emissions are changing the environmental conditions (such as temperature and precipitation) within which ATEs are established. Second, pollution of the atmosphere, water, and soil becomes a serious concern with the advent of industrial activities, including mining, oil field development, and hydroelectric power generation. Whether intentional or not, human activities also result in invasion of many exotic species, with effects on ecosystems comprised of native species. It is anticipated that southern species will invade northern regions due to climate change; an example is the entry of woody plants into tundra through northward movement of the tree line. It is conceivable that an increase in harmful ultraviolet insolation caused by the depletion of the ozone layer (the influence of which is especially significant in polar regions) will impact ecosystems, although there are prospects of mitigation in sight.

There are also problems arising from both direct influences of human activities and indirect influences through climate change. Wildfires have a serious impact on ATEs, but our overall understanding of their mechanisms has not advanced, due to the complexities of ignition and other aspects. Wildfire is often caused by human activities, as well as by natural ignition (such as lightning). It has become important to understand mechanisms of wildfire occurrence, including the influence of climate change and future prediction, because the severity of wildfires greatly depends on physical conditions (such as temperature, wind velocity, and soil moisture). Furthermore, impacts of wildfire on climate change are wide-ranging, and with current scientific knowledge, it is not even known whether there is positive feedback amplifying climate change or negative feedback to deter it (Figure 32).

Forest plants perform primary production in ecosystems, and changes in vegetation influence fauna and microflora. Vegetation changes result from both climate change and direct human activities (such as deforestation). These in turn influence various ecosystem services, such as carbon sequestration, as well as affecting biodiversity. In Q3, we discuss the indirect influence on animals through climate change. In terms of direct influence, we must not ignore habitat fragmentation by deforestation and by construction of roads and railroads. Habitat fragmentation is a particularly serious problem in ATEs because there are many migratory animals, such as

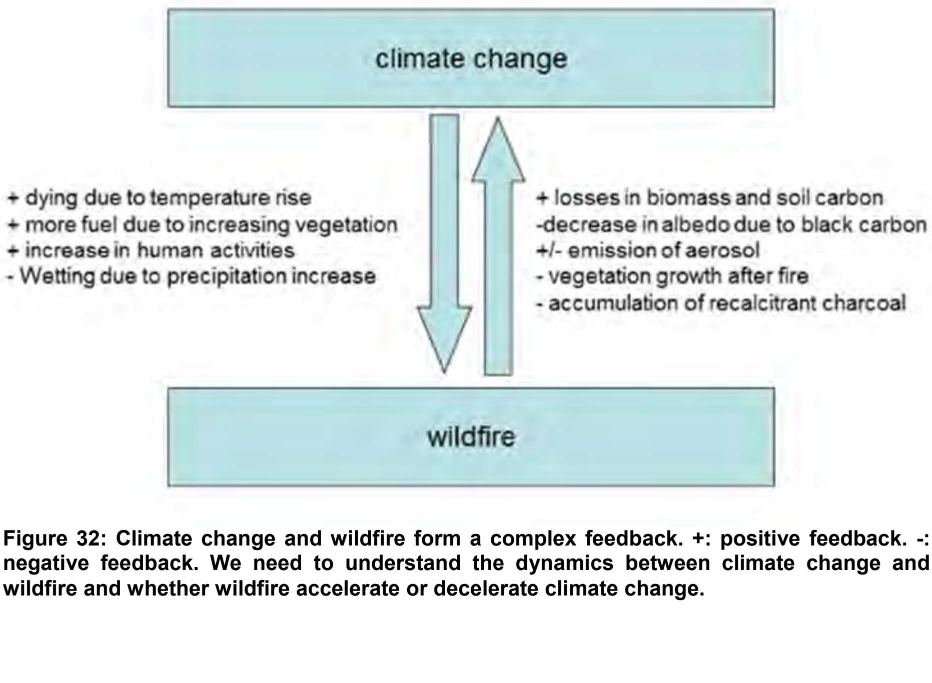


Figure 32: Climate change and wildfire form a complex feedback. +: positive feedback. -: negative feedback. We need to understand the dynamics between climate change and wildfire and whether wildfire accelerate or decelerate climate change.

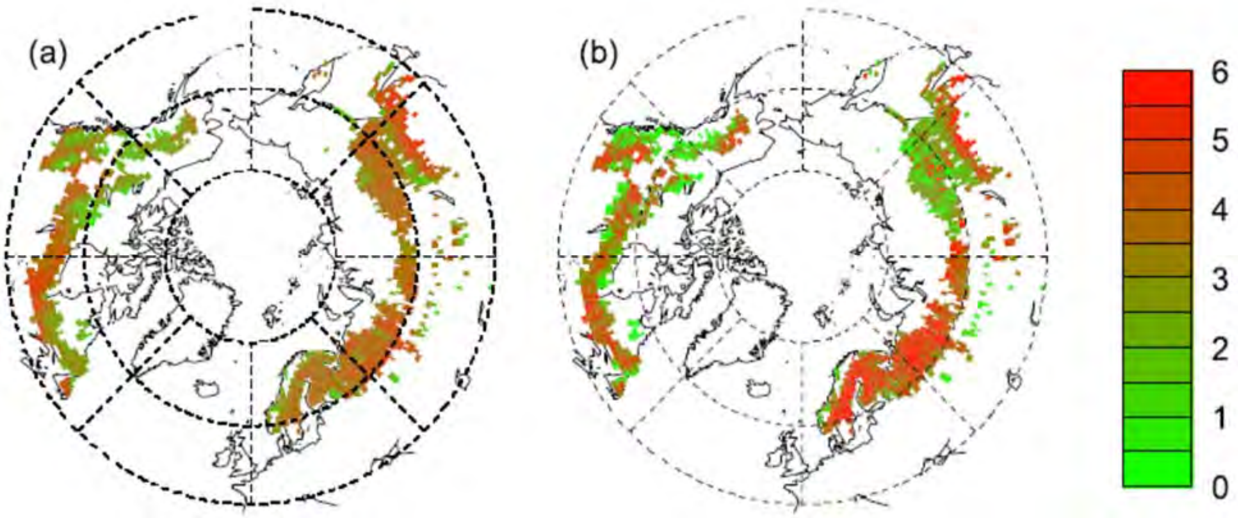


Figure 33: Leaf area index distribution in the circumpolar terrestrial area. (a) Estimate from observation by MODIS. (b) Simulation by the terrestrial ecosystem model (Ise and Sato 2008). Simulations promote understanding of mechanisms in ATEs and biological diversity, through appropriate estimation of the types and size distribution of vegetation.

large mammals. In addition, we must consider the effect of human immigration in terms of epidemics and insect damage in relation to the expansion of infected zones, as well as considering the effects of climate change.

We also need to pay attention to urban development and agriculture. Historically, human activities such as agriculture have not been widespread in this area (particularly inland) and the population density of the area was low. However, it is possible that human activities increase in future if the environment becomes suitable for human activities through climate warming. It is necessary to be cautious about future development (for example, agricultural development through artificial draining of peat bogs in Scandinavia). Changes in ATEs diverge into many branches and their influence may be serious; however, there have been delays in developing an observation system to understand present conditions. Moreover, because biological processes in ecosystems are subject to theoretical generalization difficulties, development of models that are applicable to a wide area in a comprehensive manner has not advanced significantly; the need for such models has started to be discussed (Purves, 2013). Since data acquisition to support validation of such models is often more difficult in the Arctic terrestrial area than in other areas, due to the harshness of the environment, there is expected to be intensive promotion of research for both modeling and observation.

b. Future studies

First, to understand changes in ATEs and conservation of biodiversity, basic ecological studies (such as studies of plant and animal physiology and their responses to environmental change) are important. It has become more and more important to monitor wide areas, utilizing satellite remote sensing, and to develop mechanical understanding and prediction capabilities via simulation. These should simultaneously be accompanied by continuous field observation.

Over the medium- to long-term, observation systems should be more stable, spatially broader, inexpensive, and real time. We should therefore emphasize utilization of automatic observation equipment, including fixed-point observation cameras and observation networks. It has become possible to estimate an ecological variable with higher accuracy by optimizing analysis of remote sensing data through field observation. In addition, and as Figure 33 shows, it is vital to enhance accuracy of simulation models for the entire circumpolar terrestrial area, performing data assimilation through observation, and encouraging the establishment of appropriate future prediction studies. Based on simulation studies of Alaskan and European ATEs conducted to date, we should promote model development and improvements in process models, for example in relation to plant physiology, population changes, community changes, and biogeochemical cycling in ecosystems of the circumpolar terrestrial area; these developments would allow us to improve predictive capabilities.

In order to conserve biodiversity, we should establish conservation priorities based on objective evaluations of various species and ecosystems. In this way, it would be possible to more effectively protect ATEs where significant changes are expected. We should also define keystone species and key ecosystems (hotspots) to perform focused conservation. In addition, as Japanese researchers, there will be a greater demand for us to maintain close communication with local researchers and research organizations in future, and to promote studies through a mutually beneficial relationship. Given this international framework, it is important to cooperate constructively with IPBES[37], CAFF[38], and GEO BON[39].

[37] IPBES: Intergovernmental Platform on Biodiversity and Ecosystem Services
[38] CAFF: Conservation of Arctic Flora and Fauna
[39] GEO BON: Group on Earth Observations Biodiversity Observation Network

In the northern forests of Alaska, forest recovery processes following the large 2004 wildfire are under investigation. Recovery processes after tundra fires are also under investigation (Tsuyuzaki et al., 2009). In future, based on these results, a plan to clarify short- to long-term influences of fire disturbance will be developed. Fire experiments will also be an important study topic, in addition to observation. Furthermore, it will be necessary to estimate carbon budgets accurately over a wide area using a combination of satellite remote sensing and field observation.

Q2: How is biodiversity affected?

a. Importance of this topic and current conditions

In order to understand change in ATEs and to make future predictions, it is fundamentally important to conduct research and gather information about biodiversity (Box 2). However, when compared to low- and mid-latitude regions, interest in the biodiversity of ATEs is low and studies of biodiversity are scarce. In particular, there are few studies by Japanese researchers at present, but we should highlight the intensification of future research efforts. Here we describe the current state of biodiversity research and discuss directions for future work.

There are two threats to plant species diversity in ATEs: threatened species and exotic species. Although Red Lists (exhaustive lists of regionally-threatened species) have been established for each country and area, it is necessary to also compile lists that consider other aspects. For example, there may be a need to consider larger scales over multiple countries, or smaller scales to develop specific conservation plans. Given that there have been delays in compiling a list of exotic species (blacklist), data integration should be performed as soon as possible.

(1) About biodiversity

Species diversity of the northern forest ecosystems is lower than that of tropical or temperate forest ecosystems, but it is thought that ecosystem variation is so high as to equal that of tropical or temperate forests. The environment of the northern forests is characterized by low temperatures and drought, and under such environmental conditions, light stress (i.e., when the light energy that plants absorb for photosynthesis becomes excessive, active oxygen species are produced, damaging plant tissues) is amplified. This thus constitutes a very challenging environment for plants to survive in. Plants use a variety of strategies to live and reproduce here (e.g., seed propagation vs. clonal propagation, broadleaf forests vs. needleleaf forests, and evergreen trees vs. deciduous trees). In this sense, the diversity of boreal forest ecosystems is high. However, even though boreal forests occupy about 1/3 of the global forest area, there has not yet been detailed investigation and research about their biological diversity, with some exceptions in places that have been intensively studied (e.g., super sites around Yakutsk in Siberia or the Canadian BOREAS site).

(2) About peat bogs

The peat bogs that are distributed over circumpolar zones play an important role in global carbon cycling due to their significant accumulation of organic carbon (Clymo, 1983). Moreover, peat bogs have a unique flora and fauna and are an important ecosystem in terms of their biodiversity. Peat ecosystems, which are established on the border of terrestrial and aquatic ecosystems, have environmental characteristics of both. Biodiversity is high because there are varying environmental conditions with fluctuating water levels (Mäkilä et al., 2001). Although studies to analyze the relationship between environment and biodiversity in peat ecosystems have been conducted in many wetlands, studies analyzing the heterogeneity (variations in space and time) of peat bogs or that analyze the long-term change have, to date, been scarce. It will be necessary to intensify such research efforts in future.

(3) About environmental responses

It is also necessary to appropriately examine the diversity of responses of life forms, in order to evaluate impacts of prospective environmental changes in ATEs. When considering the stability of ecosystems under climate change, the importance of diverse ecological responses has been pointed out (Elmqvist et al., 2003; Mori et al., 2013). Since responses vary with different places and species, if the diversity of ecological responses to climate change and disturbance is high, it is thought that the ecosystem can tolerate environmental change to a larger degree, i.e., it has more resilience. It is therefore necessary to evaluate species- and ecosystem-specific responses to climate change.

Box 2 What is biodiversity?

Biological diversity refers to biological variation (terrestrial ecosystems, marine and other aquatic ecosystems, the ecosystems compounded these), and is a concept that includes variety at three different levels: (1) genetic diversity, (2) species diversity, and (3) ecosystem diversity (definition established in the "Convention on Biological Diversity" during the 1992 Rio de Janeiro United Nations Conference on Environment and Development (Earth Summit)). Genetic diversity is variation within a species. Ecosystem diversity is the variation in functions and interactions of each species in an ecosystem. The word “biodiversity” conjures up the image of species diversity to many; however, we should consider not only species diversity but also genetic diversity and variations in life history and adaptation.

b. Future studies

There are two fundamental needs to address the biodiversity issues noted above: (1) compiling research results and knowledge into a database, and disclosing it to the public; (2) extending the geographical scope of research. In addition, active promotion of nature conservation both within and outside Japan will also be necessary. Moreover, it will be necessary to taxonomically reclassify scientific names (Box 3).

Research into geographical shifts in biological boundaries due to climate change is worthy of special mention. For example, since the northward advance of northern forest species into the tundra due to warming will bring with it significant changes to biogeochemistry and surface physical processes, the relevant contributions to climate change studies will be large. It is important to quantitatively predict these dynamic and transient changes.

Further studies are needed to understand biodiversity changes and responses of ecosystem functions to climate change. There is concern that rapid global climate change not only changes ecological community structures, but also influences ecosystem functions (Loreau et al., 2001). Recently, there has been significant progress in studies of the relationship between biodiversity and ecosystem functions, and it is thought that a rapid decrease in biodiversity degrades ecosystem functions (Cardinale, 2012). The characteristics of ecosystems with high vulnerability to climate change include low resource availability and low species diversity. In this kind of ecosystem, it is expected that the impact of even a slight increase or decrease in species diversity and functional properties will be significant. In addition, future monitoring studies are important because it is possible that climate changes in the Arctic terrestrial area (e.g., extension of a growth period due to warming) enable new invasions of species that have to date been limited by the severe environmental conditions.

It will also be necessary to examine ecological responses to movements of exotic species due to climate change, given that serious effects on ATEs are anticipated. This includes those phenomena that may bring about dramatic changes, such as advance of species from the temperate zone to boreal forests, and tree invasion into the tundra. In order to understand these phenomena, it is necessary to clarify ecosystem function changes by identifying species with the potential to invade ATEs and through experiments. Furthermore, while the importance of ecosystems with high biodiversity is recognized, it will also be necessary to indicate specific ecosystem functions in low-biodiversity ecosystems.

Japanese researchers should highlight, in particular, studies of subarctic ecosystems that are also present in Japan (including Hokkaido as a case study). Given that there is a strong relationship between the alpine belt of Hokkaido and the Kuril Islands, Kamchatka, and Sakhalin, we should use domestic research results to understand the ecosystems of the circumpolar Arctic terrestrial area. Since terrestrial ecosystems feature high local specificity, it may be possible to make use of studies accumulated in Japan, for example, concerning exotic species and their management, even if we must be wary of extreme generalization.

Q3: What are the impacts of changes in ATEs on climate and animals?

a. Importance of this topic and current conditions

Various kinds of species adapted to severe environmental conditions in ATEs form a unique biota. For example, polar bears and blue foxes, which have been flagship species of conservation in ATEs, are species whose morphology and life history has evolved to be suited to this specific environment, and they can inhabit polar regions throughout the year. In addition, migratory species such as reindeer and waterfowl use rich food resources to breed during the ATE's short summer, and winter at lower latitude; that is also a strategy to avoid competition with other species. Q1 and Q2 consider vegetation changes, wildfire, and land use changes in ATEs. It is thought that these factors have a significant influence on the variety of animals inhabiting ATEs directly and indirectly through vegetation changes.

For example, there have been reports of changes in the behavior and reduced distribution area of animals such as musk ox, reindeer, and polar bears (Box4). Several other changes are also known; northward movement of forest herbivores (e.g., squirrels and deer, Box4) and carnivores (e.g., wolves and brown bears), population increases and an expansion of the distribution area of geese, ducks, and swans breeding in the polar area (cf. Box 5), and large

Box 3 Disagreement over scientific names

There has been progress in field studies based on international collaboration, but there are still problems related to international disagreements on taxonomic names. The distribution of plant species does not have a national border, but there is often a border in terms of taxonomic name. Different taxonomic names are frequently used for an identical species in different countries. The reason for this is that there is no accord on species recognition by countries/researchers (clumper and splitter) and there has been insufficient work in terms of the compilation of databases and data publication of type specimens/descriptions of new taxa. A universal approach to taxonomic names that is understandable to ecologists and other researchers is needed. Taxonomic names should be established for such a purpose from the start, but this is often not the case in practice. We therefore need international exchanges of specimens and information, including old documents and types. This demands that we promote use of academic specimens held by each country through networks such as the GBIF.

outbreaks of pests in the taiga (Post et al., 2013). Future concerns include further vegetation changes, increases in competition and predatory pressure, mismatches in the timing of migration, snow thaw, food production, and the spread of epidemics and exotic species because of warming. Though ATEs are exposed to such serious changes, there are many uninvestigated responses. Since changes in animal populations have a significant impact on human society (cf. Theme 7), the relationship between ATEs and animals has to be clarified.

Vegetation changes in ATEs affect not only animals but also global climate, through processes such as carbon cycling (related to theme 3: feedback to the atmosphere). In order to clarify such feedback, earth system models that incorporate terrestrial ecosystem models into climate models have been developed so far;which include not only the carbon cycling models handling carbon dynamics in the ecosystem, but also the vegetation dynamics models that able to predict spatiotemporal changes in plant functional types. However, as compared to land surface process models that are explained mainly by physical factors, the uncertainty of carbon cycling models and vegetation dynamics models based on biological factors is likely to be high. Models have predicted remarkable warming in the Arctic but there are large uncertainties as to how warming influences plant species and vegetation distribution related to biological diversity; there is also uncertainty related to the influence of climate feedback through carbon cycling and water/energy budgets in the terrestrial area.

Within the permafrost zone of the Arctic terrestrial area, physical characteristics of water (e.g., fluidity and heat capacity) largely change with the threshold (i.e., zero degrees Celsius). Although it is feared that local vegetation that is intrinsically linked to the climate, frozen ground, and snow cover may suddenly collapse and transition to an irreversible state with climate change, there are still insufficient predictions using mechanistic studies and numerical computation. In addition, there has not been much progress in field-based studies of vegetation in ATEs with respect to understanding biota responses and life history, particularly in comparison with biogeochemical studies. There are many unexplained points regarding responses to climate change. Furthermore, there are many unexplained aspects relating to positive-negative feedback to climate change by biota.

Box 4 Changes in reindeer habits

Tundra reindeer are characterized by seasonal migrations of several thousand kilometers, with wide distribution over the circumpolar region. However, population decreases and a reduction in distribution range have been reported for many populations. This decrease has also been noted to be remarkable in east Siberia (e.g., from approximately 1 million individuals in the Taymyr peninsula to tens of thousands). After tracking approximately 20 individuals using satellite telemetry, it became possible to reveal influences in terms of behavioral inhibitions caused by warming; relevant aspects include ice board formation by icy rain and ROS (rain on snow) in early winter, and earlier river thaw in spring. These individuals gathered in the upstream portion of the Olenek river (the east end of the Siberian Highlands) where the progress of warming is slowest in summer; however, their migration route and wintering places were not fixed and the ratio of newborns dropped by half or less compared to 30 years prior. This collaborative Japanese and Russian investigation, carried out also in cooperation with indigenous hunters (including the Even and Evenki peoples), led reviews of protected and hunting areas by the Government of the Sakha Republic, and new monitoring procedures have been adopted by the municipalities of several parts of eastern Siberia.

Box 5 Monitoring of waterfowl

Since most waterfowl distributes over ATEs and overwinters in low latitudinal zones, there should be global monitoring and the actual state of population change should be clarified. The Japanese Ministry of the Environment carries out long-term monitoring with NGOs; as a result, it has become clear that the population of many shorebird species has decreased, but that fluctuations differ by species of wild geese, ducks, and swans. Some populations that have spread into ATEs have been increasing. As a result of warming, the breeding environment temporarily improves in some cases, but it has been noted that breeding habitats may be greatly affected by vegetation changes in the long-term, as well as by mismatches in the timing of migration, food availability, and snow melt. The northward movement of predators, diseases, parasites, and competing species (Ganter and Gaston, 2013) may also be a concern. It is therefore necessary to monitor future population changes.

b. Future studies

It is necessary to construct database and monitoring systems in ATEs so as to understand actual habitat conditions of animals on a wider scale (related to Q1, Q2, and theme 7, Q2b). In order to perform effective monitoring in ATEs that pose challenges for field investigation, we should mainly identify the species (indicator species, key species), ecosystems, and regions that should be investigated (related to Q1), and integrate existing monitoring data (e.g., CAFF sites and waterfowl monitoring sites), identifying areas where future research is needed. In addition to field surveys, large-scale studies using satellite tracking and airplane investigations are also necessary, as well as the establishment of researcher networks (related to theme 7Q 2b), and analysis of long-term population trends of migratory animals. Furthermore, using databases, it is necessary to analyze the relationship between the distribution of animals and the environmental conditions of their habitat. For example, through animal observation data and environment data (e.g., climate and vegetation), it is possible to construct statistical models to estimate potential habitats at large scales. Habitat suitability maps developed in this manner make it possible to determine new study areas. In addition, it may also be possible to estimate habitat change under warming scenarios if a simulation is performed using the vegetation model (related to Q1 and theme 3). However, because there are many unexplained aspects of ecosystem change in response to warming, it is necessary to perform overall reviews based on literature, identifying unexplained processes in the relationships between climate and vegetation (Figure 34-①), climate and animals (Figure 34-②), vegetation and animals (Figure 34-③), and animals and animals (Figure 34-④). Several field-based studies will also be necessary to clarify these relationships.

To better understand feedback to the atmosphere (Figure 34–①), we need to improve the precision of carbon dynamics and vegetation models. For example, it is necessary to acquire vegetation observation data (field and satellite data) and to develop related data assimilation techniques, in order to estimate model parameters (related to Q1). In addition, through field-based studies, it is necessary to encourage the elucidation of unexplained processes and model improvement. It is also necessary to clarify the actual state of positive-negative feedback to climate changes from biota (e.g., albedo changes by strong foraging pressure of reindeer and snow, Figure 34 -③①, influence on vegetation by large insect outbreaks, Figure 34 -③).

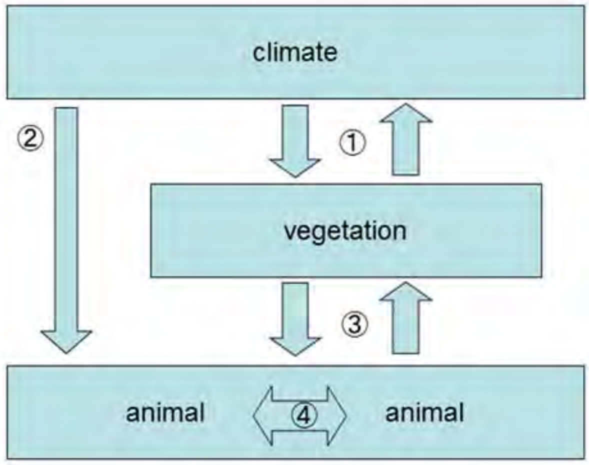


Figure 34: A conceptual diagram of interactions among climate, vegetation, and animal.

Theme 9: Influence on marine ecosystem and biodiversity

Abstract

Because the surface of the Arctic Ocean is extensively covered by sea-ice, inhabiting marine biota thrive by adjusting to the unique environment formed according to the characteristics of the ecosystem. However, the Arctic sea-ice ecosystem has been disappearing due to the rapid decrease of sea-ice cover caused by the recent warming. We now list the following four questions and describe our long term view for future research by focusing on the changes occurring from perennial to seasonal sea-ice formation, which affect the marine ecosystem and biological diversity in the Arctic Ocean.

Q1: Are the ecosystem and biodiversity of the Arctic Ocean significantly affected by the substance in the atmosphere and from the terrestrial areas?

Q2: How do the biota of the Arctic Ocean transport and change in quality of substance?

Q3: How the food chain and changes in ecosystem and biodiversity are related in the Arctic Ocean?

Q4: How does ocean acidification and denitrification in the Arctic Ocean influence the ecosystem and biodiversity?

The dramatic environmental changes in the Arctic Ocean are of concern because, not only is biological production in the Arctic Ocean altered, but also the disappearance of biota and entry of new biota may occur, as well as additional influences on material transport, biodiversity via food chain and competitive relationships. The change in species diversity significantly affects productivity and decomposition of the ecosystem. Therefore, quantitative interpretation of the environments surrounding the sea-ice ecosystem of the Arctic Ocean and each of the processes and mechanisms in the ecosystem is important for assessing the influence on future sea-ice ecosystem and biodiversity of the Arctic Ocean.

However, most of the knowledge that has been obtained thus far is tempo-spatially fragmentary because that it is based on the limited data from open waters during summer season when research vessels can safely cruise around in the Arctic Ocean. Furthermore, the sea-ice ecosystem has aspects where almost no information is available due to the complex relationships among physical, chemical, and biological processes. Therefore, our long-term goal is to clarify the influence of the Arctic Ocean on the ecosystem and biodiversity, not only by conducting multidirectional observations in extensive areas with the use of ice breakers and mooring systems, but also by conducting interdisciplinary research that links process experiments and numerical modeling.

Introduction

The marine biotas that live in the Arctic Ocean form characteristic ecosystem called sea-ice ecosystem by adapting the ambient environmental conditions of sea-ice and ice margin. However, they are currently facing with rapid environmental changes, which have not been experienced thus far, such as the decline in sea-ice cover, that is a basis for the unique ecosystem, and ocean acidification. Such changes cause disappearance of the biotas constituting the Arctic sea-ice ecosystem and introduction of new biotas and therefore the marine ecosystem will drastically change in the Arctic Ocean. Furthermore, the changes at the same time mean the loss and/or increase of biological diversity in the Arctic Ocean. The Convention on Biological Diversity (CBD) had concluded in 1992 that in order to conserve the ecosystem and support the human survival it is important for us to conserve the biological diversity. In the Arctic Ocean, much knowledge has been accumulated concerning biological diversity by the Arctic Ocean Diversity (ArcOD) project, which was pursued during the 2,000-2,010 Phase One of the Census of Marine Life (CoML). The ArcOD has listed more than 7,000 species and reported that invertebrates and fishes have been extending their habitats to the north and that the percentages of warm-water taxa relative to cold-water taxa have increased. Furthermore, the CoML predicted that the biological diversity would increase in the region of 50-70˚N (CoML, 2010). However, it is uncertain how the Arctic ecosystem and biological diversity as well as the rates would change, responding to the anticipated continuous decline in sea-ice cover and marine environmental change in the future (Conservation of Arctic Flora and Fauna (CAFF), 2013).

Here, the needed research contents for the future will be described in order to evaluate the effects of the environmental changes occurring on the marine ecosystem and biological diversity in the Arctic Ocean. Note that biological diversity is defined in three different ways in the CBD as “ecosystem diversity”, “species diversity”, and “genetic diversity” (see Box 2, Theme 8). We describe mainly “species diversity” herein.

Q1: Are the ecosystem and biodiversity of the Arctic Ocean significantly affected by the substance in the atmosphere and from the terrestrial areas?

a. Importance of research and state of the art

Greater than 10% of total dissolved organic carbon, that is discharged by rivers of the world to the oceans, is delivered to the Arctic Ocean, but it has been considered that most of it was refractory and hence the effects on the Arctic ecosystem was small. However, the importance of the delivery of terrigenous substance to the Arctic Ocean and the effects on the ecosystem and biodiversity has been recognized recently by the research conducted in the last few years (e.g., McClelland et al., 2012). The results of research include, for example, the delivery of substantial amount of labile dissolved organic carbon, which can readily be decomposed by bacteria and photooxidation. While the direct river discharge of dissolved inorganic nutrients required for photosynthesis such as nitrogen and phosphorus is small, the effect by the nutrients derived from terrigenous material on marine primary production cannot be ignored. Furthermore, the importance of the

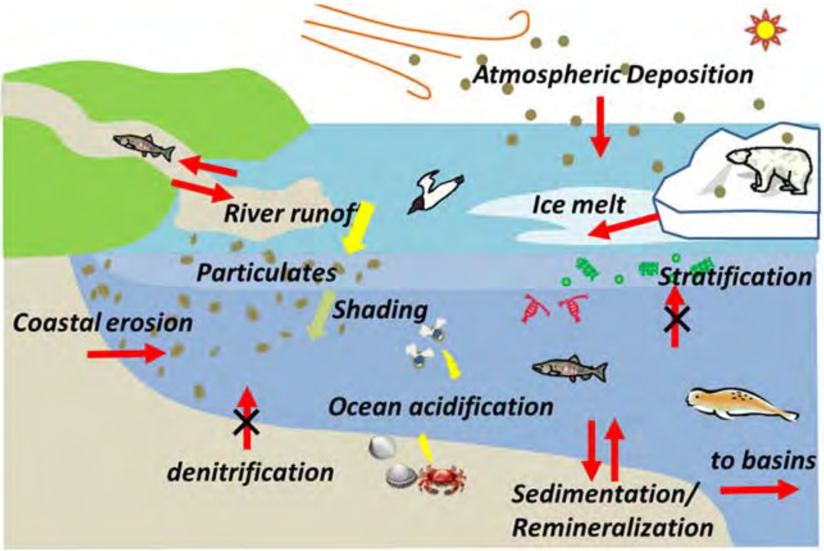


Figure 35: Schematic illustration showing material transport from land and atmosphere to the oceans and influences impacting on biotas in the interior of the oceans. The supply of nutrients and pollutants to the ocean would increase due to rivers, atmosphere and the processes such as coastal erosion and glacier melting driven by the global warming. On the other hand in the interior of the oceans, direct and indirect impacts on marine biotas such as accelerated ocean acidification, stratification, and removal of nitrogen nutrients (denitrification: see Q4) are also predicted. Red arrows indicate the supplies and removals of nutrients and pollutants.

delivery of trace metals such as iron due to continental ice sheet melting has recently been pointed out. Therefore, the materials transported from land impact on particularly bacteria and phytoplankton with high bio-diversity and bio-volume in the coastal regions. Moreover, zooplankton, which consumes the biotas described above, and those at higher trophic levels can also possibly be affected. While it has been pointed out that terrigenous materials once deposited on the sea floors in the coastal regions have been transported from the continental shelves to pelagic realm and utilized for biological production, quantitative estimates have not been elucidated due to the complexity in the concerning biophysicochemical processes.

The influence by the material transport through atmosphere on ecosystem along with global warming will also likely be changed. While anthropogenic pollutants that are emitted in the mid-low latitudes, for example, can be transported to the Arctic Circle through atmosphere（AMAP, 2009）, the presence or absence of sea-ice can possibly alter processes such as the supply process of these pollutants to marine biota and the alteration process by photoreaction in seawater. It is possible that the contribution by nutrients through atmosphere will increase. In general iron that is a micronutrients tends to be deficient in marine regions away from terrestrial regions, but they are supplied via atmosphere to the sea surface layer of the regions away from lands. It is possible to have an increased supply of iron attributing to the increases in exposed land area and storm activity that are caused by loss of snow and ice due to the global warming.

b. Future research (see Figure 35)

It is urgent to pursue the researches that can elucidate the influence on marine ecosystem by the materials from terrigenous and atmospheric origin and that can contribute in prediction of the changes caused by the global warming. It is possible in the future that the supply of carbon and nutrients originated from land for marine low trophic level ecosystem would increase by the processes such as the increase in organic matter supply due to the melting of permafrost and continental ice sheets, the increase in supply of the material from atmospheric origin, the increase in activity of microbials due to water temperature rise, and the increase in light penetration due to the decrease in sea-ice cover. However, the increased remineralization of the terrestrial organic matter would accelerate ocean acidification and negatively impact on benthos at the same time (see Theme 3, Theme 9, Q4). Furthermore, the increased supply of freshwater discharge from land (see Theme 4) could possibly strengthen stratified marine surface layer, and lower biomass, and cause species change by the limited nutrient supply to the phytoplankton in the surface layer. Moreover, pelagic biological production can also be affected because that the lowered density of coastal waters can alter transport pathways of materials from continental shelves to pelagic realm. The increased supply of the terrestrial materials can lower light transmission rate in seawater and possibly impede photosynthesis. Because that the materials from terrestrial and atmospheric origin can multifacetedly and significantly impact on marine ecosystem and diversity, integrated research must be pursued for elucidation such as intensive observation in coastal regions, observation in extensive areas including pelagic realm, and laboratory culture and numerical modeling.

It is important to grasp the overall trend of the influence by clarifying the taxa present and populations in the areas such as river mouths and coastal erosions and studying their relationships with quantity and quality of terrigenous matter. Furthermore, in order to elucidate the impact on ecosystem via remineralization of nutrients by decomposition of terrigenous matter and via acidification, it is important to determine the areas of significant impact, conduct time-series biophysicochemical measurements, and understand material cycles and seasonality of biological species and populations.

Furthermore, it is also important to study the responses by microbials and phytoplankton by conducting experimental additions of the substance from atmosphere and land and thereby lead into future predictions. Furthermore, because that the alterations in supply rates and quality of the substances from atmospheric and terrestrial origin depend on the changes in remote areas, integrated interdisciplinary research such as oceanography, meteorology, glaciology, and ecology is needed to assess the impact on ecosystem.

Q2: How do the biotas of the Arctic Ocean transport substances and alter their quality?

a. Importance of this research and state of the art

Ecosystem plays a role in altering and transporting marine substances. It is considered that the substances produced by low trophic levels are transported downward towards deep layers and also transported horizontally by own advection and by assimilation by higher trophic levels. Today, our understanding of the relationships between biotas and material transport throughout seasons in each region of the Arctic Ocean is still inadequate. This is because that research has been pursued mainly on biological production and vertical transport of low trophic levels within limited seasons. Furthermore, our knowledge concerning the material transport from zooplankton to fishes and then to birds is limited to early summer. The transport roles of high trophic level predators such as marine mammals and sea birds, which migrate extensively, are also not well understood. Predictions and opinions have not yet been formed because of the fragmentary knowledge regarding the relationships between species and ecosystem diversity and material transport in the Arctic Ocean. This is because that we do not know how the ecosystem, which has been developed through geologic time thus far, would respond to future various progressive environmental changes and how the interactions between the biotas and marine material cycles would be altered.

(1) Material transport via low trophic level ecosystem

The relationships between water mass environments and species diversity of low trophic levels and material cycles have been understood primarily in the continental shelf regions such as coastal areas of the Chukchi Sea, Beaufort Sea, Amundsen Gulf, and Laptev Sea where sea-ice cover is insignificant during summers (e.g., Bluhm et al., 2011; Wassmann, 2011). Carbon dioxide and nutrients, which dissolve in seawater, are transformed into organic matter mostly by photosynthesis. In the region of continental shelf, a large amount of particulate organic matter, which is produced by phytoplankton and ice algae, supports the production activities of low level consumers such as zooplankton and benthos as well as high level consumers ranging from fishes to birds to marine mammals. Because that most of the nitrate supplied to the photic layer is taken up by biotas, this region tends to be primarily under nitrogen control during summers (Tremblay and Gagnon, 2009). The part of phyto-zooplankton, which is not consumed by higher trophic level consumers, is transported by zooplankton's own migration and gravitational sinking of body remains, fecal pellets, and aggregates and a part of which will be buried in sediments. The microbial assemblage in the Arctic Ocean demineralizes organic matter, which is supplied from the water column and land, and recycles nutrients and thus significantly participates in the material cycling through denitrification in the anaerobic environments. In the regions of deep basins, the following differences are observed for vertical material transport via biotas. In the regions of the Amundsen and Nansen basins, where diatom production is relatively high due to nutrients supplied together with Siberian river waters, diatom fluxes towards sea floor have been increasing due to the reduction in sea-ice cover and becoming an important diet for benthos (Boetius et al., 2013).

The primary production of the phytoplankton mainly consisting of picoplankton size in the Canada basin, which is under the influence of the anticyclonic Beaufort Gyre, is recognized, On the other hand, most of the particulate organic matter produced in the surface layer is decomposed in the subsurface layer and little would reach the deep layers. This is because that particulate organic matter, such as diatoms and coccolithophores, which play a role as sinking ballast, and zooplankton which consumes the phytoplankton, is scarce（Honjo et al., 2010）. However, it is not well understood how the future reduction in sea-ice cover would impact on material transport via ecosystem in the Canada basin. Because that many of the works on material cycles emphasized on the roles of primary producers such as phytoplankton and ice algae (e.g., primary production and nutrient uptake rates), the knowledge concerning the role of zooplankton, which control material cycles, is significantly lacking（Wassmann 1998）.

(2) Material transport by fishes and fowls

It is known that seafowls transport substantial amouont of various materials from the sea to breeding grounds with feathers, feces, eggs, and dead bodies of chicks in the Arctic Ocean （Michelutti et al., 2009）. However, the contribution by fishes and fowls to material transport has not yet been adequately elucidated for the detailed processes and quantitative understanding. Furthermore, it is known that various seafowls utilize the Arctic Ocean during summers and many seafowls and ducks flock together in polynyas during winters（Cooper et al., 2013）. However, it is not well understood what roles does the migration of seabirds and sea ducks play in the transport of materials in these periods.

b. Future research

(1) Roles of low trophic level ecosystem in material cycles

It is important to consider process studies which are concerned with the understanding of primary producers dynamics, feeding of zooplankton, excretion and remineralization, and furthermore three-dimensional relationships such as the pelagic-benthic coupling (Box 6), which will be described in Q3 later. In order to accomplish this, it is necessary to conduct diversified field research by combining the following items during the periods including springs when phytoplankton productivity increases and winters which serve as preparatory periods for production: (1) sampling from icebreaker research vessels; (2) on board culture experiments of zooplankton; and (3) mooring experiments with observational instrumentation such as sediment traps. Furthermore, it is also necessary to conduct joint research with satellite observation and ecosystem modeling, both of which can cover wide geographic areas at once. Japan has been contributing in the field observations primarily in the Pacific side of the Arctic Ocean employing R/V Mirai, Japan Agency for Marine-Earth Science and Technology, and T/V Oshoro-maru, Hokkaido University, thus far. However, these vessels are not icebreakers and thus their field works are limited only to open waters and summer seasons. While field works in sea-ice areas employing icebrakers have been conducted by collaborating with international institutions such as the Institute of Ocean Sciences （IOS）, it is also necessary in the future to actively pursue cooperative observations with international institutions such as the IOS and Arctic Net.

(2) Material cycle mechanisms driven by microbials

For mechanism elucidation of material cycles that are driven by microbial assemblages, it is important to quantitatively describe spatiotemporal changes of various parameters of microbials and to characterize their factors. Recent vigorous research development by many countries has led the understanding that various parameters of microbials in the Arctic Ocean are tempospatially extensively changing in response to diversified organic carbon sources (primary production, fresh water, sediments) and physical environments (distribution of watermass, temperature) （Uchimiya et al., 2011）. These facts suggest that the impact by the rapidly progressing marine enviroenmental changes in the Arctic Ocean would sensitively affect material cycles via microbial assemblages. With all these matters in mind, the followings are the issues to work on in the future: (1) mid-long term evaluation of the effects on microbial ecosystem by climate change, and elucidation of the differences among different geographic areas; (2) the processes that will be further manifested in the future (e.g., elucidation of the effects on microbial ecosystem cuaused by weather disturbance due to sea-ice disappearance); and (3) analytical diversification of tempospatial changes by introduction of molecular biological methods whose technological innovation is rapidly progressing in recent years.

(3) Material transport to ocean-land ecosystem by high level predators including salmonoid fishes and seafowls

Movements of seafowls and marine mammals can be tracked by biologging method and the areas for feather molting and frequent visit can be characterized. Likewise, the amounts for molting and excretion are estimated and their supply rates of organic matter can be estimated. Furthermore, by estimating tempospatial changes of predation amounts the roles for material cycles played by seafowls and marine mammals can be evaluated. The distributional areas of salmonoid fishes are expected to extend into the Arctic Ocean due to the acceleration of the global warming （e.g. Kaeriyama, 2008; Kaeriyama et al., 2014; Abdul-Aziz et al., 2011）. While it is well known that salmonoid fishes transport significant amount of marine-derived nutrients （MDN） into land ecosystem (Kaeriyama et al., 2012; Koshino et al., 2013), the elucidation of the MDN transport mechanisms by salmonoid fishes to the surrounding marine areas and land ecosystem, due to the environmental changes of the Arctic Ocean, is warranted (Figure 35).

Q3: How are the food chain and changes in ecosystem and biodiversity related in the Arctic Ocean?

a. The importance of this research and state of the art

There are several species that extended their distributions to the north due to the global warming and sea-ice reduction. Primary production tends to increase due to the improvement of light environment（ Pabi et al., 2008）. One prediction states that when sea-ice is reduced the main food chain would change from surface (production)-benthos (consumption) ecosystem to surface (production)-surface (consumption) ecosystem, which is called “pelagic-pelagic coupling” (Box 6). As a result of this, there is a concern over the influence on biological species diversity. The consequence of the influence would impact land ecosystem via the material transport to land by seafowls and via the influence on polar bears.

(1) Distribution, species composition, and production of microbials and planktons

The changes in seasonal and spatial distribution and species composition of phytoplankton and microbials would affect not only their own species diversities but also the species diversity of consumers as well. Biological production under sea-ice cannot be ignored during winter and spring in the Arctic Ocean, but studies in these seasons are meager and the information concerning microbials is further less. While a lot of knowledge on zooplankton has been accumulated in the Atlantic side of the Arctic Ocean, such reports in the Pacific side are limited. There are reports documenting that temperate zooplankton extended distribution (Matsuno et al., 2011) and began reproduction (Buchholz et al., 2012) within the Arctic Circles. However, it is not known how these occurrences affect the whole zooplankton community.

(2) The formation of biological hotspots including low to high trophic level biotas

There are places, which are called “biological hotspots” (Box 7), where biological production is high and energy flow to higher trophic level predators is significantly high. Clear understanding is lacking in the Arctic Ocean concerning their loci and dynamics including their spatiotemporal scales. It is not known how the following changes would alter species diversity via the changes in food chain in the biological hotspots. The changes include: (1) migration of temperate species including whales; (2) biological pump (the process which transports the organic matter produced by phytoplankton in the surface layer to benthos and biotas in deep layers) essential for surface (production)-benthos (consumption) ecosystem; and (3) biomass and distribution of large fishes. There are concerns about pollutions due to atmosphere and river transportations and oil field development（Mallory & Braune 2012）and impacts due to introduced species carried by transport boats.

b. Future research

It is necessary to focus on the biological hotspots concerning how the global warming and sea-ice reduction would impact on biological species diversity via low level production and food chain. It is also necessary to carry out studies concerning distribution change of biotas including the seasons when sea-ice is present (winter, spring), which will lead into more accurate grasp of state of the art and future predictions.

(1) Changes in water mass structure and microbial and zooplankton assemblages and elucidation of production processes

It is necessary to elucidate the mechanisms how the global warming and sea-ice reduction would affect low trophic level production scheme and diversity including microbials. The elucidation can be achieved by pursuing the process researches concerning: (1) timing of sea-ice melt, (2) phytoplankton bloom (the state at which assemblages would at once reproduce and increase) under sea-ice and ice margin and grazing by zooplankton, and (3) reproduction by zooplankton and growth timing.

In order to accomplish this, we ought to elucidate the relationships between sea-ice change and phytoplankton assemblages by studying changes in distribution, composition, size, and dominant taxa of phytoplankton including ice algae, and by utilizing the output by Theme 3. The changes in zooplankton diversity, grazing, reproduction and growth timing can be explained by seasonal and spatial changes in production, size, and composition of phytoplankton as well as by transport of the Pacific taxa. The relationships are elucidated between seasonal and spatial changes of the plankton assemblages and composition, mode, sinking flux of biogenic sinking particles. Samplings throughout the year including underneath sea-ice should be conducted on icebreakers as well as by mooring systems in reference to the past occupied stations.

(2) Biological hotspots and the elucidation of formation factors

The relationships among supply rates of nutrients, biological production, consumption, food chain length, and species composition (species diversity) will be studied by grasping biological hotspots through distribution and population density of each of the trophic levels of plankton to higher trophic biotas (fishes, fowls, mammals) and benthos. The formation factors for biological hotspots must be elucidated by pursuing habitat modeling employing physical oceanographic conditions as independent parameters and ecosystem modeling employing food web data. Regarding the salmonoid fishes, which can become important fisheries resources, distribution and their changes will be studied based on environmental carrying capacity, growth, population dynamics, and feeding nutrition ecosystem. Based on these it is necessary to comprehensively understand the formation mechanisms of the biological hotspots.

Therefore, predictions for distribution change of each of the species based on future marine environmental predictions will be made employing habitat models. Moreover, predictions will be further made by considering migrations of temperate taxa by the global warming and transportation, bottom up and top down effects due to distribution expansions of prey biotas and large-sized whales, artificial hatching and stocking for salmonoid fishes, and inter-species relationships such as potential influence of pollutants. Distributions of benthos, seafowls, and marine mammals will be studied by conducting sampling from vessels and visual observations. Tracking methods with mounting type small sized apparatus will also be employed for seafowls and marine mammals. Food web will be studied based on the distribution of preys (e.g., viewing of specimens, stable isotopic ratios, fatty acid composition). Pollutant measurements of sediments and biotas will be conducted as one of the monitoring items for the anthropogenic effects.

Q4: What are the impacts on the ecosystem and biodiversity in the Arctic Ocean by ocean acidification and denitrification?

a. Importance of this research and state of the art (see Figure 35)

It is no exaggeration to say that all the production of marine biotas is supported by phytoplankton in the surface layer with exceptions in specific areas. In addition to light and temperature, the deficiency of nitrogen nutrients is a limiting factor for production in the Arctic Ocean. The supply of nitrogen nutrients will become a further important factor for the future biological production of the Arctic Ocean since it is considered that light and temperature conditions will be improved due to the global warming and sea-ice melting. The following two processes determine nitrogen supply rates: (1) denitrification process which removes nitrogen nutrients on the continental shelves; and (2) nutrient supply process from subsurface layers due to vertical mixing. It is possible that the changes in these processes would significantly affect ecosystem and diversity in the Arctic Ocean.

On the other hand, due to the CO2 emmission by the anthropogenic activity the following processes have been globally progresssing: (1) increase in CO2 concentrations in seawater; (2) increase in hydrogen ion concentrations (acidification in the narrow sence); and (3) decrease in the saturation degree of calcium carbonate（Orr et al., 2005）. These are collectively called as “problems in ocean acidification” and they have been discussed. There is a possibility that ocean acidification would give some kind of effect on almost all the marine biotas, regeneration, and growth. However, adequate research has not yet been conducted about the effects by ocean acidification on the biotas in the Arctic Ocean and thus this has been recognized as an urgent task (AMAP, 2013).

Box 6　The pelagic-benthic coupling

Large-sized diatoms begin blooming as soon as light environment becomes prefereble in the early spring of the specific years with late sea-ice retreatment in the sea-ice margin areas, when adequate solar radiaton is available, of the southeastern and northern Bering Sea. Large zooplankton feed on the daitoms but grow weakly since seawater temperature has not yet risen adequately and thus the large-sized daitoms, which were not consumed, sink. This process supports abundant lives of bethos and further contributes in the increased energy flow towards benthic food chain represented by large predatory fishes such as flounders and sculpins. On the other hand, large-sized diatoms do not bloom in the warm years when sea-ice retreats early when solar radiation is still weak and the surface layer is mixed by winter seasonal winds. Small-sized diatoms bloom when stratification begins as season goes further when seawater temperature rises. Small zooplankton, which feed on these diatoms, actively grows at this time since the seawater temperature has already risen. Therefore, most of the diatoms are grazed more or less completely. The increased small zooplankton is directly consumed by surface dwelling fishes. Likewise, there is a hypothesis explaining that the surface production would flow into the benthic food chain when sea-ice is abundant during the cold interval and the surface production would flow into the food chain in the surface layer when sea-ice is reduced during the warm interval (e.g., Grebmeier et al., 2006, Figure 36).

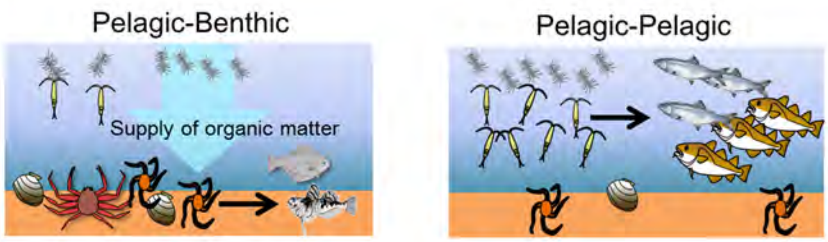


Figure 36: The change from the pelagic-benthic coupled ecosystem to the pelagic-pelagic ecosystem,pelagic ecosystem.

Box 7　Biological hotspots

Biological hotspots represent the loci where low trophic level biological production is high compared to the adjacent areas, benthos is also abundant, and plentiful seabirds and marine mammals dwell and/or are spotted with their high flocking concentrations. The low trophic level organisms stated above are represented by zooplankton which plays an important role since it transfers substances to higher trophic organisms by feeding on phytoplankton and ice algae which are primary producers in the polar oceans. Furthermore, because that the productivity of these low trophic level organisms is high in the water column, generally benthos is also abundant in the regions compared to the surrounding areas. The results of research thus far suggest the following areas can be designated as biological hotspots: North Water polynya of the northern Baffin Bay and Cape Bathurst polynya of the Amundsen Gulf.

(1) Effects by stratification

The biological assemblage that supports high biological production is phytoplankton which receives adequately supplied nutrients from deep layers due to upwelling and winter vertical mixing. It is said that phytoplankton has been maintaining characteristic ecosystem for a long time thus far by being composed of large sized taxa (diatoms) and adapting fertile marine environments. The global warming and desalination processes due to fresh water supply from land and sea-ice melting play physicochemical roles and they would cause marine stratification and prevent nutrient supply by upwelling from deep layers to surface layer. The stratification, which reduces nutrient supply from deep layers, would decrease photosynthesis (primary production) of phytoplankton distributed in the surface layer and thus would biologically impact on instability of the ecosystem. This would, at the same time, cause species replacement from large-sized phytoplankton (diatoms) to small-sized algae (coccolithophores and parmales), which enable to reproduce in oligotrophic environments.

Furthermore, it is inferred that the stratification of the surface layer due to the global warming would lead into a highly stressed situation by high light intensity to the phytoplankton community distributed in the mixed layer due to the reduction in surface mixed layer thickness. While the knowledge is meager concerning the photoprotection mechanisms of the phytoplankton distributed in the polar regions, the biological effects by stratification would appear more significantly in the ploar and sub-ploar regions.

(2) Effects due to denitrification

Nitrogen deficiency is especially apparent in the regions of the Pacific Ocean side. This stems from so-called denitrification process, which removes nitrogen from the oceans. The process is a microbial metabolic activity that actively alters nitrate and nitrite into the inert gas. The denitrification in these regions plays a significant role in the nitrogen cycle of the world oceans. It is possible that marine primary production would be limited by the increased removal of nitrogen due to the denitrification that is attributed to the increases in water temperature and organic matter flux to benthos. However, quantitative knowledge and elucidation of the effects by denitrification are meager.

(3) Effects due to ocean acidification

There is a concern that the decrease in saturation degree of calcium carbonate due to the ocean acidification would negatively impact on, for example, coccolithophores which represent phytoplankton, planktic foraminifers which represent zooplankton, pteropods, and shelled molluscas by reducing their ability for calcium carbonate shell and/or skeleton formation. They are important biotas also in the ecosystems of the Arctic Ocean and the subarctic region. The concern is also the effects on higher trophic level biotas, which predate the above listed biota, such as fowls and mammals. It has been known by laboratory cultures and in situ experiments that the ocean acidification works on the biotas that do not form calcium carbonate shells either advantageously or disadvantageously depending on species. However, the effects by the ocean acidification is not understood in the ecosystem of the Arctic Ocean because that our knowledge has mostly been derived from the works performed in the low-mid latitudes. However, the Arctic Ocean tends to be readily affected because that the Arctic Ocean by nature has low ability to alleviate acidification. Furthermore, it is anticipated to witness other stresses simultaneously due to water temperature rise and the immigration of mid-low latitude biotas caused by water temperature rise.

b. Future research

The understanding of the current status of phytoplankton and zooplankton biomass and species composition in the surface layer of the oceans has been usual practice for ecosystem research and many scientists published their contributions thus far. However, most of the works are concerned with large-sized diatoms and copepods and thus little knowledge has been accumulated on coccolithophores, planktic foraminifers and pteropods that are concerned about being affected by the acidification. For elucidation of the diversity characteristics of the polar biotas it is significant to sufficiently understand the distribution dynamics of coccolithophores and planktic foraminiferes and pteropods, which are zooplankton feeding on particulate matter. Such an understanding will be achieved by long term monitoring in the areas of serious influence under the expectation that phytoplankton size will be reduced due to the reduction in nutrient supply from the subsurface to the surface layer caused by the future stratification. Furthermore, it is considered that phytoplankton distributed in the surface mixed layer will be exposed to high light intensity for a long time due to the reduction in the thickness of the surface mixed layer caused by stratification. It can be anticipated that the plankton adapted to low light thus far in the Polar Regions would be faced with an increased stress due to high light intensity. Therefore, research on light protection mechanisms is also needed together with direct acidification experiments for phytoplankton production.

While the current denitrification rates have been estimated in the Chukchi Sea and Bering Sea, the denitrification rates are not understood in the vast areas of the continental shelf on the Siberian side. Furthermore, there has been no quantitative estimate of how do the microbials, which perform denitrification, respond to the future warming and the increase in organic matter flux originated from terrigenous and marine biotas in the Arctic Ocean. For example, it has been known that the changes in denitrification rate along with seawater temperature rise are different depending on the microbial taxa. Integrated works of the following items with elucidation of seasonal and inter-annual changes would benefit the predictions of future changes in primary production in the Arctic Ocean: installation of sea floor monitoring platforms in each of the areas, changes in organic matter flux and temperature, redox state, denitrification rate, and sampling of microbials. It is also necessary to assess the influence on marine ecosystem and diversity by adding the changes of denitrification rate in numerical model simulations.

Furthermore, the experimental studies for the effects on marine biotas by future acidification have been progressed in the mid-low latitudes, but the experimental studies for the effects on phytoplankton, zooplankton and higher trophic level ecosystem are extremely rare in the Arctic Ocean. Prediction experiments in the laboratory have not even been performed concerning most of the biological taxa, while only limited studies are going on regarding limited areas, biological taxa, and assemblages. Vast continental shelf areas exist in the Arctic Ocean and benthos plays important roles in ecosystem. Thus, it is necessary to study the effects by the ocean acidification on phytoplankton, zooplankton, shelled molluscas, and diversified benthos.

In order to accomplish these tasks it is warranted to proceed with the studies concerning biotas dwelling in the diversified areas and the reality of acidification of the Arctic Circle, with and the experiments for acidification shift by laboratory experiments and in situ ventilation of CO_2 flow employing key species. It is essential to pursue international cooperative projects together with the nations facing the Arctic Ocean. Because that the acidification in the Arctic Ocean has been reaching the serious state first ahead of other oceans, the studies in the Arctic will be able to offer important information for future predictions of the impact by the acidification in other oceanic areas by elucidating the responses of ecosystem and diversity to be understood with long term monitoring. It is considered that the knowledge obtained in Japan regarding ecosystem prediction models, plankton, and ecosystem can contribute significantly to the assessment research on the changes in the Arctic ecosystem and diversity in response to the ocean acidification.

Chapter 7: Broad and important subjects on the Arctic environment

Important environmental research that is not included in the focus of the previous two areas are also underway for the Arctic. We selected activities which were highlighted as research themes by the JCAR community. Following advances in research, this work will potentially provide further information relating to the former two focal points. In addition, it includes the research areas that describe the basic information on the focal points.

Theme 10: Geospace environment

Abstract

Due to the precipitation of charged particles and the propagation of electromagnetic waves from geospace (space around the Earth that is part of the active region for humans), it has been noted that in recent years the upper and lower atmosphere of the Arctic region is subject to change. In particular, minor constituent variations in the middle/upper atmosphere and its impact on the ozone concentration and stratosphere-troposphere coupling such as the downward propagation of the Arctic Oscillation — effect of the upper atmosphere on the lower atmosphere attracted the interest in the recent. It has also become clear that the atmospheric waves excited in the lower atmosphere have a great influence on the thermal and dynamical structure of the middle/upper atmosphere. In addition, the results also suggest a significant increase in the cooling of the middle/upper atmosphere with increasing greenhouse gases. It is believed that understanding the various coupling process between the lower atmosphere and the upper atmosphere is important in order to appreciate the full extent of the Arctic environment. However, little progress has been made with a quantitative impact assessment.

Electromagnetic and particle energies entering from the Solar wind and magnetosphere to the polar upper atmosphere cause fluctuations in the upper atmosphere at the low/middle latitudes (including large-scale fluctuations such as magnetic storms). In addition, atmospheric waves generated from the lower atmosphere may contribute to driving the global scale atmospheric circulation. However, the full extent of such changes on a global scale is still unknown. As one of the important information infrastructure businesses that support the human society, it is necessary to monitor the polar upper atmosphere in order to provide effective, reliable detection and prediction of ionospheric disturbance phenomenon. It is expected that in the next few years, geospace exploration, including the middle/upper atmosphere, will be achieved using new satellite/rocket observations and large atmospheric radar observations. In conjunction with these enhanced observations, there is a need to develop a research framework to evaluate and predict the influence of geospace on the upper atmosphere and lower atmosphere. Questions about the impact of the geospace environment on the Arctic environment and the connection between the geospace and Arctic environments are summarized as follows:

Q1: What are the effects of geospace on the upper atmosphere and lower atmosphere?

Q2: What are the effects of the upper atmosphere on the lower/middle atmosphere?

Q3: What are the effects of the lower/middle atmosphere change on the upper atmosphere?

Q4: How important is the energy flow from the polar region into the middle/low latitudes through the upper atmosphere?

Introduction

Geospace is a term used to describe the space around the Earth that falls within the zone of human activity; this includes the area within which we find many satellites, the International Space Station, and the flight paths of planetary exploration spacecraft. The geospace has been distinguished from the distant universe that lies beyond the reach of humans, and its researches and observations have been made to better understand its environment.

Recent studies have revealed that changes in solar activity and in the space around the Earth affect the global environment. In particular, since the polar region is susceptible to solar winds and to interplanetary magnetic fields[40], and is affected by various types of energy input from above, detailed understanding of physical and chemical processes is required. It is also becoming apparent that the upper atmosphere particularly experiences short-term and long-term variations due to various factors, such as energy and momentum transport by atmospheric waves[41] excited in the lower atmosphere and an increase in greenhouse gases. Research on "coupling processes between the lower and upper atmosphere" to understand these effects from above and below has become a priority in the Arctic; this also applies to research that examines interactions across the whole atmosphere. Various modulations in solar activity, such as the absence of sunspots for more than one year, have recently been reported. There is concern that this might affect the Arctic environment through coupling processes between the upper and lower atmosphere. In order to address these issues, cross-cutting interdisciplinary research is required.

In addition to space utilization by human society (as

[40] Interplanetary magnetic field: The solar magnetic field carried by the solar wind to interplanetary space (i.e., space where planetary orbits in the solar system exist). Because of the rotation of the sun, the magnetic field lines of the interplanetary magnetic field are spread in a spiral form from the sun.

[41] Atmospheric waves: Waves in the atmosphere generated by a variety of atmospheric disturbances. There are more localized atmospheric gravity waves and global-scale atmospheric tides and planetary waves, whose restoring force is generated by atmospheric density stratification with gravity and by the conservation of angular momentum due to the rotation of the Earth, respectively. Atmospheric waves generated in the lower atmosphere propagate upward and release energy and momentum in the mesosphere and thermosphere due to their breaking caused by amplification with altitude; this drives the meridional circulation and zonal wind change in the upper part of the middle atmosphere.

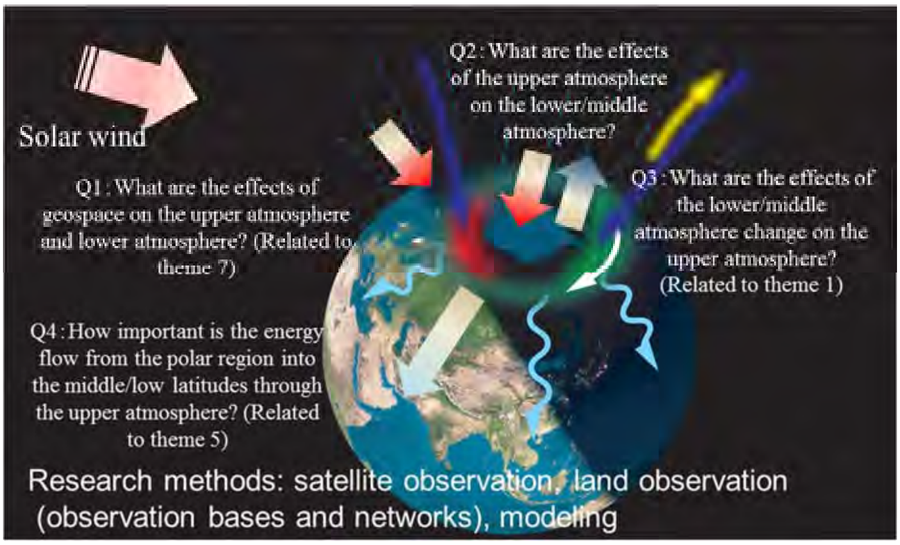


Figure 37: Relationship between four key questions of theme 10.

represented by positioning satellites), study of the geospace environment has also been utilized to improve the accuracy of space weather[42] forecasts required for the operation of satellites. Thus, in the Arctic, study of the geospace environment is becoming important also as a practical science to reduce the risk to social infrastructure (communications, power supply, and positioning). In particular, in Arctic countries (e.g., Norway), various space weather phenomena resulting from changes in the geospace environment have been recognized as a social concern. Specific social impacts are described in Q4 of Theme 7, "Effects of the Arctic environment on human society."

Many of these solar-terrestrial studies have been led by Japan as international collaborative research projects. Enhancement of geospace exploration can be expected within the next few years, such as through new satellite/rocket and large radar observations, including the exploration in the middle/upper atmosphere; this is expected to occur within the framework of international cooperation initiated by Japan. In order not to miss this opportunity, there is a need to develop a research system to assess and predict the influence of the geospace on the upper and lower atmosphere and their interaction.

In this section, the influence of the geospace environment on the Arctic environment and the connections between these (in other words, coupling processes) is described separately through four key questions. First, in "Q1: What are the effects of geospace on the upper and lower atmosphere?" with the keyword "space weather research", the impact of solar activity and changes in the space around the Earth on the global environment are mainly described. Next, in "Q2: What are the effects of the upper atmosphere on the lower/middle atmosphere?", we specifically describe research into "lower and upper atmospheric coupling processes", including the downward propagation of atmospheric minor constituents. In "Q3: What are the effects of lower/middle atmosphere change on the upper atmosphere?", we summarize impacts from the lower to the upper atmosphere, including the cooling of the middle/upper atmosphere coincident with global warming. Finally, in "Q4: How important is energy flow from the polar region into the middle/low latitudes through the upper atmosphere?", the importance of the study of latitudinal coupling is discussed.

Q1: What are the effects of the geospace on the upper and lower atmospheres?

a. Importance and current status of research

It is known that energetic particles emitted from the sun and galaxies and found in the radiation belt that are trapped by the geomagnetic field precipitate into the upper atmosphere; these can cause such effects as ionization in the altitude region below the mesosphere (Rishbeth and Garriott, 1969). For example, in the event of a large-scale magnetic storm[43] and solar energetic particles (SEP), a decrease in ozone in the polar mesosphere and upper stratosphere has been noted (e.g., Jackman et al., 2001). In recent years, it has also been suggested that mesospheric ozone is depleted by electron precipitation from the radiation belt (Rozanov et al., 2005). However, quantitative evaluation of the impact of these processes on the middle atmosphere has not been sufficient. Since air shower of these energetic particles causes radiation

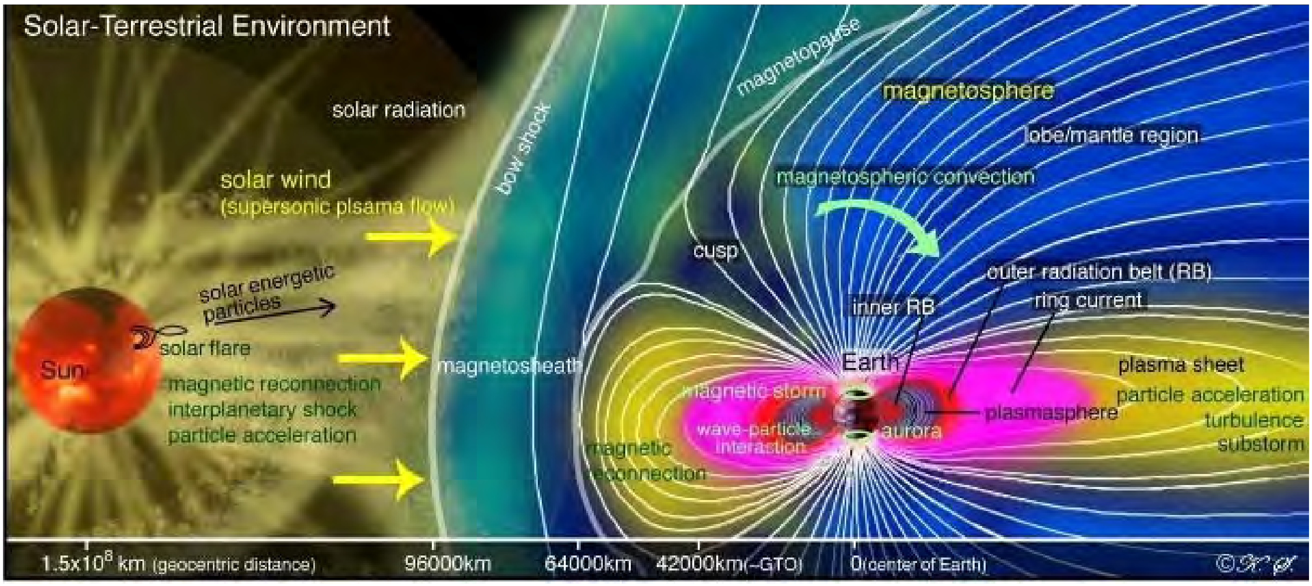
[42] Space weather: Since the human activity area has extended into space, the space environment and its fluctuation phenomena have come to be referred to as space weather, in a similar fashion to the terrestrial weather that affects human life. Electromagnetic fields, radiation belt particles, and cosmic rays are major elements of space weather. Energy associated with space weather disturbances enters the polar ionosphere along the Earth's magnetic field lines and affects the thermal structure and chemical composition of the upper atmosphere.

[43] Geomagnetic storm: The largest disturbance phenomenon in the geospace caused by large-scale disturbances in the sun. It has also, as of recently, been referred to as a geospace storm. During this phenomenon, a large current flows through the space around the Earth and the amount of cosmic radiation increases. In addition, it has a significant impact on the Earth's atmosphere, such as the ionosphere, thermosphere, etc., and energy input from space to Earth increases rapidly.

exposure at flight altitudes, especially around the polar region, prediction and impact assessment of this change is important for space weather research.

Although the energy input from the geospace into Earth's atmosphere causes a variety of variations in the polar upper atmosphere, understanding of these processes is still insufficient (e.g., Gray et al., 2010). In high latitudes, large currents flowing through the ionosphere, along with auroral activity, generate an induced current on the ground, causing failures in transmission line networks and pipelines, etc. It has also been reported that thermospheric air expansion due to rapid increase in solar ultraviolet radiation caused attitude disturbances of satellites, with these ceasing operation. In addition, disturbance phenomena in the ionosphere (e.g., ionospheric storms, plasma bubbles, etc.) significantly affect the accuracy and reliability of satellite positioning (the use of which has increased very notably in recent years) and of aircraft navigation systems that rely on it. In particular, "extreme space weather phenomena", which are less frequent but which occur on a large scale, are expected to have very large impacts, even though there has been limited observation of these so far and quantitative evaluation is difficult.

Furthermore, various modulations of solar activity have been reported in recent years (e.g., Shiota et al., 2012). In particular, the current situation is similar to the Maunder Minimum[44], with a longer-than-usual minimum period and limited sunspot number increases even during the maximum period. There is therefore speculation that cooling of the Earth's atmosphere, similar to that which occurred during the Maunder Minimum, will take place. On the other hand, because global cooling during the Maunder Minimum cannot be explained only by



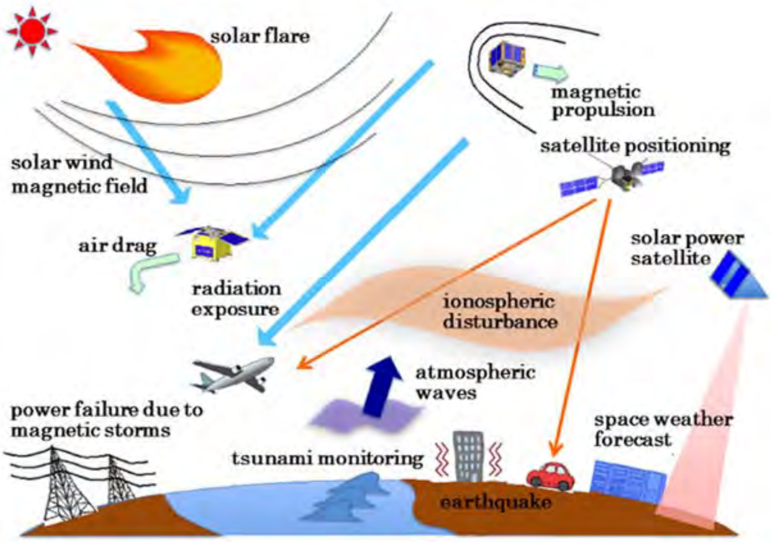


Figure 38: Solar-terrestrial region: (top) phenomena that occur in the region and (bottom) influence of geospace disturbances on society. Both figures are cited from "Present and Future of the Society of Geomagnetism and Earth, Planetary and Space Sciences" (SGEPSS, January 2013).

----- Courtesy of K.Seki

[44] Maunder Minimum: The period during which hardly any sun spots appeared over several decades in the second half of the 17th century. During this period, while solar activity was distinctly weak, the Earth's atmosphere was believed to be colder. It has therefore been suggested that solar activity affected the global climate.

fluctuations in the solar constant, several mechanisms in the middle/upper atmosphere have been proposed as its cause. However, quantitative verification of these processes is still insufficient, both in terms of observation and modeling.

b. Future research

In order to evaluate the impact on the atmosphere (especially in the polar region) of energetic particles from the geospace, it is important to have precise observations of the upper atmosphere and comparative observations of the ionosphere and magnetosphere by radars, spectrometers, and electromagnetic field measurement equipment on board satellites and from the ground. In particular, it will be essential to effectively utilize the geospace exploration satellite (ERG) scheduled to be launched in the next few years, as well as new large network observations and large observation bases (such as the next generation incoherent scatter radar program (EISCAT_3D) scheduled to be installed in North Europe by the international joint framework). In addition, there is also a need to build a system to advance research through close collaboration between the sun-heliosphere, geospace science community and the upper/middle atmospheric science community.

In order to quantitatively evaluate and predict changes in the impact of electromagnetic waves and energetic particles from the sun on the middle/upper atmosphere in the polar region, we need to build a model to evaluate impacts on each altitude layer in response to inputs of ultraviolet radiation and energetic particles from the geospace. Also, with regard to less frequent but large-amplitude phenomena called extreme space phenomena, it is important to assess impact on the basis of past case studies, and to reproduce and predict such phenomena through physical modeling. Thus, as one of the important information infrastructure businesses supporting human society, we consider it necessary to advance monitoring of the polar upper atmosphere and research into ionospheric disturbance phenomena, allowing for their effective and reliable detection and prediction in conjunction with the engineering community (such as communication and aeronautical engineering).

Japan is playing a leading role in international joint research projects such as CAWSES-II (Climate And Weather of the Sun Earth System, 2009 ~ 2013) and VarSITI [45] (Variability of the Sun and Its Terrestrial Impact, 2014 ~ 2018), promoted by researchers of sun earth system science, for example by producing project leaders. In addition, Japan has international research centers focused on sun earth system science, and is deploying observation bases overseas, including in the Arctic. Taking advantage of such Japanese superiority and in order to clarify the response of the Earth's atmosphere to changes in future solar activity, aggressive approaches are expected from the solar-terrestrial science community.

Q2: What are the effects of the upper atmosphere on the lower/middle atmosphere?

a. Importance and current status of research

The basic nature of the Earth's atmosphere, in which the lower atmosphere affects the upper atmosphere, originates from the stratified structure of the Earth's atmosphere, i.e., decreasing density with altitude. On the other hand, in recent years there has been more attention focused on influence from the upper to the lower atmosphere, such as through stratosphere-troposphere coupling represented by downward propagation of the Arctic Oscillation (e.g., Baldwin and Dunkerton, 1999). The polar region, in which there is energy input into the ionosphere and thermosphere associated with solar activity, is considered to be subject to effects from the upper atmosphere on the lower/middle atmosphere. In order to understand and predict medium- and long-term fluctuations of the polar lower atmosphere, it is therefore particularly important to understand mechanisms of vertical coupling processes through cumulative observations of influences from the upper to the lower atmosphere, combining these with studies using numerical models.

It is becoming clearer that variations in atmospheric minor constituents (e.g., nitric oxide (NO)) due to precipitation of energetic particles and to changes in solar ultraviolet radiation propagate downward and affect ozone concentrations in the stratosphere (e.g., Randall et al., 2007). However, there has as yet been no quantitative assessment of the extent to which changes in stratospheric ozone concentrations originating from variations in the upper atmosphere influence atmospheric circulation in the stratosphere and further in the troposphere. Energetic particle precipitation and variations in solar ultraviolet radiation are closely related to solar activity. Quantitative evaluation of the degree of influence the solar activity has on atmospheric general circulation[46] in the stratosphere and troposphere through changes in atmospheric minor constituents is thus also a future challenge.

On the other hand, it is also becoming clear that planetary waves excited in the troposphere propagate to the stratosphere, changing stratospheric circulation, which further affects tropospheric general circulation (Plumb and Semeniuk, 2003). However, it is not well understood what influence variations in the mesosphere and thermosphere, due to various waves of tropospheric origin, have on the troposphere through vertical coupling processes. In addition, there is a need for future research into the types of effects that stratospheric ozone variations due to energetic particle precipitation have on the troposphere, through changes in stratospheric general circulation.

In addition, there is also a possibility that a decrease in stratospheric ozone will affect the lives of Arctic residents through an increase in the surface ultraviolet dose. Since ozone depletion is closely related to planetary wave activity in the stratosphere, it is an issue that must be considered within the framework of troposphere-stratosphere coupling processes. For example, although

[45] VarSITI: Variability of the Sun and Its Terrestrial Impact (VarSITI) is an international collaborative research program in solar-terrestrial science spanning the five-year period 2014-2018; it is organized by the international organization SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) under the umbrella of ICSU (International Council for Science). Related website: http://www.stelab.nagoya-u.ac.jp/varsiti/.

[46] Atmospheric general circulation: Atmospheric general circulation is global-scale atmospheric flow. This circulation occurs in order to eliminate the temperature difference between equatorial and polar regions created by differences in incident solar radiation energy. In addition, global-scale circulation is generated also due to the influence of vertically-propagating atmospheric waves in the middle/upper atmosphere.

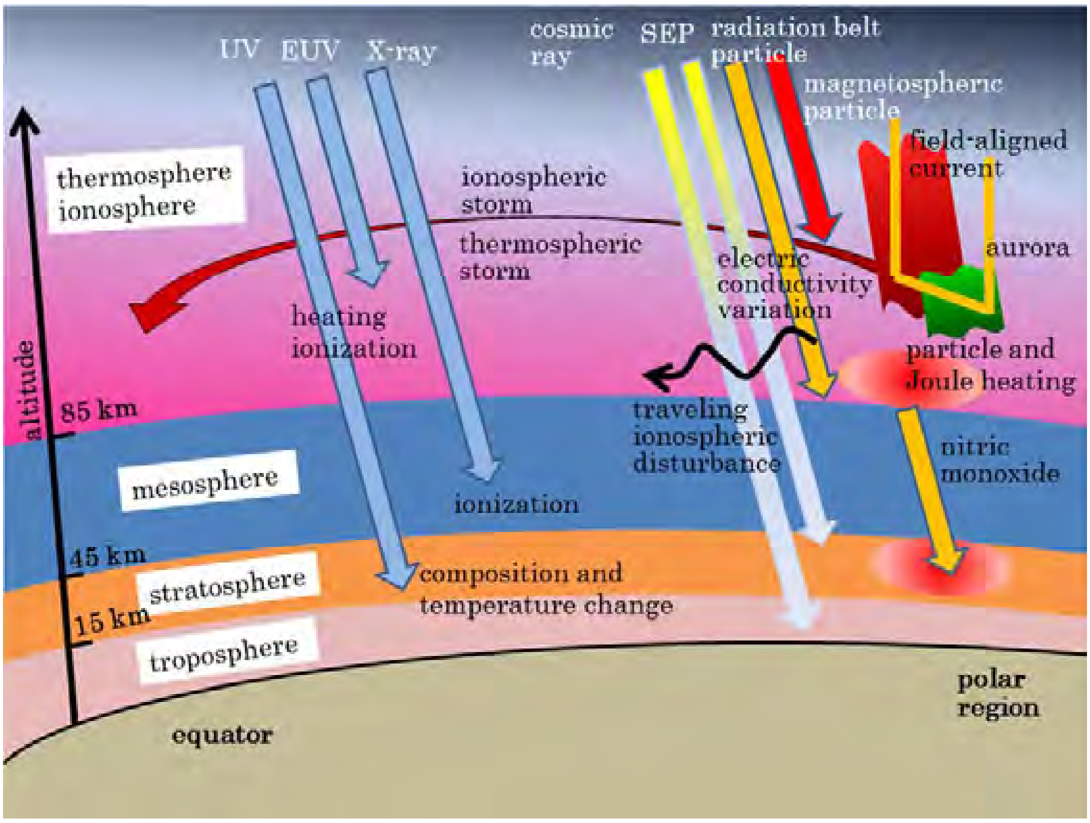


Figure 39. Impact of the sun on the Earth's ionosphere and atmosphere. The figure is cited and partly modified from "Present and Future of the Society of Geomagnetism and Earth, Planetary and Space Sciences" (SGEPSS, January 2013).

the ozone hole formed in the Arctic during the spring of 2011, whether similar ozone depletion will occur in future cannot be predicted well at present (e.g., Manney et al., 2011).

b. Future research

To examine variations in minor atmospheric constituents associated with energetic particle precipitation in high latitudes, it is important to make observations using large atmospheric radar and ground-based network observations of atmospheric composition, temperature, and wind in the middle/upper atmosphere, using various measuring instruments at high latitudes. In particular, precise observations using large observation equipment (such as the EISCAT_3D radar) and expansion of ground-based observation networks for examining global atmospheric fluctuations are essential to enable quantitative understanding. Furthermore, we need to combine these ground-based observations with satellite observations of the neutral and ionized atmosphere at altitudes from the middle atmosphere to the thermosphere and ionosphere, in order to reduce assumptions behind individual observation instruments and to reach an understanding of their nature.

In order to investigate the effect of the upper atmosphere on the lower/middle atmosphere, it is important to have a quantitative understanding using numerical models. In addition, to understand to what altitude and to what extent the upper atmosphere affects the lower/middle atmosphere, we need overall verification by various models covering different altitude regions, including models that do not include the thermosphere and ionosphere, models that do not include the mesosphere and above, or on the contrary, models that do contain the thermosphere and ionosphere. Globally, there has been upward extension of model top height and models that include the altitude region from the troposphere up to the thermosphere/ionosphere have been developed in Japan (GAIA model; Jin et al., 2011). In future, further improvement of model accuracy will be important. Also, in order to consider photochemical processes (including ozone depletion), it will be necessary to develop a model including photochemical reaction processes in the altitude region from the troposphere up to the mesosphere and thermosphere, and to improve its accuracy. The solar-terrestrial science research community in Japan has a great interest in coupling processes between the lower and upper atmospheres, and is actively developing the observational and modeling studies described above.

Q3: What are the effects of lower/middle atmosphere change on the upper atmosphere?

a. Importance and current status of research

While global warming due to an increase in greenhouse gases has occurred in the troposphere, ground-based and satellite observations and modeling studies have indicated progressive cooling in the middle/upper atmosphere (e.g., Roble and Dickinson, 1989). Cooling of the middle/upper atmosphere coincident with global warming in the lower atmosphere appears more pronounced in this altitude

Figure 40: Relationship of the upper atmosphere with global warming and climate change (left: cited from "Present and Future of the Society of Geomagnetism and Earth, Planetary and Space Sciences" (SGEPSS, January 2013)) and mesospheric clouds photographed in Paris sky (right: http: //www.spaceweather.com/nlcs/gallery2009_page12.htm).

region because of low atmospheric density. For example, an increase in water vapor in the vicinity of the mesopause, associated with increasing methane, and cooling in the middle/upper atmosphere due to an increase of carbon dioxide have resulted in increase of the occurrence of polar mesospheric clouds in the Arctic and their associated specific radar echoes in the mesosphere (PMSE, MSE), and in the equatorward expansion of the generation region of mesospheric clouds (see Figure 40); the latter are thought to be an indicator of global warming in the lower atmosphere. It is thus possible to examine to what extent changes in the middle/upper atmosphere due to global warming are occurring. However, since long-term data for the middle/upper atmosphere is very limited, the study of inter-decadal variations has only just begun. In particular, it is very important to carry out bipolar comparative studies between the Arctic, which is an active region of human activity, and the Antarctic, which differs, in order to understand and identify the process of cooling in the middle/upper atmosphere associated with global warming.

Since 2000, sea level rise and surface warming have increased in the Arctic due to the amplification of Arctic warming. If the AO index[47] becomes negative, there is a possibility of enhancement of its spatial pattern, and in winter, it is likely to lead to an increase in disturbances, as represented by stratospheric sudden warming[48] (e.g., Turner et al., 2007). It becomes clear from recent observations and numerical simulations that a distinct indicator of stratospheric sudden warming may be emerging in the atmospheric circulation in the mesosphere and the lower thermosphere, prior to variations in the stratosphere. It has been observed that variations in the middle atmosphere due to stratospheric sudden warming modulate the atmospheric waves propagating from the lower atmosphere and cause fluctuations in the thermosphere and ionosphere at low latitudes (e.g., Chau et al., 2012). Although these variations are thought to be induced by global-scale variations of atmospheric waves, such as planetary waves and gravity waves, overall understanding of these processes is still lacking. It has therefore become necessary to utilize a new viewpoint, considering Earth's atmosphere holistically and connecting all atmospheric regions, from the lower atmosphere, which is the realm of meteorology, to the upper atmosphere. Such studies are expected to be able to allow, among other aspects, prediction of the occurrence of stratospheric sudden warming, which may become frequent in the Arctic in future.

Furthermore, recent development of GPS networks has made it clear that atmospheric waves excited by tsunamis occurring after earthquakes, typhoons, and hurricanes, are transmitted to the ionosphere and modulate plasma density in the ionosphere (Tsugawa et al., 2011). This result indicates that ground and sea-level changes can affect the upper atmosphere, reflecting an image of a dynamically-varying Earth and suggesting a new possibility, i.e., that ionospheric research could develop as a disaster prevention science, for example, for predicting tsunami arrival.

b. Future research

The middle/upper atmosphere changes associated with global warming have a global impact through changes in the vertical profile of atmospheric temperature, disturbances in the Arctic, and modulation of atmospheric wave propagation from the lower atmosphere. In this area where long-term data acquisition has just begun, it is most important to continue ground-based and satellite observations and model calculations. In the Arctic, it is desirable to enhance network observations longitudinally, and it is essential to continue to operate observation sites in Alaska, Canada, and northern Europe (where observation instruments are already installed), and to

[47] AO index: The AO index is obtained by projecting geopotential height anomalies in the Northern Hemisphere troposphere on specific days or months onto the first principal component vector obtained from principal component analysis of the geopotential height field in the troposphere (i.e., 1000hPa and 500hPa) of the Northern Hemisphere (i.e., poleward of 20 °N). Positive and negative indices represent the strengthening and weakening of Arctic low pressure regions, respectively. For more information, refer to URL: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html.

[48] Stratospheric sudden warming: The phenomenon in which temperature rises rapidly over a short period in the winter polar stratosphere. While it occurs frequently in the Arctic, it rarely occurs in the Antarctic. The definition given by the World Meteorological Organization (WMO) refers to a phenomenon in which temperature rises more than 25 K within a week and zonal mean temperature at or above 10 hPa increases towards the poles from 60 ° latitude.

strengthen further cooperation with large observation bases (such as the EISCAT_3D radar, the SuperDARN radar, and AMISR). In particular, we should consider cooperation with Russia where few observation points presently exist. In addition, it is also important to further enhance model calculations in middle/upper atmosphere research with limited observation methods.

With regard to future research directions, it is more important than ever to understand various atmospheric waves as an important process for linking atmospheric regions. We need to understand, on a global scale, how atmospheric waves excited in the lower atmosphere propagate, where they dissipate to, and the characteristics of turbulence considered to be generated by the dissipation of atmospheric waves and secondary-generated atmospheric waves. In particular, turbulence in the middle atmosphere is an important research issue, since it can greatly affect the structure of the thermosphere above it. Additional future issues to be resolved include how atmospheric waves present in the whole atmosphere modulate the structure of ionospheric plasma and how ionospheric disturbances are induced. It would be very significant to understand the characteristics of ionospheric disturbances and to predict their occurrence, also because of implications for infrastructure, such as satellite positioning and communication methods using radio waves that propagate through the ionosphere.

In order to capture the variation in atmospheric general circulation and global-scale change, it is necessary to also strengthen cooperation with observations in middle and low latitudes and in the Antarctic. It is especially important to continue ongoing cooperation with Syowa Station in Antarctica, which has many observation instruments such as the PANSY radar, lidar, and MF radar, and with each Japanese observation site in the Arctic. Research focusing on bipolar comparisons will be important for understanding and identifying middle/upper atmosphere cooling processes coincident with global warming and its prediction.

Japan is planning and maintaining infrastructure (i.e., observation bases and network observations) in order to advance such studies, and is expected by the international community to contribute to the development of research.

Q4: How important is the energy flow from the polar region into the middle/low latitudes through the upper atmosphere?

a. Importance and current status of research

Energy inputs of plasma and electromagnetic field fluctuations from the solar wind into the upper atmosphere through the Earth's magnetosphere mainly occur in the polar region, where Earth's magnetic field lines converge. Inputs of plasma and electromagnetic energy heat and vary the upper atmosphere through the Joule heating and the Lorentz force. Such dynamic variations propagate to the middle/low latitudes as atmospheric waves. Changes in atmospheric composition due to heating also spread into the middle/low latitudes through material transport. In addition, electromagnetic field fluctuations that have entered the polar region are transferred to the low latitudes, as geomagnetic pulsation trapped in the ionosphere and as electric field fluctuations trapped between the ionosphere and the ground. Through these various processes, electromagnetic energy that has entered the polar region from the solar wind and the magnetosphere causes

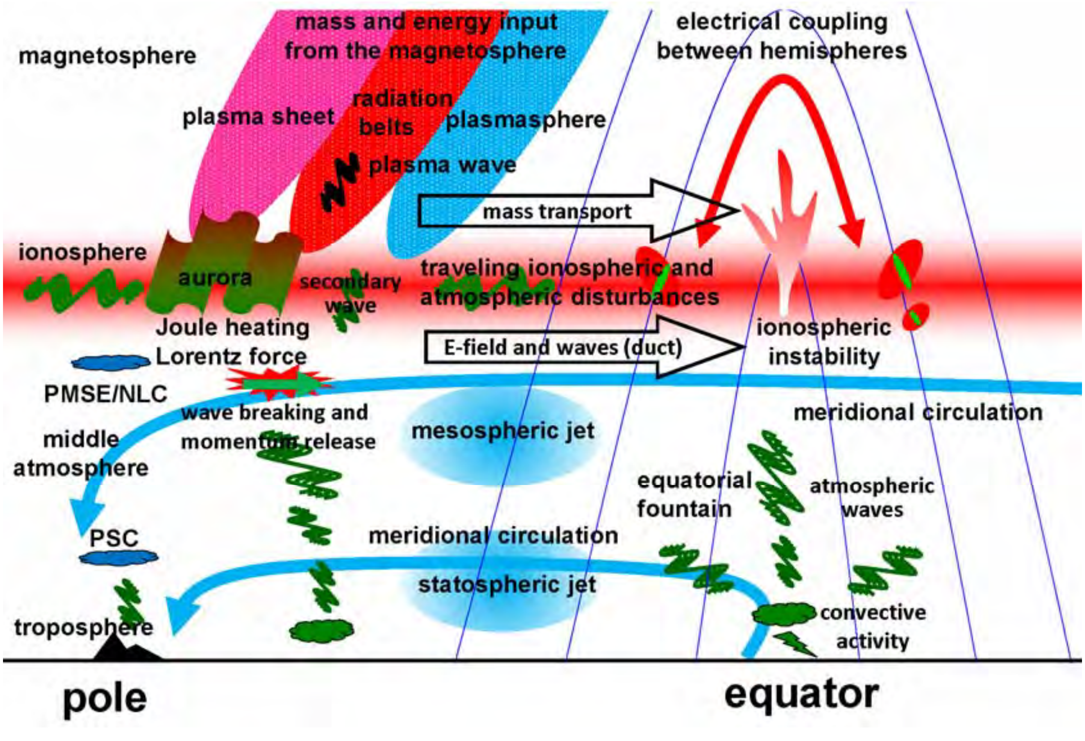


Figure 41: Schematic diagram of energy input from the polar region to the middle/low latitudes through the upper atmosphere, and related phenomena.

fluctuations in the upper atmosphere in middle/low latitudes. Typical examples are positive/negative-phase ionospheric storms with unusual increase/decrease of electron density in the ionosphere, respectively, and the equatorial ionospheric instability induced by the intrusion of the electric field. These phenomena are important because they have a significant impact on communication between a satellite and the ground and on positioning using GNSS satellites. However, it is difficult at present to understand, through observations, the overall propagation process of these energies and materials to middle/low latitudes. In the model, it is also difficult to solve electromagnetic field fluctuations and dynamic fluctuations of the neutral atmosphere under the boundary conditions at the model top and bottom (e.g., Schunk and Nagy, 2000).

It has been noted that atmospheric waves generated in the lower atmosphere drive global-scale meridional circulation by dissipating and releasing momentum near the mesopause. However, exact quantification of their effects (i.e., parameterization) presents a challenge in terms of improving the accuracy of future predictions. In addition, it has become apparent from recent studies that secondary waves generated by the momentum deposit and waves that are not dissipated in the mesosphere propagate into the thermosphere, causing global-scale variations in the ionosphere (e.g., Vadas and Crowley, 2010). These processes have been found to occur widely for various waves, from gravity waves with a period of several hours, to planetary waves with a period of several days. Moreover, it is known that the effect of these processes, having a driving source in the polar region, is gradually transmitted to the middle/low latitudes. As also mentioned in Q3, recent observations have made it clear that the effect of sudden warming which occurs in winter in the Arctic stratosphere appears in the distant equatorial ionosphere and in the Southern Hemisphere mesosphere, as well as over the Arctic. Propagation of atmospheric waves and associated momentum transport are considered to be leading possible causes of these phenomena, and a number of researchers are working on developing a more comprehensive understanding of these mechanisms. In addition, propagating ionospheric disturbances frequently observed in the ionosphere are believed to be caused by atmospheric waves coming from the lower atmosphere and the auroral zone, and also by ionospheric plasma instability dependent on electromagnetic field fluctuations. There is also a need for research to isolate the two (e.g., Makela and Otsuka, 2012).

b. Future research

In order to understand latitudinal coupling in the upper atmosphere, where neutral atmosphere changes and electromagnetic field fluctuations are complexly intertwined, it is first important to utilize various ground-based observations. These include those obtained from a large atmospheric radar that measures coupling of the upper and lower atmosphere in the polar and equatorial region - such coupling is key to driving variations in the upper atmosphere - and from ground-based multipoint network observations deployed in the latitudinal direction along the three main meridians in Asia, Africa, and America. Base observations from a large radar (such as the EISCAT_3D), enabling observation of three-dimensional structures with high time resolution, are especially needed in the polar region, in order to observe the complex spatial and temporal variations of the plasma atmosphere. In addition, at ground-based multipoint network observations along a meridian, simultaneous and multipoint observations of electromagnetic field fluctuations and neutral atmospheric variability at multiple altitudes are needed; these can be obtained by combining data from high sensitivity airglow cameras, GNSS receivers, Fabry-Perot interferometers, meteor radars, large HF radars, magnetometers, etc. Also, because atmospheric tides and planetary waves have a longitudinal structure, it is important to expand observation points longitudinally around the polar region. It is essential to measure global-scale atmospheric coupling in conjunction with these ground-based remote sensing observations, with direct satellite observations of neutral atmosphere and plasma in the ionosphere, and with imaging observations from satellites with wide-area coverage. The research community in Japan has much experience of ground-based multipoint network observations, base observations, and satellite observations, and should play a central role in promoting latitudinal coupling research within a framework of international cooperation, through maintenance and expansion of future observations.

In terms of model development, under Japan's initiative, a whole atmosphere model that can be solved in a consistent way from the ground to the thermosphere/ionosphere has been developed (e.g., Jin et al., 2011). However, it does not have a spatial resolution that can explicitly[49] generate atmospheric gravity waves, which are an important driver of atmospheric general circulation. Furthermore, electrical coupling processes with electromagnetic energy entering from the solar wind and the magnetosphere are not yet sufficiently represented. In future, it will be necessary to incorporate these physical processes into the whole atmosphere model. In addition, we must also consider developing a technique for data assimilation in order to include the data of ground-based and satellite observations into the model. Moreover, in order to take advantage of the dense network of long-term ground-based magnetic field observation data, it will be necessary to carry out a comparative study between ground-based magnetic field observations and magnetic field fluctuations simulated by a thermosphere-ionosphere model.

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[49] In the field of modeling, "explicitly" is often used with reference to directly writing down a specific process (e.g., temporal change of a variable) in model equations.

Theme 11: Interaction of the surface environment changes with solid earth

Abstract

Large-scale surface activity of the earth occurs due to the spreading and subduction of the ocean floor by thermal convection of the Earth's interior. This causes phenomena, such as the formation of new marine floor and the collision of continents. The change in configuration of the ocean and the continents at the earth's surface due to thermal convection of the Earth's interior is an important factor that causes a shift in the Earth's surface environmental changes, such as atmospheric and oceanic circulation, and the development of ice sheets. On the other hand, changes in the volume and geographical location of the ice sheets and seawater on the surface of the earth due to climate change lead not only to changes in sea level, but also to the deformation of the Earth, such as crustal movement and mantle flow of the earth's interior. As just described, it has been thought that the climate and Earth interact with each other over a range of time and space scales. However, the mechanisms are not clear yet and to understand the whole Earth system comprehensively is an essential issue. In particular, the Arctic region where interactions on various scales appear, such as the current crustal movement phenomenon due to changes in load from ice sheets and the formation and fragmentation of the continents, which happens on a scale of several billions of years, is key to understanding the problem. With this theme, we have set the following four questions to be researched on the Earth changes with different time and space scales in the Arctic region in order to understand the interaction between the Earth and surface environmental change under such conditions.

Q1: What is the interaction between the currently active hydrothermal system of Arctic mid-ocean ridges and the marine environment?

Q2: How is the solid earth deformed by an ice sheet change?

Q3: In the process of the Arctic Ocean formation, how did the interaction of the atmosphere - ice sheet - ocean change?

Q4: How did the development process of the Arctic Ocean and surrounding continents affect the surface environment change on the time scales from tens of millions of years to several billions of years?

Question 1 focuses on the hydrothermal system of the Gakkel ridge, which is one of the currently active mid-ocean ridges under multi-year sea ice and has not been well researched. The aim of the research regarding Q1 is to clarify the causes, the local ecosystem, and the effect of oceanic circulation on the hydrothermal system of the Gakkel ridge.

Question 2 applies to the observational study on the current crustal deformation with the load change of ice sheet, which is a unique phenomenon of polar regions with a spatial scale of several thousand kilo-meters and a time scale of tens of thousands years. This study, in the areas of Greenland ice sheet, northern Canada and their marginal ocean, aims to clarify the mechanisms of ice sheet changes and viscosity structure of earth's interior by geomorphological, geological and geodetic investigations together with modeling study.

Question 3 applies to establishing the formation history of the Arctic Ocean on a scale with hundreds of millions of years and the changes of atmosphere - ice sheet - ocean interaction. Most of the Arctic Ocean floor remains uninvestigated due to sea ice cover. The objectives of this study are to (i) determine the history of the Arctic Ocean seafloor via geophysical and geological investigations, (ii) clarify the changes in the atmosphere - ice sheet - ocean interaction by investigating the reconstruction of the paleoclimate and paleoenvironment by the sediment collection, and (iii) estimate the time for ice sheet expansion in Arctic Ocean formation and the expansion associated with the tectonic history of the Arctic Ocean.

The last question Q4 is on a change of the solid earth on the several billions of years scale, and aims principally

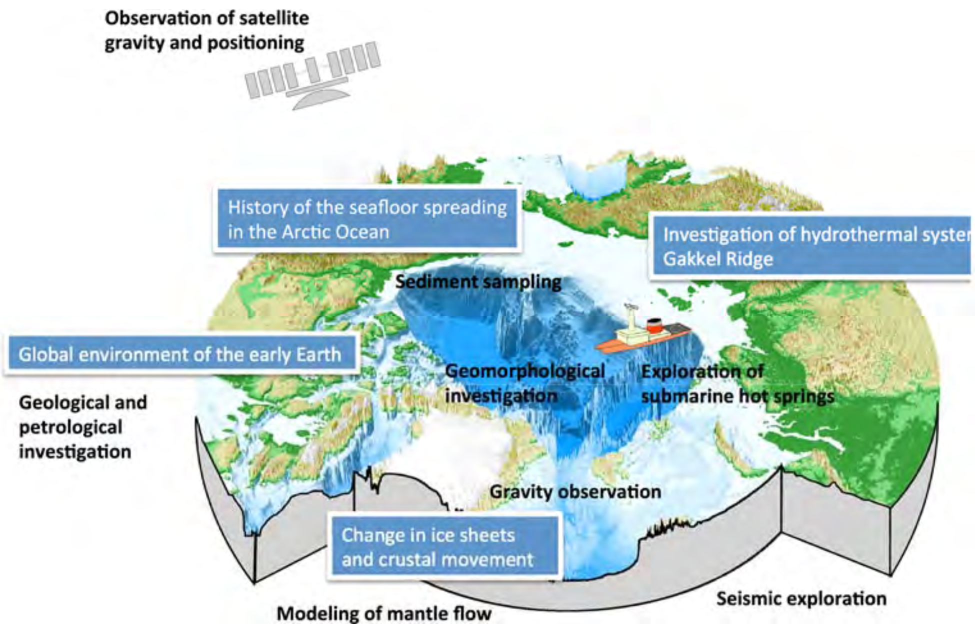

Figure 42: Important research topics regarding interaction between solid earth and the surface environment changes

to analyze the earth's surface environment change on the scale of 3-4 billion by the earth crust study with mainly the geological investigations in the continent around the Arctic region. The promotion of the research on the history of global environment change on the long geological time scale from the early days of the earth formation to now by a geological investigation in the Canadian Arctic and west coast of Greenland, where exists a stratum of approximately 3-4 billion years old, is suggested.

Introduction

In the Earth, changes on various time and space scales are complex, such as movement caused by changes in the loads on the surface of the Earth along with changes of the sphere of fluid, including the atmosphere and the ocean, as well as changes like formation and fragmentation of a supercontinent. Changes in the configuration of the continents and the ocean on the surface of the earth over hundreds of millions of years through to several billions of years due to formation of the ocean and supercontinent by continental fragmentation brought around transformations to oceanic circulation and atmospheric circulation, and greatly changed the surface environment. On the other hand, like the change of the Earth with the change in ice sheet load, the Earth's responsive phenomenon for the changes to the surface environment exists as well. The Arctic region is a perfect field to understand the interaction between the Earth and surface environment changes over various time and space scales, including the current activity in the mid-ocean ridges, which are plate boundaries, crustal movement phenomenon due to the load changes of ice sheets over tens of thousands of years, which is a unique phenomenon in polar regions, and the formation and fragmentation of the continent over several billions of years.

In this theme, we will describe the goals of observational research for the four questions about changes to the Earth on different time and space scales, which are necessary to understand the interaction between the Earth and surface environment changes, and should be developed intensively in the Arctic region in the future. By promoting research based on these four questions and integrating the results, we will clarify the relation between changes to the Earth and the surface environment as a summation of various time and space scales, and aim to elucidate the interaction between the solid geosphere subsystem as well as atmospheric and oceanic subsystem in the Earth system.

Q1: What is the interaction between currently active hydrothermal systems of the Arctic mid-ocean ridges and the marine environment?

a. Importance and current status of research

The mid-ocean ridges and back-arc spreading system are a series of active volcanoes, and many seafloor hydrothermal systems have been found along with them so far. A seafloor hydrothermal system is a place to emit the earth's internal energy and reducing gases, such as hydrogen sulfide, methane, and hydrogen. It is also important for the concept of circulating the Earth's heat and substances, such as forming hydrothermal deposit. It is known that the chemical composition of the hot water which erupts there varies depending on the kind of rocks or heat source of the seafloor and each fountain supports different type of ecosystems respectively.

The Gakkel Ridge is one of currently active mid-ocean ridges located almost at the center of the Arctic Ocean and is a boundary between the North America Plate and the Eurasian Plate. Since it exists under sea ice of the Arctic Ocean, it is a difficult region to investigate (Figure 43). The Gakkel Ridge is classified as ultraslow spreading (<12 mm/year) and it is a unique end member among the mid-oceanic ridge systems in the world because of its spreading speed, geographical location, and structure.

Several investigations by observation vessels, aircraft, and submarines have been conducted at the Gakkel Ridge so far. As a result of such an investigation between the United States and Germany conducted in 2001 as AMORE[50], it is estimated that many hydrothermal activities are distributed with high density on the ridge axis of the ultraslow-spreading Gakkel Ridge (Edmonds et al., 2003 (Figure 44)). Generally, it is thought that magma activity is less active and the amount of thermal release is small along the axis of ultraslow-spreading ridges. In the Southwest Indian Ridge, which has a similar axis of ultraslow-spreading ridge, high-density hydrothermal activity, like that found in the Gakkel Ridge, has not been found. Even in the slow-spreading Mid-

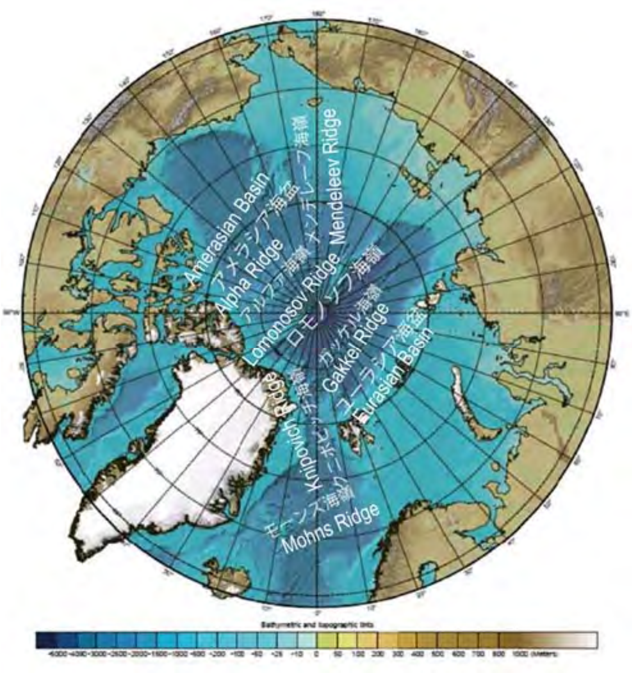

Figure 43: Bathymetric chart of the Arctic Ocean, information added to Jakobsson et al., (2008)

[50] AMORE: Arctic Mid Ocean Ridge Expedition

Atlantic Ridge, such high-density hydrothermal activity has not been confirmed. For the Southwest Indian Ridge and Mid-Atlantic Ridge, it has been thought that the fault is largely associated with hydrothermal activity but this does not explain everything for the hydrothermal activity of the Gakkel Ridge. It is suggested that such hydrothermal activity may be related to the kinds of rocks around the hydrothermal system as well (Michael et al., 2003). In addition, biologically, it is expected to find a new chemosynthetic community in the unique hydrothermal system of the Gakkel Ridge where high-density hydrothermal activity exists. In 2007, the AGAVE [51] expedition investigated the hydrothermal system in the Gakkel Ridge under the initiative of the United States by using a joint AUV including Sweden, Germany, and Japan.

Unfortunately, they could not find hydrothermal vents. However, with the investigation around the extremely deep ridge axis at approximately 4,000 m at 85° E, the data collected suggested explosive volcanic activity (Sohn et al., 2008) and yellow fluffy mats of bacteria which grow in low-temperature region (Shank et al., 2007). After that, a hydrothermal system with black smokers was found in the Mohns Ridge, south of the Gakkel Ridge, for the first time and it is confirmed that biota with the hydrothermal system is different from the one in the Mid-Atlantic Ridge, south of the Mohns Ridge (Pedersen et al., 2010). From the AMORE expedition, it is only estimated that there is high-density distribution of hydrothermal activity in the Gakkel Ridge so further detailed exploration on the axisof the ridge is required in order to search for the distribution of hydrothermal vents, the cause of hydrothermal activity, and a biological community existing off such activity, which are unique among the ridges in the world but have yet to be confirmed. In addition, an influence on oceanic circulation of heat flux by hydrothermal activity of the Gakkel Ridge is estimated to be low because it is a spot contribution even though the density of the hydrothermal activity is estimated to be high. However, this also needs to be verified by actual observation data.

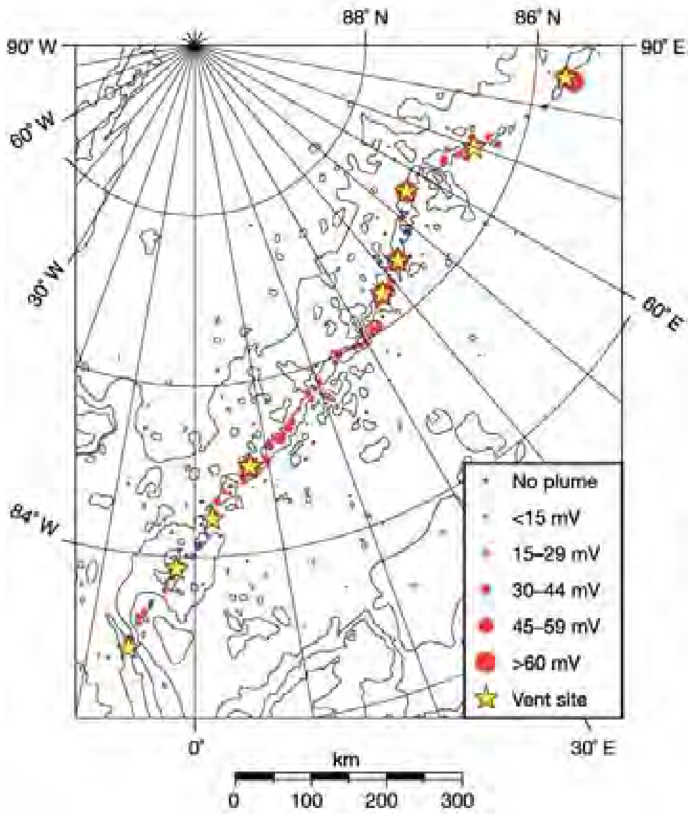

Figure 44: Areas where hydrothermal activities are suggested in the Gakkel Ridge (Edmonds, et al., 2003)

b. Future research

For identifying hydrothermal vents of the Gakkel Ridge, investigations using subsea robots, such as ROV or AUV, are necessary. Since the Gakkel Ridge exists under sea ice, icebreakers are required to deliver the subsea robots. For explorations with subsea robots, it is essential to conduct seafloor topography and ocean observation on a ship by icebreakers in advance. In addition, since there are not many actual exploration examples yet for explorations under sea ice by subsea robots, it is also necessary to consider specifications and operational forms.

For identifying hydrothermal vents, we narrow the range of investigation by acoustic probing of seafloor topography by observation vessels, understand the composition of hot water by detailed physical and chemical measurements, and estimate existence and location of areas of hot water. Then, we conduct an observation and investigation of seafloor. For exploration of the cause of hydrothermal activity and a biological community existing with such activity, after identifying the hydrothermal vents, we observe the hydrothermal vents and their periphery by ROV as well as the rocks and organisms. Furthermore, in order to search for the cause of hydrothermal activity, it is necessary to clarify the structure below the seafloor by conducting seismic exploration around the hydrothermal vents, electromagnetic exploration, and geomagnetic exploration. For estimating the temperature of the hot water area and fluctuations in the material flux, it is also necessary to carry out long-term fluctuation measurements of the marine physical and chemical composition in the hot water area.

Q2: How is the Earth deformed by changes in ice sheets?

a. Importance and current status of research

This question applies to deformation phenomena of the Earth caused by changes in ice sheets over a time scale of several years to several tens of thousands of years. The load from the ice sheet is one of the surface forces (surface loads) which works as pressure on the surface of the Earth. The changes in ice sheets are associated with the mass of the ice sheet and the mass change of seawater, for example when ice sheets melt and flow into the sea, it brings a change of sea level. This generates changes in the surface load which in turn produces a deformation of the Earth. This phenomenon is called glacial isostatic adjustment

[51] AGAVE: Arctic Gakkel Vents Expedition

(GIA) and it differs according to the time and space scales of the change of load. It is known that the Earth responds elastically to load changes on a short time scale and responds viscously to load changes over several thousand years. Since the change in ice sheets covered in this question is a phenomenon which is on a time scale of several tens of thousands of years at the longest and on a space scale of several thousand kilometers, it brings both viscous and elastic deformation to the Earth on a global scale.

The GIA research in the Arctic region is being advanced mainly with three approaches of geomorphic and geological investigations, geodetic observation, and numerical modelling. These are for crustal uplift after the end of the last glacial period, or post glacial rebound (PGR) (for example, Peltier, 2004). PGR is a viscous deformation phenomenon in which most of the continental ice sheets covering North America and Northern Europe in the last glacial maximum[52] melted and disappeared approximately 6,000 years ago but the crust still continues to rise slowly by buoyancy. In recent years, as an impact of ongoing global warming, a rapid decrease in the Greenland ice sheets and glaciers of the Canadian Arctic Archipelago have been reported and it is becoming clear that the changes in these ice sheets create elastic deformation of the Earth as well.

The most important issue for research on deformation of the earth with the changes in ice sheets is to clarify the history of expansion, shrinkage, and increase and decrease of distribution of ice sheets after LGM (the history of ice sheet melting). If we can determine this history of ice sheet melting with high accuracy, we can accurately calculate the impact that the deformation of the Earth with ice sheet melting has on sea-level changes. This will be an important contribution to improve a degree of accuracy when predicting sea level rises with ongoing global warming. If we can understand details of the size and distribution of deformation of the Earth from past to present, we can reconstruct the history of ice sheet melting after LGM. Therefore, we hope that this shows the importance of this question, which is an investigation of the deformation of the Earth with the changes in ice sheets.

As physiographic and geological approach, by clarifying a relative altitude of sea level in the past through distribution of fossil shells and coral reef, the geological investigation on beach topography and glacial topography, and investigation on seafloor sediments, the changes of volume of seawater (volume of ice sheet) over the past several tens of thousands of years and the history of uplift and sedimentation of crust are estimated. Based on this, the change in the past distribution of ice sheets of polar opposites can be reconstructed by comparison with calculated values of GIA model taking into account elastic deformation of the Earth (for example, Peltier, 2004). However, with regard to the distribution of ice sheets by region, there is a large difference between the suggested models. For example, for a contribution of each ice sheet for an ice sheet melting event with rapid climate change, which occurred approximately 14,000 years ago, a decisive conclusion has yet to be made.

As for geodetic observation, crustal uplifts in the region, where PGR is progressing, is observed as a decline in average tide level according to tide level observations over the past 100 years (for example, Barnett, 1984). In Sweden, change in height and gravity in a long-distance leveling route is measured (Figure 45) and estimation of mantle viscosity is made as well (for example, Ekman and Mäkinen, 1996).

When ground-based observation by space geodesy technology, such as Global Navigation Satellite System (GNSS), became widely used in the late 1990's, continuous observation of crustal movement using this technology began in many spots of the polar region. Currently, monitoring observation of crustal movement by GNSS is being conducted in considerably high density in North America and Greenland (for example, Sella et al., 2007, Figure 46). In addition, in the beginning of the 2000s, observation of changes in ice sheet volume using satellite gravity mission and satellite altimeters started making it possible to estimate variation by PGR as well (Barletta and Bordoni, 2009). Recent satellite geodetic observation allows for high spatial and temporal resolution, however, a phenomenon reflecting the viscose structure of the mantle is characterized by its slow fluctuation velocity and small amount of displacement so approximately ten years' worth of observation data must be accumulated in order to detect accurate crustal movement velocity with GIA even with the current state-of-the-art observation technologies. Also, as described above, these observation data include crustal movement with the past changes in ice sheets (viscous movement) and crustal movement with the current changes in ice sheets (elastic movement), and since the former is mainly necessary for reconstruction of the history of ice sheet melting and estimation of mantle viscosity rate, separating these is also a big issue.

The viscosity rate of mantle is an important parameter to determine movement of the earth's interior related to plate tectonics, but there are only a few methods to estimate the viscoelastic structure of mantle based on known phenomenon. If it becomes possible to estimate

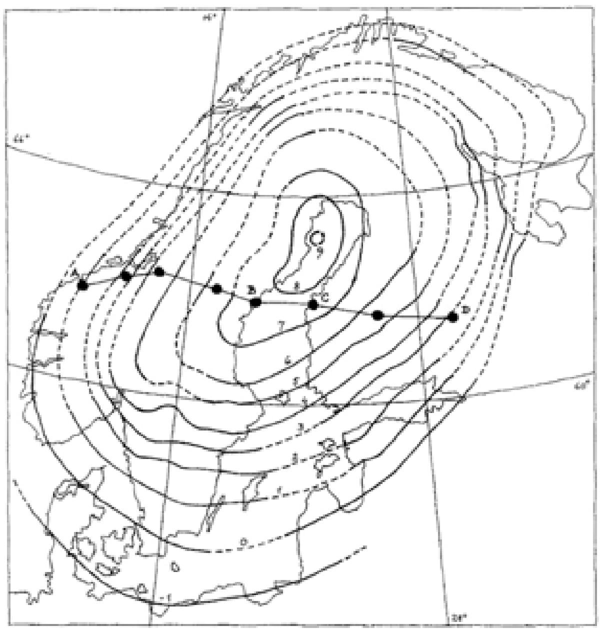

Figure 45: Postglacial uplift in Scandinavian region which was observed from 1892 through 1991 (unit is mm) and gravity measurement line (after Ekman and Mäkinen, 1996)

[52] Last Glacial Maximum (LGM) approximately 20,000 years ago

viscosity rates or distribution of mantle more accurately by comparative research of ground-based and satellite observation at high spatial and temporal resolution as well as numerical model calculations taking into account various viscoelastic structures of mantle, it will be a significant contribution to research fields in physics dealing with the Earth's interior.

As the Japanese contribution to the GIA research in the Antarctic region, the Japanese Antarctic Research Expedition conducts organized observation of crustal movement, gravity measurement, and geomorphic and geological investigations at Syowa Station and the surrounding bare rock area. As a result, it became clear that the crust currently up-thrusts at a rate of 2-3 mm per year at Syowa Station and its surrounding area, and this produces corresponding changes to gravity.

Also, it clarified that the neighborhood of Syowa Station has not been covered by ice sheets since 45,000 years ago, including LGM, and it necessarily did not synchronize with expansion of ice sheets in the Northern Hemisphere. However, in the Arctic region, observation of crustal movement and gravity measurements are conducted in Alaska and Ny-Ålesund in Norway. Annually 5-7 mm of uplift is observed in Ny-Ålesund.

b. Future research

In order to advance the understanding of this question further, there is an urgent need to develop observational research in areas with little observation data. For example, so far the investigation area is limited mainly to land and the seafloor largely remains unobserved. Not surprisingly, changes are occurring on the seafloor, such as to continental shelves, and it is expected that detailed terrain observation of continental shelves will contribute to control the area where ice sheets are expanding. In addition, observation of crustal movement at the bottom of the sea, away from ice sheet loads, is important to control the ice sheet model and viscosity structure as well.

First, with geomorphic and geological investigations, it is necessary to conduct traditional investigation, such as the current geomorphic investigation, material sampling, and drilling of sediment in regions including Northern Greenland and the Canadian Arctic Archipelago, which have been observed very little. Especially in the past, sea level altimeter data of the coastal area of Greenland is lacking in both quantity and quality, and this is a factor of indeterminate reconstruction of the history of ice sheet melting in Greenland. In order to enable observations like this, it is essential to improve the convenience of field investigation by making it possible to move to targeted local coastal observation point using icebreaker-based helicopters and to introduce new geomorphic investigation technologies, such as ground-based laser scanner.

On the other hand, regarding the seafloor and continental shelves, it is necessary to conduct seafloor topography and geological investigations using ROV[53] or AUV[54] as well as material sampling and to advance development of seafloor sediment core collection technologies.

Next, regarding geodetic observation, ground-based observation has already been conducted in considerable high density and we should move towards observations at the bottom of the sea for the next ten to twenty years. To do so, we should develop and introduce a system for observing submarine crustal movement, which combines marine GPS operable in the Arctic region and equipment for echo ranging and seafloor observation. Also, the establishment of an observation network which can detect crustal movement with an accuracy of 1 cm at the bottom of the sea should be promoted. In addition, in order to calculate wide-area ice sheet changes and crustal movement, it is clear that we should use satellite geodetic data, such as satellite gravity mission, satellite altimeters, and synthetic aperture radar, more than ever.

For improving accuracy of future forecasts of global warming, it is essential to reduce the indeterminacy in the model. To do so, it is necessary to develop a model which takes into account various complexity and processes as well. For example, we can incorporate the influence of horizontal heterogeneity of viscosity of the earth's interior and combine this with ice sheet flow models into the

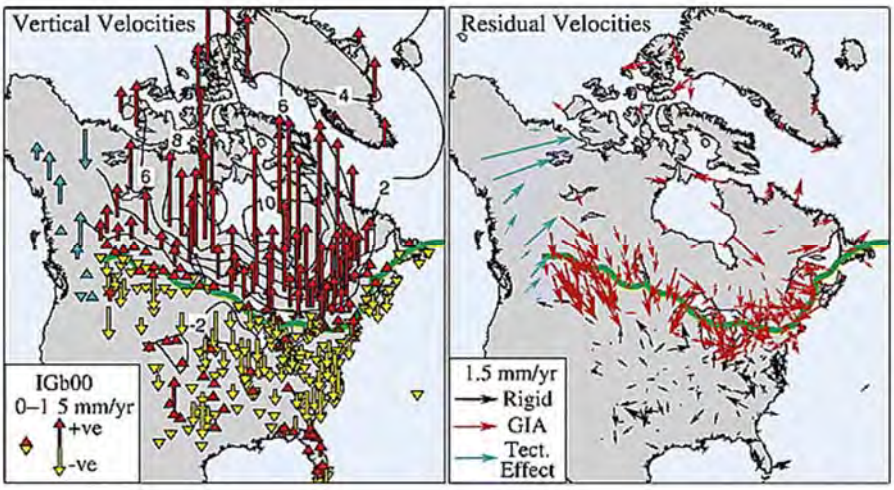

Figure 46: Crustal movement observed by GPS (Left) vertical component (Right) horizontal component (after Sella et al. 2007)

[53] ROV: Remotely Operated Vehicle
[54] AUV: Autonomous Underwater Vehicle

current model. Also, to establish these models, it will be necessary to develop computational skills and high-resolution data analysis methods.

With regard to observation and research structures, observation in the Arctic region in this field is still conducted by individuals and observation by a small number of researchers so we need to work on organizational research and observation activities. Furthermore, model development research is in a similar situation and we should advance cooperation with other fields, such as the field of paleoclimate modelling, and we should urgently establish a further framework, including development of researchers who will be engaged with such observations.

Q3: In the process of forming the Arctic Ocean, how did interactions between the atmosphere, ice sheets, and the ocean change?

a. Importance and current status of research

The configuration of the continents and the ocean on the surface of the earth changes by thermal convection in the earth's interior, such as expansion and subduction of the ocean floor as well as formation of concomitants and fragmentation of the continents, and it largely affects the earth's surface environment, including oceanic circulation and atmospheric circulation. Especially the formation of the ocean floor becomes a factor to largely change oceanic circulation, so research combining a history of development Arctic Ocean floor, which is a starting point of the current deep circulation, and reconstruction of the paleoclimate and paleoenvironment will clarify the history of change in oceanic circulation change in the process of formation of the Arctic Ocean and a history of continental ice sheet development, and it will largely contribute to elucidate temporal change in the interaction between the atmosphere, ice sheets, and the ocean. Since the seafloor of the Arctic Ocean is covered with sea ice, it is difficult to conduct investigations so there are still many matters to solve regarding geological structure, etc. under the seafloor. The Eurasian Basin was created in the Cenozoic Era by activity of the Gakkel Ridge in the Arctic Ocean, which still continues today.

The Arctic Ocean is a basin divided into two large basins; the Eurasian Basin and the Amerasian Basin, by the Lomonosov Ridge, and its history of development is relatively well understood from geomagnetic anomaly lineation, which is used for identifying the age of the seafloor. On the other hand, it is considered that the Amerasian Basin was created after the Mesozoic Era, however, its geomagnetic anomaly lineation is only identified in part of the Canada Basin (Vogt et al., 1982) and most of its development history remains unclear. Especially for the causes of the Alpha Ridge and the Mendeleev Ridge in the Amerasian Basin, there are still various theories, including; 1) by continental origin 2) by the expanded axis of the seafloor in the past, 3) by plume origin, or 4) by subduction, making this a controversial issue. So far little research, such as seismic experiment, has been carried out and it is suggested that the Alpha Ridge is ocean crust (Jokat, 2003). On the other hand, the research shows that continental crust may be included in the Mendeleev Ridge (Lebedeva- Ivanova et al., 2006). Research estimating the structure under the Amerasian Basin using gravitational data is being conducted as well (Alvey et al., 2008). However, there are still not enough investigations and we hope to elucidate the history of development of the Arctic Ocean, including the Eurasian Basin.

The ACEX (Arctic Corning Expedition-IODP Leg 302) (Backmanet et al., 2006), which was conducted in 2004 in the Lomonosov Ridge, was able to obtain a record that dates back to 55 million years ago and it became clear that cooling of high latitude of the Northern Hemisphere unusually began with the Antarctic region in the middle Eocene epoch (Moran et al., 2006). This suggests that a decrease in atmospheric CO_2 concentration for seafloor sediments through fixed organic matter by establishment of the Arctic Ocean is a major cause of global cooling in the Cenozoic Era rather than regional climate change by tectonic events, such as establishment of the Drake Passage.

However, in order to understand the relationship between the development process of the Arctic Ocean and the surface environmental changes, especially the relationship to absorption of greenhouse gases, fixation as organic matter or hydrates, transition of oceanic circulation, and history of the development of continental ice sheets, it is necessary to reconstruct and analyze the paleoenvironment in detail by using sediments together with tectonic research of the Arctic Ocean.

b. Future research

The Alpha Ridge and the Mendeleev Ridge will be a key to understand the history of the Arctic Ocean development, especially the tectonics of the Amerasian Basin. To clarify the causes of these, it is important to

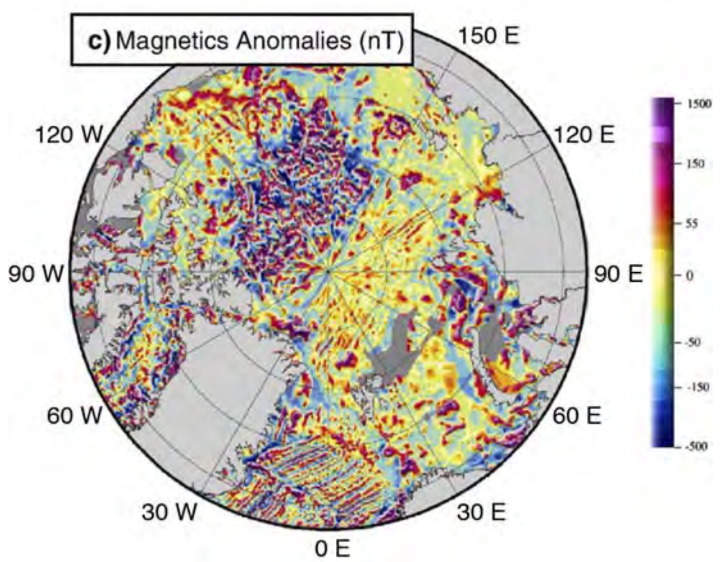

Figure 47: Color image of geomagnetic anomaly data of the Arctic Ocean (Verhoef et al., 1996 and Glebovsky et al., 1998)

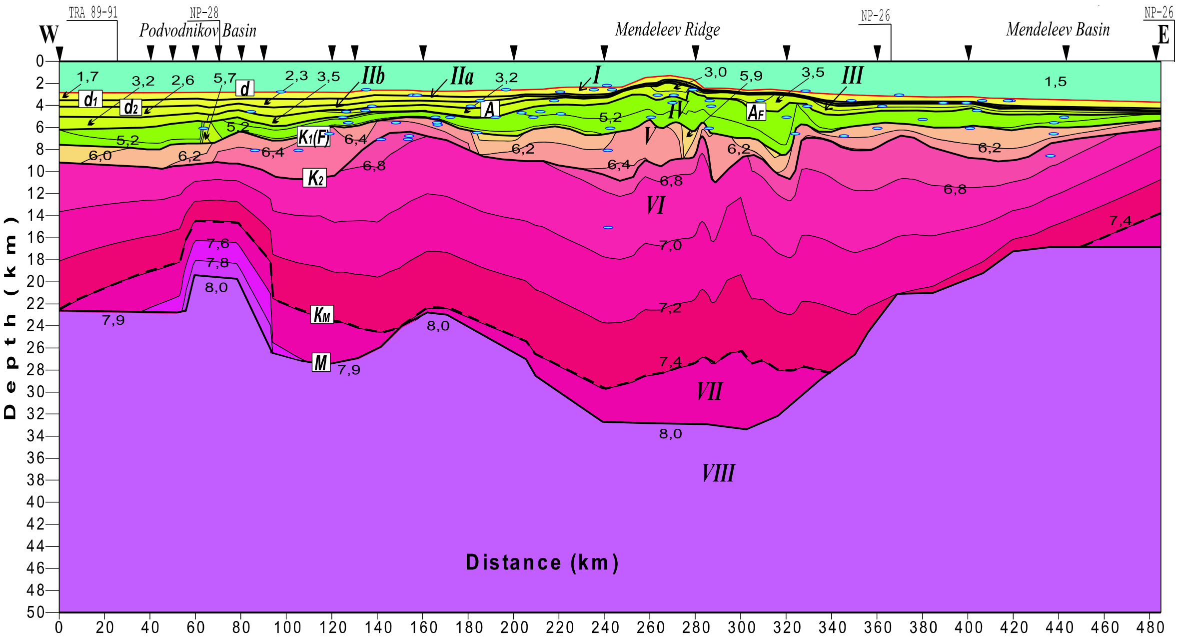

Figure 48: Seismic velocity structure near the Mendeleev Ridge (Lebedeva-Ivanova, et al., 2006)

conduct an Earth geophysical exploration, including seismic experiments, and geological explorations, such as rock collecting, at the widest area possible for these ridges and their surrounding ocean area. For verification of reconstruction and consistency of geological structure before the ocean floor was formed, understanding the geological structure of the continent around this ocean area will be necessary as well. Based on these, we aim to clarify the development history and the origin of the Alpha Ridge and the Mendeleev Ridge as well as their surrounding ocean area, and to elucidate the tectonics of the whole Arctic Ocean.

Also, in order to clarify the surface environmental changes along with these developing processes, we will conduct reconstruction of paleoenvironment and paleoclimate from sediment samples. In addition, to understand transition of oceanic circulation after the Cenozoic Era and history of ice sheet development, we will conduct sediment collection in the Eurasian Basin as well. Ultimately, we will clarify the transition of the interaction between the atmosphere, ice sheets, and the ocean with the formation process of the Arctic Ocean by combining tectonic information of the whole Arctic Ocean and analysis of the paleoenvironment and paleoclimate, such as transition of oceanic circulation and the history of continental ice sheet development.

Observations described above will lead to future international deep sea drilling projects in the Arctic Ocean area, such as IODP. For deep sea drilling in the Arctic Ocean area, Japanese researchers participated in, and made significant contributions to ACEX, which was conducted in the Lomonosov Ridge in 2004. However, the Japanese research community has not participated in the deep sea drilling project in the Arctic Ocean area by IODP, which is currently being discussed. We hope Japan will participate in, and contribute to, such international drilling projects in the Arctic Ocean area and it is necessary to develop the Japanese research community by activating research and observation activities regarding the Earth science in the Arctic Ocean area.

Q4: On time scales of tens of millions, to billions of years, how did the development process of the Arctic Ocean and the surrounding continents affect changes in the surface environment?

a. Importance and current status of research

To understand changes to the Earth's environment on time scales of tens of millions to billions of years, which is a relatively long geological time, is a major research theme in the geosciences. The formation and development of the Arctic Ocean goes back approximately one to two hundred million years ago and, so far, information on such a time scale was obtained from exploration of the Arctic Ocean floor (Figure 49).

In addition, complex geological information on crust development is recorded that dates back to the Precambrian (> five hundred million years ago) in the continental region around the Arctic Ocean. By analysis, combining continent's geological information and geophysical exploration of crust in the oceanic area, research on the formation process of the Arctic Ocean and the configuration of the continents and the ocean in the Arctic area (paleogeography) has advanced until now (Figure 50).

As described above, only with analysis by combining both continental and oceanic information, reconstruction of the past oceanic and continental developing processes in the Arctic region can become possible. Also, we can obtain information which will be a basis to examine the

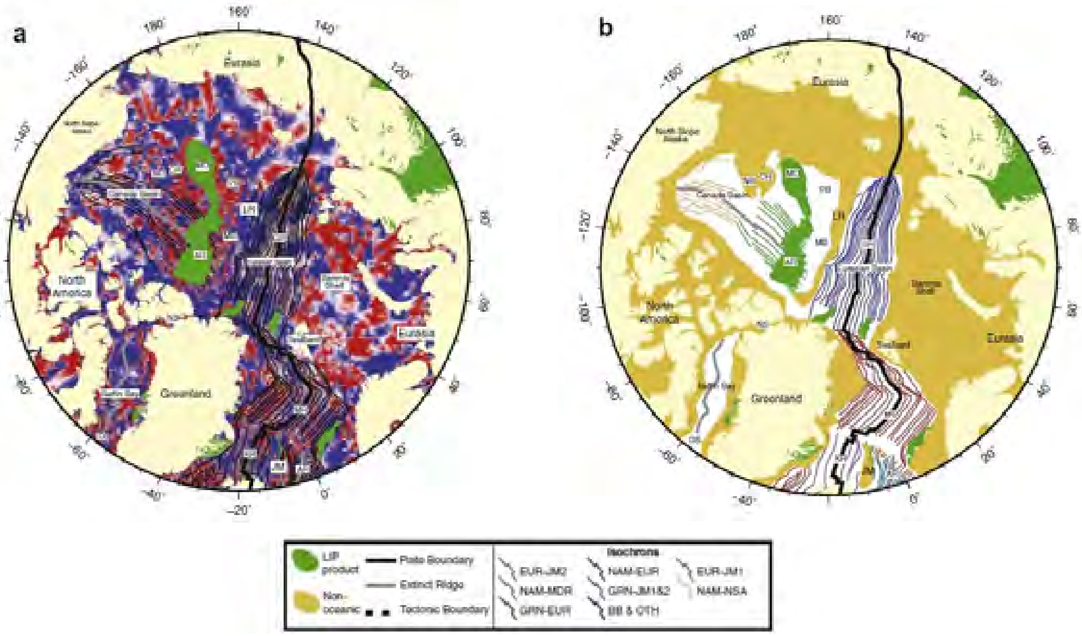

Figure 49: Geophysical and geological information of the seafloor in the Arctic region (Seton et al., 2012)

environmental changes on time scales of tens of millions to billions of years.

Furthermore, one important point of the Arctic region is the existence of a 3.8-to-4-billion-years-old stratum dating from the time the earth was created, which can be seen in the Canadian Arctic and the west coast of Greenland (for example, Bowring et al., 1989; Nutman et al., 2007). Geographical restrictions like the "Arctic region" does not carry any special significance on such a time scale. The research theme we discuss in this Q4 does not aim specifically for Arctic environmental research like that described in Q1 through Q3 above, it rather aims for environmental change research on a time scale of the history of the Earth by using geological information, which is distributed throughout the Arctic region.

Due to the importance of that stratum distributed throughout the Arctic region, a lot of geological research has been conducted so far. However, compared with other areas that are more easily accessible, geological data obtained from the Arctic region cannot be said to be qualitatively or quantitatively sufficient. Regarding the comparison with the past geological conditions of the continent and process of formation and development, various models have been suggested (Figure 51).

As described above, research up until now has clearly shown that stratum of various eras are distributed in the Arctic region. Especially the existence of the oldest rock on the earth (the Acasta Gneiss), which is approximately 4 billion years old, in the Canadian Arctic and approximately 3.8 billion-years-old rock, which is found in the Isua region in the west coast of Greenland, proves that the Arctic region is an appropriate field for research on environmental change of the earth on an extremely long geological time scales from the formation of the Earth until today.

Also, in continental regions distributed in the Arctic region, there are rocks which have undergone high-grade metamorphism equivalent to exposure to the deep crust, and low-grade metamorphism which originate in shallow regions of the crust where the extent of metamorphism is considerably less. Especially the latter can be an appropriate research object for reconstruction of the

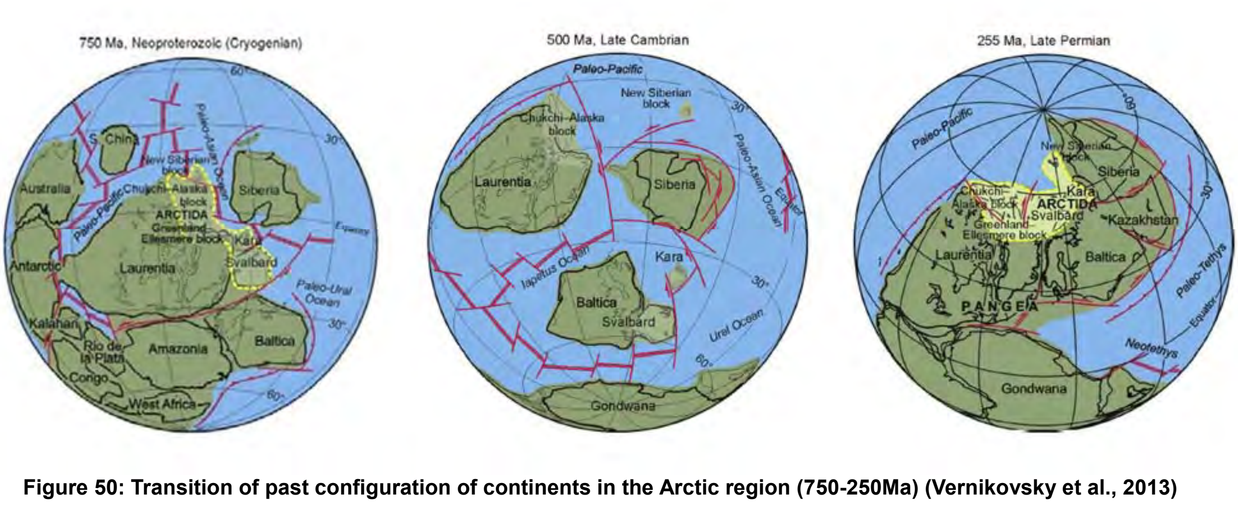

Figure 50: Transition of past configuration of continents in the Arctic region (750-250Ma) (Vernikovsky et al., 2013)

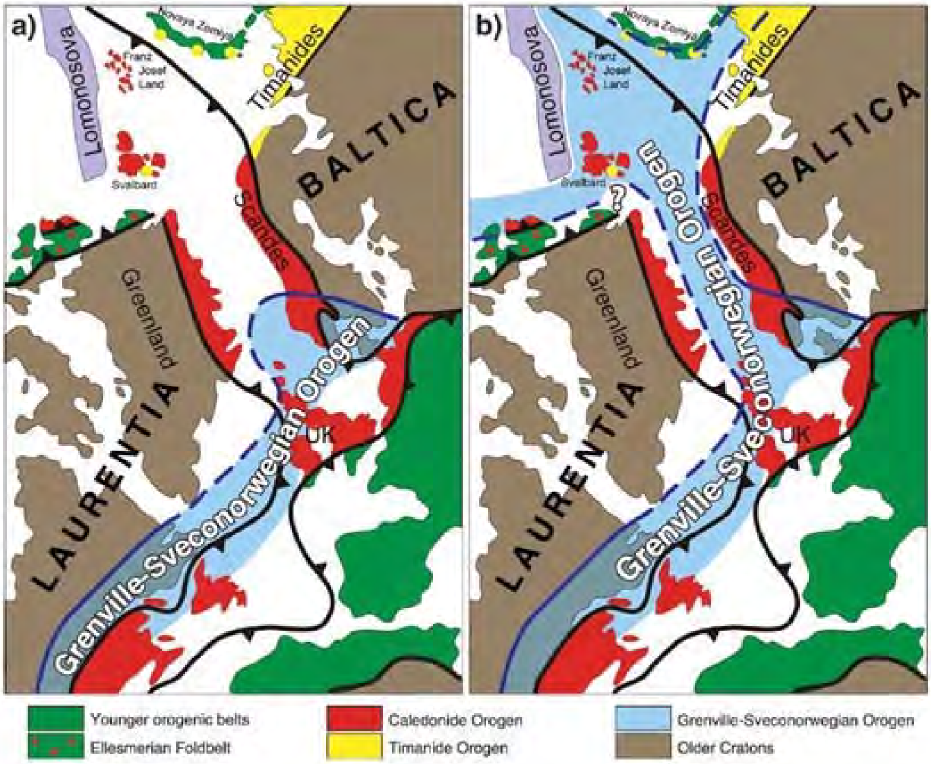

Figure 51: Reconstruction figure of past configuration of continents in the North Atlantic Ocean area (Lorenz et al., 2012)

Earth's surface environment on a time scale such as the age of the Earth. This means that analysis of changes to the Earth's surface environment on a time scales of 3 to 4 billion years will become possible through crustal research in the Arctic region. In addition, by comparative research with exposed deep crust (high-grade metamorphic rock) from the same period, it is possible to promote research from the perspective of the interaction between the Earth's surface environmental changes and phenomenon occurring deep in the continental crust.

b. Future research

For a method to understand the question mentioned here, it is necessary to comprehensively combine data from ground-based geological investigation and geophysical exploration in the oceanic area. Specifically, we will clarify the development history of the ocean floor that dates back 100 to 200 million years ago through ocean floor geophysical exploration. Due to a recent decrease of sea ice in summer in the Arctic region, more regions have become accessible to research vessels, and it is also possible to obtain new information by undersea geophysical exploration using unmanned exploration ships. Also, field geological investigations in continental area will allow for the analysis of material circulation on geological time scales for deep crust and surface crust from petrological, geochemical, and chronological research on matter constituting crust in the Arctic region. In addition, we can conduct more accurate reconstructions of past configurations of the continents by comparing geological conditions of the continental areas to the development history of the ocean floor obtained from the oceanic areas. In order to clarify processes on such geological time scales, we need highly accurate analytical methods for dating and analysis with a combination of isotope analysis focused on isotope (geochemical tracer), which will be an indicator of previous environmental changes. The two secondary ion mass spectrometers installed at the National Institute of Polar Research, will be extremely important for such material scientific understanding.

Furthermore, based on research on component materials of the crust, it is possible to conduct analysis of continental crust heat flow under ice sheets, which is difficult to measure directly (for example, Carson et al., 2014). For information of crust under ice sheets, analyzing data from geophysical explorations (gravity and geomagnetism) is essential. By combining such physical information and information from rocks exposed on the margin of ice sheets, we can attempt to estimate geological conditions under the ice sheets. Also, by precisely estimating geochemical information of rocks and radioelement content, which will be a heat source, we think we can estimate heat flow in the crust under ice sheets. As described above, it becomes possible to clarify characteristics of the solid geosphere in the Arctic region on time scales of tens of millions to billions of years through closely linking estimation data of crustal structure with analysis of data from geophysical exploration.

Geological investigations to obtain basic data for research does not require special devices or preparation and it is possible to conduct field investigation promptly. Due to the remoteness of the Arctic Circle, as well as the Antarctic, data from field investigations is severely lacking. For geological investigations in Greenland and geological research in Scotland and the Canadian Arctic geological conditions there are considered to be an extension of Greenland's, the Japanese research community has contributed more than a little so far. In the future, we also need to efficiently organize field investigative teams within five to ten years and should actively work on research, including on-site geological investigations in the Arctic region. Through conducting efficient on-site geological investigations in the Arctic region based on accumulated know-how from investigations of the Antarctic, we will obtain the necessary base geology data to begin answering the question.

Theme 12 Basic understanding on formation and transition process of permafrost

Abstract

Permafrost regions occupy approximately 25% of the land area. It is one of the major factors affecting the Arctic environment through the complicated feedback of heat and materials with atmosphere and vegetation, etc. It is a potential GHG source due to the surface thawing. However, there is a lack of detailed scientific understanding on the present state and dynamics of changing permafrost distribution. Therefore, there is considerable uncertainty regarding the future projection of permafrost variation. The main reason for this situation is that the spatial heterogeneity of the permafrost is large, the observational sites are limited in terms of representing the whole region, and observation from satellites is challenging. It is therefore necessary to develop new observation techniques and to improve the existing methodology, as well as to expand the observation sites and to carry out multi-point measurements. It is becoming increasingly important to improve the knowledge of detailed permafrost distribution and the heterogeneity of its composition, and to increase the information regarding the change of ground temperature, the amount and the state of ice and organic carbon storage. Permafrost study should focus on modeling and quantifying the process of changing permafrost based on distributional information. We need to integrate our scientific knowledge and techniques with the modeling in order to understand the behavior of the permafrost land system and the variation of arctic environment system.

In this theme, the following four questions will be discussed.

Q1: Permafrost distribution: how is the permafrost in the arctic distributed, both horizontally (in terms of space) and vertically (in terms of depth)?

Q2: Permafrost composition: what material does the permafrost consist of, and how heterogeneous is it?

Q3: Warming and thawing of the permafrost: what is the process, and on what scale does it happen?

Q4: Permafrost-Atmosphere-Snow-Vegetation system: what is its structure and behavior?

Introduction

Permafrost (please refer to explanations in “Box 8” for terms underlined throughout this document) exists throughout most of the circumpolar region (Figure 52a), and is believed to occupy approximately 24% of the total land area in the Northern Hemisphere (Brown, 1997). Not only does it represent the largest snow and ice phenomenon on Earth in terms of area, but it also enables a complex exchange of both heat and substances between the atmosphere and vegetation. It is therefore of considerable importance in relation to fluctuations within the Arctic environment. In this respect, there are concerns relating to its impact on the future global climate from the release of greenhouse gases accompanying the melting of underground ice, and the release of methane hydrate due to destabilization of seabed permafrost. There is a strong possibility of the irreversibility of potential changes in permafrost in relation to global warming. For example, thermokarst causes a chain of changes in the circulation of local water, materials, and ecosystems due to the melting of permafrost. In Eastern Siberia, permafrost with a high ice content melted under a coniferous forest, causing wetlands and lakes to form in depressions where the land had subsided. Although these changes take several tens to hundreds of years to occur, organic carbon that has been fixed over tens of thousands of years becomes fluidized through these processes. Impacts on ecosystems and hydrological processes are major issues for regional communities; however, damage to social infrastructure such as buildings, pipelines, roads, and train tracks due to the subsidence of land is already becoming apparent. On the coast and islands of the Arctic Ocean, shore erosion due to waves has intensified with the melting of frozen ground, and some regional communities have been forced to relocate.

Until now, many studies have been conducted on the various phenomena and issues arising from the presence of permafrost, using a number of typical and characteristic locations as targets to gather information (e.g., Harris et al., 2009; Matsuoka and Ikeda, 2012). However, to quantitatively predict the effects of melting permafrost on water circulation, vegetation, climate, and human society over a wide area, there is an insufficient amount of currently available basic information relating to permafrost (e.g., physical properties, amount of stored carbon, spatial distribution of underground ice, etc.) and a lack of understanding of feedback processes (e.g., changes in vegetation due to the fluctuation of permafrost, impacts on climate due to such changes, etc.). Since permafrost fundamentally does not exist on the ground’s surface, remote and non-contact observation methods (remote sensing) have not yet been established for use, and direct observations require efforts such as excavation. Therefore, limited observational and monitoring examples exist for use in gaining an understanding of the current condition and fluctuation of permafrost over a wide area. Compared to other snow and ice elements (sea ice, snow cover, and glaciers), there is a significant delay in gaining an understanding of the spatial distribution and fluctuating patterns of permafrost, and predictions of responses to global warming have a wide range of uncertainties.

This report shows that permafrost is closely related to changes in ecosystems (Theme 3), effects on water circulation due to changes in snow and ice elements (Theme 4), and that it is important as an information source for use in paleoenvironment reconstruction (Theme 6). Discussions herein also mention the effects of melting permafrost on regional communities in the Arctic region (Theme 7). Using a number of various research topics, this study aims to gain an understanding of how the effect of permafrost changes needs to be quantitatively reflected in predictions of future global environmental changes. In this respect, data accumulation is being initiated internationally, and some projects are now connecting observational data with models. In relation to this Theme, we present areas in which there is an insufficient understanding of permafrost over a wide area (Arctic regions), and we then propose certain research topics that need to be tackled in order to clarify future changes and impacts on the climate and environment.

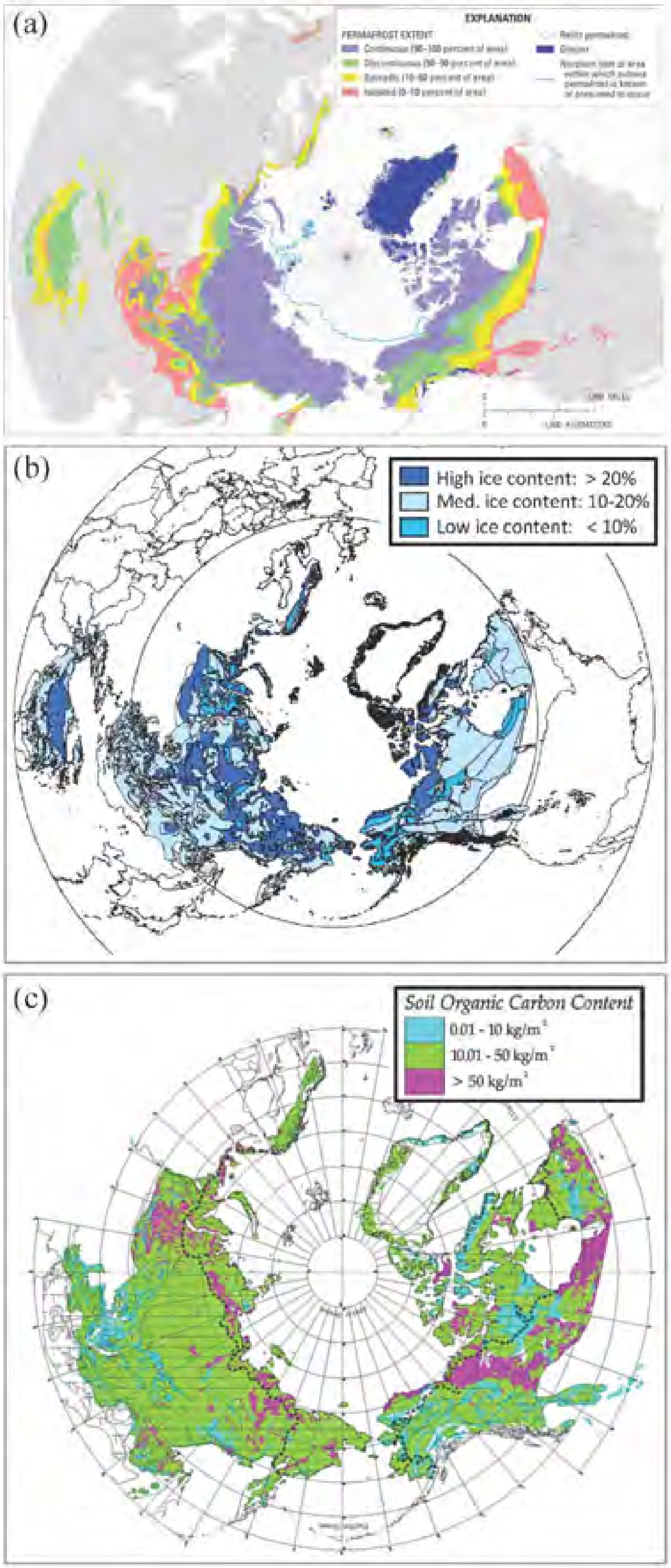

Figure 52:

(a) Permafrost distribution map based on ground temperatures (from USGS Professional Paper 1386-A). Prepared by Dmitri Sergeev (UAF) based on the IPA Circum-Arctic Map (Brown et al., 1997). http://pubs.usgs.gov/pp/p1386a/gallery5-fig03.html

(b) Distribution of ice content. Revised IPA Circum-Arctic Map. Ishikawa and Saito, Journal of the Japanese Society of Snow and Ice (2006).

(c) Distribution of amount of organic carbon in permafrost. Tarnocai et al. (2009).

b. Characteristic properties of permafrost

The characteristic properties of permafrost are often due to the dynamic behavior of water contained within it. For example, since permeability of wet ground decreases significantly due to freezing, the permafrost layer functions as an aquiclude, and determines the growth environment of the vegetation above. In addition, due to the effects of latent heat being released/absorbed during freezing/melting of soil pore water, the soil temperature change of permafrost tends to be suppressed, particularly at around 0°C. As mentioned earlier, the damage to infrastructure due to ground subsidence and rising accompanying thermokarst and frost heave, depends on the growth and disappearance of underground ice. To understand fluctuations of permafrost and various phenomena arising from such fluctuations, it is important to conduct any evaluations with respect to the dynamic behavior (amount and phase) of groundwater. Zhang et al. (1999) estimated that the total amount of underground ice, down to 20 m underground, over the entire Northern Hemisphere measures between 3 and 10 cm, with adjustments made for sea-level fluctuations. However, heterogeneity in the distribution is significant, and the reliability of the estimated values is low (Figure 52(b)).

The dynamic behavior of the organic carbon content in permafrost is also of interest in relation to climate change. From a global-scale soil database, the total amount of organic carbon stored in permafrost has been estimated by Zimov et al. (2006) as measuring approximately 1,000 Gt, and by Tarnocai et al. (2009) as 1,700 Gt (Figure 52(c)). These values are equivalent to approximately half of the organic carbon on land, and twice the amount of carbon in the atmosphere. If all the permafrost containing organic carbon melts, the carbon will be released into the atmosphere as greenhouse gases in the form of carbon dioxide or methane (permafrost carbon feedback), potentially further accelerating global warming (Schuur et al., 2011). However, these processes require several thousands to tens of thousands of years to occur, and such predictions are calculated based on limited field survey results with many assumptions; thus, significant estimation errors exist.

c. Distribution of permafrost and the time scale of fluctuations

Fluctuations in the ground temperature of permafrost can be considered to be approximately controlled by heat conduction from the ground's surface. This can be mostly explained as the result of propagated fluctuations of the ground surface's temperature through attenuation and delay (Lachenbruch and Marshall, 1986). Thus, the response time of changes in the permafrost ground temperature is short at shallow depths, and becomes longer with depth.

Thick permafrost in Siberia, reaching down to several hundreds of meters underground, contains a record of climate change on a scale of several tens of thousands of years. This is because temperature changes at the ground's surface influence the temperature of the soil at depths of hundreds of meters underground, over periods of several thousands and tens of thousands of years. However, since the current climatic environment is reflected in the permafrost temperature at shallow depths, the planar distribution boundary of the surface layer of permafrost is mostly determined by the current climatic conditions.

d. Key Questions in this Theme

To improve our basic understanding of the formation and transition processes of permafrost, it is necessary to examine the following four topics, and any gaps in our knowledge will be filled within the next five to ten years:

Q1: What is the distribution and depth of Arctic permafrost?

Q2: What substances constitute permafrost, and what is the level of heterogeneity?

Q3: In what manner and on what scale does permafrost warm up and melt?

Q4: What are the structural and behavioral characteristics of the permafrost–atmosphere–snow cover–vegetation subsystem?

The above topics are closely related to one another; for example, the issues in Q1 and Q2 are related to an estimation of the temperature of permafrost and the active layer above (Q1), and the horizontal and vertical differences in the constituent (Q2), at a higher resolution than presented in previous estimates. Therefore, this relates to an improvement in the accuracy of estimates for areas that cannot be directly observed.

The answers to Q1 and Q2 determine criteria such as an evaluation of the spatial scale of changes and the speed of changes, which are then considered in Q3. While focusing on changes in the conditions that can occur over a relatively short time frame, such as changes in the active layer (Q3(1)) and the thermokarst (Q3(2)), it offers information on the history of changes and the prediction of future changes on a time scale of one hundred years or more. It also touches on ground temperature changes in a deep part of permafrost that is climatologically important (Q3 (3)). Q4 focuses on the interaction between permafrost and vegetation, snow cover, and atmosphere. In addition, the importance of gaining an understanding of the climate and ecosystem of this frozen ground is emphasized, in addition to clarifying behavior.

Q1: Permafrost distribution: how is the permafrost in the arctic distributed, both horizontally (in terms of space) and vertically (in terms of depth)?

a. The importance of research and its current state

Gaining an understanding of the distribution of permafrost gives us fundamental information, and based on previous research the International Permafrost Association (IPA) is compiling a permafrost distribution map (Figure 52(a)). In addition, at the international observation network known as GTN-P, which is promoted by the IPA, the results of soil temperature change observations and changes in active layer thicknesses are being accumulated. However, since permafrost is defined by its temperature, an accurate distribution cannot be observed in the current condition due to the following: 1) boreholes are required to enable direct observations of ground temperature measurements, and such measurements are limited in terms of the spatial representation of individual data; 2) as permafrost is distributed over differing depths, there are only a small number of boreholes that are sufficiently deep to access

Box 8 Fundamental understanding of the formation and transition processes of permafrost

Permafrost is defined as ground (sediments and bedrock containing ice and organic matter) that remains at a temperature of 0 °C or lower for a period of at least two years. However, permafrost may melt with climate change and anthropogenic activities, and therefore is not "permanently" frozen ground, as the name suggests. To express the temperature change, growth, and disappearance of permafrost, the use of a term such as "multi-year frozen soil" has been proposed. The permafrost zone is an area that contains permafrost, and is found in areas of high latitudes and at high elevations; the latter has a complex distribution depending on the terrain. Figure 53 shows a schematic diagram of the 3D distribution of permafrost and its classification based on horizontal distribution in areas of high latitudes. The percentage of permafrost for an area of ground surface is determined in relation to continuous, discontinuous, and sporadic permafrost.

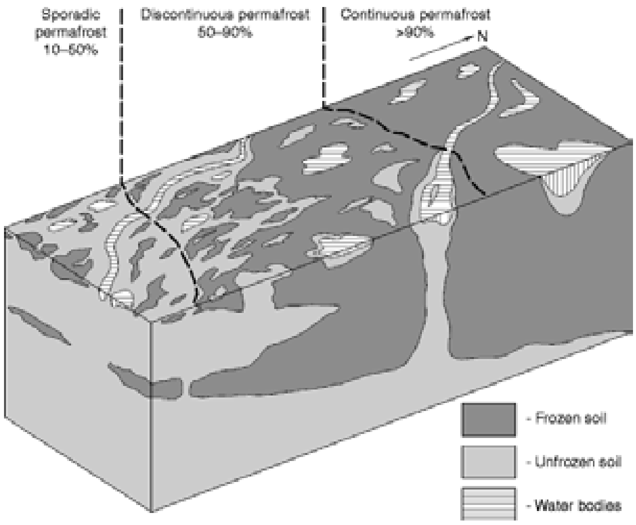

Figure 53: Schematic diagram of three-dimensional distribution of permafrost and the classification of continuous, discontinuous, and sporadic permafrost (Encyclopedia of Snow, Ice and Glaciers).

Active layer: This is the surface layer of permafrost that undergoes a repeated cycle of melting (summer) and freezing (winter), and is an important place for the movement of soil moisture, plant activity, and microbial activity.

Thermokarst: A process that forms uneven terrain through the melting of ice-rich permafrost. In addition to land subsidence from melting, it leads to erosion along ice ridges and large-scale slope failure along coasts and areas of incline. Lakes that form in depressions due to thermokarst are called thermokarst lakes (melting lakes). Depressions known as Alas, which are commonly found around Yakutsk in Siberia, are also a type of terrain related to thermokarst.

Talik: An unfrozen part of permafrost; although it is surrounded by permafrost, talik remains unfrozen throughout the year.

Yedoma layer: A permafrost layer with a high ice volume of 65–90% and a large storage of organic carbon. The name is derived from the native language of northeastern Siberia, and is occasionally referred to as complex ice. It is found in the northeastern and central parts of eastern Siberia, north-central Alaska, and northwestern Canada, and measures several meters to several tens of meters thick.

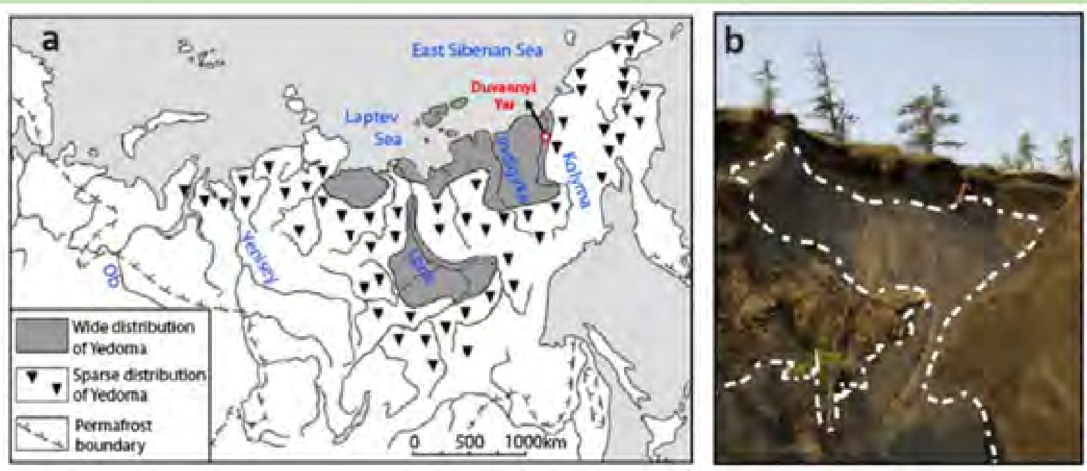

Figure 54: (a) Distribution of the Yedoma layer in Siberia. (b) An outcrop of the yedoma layer in the process of being eroded at the Duvannyi Yar site on the Kolyma river (the body of ice is outlined by the dotted line); from Vonk et al. (2013).

such depths, and therefore the accuracy of vertical distribution estimates remains low; and 3) definite identification cannot be made using remote observations such as those of satellites. Due to these limitations, our current knowledge of the distribution of permafrost relies on estimations made from a limited number of observation points, both geographically and in terms of vertical distribution.

In addition, the distribution of permafrost is characterized by significant heterogeneity. For example, Figure 53 (Box 8) presents a schematic diagram of permafrost distribution, where it can be seen that taliks form downstream of lakes and large rivers, and that the boundary areas of distributions reflect various conditions, resulting in a spatially complex structure. However, classifications of continuous, discontinuous, and sporadic permafrost, that are used in the current distribution map, have succeeded to a certain degree in representing the environment of frozen ground as it changes from a continuous distribution to a mottled and island-like distribution. Although the division boundaries are marked with lines in the Figure, the position of these lines changes depending on the areas chosen to calculate the distribution ratio of permafrost. In addition, although the continuity of the permafrost distribution decreases, the thickness of the active layer may be extremely thick depending on the location, and contain fossil permafrost at depths (formed during the past cold periods–which may be in the process of melting), and thus the spatial patterns of permafrost boundaries become complex, as shown in the Figure. Similarly, the ground surface conditions of permafrost in steep mountain regions vary greatly depending on the slope direction and snow cover distribution, and thus heterogeneity of the distribution increases in relation to these conditions. These large variations are currently not included in the distribution map of wide areas.

Under such conditions, it is difficult to identify any changes in the distribution in response to climate change. Furthermore, as observation points are limited, it is difficult to separately identify changes in permafrost distribution that progress in response to factors associated with climate change other than temperature. As a starting point in various discussions relating to changes in frozen ground over a wide area, it is important to advance beyond the rough understanding presented in the distribution map and to determine the heterogeneity, as such knowledge will give us an understanding of the distribution of frozen ground.

b. Future studies

To gain a better understanding of permafrost distribution, it is considered that studies should be conducted in the following areas:

(1) Development of observation and identification methods

We intend to develop new observation methods based on novel principles, and develop and improve an algorithm that can extract information highly correlated with the distribution of permafrost determined using satellite data. There is currently a difficulty in determining the bedrock structure from satellite data, and therefore a breakthrough is required in this respect. Granted, exploring possibility is always necessary.

(2) Improving and combining existing technologies

To enable identification of changes in distribution, the improvement of existing observation methods is also necessary. In addition to the continual expansion of direct observations of ground temperature through boreholes collected by GTN-P, developments in the following directions are also required:

(3) Utilizing satellite data, and data analyses in combination with climate models

To handle planar information, utilization of satellite data is necessary. For example, information of ground surface classification, brightness temperature of the ground's surface, and snow cover are gathered from satellites, and the condition of frozen ground can be estimated using a combination of such information. By inputting this information into a land surface model, it would thus be possible to obtain the ground temperature distribution as a model output.

(4) Development of an estimation method that combines multiple observation methods

In addition to the above-mentioned satellite data, multiple index data (such as physical survey data and ground surface temperature observations) can be combined, and a comprehensive method that estimates permafrost distribution can be developed.

(5) Improvements in presenting the permafrost distribution

In addition to previous monovalent expressions of distribution, information related to the distribution on a scale which is the same as, or below, the estimated grid size can be treated as a probability distribution function. Furthermore, a distribution boundary with a sufficiently large width could be defined to improve the expression of distribution. When matching the permafrost distribution with the model output, or when matching it with the physical values obtained from satellite observations, the necessary data expression format could then be prepared to enable various expressions.

(6) Evaluation of heterogeneity

There are various levels of heterogeneity in ground surface conditions such as ground temperature, thickness of the active layer, thermophysical properties, and snow cover. If only one measurement point is used, it is not possible to evaluate heterogeneity. Although the CALM site sets a 100 m x 100 m grid to determine the thickness of the active layer in which to conduct multi-point observations, most other observation areas have only a very small number of observation points. If a simple observation method is employed, multi-point observations can be carried out in which the spatial spread is taken into consideration for each site, and the heterogeneity (variability in values) can then be evaluated.

Q2: Permafrost composition: what material does the permafrost consist of, and how heterogeneous is it?

a. The importance of research and its current state

Permafrost is defined by its soil temperature, but it is also a mixture of substances in various proportions, such as base materials (soil particles and bedrock), water (ice and unfreezable water), and organic carbon. The content ratios of these substances determine the soil mechanical characteristics and thermal properties, and control changes in permafrost conditions (which are discussed in Q3 along with external factors such as temperature and precipitation). The melting of permafrost fluidizes these substances, and sends a feedback to the climate via the land and atmospheric composition in the form of a transformation of the terrain, wetting of the soil and the release of greenhouse gases. Gaining an understanding of the substance group that constitutes permafrost, in particular the content ratio of carbon and ice, is essential for understanding the effect of the dynamic behavior of carbon and water circulation processes on the Arctic land surface, and the future of these processes. It also contributes to predictions of global climate change.

Although these issues have been considered by scientists from various fields for a long time, there is a lack of understanding over a wide area, and estimates of organic matter and underground ice discussed earlier (Figure 52(b), (c)) contain significant uncertainties (Zhang et al., 1999 ; Zimov et al., 2006 ; Tarnocai et al., 2009) because there is a definitive lack of quantitative data. In addition, it should be noted that such estimates are total values, which although useful when evaluating the potential effects of the total loss of permafrost, they do not consider the actual fluctuations of permafrost and how this varies greatly over both time and space. To understand the circulation processes of these interacting dynamic behaviors (Q 3), the content ratio of the substance group that constitutes frozen ground, and its heterogeneous spatial distribution must be considered in the analysis.

Among studies using numerical models, few have used the underground distribution of permafrost ice and the carbon cycle, and models that do exist are simplified. Earth system models that include the carbon cycle model already exist; however, to simulate the environment of permafrost for the above-mentioned purposes, calculations need to begin in the last interglacial period, and changes should be tracked. It is extremely difficult to conduct such a long-term experiment in combination with advanced climate models, given the ability of current computers and the reproduction capability of models, and also because of the lack of data available to determine boundary conditions. Currently, heterogeneities in geological and topographical constraints have not been taken into consideration in such analyses of material circulations.

b. Future studies

There are limitations for any future studies that focus solely on carbon and ice because of the insufficient information relating to distribution, and it is therefore necessary to begin by understanding the range of uncertainties in the estimated amount. However, information pertaining to base materials is also quite limited and vague at this point. Previous studies have estimated the amount of ice and organic carbon by making full use of limited information, but it is necessary to remember that this information is currently insufficient. Therefore, it is necessary to quantitatively discuss the levels of errors inherent in each method.

In future studies, it is considered essential to steadily improve the estimation accuracies by expanding observations and by gradually integrating already-available information. Ingenious ideas are required to enable efficient observations, such as selecting observation points using ground surface classifications obtained from satellite data. There is also room for further improvement in presenting distribution information. Generally, as discussed in Q1, the temperature of permafrost and the content ratio of its constituents have a high spatial heterogeneity, and are dependent on the scale; thus, a method of presentation is required that would retain the obtained observational information. The content of underground ice at a given point reflects the current conditions such as weathering of base materials, climate, terrain, and vegetation as well as its history. If the predominant factor for each area could be determined using such information, the size of the uncertainty could be reduced.

One possible direction for future study would be the generation of data that includes a sub-grid (on a grid size or less) of geographical information. With typical data presentation, the status values in each grid (terrain, vegetation, snow cover, temperature, thermal properties of soil, and grain size characteristics) have been implicitly assumed as uniform, even though it is difficult to handle data from areas where heterogeneity in the grid becomes significant, such as in mountain ranges and areas of discontinuous permafrost. However, it is not realistic to use a differential approach that makes the grid even smaller to deal with this issue. Thus, a framework could be designed to present the constituent ratio of permafrost as a statistical representation that includes heterogeneity (probability distribution, variance, maximum, minimum, etc.), by retaining the current grid size and combining the value of each status inside the grid. This idea has not been sufficiently implemented internationally yet; thus, there is a high possibility that Japan will lead its development, as discussed below.

The mid-latitude alpine regions and discontinuous permafrost zones (near Fairbanks, Alaska; western Siberia; alpine regions of Mongolia and Japan) are areas currently studied, and are suitable for testing the above-mentioned various approaches to present permafrost compositions. In these areas, distribution and composition of permafrost are not uniquely determined by climate, but they are strongly controlled by local terrain, hydrology, and ecological conditions and have large variations (e.g., Ishikawa et al., 2012). Therefore, explanatory variables (status values) and objective variables (permafrost composition) can be easily compared and examined.

It is also considered that observational design is necessary, with a refinement and generalization of models that allows a systematic and seamless increase in scale (from previous point-observations conducted at sites using various methods) to multi-point observations, or to wide-area evaluations using aircraft and satellite observations. Furthermore, an understanding of the development process of permafrost over a time scale of several tens of thousands of years accompanying glacial cycles should be performed simultaneously with obtaining the past history (Theme 3 Q2, Theme 6, and Theme 12 Q4).

To roughly define the maximum amount of carbon stored in permafrost, an approach using a carbon cycle model to estimate stored carbon amount in permafrost is effective. However, since calculations are made over a long time scale, studies are currently limited to simple models. We consider that certain indications can be obtained from quantitative discussions. However, it is necessary to develop a model that appropriately expresses the carbon cycle of permafrost, and provides an ingenuous way of defining valid boundary conditions. With improved computing power, in the future we hope that an approach using an Earth system model that combines a climate model and a material circulation model will be possible. In addition, we hope that with the accumulation of observational data, adequate information will have been gathered by that time, so that the full capacity of a complex model can be exploited.

Q3: Warming and thawing of the permafrost: what is the process, and on what scale does it happen?

a. The importance of research and its current state

The possible status changes of permafrost are discussed in this section, and the topics are divided into those occurring in the active layer (Q3(1)) and the thermokarst (Q3(2)), which are also related to the deep soil temperature of permafrost (Q3(3). To consider recent changes in permafrost, in Q3(2) and Q3(3) it is necessary to understand the history of permafrost development over a long time scale. Permafrost formed in the most recent warm period (interglacial period) of over 10,000 years, which exists in between several tens of thousands of years of repeated glacial periods in the paleoenvironment.

(1) Changes in the active layer

Changes in the spatiotemporal distribution of melting parts of the active layer affect ecosystems and hydrological processes on the ground's surface over a relatively short time period. This is because spaces for the root systems of vegetation and the biological activities of microorganisms lie within the melting area in the active layer of permafrost, and such areas regulate hydrological movement. Changes in the active layer are not limited to changes in the maximum melting depth (the thickness of the active layer), but also present as changes in the timing of melting or freezing at the ground's surface. Temporal changes in the active layer due to global warming are characterized by an earlier melting and a delay in freezing. Furthermore, along with changes in the ground's surface heat and water balance, there is an increase in the amount of heat entering the ground, and an increase in the thickness of the active layer. Such seasonal changes in the distribution of the active layer can also occur without any long-term average changes in global warming, as they are also related to changes in the amount and timing of precipitation, and changes in time periods of snow melting. The dynamic behavior of the active layer has a significant spatial heterogeneity, and thus to understand the trend and the cause of changes it is necessary to measure the changes in temperature and soil moisture at the ground's surface (which includes the upper permafrost) on a high spatiotemporal density. However, excluding the observation points that are specialized for a particular distribution (such as CALM), such factors are currently only monitored at one observation point, as in a supersite.

(2) Thermokarst

As mentioned in the introduction, thermokarst forms from the melting of permafrost and is accompanied by changes in terrain. As it significantly changes the ecosystem and hydrological environment of the ground's surface, we need to urgently gain an understanding of its conditions and changes. In particular, it is important to evaluate the stability, spatial distribution, and melting speed of the yedoma layer, as discussed below (Schirrmeister et al., 2013, and others). The yedoma layer is found in the northeastern and northwestern parts of Eastern Siberia, and is a permafrost layer with extremely high content of ice (volumetric ice content of 65–90%). Furthermore, it has an extensive distribution, is a sedimentary layer with a large organic carbon content, and half of its volume, or more, is occupied by ice. The melting of the yedoma layer will therefore create a large-scale thermokarst, and due to the warm climate of the current interglacial period and the disturbance of the ground's surface caused by human activities and global warming, a large amount of carbon accumulated mainly during the ice age and fixed in the frozen ground will again begin to circulate. It is thus important to quantitatively evaluate the impact of such an event. However, as these permafrost layers are in remote locations, the current conditions and changes in the geographical and vertical distributions are not clearly understood. Any changes in areas of permafrost with a thermokarst add an element of large uncertainty to the prediction of climate change and changes in the polar region.

Thermokarst is formed not only due to a deepening of the active layer and a temperature increase in the permafrost, but also in relation to erosion by waves and rivers. In other words, as the protocol of the above-mentioned CALM and GTN-P alone cannot sufficiently decipher the dynamic behavior of this phenomenon, it is necessary to design a new observation system (→ Theme A: Monitoring).

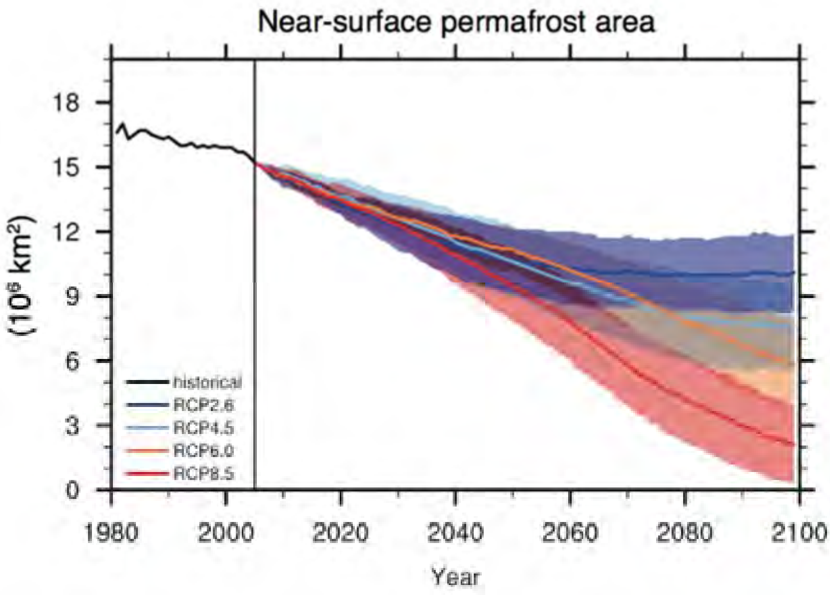

Figure 55: Predicted permafrost areas until the end of this century (Slater and Lawrence, 2013; IPCC AR5). Using the published results of future climate prediction by CMIP5, the monthly average temperature and snow cover amount are bias-corrected and input to obtain diagnostic results. Representative concentration paths (RCP scenarios) are color-coded. Thick lines represent the model means, and the bands represent the variations between the models.

(3) Ground temperature changes in permafrost layers

The above-mentioned international observation network, GTN-P, has been accumulating observational measurements of ground temperature changes (TSP) and changes in the active layer thickness (CALM). In the Arctic region, the recent global warming trend is reflected in an increase in the ground temperature of permafrost and the formation of For example, according to Romanovsky et al. (2010), the temperature of the depth at which the annual soil temperature amplitude disappears in Russian permafrost has increased by between 0.5 and 2°C in the last 20–30 years. In addition, melting of permafrost from the last ice age has been observed in areas of discontinuous permafrost. It has been concluded that the southern edge of continuous permafrost has migrated northwards, and that there have been changes in the thickness of the active layer; it is increasing at some observation sites although many sites that do not exhibit a clear trend.

The observational activities of TSP and CALM are implemented by various research groups and projects (depending on the site), but long-term observations are still rare due to limitations such as research funding and manpower. In addition, monitoring activities are not standardized over networks, and the methods of measurement implemented are different depending on the research organization: for example, important influential factors related to changes in permafrost, such as temperature and snow cover depth, are not monitored at all observation sites. Other discrepancies exist in that observation sites are usually concentrated in areas where access and infrastructure are good. Research organizations engaged in GTN-P have thus far conducted permafrost monitoring many times, but due to various implementation conditions at each observation site, and the biased distribution of observation points as mentioned above, it is difficult to make wide-area evaluations based on measurement values related to the speed of changes in

Table 2: Prediction of rate of diminution of permafrost distribution area near the ground's surface, and rate of increase in the thickness of the active layer until the year 2100 (Schaefer et al., 2012).

Marchenko et al. [2008]	7[a]	162[b]
Schaefer et al. [2011]	20-39	56-92
Euskirchen et al. [2006]	27[a]	-
Saito et al. [2007]	40-57	50-300
Eliseev et al. [2009]	65-80[a]	100-200
Lawrence and Slater [2010]	73-88	-
Lawrence et al. [2008]	80-85	50-300
Zhang et al. [2008a]	16-20[a]	30-70
Schneider von Deimling et al. [2011]	16-46	-
Zhang et al. [2008]	21-24	30-80
Koven et al. [2011]	30	30-60[a]
Lawrence and Slater [2005]	60-90	50-300

[a] calculated from numbers or tables in text
[b] calculated from estimated trends

permafrost (Schaefer et al., 2012).

Predictions of future changes of permafrost based on numerical calculations have been reported by several research groups. Figure 55 shows changes in the area of permafrost based on the results of future climate prediction (Slater and Lawrence, 2013; IPCC AR5). Thick lines represent the model means, and bands represent the variations. Although the trends agree, if the variations in scenarios of greenhouse gases concentrations (RCP) are included, the range of uncertainties in the predictions become wide, and the predicted values for the areas of permafrost at the end of this century show variations from a 20% decrease to complete disappearance. Similarly, Table 2 summarizes the rate of diminution of permafrost distribution areas, and the rate of increase in the thickness of the active layer near the ground's surface until the year 2100, calculated based on the socioeconomic scenario A1B (Schaefer et al., 2012). In each model, the expression of land surface physical processes is different, and the predicted temperature rise due to increased carbon dioxide also varies; thus, these results also indicate that there is a large variation in the predicted results (Koven et al., 2013; IPCC AR5, 2013).

b. Future studies

Changes in the condition of permafrost are not fully understood yet, and neither can it be said that fluctuation trends over wide areas are firmly understood. To determine the rates of change, it is necessary to obtain the following: the ground temperature profile as the initial condition, the distribution of the amount of ice, temperature changes as an external boundary condition, changes in snow cover, and any ground surface disturbance. Simple observations are insufficient for all of these other than for temperature change. However, the immediate challenge is to gain an understanding of current conditions. Based on the following policy, monitoring research will continue, although it is also necessary to realize future predictions through the development of prediction models.

(1) Strengthening site monitoring

The monitoring of ground temperature changes in the active layer is to be conducted in detail to a depth which includes both the transition layer (Theme 4: cryosphere, see Q2) and the upper part of the deep permafrost layer that will not melt within the next 100 years or so. These observations will not only be limited to changes in the thickness of the active layer, but observations of the seasonal distribution of the melting period will also be increased. An observation design that takes measurements will be established, including elements of micrometeorology that determine the changes of permafrost. In addition to monitoring the temperature changes of permafrost, research is to be progressed while promoting the policy of the GTN-P. In addition, it is necessary to fully determine international standards for the observation methods employed. To avoid the influence of limited access and infrastructure, the observation support system needs to be strengthened and measurement equipment requires development. Observation sites are to be expanded to cover areas of permafrost where a large-scale thermokarst is expected. There are extremely limited examples of site observation measurements of land subsidence areas and changes in the terrain due to thermokarst; thus, immediate implementation is required.

(2) Establishing a permafrost monitoring method using satellite remote sensing

Changes in permafrost occur mainly underground, and the spatial scale of the target area is in the order of meters; thus, wide-area monitoring research based on satellites is difficult. However, research on changes in the ground surface conditions accompanying thermokarst can be progressed significantly through the use of high spatial resolution satellite products that will be provided in the future. For example, some reports of observations of land subsidence due to melting of permafrost by satellite radar, and products that give information on freezing and melting of the ground's surface are becoming more available, and their future use is anticipated. To employ these satellite data efficiently, the site observation design and implementation period needs to be decided in agreement with the operation period and with the measurement content of the satellite that corresponds to the research objective.

(3) Use of permafrost layer in the reconstruction of paleoenvironment

The history of changes in permafrost is recorded in the permafrost itself to a certain degree (see Theme 6). By investigating past fluctuations, useful information can thus be obtained relating to future changes in permafrost. If we move away from the conventional idea that considers the upper layer of the ground's surface in the permafrost zone as a 2 layer-structure composed of an active layer and permafrost layer, we can instead view this as a 3-layer structure composed of the active layer, transition layer, and the permafrost layer (Theme 4, see Q2), and identify the range of past changes inherent in the active layer. Furthermore, when excavating deep layers of permafrost, undisturbed core samples can be collected and composition analyses conducted, in addition to making measurements of ground temperature, for use in reconstructing the paleoenvironment.

Q4: Permafrost-Atmosphere-Snow-Vegetation system: what is its structure and behavior?

a. The importance of research and its current state

As already discussed in Theme 3 (Q2, Q3), Theme 4 (Q2), and Q1–Q3 of this Theme, the dynamic behavior of permafrost and seasonal frozen ground (i.e., their formation, growth, maintenance, and decline) is influenced not only by the atmosphere at the time, but also by the surrounding environmental conditions such as snow cover, hydrology, vegetation, and terrain (Figure 56, Saito et al., 2013). For example, the atmospheric temperature needs to be below a certain point in order to for frozen soil to be formed. However, once frozen soil is formed it can withstand the warming of the atmosphere to a certain degree, as it maintains the adiabatic effect of snow cover, and has an organic layer on the upper ground surface layer and a vegetation layer above (Shur and Jorgenson, 2007). On the other hand, the existence of permafrost limits biological activities and hydrological processes between the ground's surface layer and the active layer (seasonal melting layer), and it affects vegetation on the upper ground. Since the temperature near the surface layer is kept low, the decomposition of organic carbon is slow, and past organic carbon is stored by accumulation in the soil as peat.

However, if an increase in the atmospheric temperature surpasses a certain level and is then maintained, diminution of frozen ground occurs in both vertical and horizontal directions (for example, an increase in the thickness of the active layer and a melting of underground ice). This affects the surrounding environment by changing the terrain and vegetation while potentially affecting the areas outside of the Arctic by delivering a release of greenhouse gases, an enhanced decomposition of soil organic matter, changes in albedo and the storage of groundwater, and changes in the transportation of nutrient salts (inorganic carbon, nitrogen, phosphorus, potassium, etc.) to rivers (Theme 3: material circulation, Theme 4: hydrology). Therefore, phenomena related to frozen ground have interactions between environmental factors (including frozen ground itself), as they all constitute a system (Francis et al., 2009). To predict future dynamic behavior by gaining an understanding of the current condition of frozen ground, it is not only important to consider frozen ground itself, but to grasp the system as a whole.

In the permafrost–atmosphere–snow-cover–vegetation subsystem, a number of interactions and feedbacks (fb) between individual elements have been recognized in previous studies (for example the snow-cover–radiation fb, snow-cover–vegetation (shrubs) fb, greenhouse gases–temperature fb, and interactions between changes in the ground surface layer due to disturbance such as fire–snow- cover/hydrology/frozen ground, precipitation amount–forest fb; see Figure 56). However, the understanding of the fundamental behavioral characteristics, such as the strength and direction of the interaction between each element in the entire system, and the stability and range of the system (i.e., which elements interact, what is the strength and direction of the associated feedback and when it this stable, and does a threshold and branching exist for that stability), and the fb differences that predominate depending on time scales remain insufficient.

In particular, phenomena with large time constants represented on a glacial-interglacial timescale are closely associated with material circulation such as deposition, storage, the decomposition of organic carbon layers (such as the peat layer), and the balance of greenhouse gases. However, studies are limited that deal with such processes as interactions between systems consistently, and at this stage most studies only describe these processes in terms of their formation to degradation.

It appears that research communities in various countries have simultaneously recognized this situation, and multilateral research projects on permafrost have thus begun at almost the same time. PAGE21 in Europe, and RCN Permafrost in the United States are examples of such projects, and they both focus on quantifying the vulnerability of the permafrost environment. In Japan, as part of the GRENE Arctic Climate Change Research Project, quantification of the impact of land area changes on climate has been targeted through the coordination of observations and model research, and research exchanges are currently being carried out between different projects.

b. Future studies

The dynamic behavior characteristics (size of fluctuations, range of impacts, and their causes) of the whole Arctic system, which is connected through interactions and feedback (atmosphere-snow cover-frozen ground-soil-vegetation) on different time scales, cannot simply be understood by examining each element separately, or by looking at the interactions between each individual element. For a comprehensive understanding it is necessary to use an approach based on dynamic system analysis. However, since the system is open and hypothetical, and the importance and range of major elements (and interaction of elements) changes on spatiotemporal scales, the results of enhanced observations, presentation methods, and the development of models proposed in Q1 to Q3, needs to be adequately employed. In addition, observations and model designs (numerical models, process models, or mathematical models for conceptual understanding) need to be simultaneously used to search for the most appropriate method for understanding the size, complexity, and spatiotemporal scale of the target system, one step at a time. As a specific subject, the following phenomena and time scales can be considered as examples:

1. The transition processes due to "disturbances" such as forest fire (on a scale of 10–100 years). In addition, the changes and recovery of atmospheric conditions (such as snow cover and temperature), vegetation, and the upper ground surface layer on a landscape scale (of about 10 km or less) needs to be considered.
2. The transition process during the Medieval Warm Period, the Little Ice Age, and the "anthropogenic warming period" (on a scale of approximately 1000 years) could be considered, along with the covariation of "frozen ground-hydrology-vegetation" on a regional scale that accompanies climate change.
3. The retreating ice sheet since the last glacial high, the marine transgressions accompanying sea-level changes, and the changes during the Holocene (scale of 20,000 years) should also be considered together with fluctuations in the cycle of the "retreating ice sheet-exposure of ground surface layer-growth of the frozen ground-formation of the ground surface layer and the deposition of peat", and "the marine transgression-submergence of permafrost-formation and preservation of seabed permafrost" in the Northern Hemisphere under large-scale climate change (global warming).

Although not included when referring to a scale of 10–100 years, the impacts of and on human and social activities (economy, design, and maintenance of social infrastructure, and agriculture) should also be considered in a similar manner, together with vegetation and all interactions with the biosphere (including animals). When considering the system as a whole, various factors that have been conventionally handled in a number of

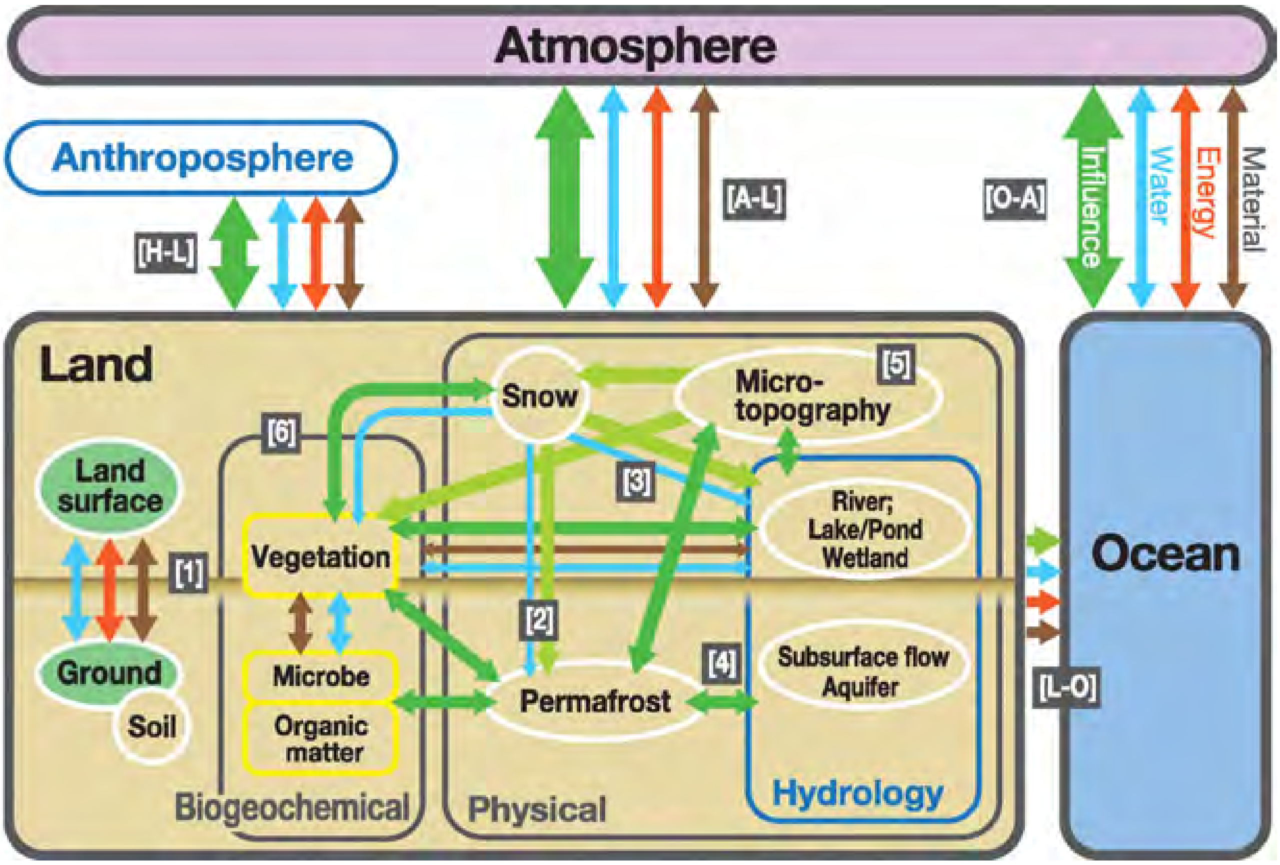

Figure 56: Linkages, flow, and feedback between components of the dynamic terrestrial Arctic system and the adjacent subsystems (after Saito et al. 2013). [1] The land component consists of "land surface" and "ground" (subsurface) portions, and the internal exchange of energy, water and material. Interactions between [2] snow-permafrost, [3] snow-hydrology, and [4] permafrost-hydrology. [3] Micro-topographical influences on those three components, and relationship between physical and biogeochemical components are shown. The terrestrial system interacts with the overlying atmosphere ([A-L]), oceans ([L-O]), and anthroposphere ([H-L]). [O-A] denotes the ocean-atmosphere interactions.

academic disciplines have become involved; thus, a multidisciplinary research system (for example the science of frozen soil, climatology, soil science, geomorphology, ecology, biology, mathematics, information science) has become necessary in relation to the following: an identification of a system and the selection of a central process, and the development of observations and modeling strategies and their implementation. Currently, research projects on permafrost fluctuations are in progress in Europe and the United States, and they focus mainly on the "frozen soil-carbon" parts. However, progress is likely to be made in the direction of viewing the whole system in the future. The further promotion of international cooperation will also become important in relation to information gathering and joint studies, and will involve the sharing of observation sites and data, a comparison of models, and participation in collaborative projects.

Chapter 8: Development of methods enabling breakthroughs in environmental research

The pioneering breakthrough research is triggered by innovative deployment of observation and modeling technique. Process research and monitoring of mutual enlightenment, system modeling and data assimilation are important. We identify the current gap, as well as efficiently conducting research and leading to the need for research infrastructure. We will overcome the handicap by the complexity and difficulty of the data acquisition of the Arctic, and contribute to the global scale study.

Theme A: Sustainable seamless monitoring

Abstract

Research monitoring of the Arctic environment has been carried out as two elements, remote sensing, including the satellite and in situ observation. Environmental change in the Arctic is important with regard to global scale influences; however, because of the severity of the Arctic environment, in situ field observations are hampered by the sparseness of observing stations and subsequent large areas with no data. Although, due to recent progress, satellite monitoring has generated new information, there are still many factors that need to be observed in situ. The most important point of monitoring is to collect continuous, representative data. International cooperation is essential to enable this; therefore, Japan is also required to play a role.

As a matter of convenience, if the subject of monitoring is classified into the oceanic, cryospheric, atmospheric and terrestrial area, then the long-term priority issues that Japan should tackle are as follows. For the ocean area, the monitorings of sea ice change, marine ecosystem and material cycle through the year, with our own icebreaker and satellites are needed. In the cryosphere, determining the mass balance and related various quantities of the Greenland ice sheet and the mountain glaciers of the Arctic Circle, coastal erosion and thermokarst associated with thawing and borehole management of permafrost is essential. In the atmosphere, precise long-term observation and understanding of the spatial variation of atmospheric minor constituents involved in the climate, cloud and precipitation are essential. For the terrestrial monitoring, maintenance and development of observing stations (super site) overall to perform monitoring of vegetation change, terrestrial ecosystems and meteorological and hydrological observations, including heat, water and carbon fluxes in the terrestrial sphere are needed. With respect to these issues, monitoring conducted by both in situ observations and remote sensing is required. Here, we describe the monitoring initiative by classifying areas into oceanic, cryospheric, atmospheric and terrestrial.

Q1: Oceanic monitoring
Q2: Cryospheric monitoring
Q3: Atmospheric monitoring
Q4: Terrestrial monitoring

Introduction

It is important to continue long-term high-precision observation and monitoring. There is, however, a view that carrying out monitoring without defining a specific phenomenon of interest lacks conviction as motivation for research; however, there are many cases where one does not know the universality of the phenomenon and where the situation has only been observed in the short-term. By observing over longer time frames (10 or 20 years), the phenomenon and related positioning of the situation may become clear for the first time. A well-known example is the increase in atmospheric carbon dioxide concentrations recorded through precise observation data gathered by Keeling in Hawaii; data gathering commenced in 1958, with data accumulated over a long period of time, allowing the possibility of scientific evaluation (Keeling et al., 1976). The sharp decrease in Arctic sea ice that has occurred in recent years has been quantitatively clarified based on satellite observations over more than 30 years. The longer the time scale of change of the phenomenon, the longer the time for which a continued period of monitoring is necessary. Continuous observation for more than tens of years is necessary to understand changes in the boreal forest, such as changes in the coniferous forest zone and in the coverage of frozen ground.

Aspects that require long-term monitoring in the Arctic vary widely. First, we outline the status and problems of international networks for each monitoring case, subdivided into ocean, cryosphere, atmosphere, and terrestrial categories. Subsequently, future required monitoring is described in detail. The Integrated Global Observing Strategy on Cryosphere (IGOS-P Cryosphere) has described the current status of monitoring in the Arctic, particularly of snow and ice, and has provided recommendations (Key et al., 2007). Based on these and other factors, we present a monitoring research initiative for Japan to tackle.

Oceanic monitoring

b. Monitoring of sea ice by satellite remote sensing

The most basic physical aspect of sea ice that is observed from a satellite is the horizontal distribution of ice volume (concentration). Prior to satellite observations, sea ice distribution was estimated by collecting information in the field. Satellite observation, notably observation by microwave radiometers, began in the 1970s, and has allowed continuous monitoring of the global sea ice area. As a result, we have been able to note changes such as the reduction in sea ice area in the Arctic (Comiso and Nishio, 2008) (Figure 57). The current mainstay of the microwave radiometer is the Japanese AMSR series, and this is widely used for monitoring sea ice. This is a sensor having the world's best performance, with about twice the resolution of the SSM/I, which was the mainstay before the AMSR series.

On the other hand, what is currently most urgently needed is monitoring of sea ice thickness. The changing characteristics of sea ice in terms of changing thickness are not well understood, and even now, the representation of sea ice variability in climate models remains inadequate. In order to estimate heat balance of the sea ice area and amounts of sea ice generation and melting (the basic amount of sea ice change), and to understand the impact of mechanical deformation of sea ice on thickness variations, observation of the spatial distribution of sea ice thickness is essential, as is monitoring of temporal change. Spatial resolution is therefore expected to be less than or equal to several tens of kilometers, and ideal temporal intervals would be of a few days, or if possible, the thickness variation per day. Currently, in the United States (NASA) and Europe (ESA), surface height and ice thickness are estimated by laser altimeter and radar, respectively. These observations are expected to be useful in future, but in terms of accuracy and frequency, they are still not sufficient. There are also uncertainties relating to aspects such as snow depth and it is necessary to estimate the density of snow cover and sea ice. There is therefore significant scope for future improvement.

In addition, observation is currently underway through many Earth observation satellites, such as synthetic aperture radar and high-resolution visible observation satellites. These high-resolution data are very useful to determine the size distribution of ice floes and the mechanical deformation of sea ice at a fine scale that could not be captured through a microwave radiometer. Furthermore, given the potential wide-area impacts of sea ice change, the utility of this data could become more evident in future.

The biggest priority for future microwave radiometer monitoring is to continue observation and to establish a long-term stable monitoring system. Of high priority in the maintenance of observation is the provision of high resolution data, which would make it possible to significantly improve its utility. Observation resolutions of about 1–2 km would make possible detailed monitoring of the coastal thin ice area (coastal polynya) and of sea ice distribution at the ice edge, as well as improving understanding of the violent change state of the sea ice surface (such as melt ponds); it would also allow observation of all weather phenomena involved in sea ice variations, such as a vortex at a scale of tens of kilometers.

With regard to the use of altimeters for measuring sea ice thickness, for example, by also observing the ice surface height in the direction perpendicular to the track of current measurements, it would be possible to significantly increase observation frequency. To understand the response of sea ice to climate change, it would then be necessary to sustain such observations. Furthermore, maximizing on the potential of existing data, such as high resolution images is the meaningful equivalent of performing new observations. By encouraging operational agencies and institutions to integrate satellite data in different formats and to manage and develop datasets, and by increasing the number of researchers and engineers who use satellite data, the study of the Arctic using such data can progress rapidly.

b. Ocean monitoring under sea ice

In understanding the climate system, we urgently need to understand the mechanism of sea ice variability in the Arctic Ocean that changes the heat balance between air and sea. So far, sea ice reduction has been mainly observed in the vicinity of the Northwind Ridge of the Pacific side of the Arctic Ocean, where warming is significant due to Pacific water. However, changes in the seasonal sea ice area are now also occurring not only near the Northwind Ridge, but also in waters where Pacific water does not extend. Progression of the ocean seasonal sea ice area means an increase in area and expansion of the period where there is contact with the atmosphere. As a result, shortwave radiation and atmospheric disturbances of the flow and vertical mixing of the ocean surface, together with heat fluxes, can lead to a change in the atmospheric field. Current and future heat balances between the atmosphere, oceans, and sea ice are therefore expected to differ significantly from those of the late 1990s, when sea ice was not as thin as at present and also did not have such a small extent in summer. In other words, in order to accurately predict future sea ice variability and

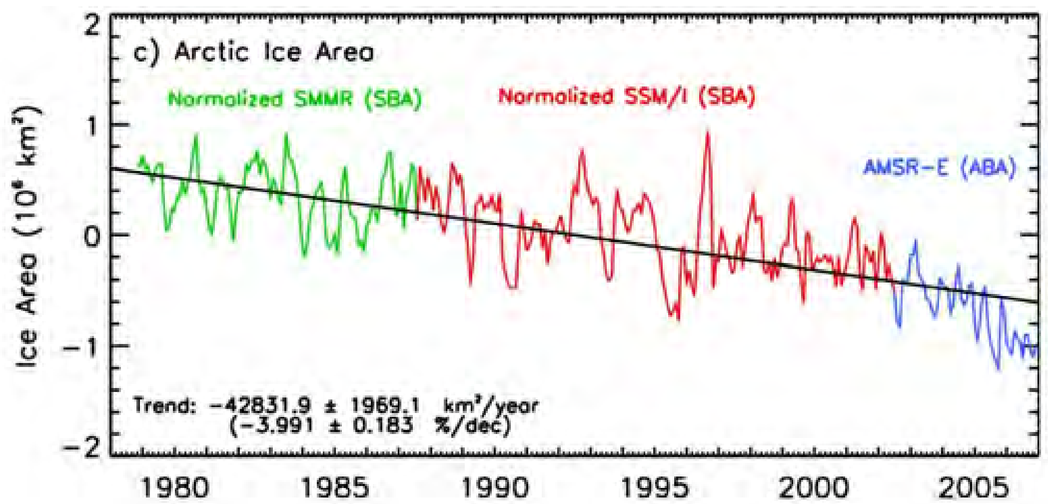

Figure 57: Changes in deviations in the northern hemisphere sea ice area, as observed by microwave radiometer (from Comiso and Nishio, 2008).

impacts on the climate system, it is essential to quantitatively clarify each physical elementary process of the ocean surface mixed layer from the atmospheric boundary layer, not simply during the melting period but rather during the ice season (winter), and the contribution of these to sea ice variability. However, Japan's past Arctic Ocean observations, carried out using its own ice class vessels or other countries' icebreakers, took place during specific observation periods, with related constraints of observation time, waters, personnel, budget, etc. On the other hand, sea ice-mounted drifting buoys are deployed and gather observations throughout the year. However, there is a bias in the spatial distribution of data frequency because of the fact these are installed only in thick sea ice areas and because the observation area is dependent on sea ice movement; it is therefore not possible to observe the same area over a period of time. Moreover, because mooring system observations are designed to avoid multiyear ice, instruments cannot be installed from the surface to about 50 m depth, and measurements are difficult (with the exception of measurement of flow rate).

Here we propose carrying out "ice season - winter air – sea ice heat balance observations" using our own national icebreaker; such observations would be difficult using ice class ships or icebreakers belonging to other states. We would specifically deploy field observation (including over ice) by the icebreaker and manned observation stations in the Northwind Ridge ~ Makarov Basin of the Pacific side of the Arctic Ocean, where seasonal sea ice changes are already recorded, considering the heat balance of air - sea - ice during the ice season over a wide area of ocean. In addition, the fixed point will be established within the sea ice reduction area, with heat balance observation of air - sea - ice through icebreaker winter observations. Such data can quantitatively reveal sea ice movement in relation to the heat budget process of air - sea ice - ocean, ocean tides (internal waves), and the contribution to heat transport of atmospheric disturbances and freezing and thawing processes. In addition, through wide area observation using existing ice class vessels and the deployment of unmanned observation stations (mooring systems, drifting buoys, etc.) during the melting season, thus revealing the heat content of the ocean surface in open water, we can determine time variations in the ocean mixed layer and preconditions before freezing. In this way, based on the time difference between icebreaker and ice class vessel observations, the elementary heat balance processes between air - sea - ice can be revealed year-round.

c. Monitoring of marine ecosystems and material cycles

Marine ecosystems in the Arctic Ocean are unique, composed of species adapted to low temperatures and to the sea ice environment. Drastic reductions in sea ice and a summer increase in water temperature that have been observed from the 1990s suggest the potential likelihood of significant change in Arctic Ocean ecosystems and in the related material cycle. In addition, since global warming over the 100-year scale causes melting, not only of sea ice but also of permafrost and ice sheets on land, it increases the amount of freshwater flowing into the Arctic Ocean and greatly changes material cycles and coastal ecosystems. It is therefore very important to efficiently monitor the ecosystems and material cycle surrounding the Arctic Ocean, and to quickly understand the changes taking place. However, most of the insights gained in Arctic Ocean ecosystems and material cycle research so far were based on observation data gathered in open water areas in summer. Because winter influences on ecosystems and material cycles have not yet been well understood, we do not have a comprehensive understanding of related processes and variations. Moreover, observations are biased in favor of water areas, with a focus on coastal zones to which access is relatively easy; studies covering the entire area are very few.

In order to develop an overview of Arctic ecosystems and material cycles, and to reveal changes and processes, regional and seasonal differences must be taken into account. It is physically and economically impossible for a single country to monitor in multiple regions and during different seasons. Japan has performed a number of observations in summer in the Chukchi Sea and Canada Basin region, using the "Mirai" and "Oshoro Maru", linking ecosystems to material cycle changes. However, to understand the ecosystems and material cycle process of the wider Arctic Ocean, it is necessary to observe over a wider area; for this, international cooperation is essential. We are currently noting the achievements of an international joint observation initiative, DBO, for which Japan is also responsible (Grebmeier et al., 2010). In future, it will also be important to strengthen the relationship with Russia and Canada, and to strategically observe the Beaufort Sea, Canada Basin, Chukchi Sea, and East Siberian Sea (Figure 58). Through international cooperation in the Arctic Ocean, it will be possible to ensure highly accurate and multiple marine monitoring observations, examples of which are provided by WOCE, performed over a single ten-year scale. In addition, to ensure efficient data operation, it is essential to cooperate with international data organizations such as the World Data System (WDS), and to aggregate and release active metadata.

Japan's Arctic Ocean observations have so far been limited to open water areas in summer. This alone is not sufficient to understand the material cycle and ecosystem change. It is important that, as part of international cooperation at appropriate locations (for example, a blank area of observation such as the Canada Basin and Chukchi Sea), Japan also establishes a research icebreaker that can allow for winter observations in future, thus being able to carry out observations of material cycles and ecosystems that include seasonal variations. In addition, full advantage should be taken of recent advances in technology, such as in mooring systems and remote observation technologies (for example, in audio equipment and underwater gliders), particularly in the Arctic Ocean where access is not easy. Above all, because mooring systems are a powerful tool for year-round observation of organisms, it is essential to install multiple mooring systems in appropriate waters through international cooperation. Satellite data is also an important tool for understanding spatio-temporal ecosystem and material variations. It may be necessary to conduct high-resolution long-term monitoring of sea ice, snow and ice, and ocean color. The planned launch of the AMSR2 successor machines and Sentinel-3A • PACE stems from the very fact that these provide an important foundation for observations aimed at understanding space-time variability of ecosystem-related parameters; we strongly hope that such a regime is established and made available with ease to many researchers.

In addition, freshwater and material supply from land is deeply involved in changes in the marine ecosystem and material cycle. The coastal areas where many organisms (ranging from large mammals to benthic organisms) live are hot spots of the Arctic Ocean ecosystem. In order to understand environmental changes in coastal areas, it is necessary to strengthen interdisciplinary cooperation and to construct a system to deploy seamless monitoring observations from rivers to the ocean.

d. Monitoring of radiation fluxes of the sea ice area

In the heat balance of the Arctic, shortwave and longwave radiation fluxes play a very significant role. The heat balance of the entire atmosphere of the Arctic north of 70 ° latitude is estimated as the sum of net shortwave-longwave radiation fluxes at top of the atmosphere, heat fluxes transported from the mid-latitudes to polar regions, and the influx of the heat flux from surface processes, including sea ice freezing/melting. It is a net longwave radiation flux that contributes most to the heat budget in absolute terms throughout the year. In particular, this becomes a dominant factor in winter when shortwave radiation is lost. In summer, shortwave and longwave radiation contribute to the same degree, and it can be said that both play an important role in the heat balance of the Arctic.

On the other hand, when we focus on the heat balance over the surface that is directly related to growth and melting of sea ice, excesses or deficiencies that occurred in the net radiation flux on the surface are basically compensated for by the turbulent flux (sensible heat flux + latent heat flux) and conductive flux through snow and sea ice, or by the latent heat of fusion of snow and sea ice on the surface. This indicates the importance of accurate measurement of shortwave-longwave radiation fluxes for estimating growth and melting of sea ice (Serreze et al., 2007). However, because of logistical difficulties in polar regions, the data obtained from long-term monitoring observation has been very limited. Since 1992, observation of the radiation flux in the Arctic has taken place at three locations, covering a relatively wide area: Barrow (71 °N latitude), Ny-Alesund (79 °N) and Tiksi (72 °N); this has been done through BSRN, affiliated to WCRP. We strongly expect to maintain and reinforce these observation systems in future.

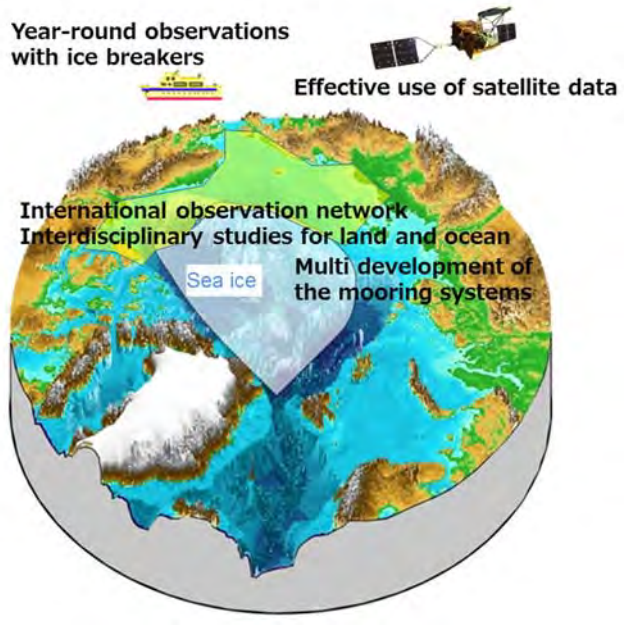

Figure 58: Elements necessary for future monitoring of marine ecology (conceptual diagram).

Cloud is another important factor affecting the surface radiation balance in the Arctic Ocean. Observations derived from SHEBA (see footnote 11) show that the net longwave radiation flux at the surface has a negative value (upward), ranging from -20 to -40 W m^{-2} throughout the year, and that the downward longwave radiation flux contributes most to variation, with the presence or absence of clouds making a particular difference by more than 70 W m^{-2}. The cloud fraction (particularly of stratus clouds appearing in the lower layer) is therefore considered to be an important component, requiring continued long-term monitoring in the Arctic region, in conjunction with monitoring of shortwave and longwave radiation fluxes.

Cryospheric monitoring

a. Meteorological and glaciological observations and monitoring of light absorbing aerosols and cryospheric microorganisms on the Greenland ice sheet

The total mass balance of the Greenland ice sheet is determined by the accumulation rate, surface ablation rate, and ice discharges from calving glaciers. Ice sheet surface elevation is determined based on these mass balance processes and ice flows. Recently, ice sheet surface elevation has been accurately measured by satellite laser altimetry. Moreover, mass changes in the ice sheet have been measured by monitoring the gravitational field using satellites, and reduction in ice mass in recent years has become apparent. Glacier flow and ice discharges from calving glaciers can be observed by satellite, but local observations are still required for understanding the internal structure of the glacier (ice thickness, bed elevation), and also for detection of changes in accumulation and ablation rates. For this reason, observation by automatic weather stations installed on the ice sheet are very important (e.g., Steffen and Box, 2001). In order to increase the accuracy of mass balance monitoring over the entire ice sheet, there is a need for more intensive satellite and field observations, greater numbers of automatic weather stations, data to fill in blank areas, and long-term maintenance of facilities.

On the other hand, snow and ice surface albedo is one of the most important factors for surface melting. Ice sheet surface albedo in the accumulation area depends on snow grain size and light-absorbing aerosols included in snow (black carbon and dust), while it is also greatly dependent on the concentration of snow and ice microorganisms in the ablation area (Wientjes et al, 2007). For this reason, there is a need to carry out, in sync with albedo monitoring, measurement of light-absorbing impurities in snow cover in the accumulation area, pit measurement of snow particle size, snow and ice microbial sampling, and cryoconite observation in the ablation area. In addition, there is a need to perform shallow ice core drilling in various places to reconstruct, with high temporal resolution, light-absorbing impurities and microbial concentrations of the past, including seasonal variations.

b. Long-term observation of the mass balance and meteorology of pan-Arctic mountain glaciers

In the study of glaciers in the Arctic, understanding of mass balance change is important. Despite the fact that the Arctic is strongly influenced by the recent warming trend, there is less glacier mass balance data than in other regions of the world (Vaughan et al., 2013). In future, it will be necessary to collect long-term data through methods such as in situ observation and satellite imagery; there is also a need to cooperate with other countries (refer to Theme 4 and the next section, "Continuous observation of the mass balance of the Greenland ice sheet and of glaciers and ice caps on the peripheral edge").

The following can be considered key elements of a future research strategy for Japan: ① initializing new observations in areas where there is no glacier observation to date, ② resuming glacier monitoring where data was gathered in the past, and ③ cooperating in the monitoring conducted by other countries. Below, we describe the current status and potential for future study in Arctic countries and regions where glaciers are present and where observations are required (Canada, Alaska, and Russia). In Alaska and Canada, the contribution of glacier mass loss to sea-level change is large. In this region, there is missing observational data for glaciers that are logistically difficult to approach, e.g., Brooks Range. In the islands of the Canadian Arctic (such as Ellesmere Island, Baffin Island, etc.), observations were initiated a relatively long time ago, but long-term mass balance data is insufficient. In Russia, there is no glacier mass balance data for recent times, even in the case of glaciers that were studied in the past. In addition, although meteorological data are relatively abundant for the period of the former Soviet Union, in recent years there has been a rapid decline in such data.

Together with mass balance observations, it is necessary to observe meteorological components that determine mass balance. In the case of such meteorological observations, there are maintained databases, such as that of NOAA. For re-analysis data, differences between observed values in the Arctic are large, and it will be important to ensure further improvement in future. Since instruments are difficult to operate in low temperature environments, it is important to develop more robust ones. More frequent and detailed maintenance of instruments is as important as having a well-organized research plan. To improve the efficiency of observations, it will be necessary to hold workshop discussions on meteorological observations in the Arctic, as well as to cooperate with other countries.

c. Continuous observation of the mass balance of the Greenland ice sheet and of peripheral glaciers and ice caps

When measuring mass change of glaciers and ice sheets, surface mass balance is one of the most important parameters (see Theme 4). In recent years, although satellite observations are underway, it has been difficult to measure accumulation and ablation rates from satellite data. Field mass balance measurements are also important for validating satellite data and better understanding mechanisms of elevation change. Snowfall and melt are responsible for mass balance, and they vary greatly year-to-year depending on meteorological conditions. Available information derived from short-term or intermittent observations is therefore limited, and it is important to perform continuous measurement over a long period of time. Currently, continuous mass balance measurements in Greenland are limited, but organized observational networks are growing through PROMICE, led by Denmark.

In future, in order to increase mass balance data for the Greenland ice sheet, mountain glaciers, and ice caps distributed over the Arctic, worldwide cooperation will be necessary. It will be important to contribute to the global Arctic research community by establishing areas that are studied by the Japanese and by providing the data acquired. Specific monitoring target areas include northwest Greenland, where observation started through the GRENE project. Data will be gathered for various locations, from calving glaciers on the coast to the inland ice sheet, as well as for independent ice caps. Research activities in this region hold promise for future development and continuation. To measure mass balance over an extended period of time, it will be necessary to continuously ensure that there are the personnel and budget to perform field measurements in remote areas. For long-term observations, we should also consider training local collaborators.

d. Long-term observations of glacier and ice sheet fluctuations by satellite

Given recent developments in satellite observation technology, in addition to basic information such as the glacier terminus position and its area distribution, it is now possible to observe many different aspects of glacier fluctuations. Important observations specifically include: ① measurement of the glacier terminus position and area through visible and microwave images, ② measurement of ice volume change by stereographic photogrammetry of visible images and by altimeter data (e.g., Bolch et al., 2013), ③ measurement of ice flow speed through image correlation and interferometric synthetic aperture radar (InSAR) (e.g., Moon et al., 2012), and ④ measurement of ice mass changes by gravity measurement. For future monitoring of Arctic glaciers and ice sheets, it will be important to utilize and develop these data and technologies.

For ①, higher resolution imagery is now available at a higher temporal resolution. In future, using techniques such as automatic extraction of the glacial periphery, we will need to process a large number of images over a greater area.

Method ② is a conventional technology. Accuracy has been improving thanks to recently-available high resolution images, and the importance of this method has increased. In stereographic photogrammetry using visible images, further results can be obtained by improving automatic DEM generation computer algorithms. In addition, we need to continue accurate monitoring through altimeter measurements, as represented by ICESat of NASA, over a wide area of the Arctic.

For ③, there has been excellent progress in studying calving glaciers on the Greenland cost, where ice motion plays a major role in glacier fluctuations. Higher temporal and spatial resolutions can be achieved in future by developing next-generation satellites and improving data analysis techniques.

④ is a new technology that emerged over the past decade through GRACE satellites, providing new possibilities, particularly in the measurement of ice sheet omethod to allow for accurate monitoring of, not only the Greenland ice sheet, but also mountain glaciers and ice caps over an extensive area. In any of the cases described above, there has been significant innovation both in satellite sensors and in data analysis techniques. In addition to using available new technologies, those who study glaciers and ice sheets are expected to provide ideas for future satellite observations and technical improvements. This will ensure the development of satellite observations and technical improvements for necessary Arctic glacier and ice sheet research. With regard to maintenance and sensor development of satellite observations, refer also to the description given in Chapter 9.

e. Monitoring of quantitative changes in snow and ice distribution, cloud distribution, and snow and ice microbial distribution and quality changes (such as snow grain diameter and albedo) by satellite

In addition to collecting observations using an artificial satellite as described in d., it is important to monitor dark areas covered with snow and ice microorganisms within the ablation area of the Greenland ice sheet, particularly since these have expanded in recent years (Wientjes et al., 2007). In addition, even for surfaces covered with snow, it is important to monitor qualitative changes, such as aspects of snow physical quantity and temperature related to albedo (e.g., snow particle size and light-absorbing impurity concentrations), as well as changes in albedo itself using satellites; this is crucial from the viewpoint of understanding albedo feedback mechanisms, and for model development and future prediction. Technical development is therefore important for extracting, with high accuracy, those snow physical quantities from the multi-wavelength imager satellite having a channel in the visible and near-infrared regions (Hori et al., 2007). Because the presence of clouds in the Arctic is an important factor for radiation balance, it is also necessary to monitor, in the long-term, information such as cloud distribution, cloud particle size, altitude, and thickness, using satellites.

f. Understanding and long-term monitoring of the distribution of thermokarst due to the thawing of permafrost

In the permafrost zone, thermokarst topography is formed by ground surface depression due to the thawing of permafrost (see Theme 12 with respect to the progression of thermokarst). As well as being due to climate change, thawing of such frozen ground is also caused by a disturbance to ground surface conditions, such as loss of vegetation due to locally-occurring forest fires causing a rapid increase in the active layer thickness of permafrost (Viereck et al., 2008), resulting in rapid formation and development of thermokarst. Because formation of thermokarst can lead to changes in the surrounding water environment, long-term monitoring of distribution and variation is needed.

In continuous-discontinuous permafrost zones around Alaska and Siberia, it is therefore necessary to understand the distribution of current thermokarst using local observations and satellite data. Thawing of permafrost appears as an observable phenomenon, and this data provides a basis for understanding future fluctuations. Understanding the cause of frozen ground thawing in each region and understanding variations in local conditions will contribute to long-term environmental change prediction.

g. Monitoring changes in coastal erosion and underground ice of the Arctic Ocean

A large amount of underground ice exists near the ground surface of the coastal Arctic Ocean (yedoma; see Box 8 in Theme 12). The process still underway involves topsoil flowing out by coastal erosion, initiating thawing, with subsurface ice exposure then proceeding; rising temperatures and sea level rise are expected to accelerate this process. This yedoma ice has been shown to contain a large amount of methane (e.g., Fukuda, 1993). Because thawing results in the release of carbon fixed in permafrost, there is also the potential to contribute to an increase in greenhouse gases. On the other hand, the thawing of underground ice causes the collapse of the ground surface, with direct impacts on human life arising from, for example, the collapse of buildings and coastline retreat. In some areas, such cases have led to movement of a whole community (Shishmaref, Alaska). However, there are no examples of temperature measurement of yedoma itself.

Against this backdrop, the importance of monitoring the progress of coastal erosion, variations in the coastline, and underground ice variability is high. Together with field surveys (that include temperature measurements of edoma not carried out so far), it is therefore necessary to

Box 9　Observations of glacier mass balance

Glacier mass balance can be measured through field observations (surface mass balance, front position, etc.), satellite imagery analysis (mass change, area change), and so on. Direct field observations are preferred for accurate measurement but remote sensing techniques using a variety of satellite data are effective to cover broader and remote areas. With regard to the latter, more extensive use of GRACE satellite data is expected. For small glaciers and regions where greater error is expected in GRACE data, mass change can be more accurately estimated from area and elevation changes measured by satellites such as ICESat and ASTER. In addition to direct observations in the field, records of glacier terminus position can also be utilized for the study. Observations of terminal position have been carried out at about 500 world glaciers (Vaughan et al., 2013).

periodically monitor coastline variations using aerial photos obtained by airplanes and satellites. In particular, in regions with wider distribution of underground ice, it is necessary to evaluate the rate of progress. It should be noted that there is a possibility that yedoma ice can be taken full advantage of for environmental restoration purposes (see Theme 6).

h. Monitoring of permafrost temperature state by borehole observation

Soil temperature provides very basic information concerning the permafrost environment. Although there have been soil temperature observations by borehole to various depths and for various purposes in countries of the Arctic, the maintenance environment varies, even having unknown abandoned sites. Maintenance by installing drilled holes for long-term temperature measurement allows for long-term monitoring of the temperature state of frozen soil in the Arctic, and is important in order to consider the response of frozen soil to climate change. With regard to soil temperature variations, since the measuring depth is deeper, there appear to be longer time scale variations (with time difference) and it is important to maintain deep borehole observations even in order to evaluate human impacts on climate change. Against this background, it is necessary to install long-term sustainable boreholes in the Arctic, centered on Alaska, Canada, and Siberia. In recent years, this has taken place through the GTN-P[55], led by the International Permafrost Association (see also the description of Q3 in Theme 12 with respect to variations across the network and in measured values). In this project, a blank area of the existing network is preferentially selected as an observation point. The target is to have 100 additional observation points.

For the installation and maintenance of drilling holes in such areas, cooperation with local research institutions is essential, making it necessary to maintain and and develop existing and new cooperation, respectively. As an example, the International Arctic Research Center (IARC) at the University of Alaska Fairbanks, has established a cooperative relationship with Japan over a long period of time. In addition, there are many researchers in the IARC, including Japanese, Canadian, and Russian, who occupy important positions, even through joint research with these countries. It would be effective to prepare, install, and maintain borehole observations using the IARC as a base, enabling long-term soil temperature observation.

Atmospheric monitoring

a. Importance and status

With regard to greenhouse gases and aerosols, long-term continuous monitoring has been conducted that is broadly representative of the Arctic, with monitoring at Barrow (Alaska), Alert (Canada), and Ny-Alesund (Svalbard) contributing to estimation of transport mechanisms and of sources and sinks, as part of a global observation network. However, there are no observation points along the vast Siberian coast facing the Arctic Ocean, with placement of observations thus being biased. Furthermore, most of the observations have been made at ground bases. Although flight-based observations, such as through aircraft, have been conducted in Alaska and around Svalbard, there is still very limited observed data from the middle-upper troposphere. Monitoring of greenhouse gases is required to continue in the long-term, in particular through high-precision observation, and it is necessary for support to be provided through international cooperation.

Meteorological phenomena and atmospheric minor constituent (greenhouse gases, short life gas, aerosol) changes not only respond to changes in the surrounding environment, but via a radiation process, influence the climate (for short-lived gas, see footnote 15). The Arctic is divided into a sea ice area (which accounts for most of the Arctic Ocean), an ocean area (with vast biological production volume), and a land area (including the vast permafrost zone, the forest zone, and the industrial area, also extending into the Arctic Circle); these incorporate processes, sources, and sinks of atmospheric minor constituents. Although secular temperature changes from the early 20th century have been observed, we have focused mainly on studying variable factors, as compared with factors such as sea ice distribution and ice core data (e.g., Yamanocuhi, 2011).

Secular changes in precipitation have different trends depending on region and cannot therefore be explained in terms of a simple increase or decrease. Current precipitation data for the Arctic is based on sparse rain gauge data. In recent years, discharge of large rivers flowing into the Arctic Ocean is said to be on the increase, and a change in discharge is likely due to changes in precipitation. However, due to the problem of low observation point density for precipitation data and to the catch ratio of precipitation gauges for snowfall, we cannot quantitatively describe the discharge increase. Use of artificial satellites is expected to contribute mostly to understanding the spatial distribution of precipitation. Previously, valuable data were acquired by TRMM in low latitudes. On the other hand, for middle and high latitudes, we have no continuous rainfall observation system to date. The main satellite of the global precipitation observation program (GPM) was launched in 2014, following much anticipation. However, high precision observation is difficult for snow.

For greenhouse gases (CO_2, CH_4, N_2O, etc.), the year-to-year increasing trend and secular variations in growth rate have been confirmed. In addition to the effects of global-scale human activities, the impacts of CH_4 emissions from wetland areas have also been noted (e.g., Morimoto et al., 2006). In the case of ss-SO_4^{2-} and black carbon (BC) in aerosols, year-to-year decline has been observed, resulting from reduced emissions since the 1980s. However, since for a part of the aerosol component (NO_3^-) and scattering coefficient, such a decline has not been observed (or more recently, an increase has been noted) (Quinn et al., 2007), the possibility of long-distance transportation from the low and mid-latitudes has also been discussed (for BC, see footnote 14). Satellite data has pointed to an increase in the distribution and secular change of clouds, which may significantly affect the radiation balance; however, there is still a large degree of

[55] GTN-P: Global Terrestrial Network for Permafrost

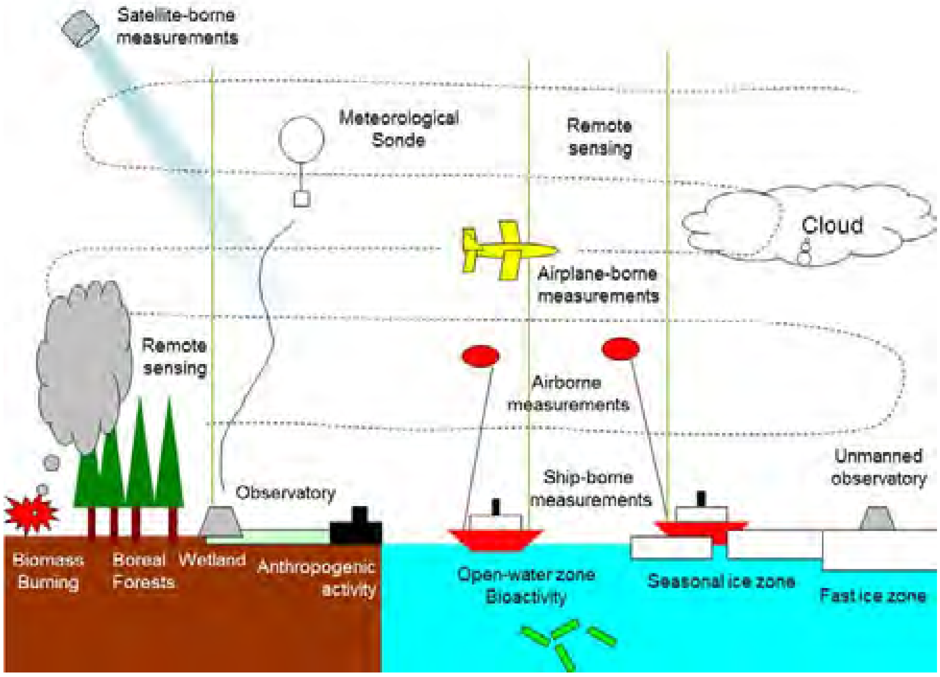

Figure 59: Elements necessary for future monitoring of atmospheric minor constituents (conceptual diagram).

uncertainty (e.g., Wang and Key, 2005) (for the relationship of aerosols and clouds, see footnote 18). These secular changes are related to other complex elements, for example, the relationship between various northern hemisphere processes and global-scale, human activities, and terrestrial and marine environmental change in the Arctic. In order to detect long-term environmental changes in the Arctic, long-term observation and observation system maintenance for meteorology and key atmospheric minor constituents are essential. However, at present, due to observation limitations and difficulties, there are still frequent blank periods and regions of observation data. Scientific data obtained in the past does not extend far enough to allow for understanding of environmental change in the Arctic.

b. Future research

Much long-term observation and research in the past were based on observations conducted near the ground and on routine meteorological observations from observation sites. In order to detect long-term variations in Arctic environments and to validate processes, in addition to long-term observation of basic parameters, it is important to understand space-time change and the actual situation. Basic parameters are temperature, amount of water vapor, precipitation, greenhouse gases, short-lived gases, clouds, and aerosols. Because the life-time of these parameters in the atmosphere varies widely in scale, from seconds to years, it is necessary to change the observation frequency and measurement resolution, depending on the phenomenon and process of interest. In order to examine the relationship between Arctic environmental change, climate change, and changes in material dynamics of the atmosphere, it is necessary to understand variations on scales of several years to several decades. It is also important to capture elementary processes at any short time scale (such as sources, sinks, etc.) of atmospheric components associated with environmental change, as well as long-term changes they are experiencing; this would allow us to not only discuss long-term variations but also changes at minute, date, or seasonal scales.

In areas where observation bases are very limited (such as the Arctic sea and Siberia), we are going to establish meteorological observation sites, with the aim of long-term operation through an observation network. In particular, we would like to see the establishment and maintenance of an aerological observation network in order to understand long-term fluctuations in basic meteorological parameters in the atmosphere (temperature, water vapor amount, and so on). Precipitation is a basic water balance quantity and we need to understand its long-term spatial and temporal variations. We should not only use ground-based observations, acquire and use global satellite precipitation radar data, and make full use of data assimilation techniques, but we should also acquire high-sophistication precipitation data. To do this, it is necessary to build a cooperative relationship with experts in fields such as remote sensing, radar, and data assimilation. For ground-based observations, as well as to improve winter snowfall observation technologies, we aim to maintain and increase observation points.

For greenhouse gases, we aim to maintain the current monitoring observation system, while adding a new observation point and capturing long-term concentration changes. In addition, there is also a need to continue to maintain and develop high-precision observations of isotopic ratios, with information about the source and sink of greenhouse gases. In addition to understanding emission increases due to the abrupt expansion of human activities in the Arctic Circle (based on the fact that changes in fluxes due to Arctic environmental change are expected), knowing the flux of greenhouse gases in terrestrial and marine areas is important. In addition to data near the ground, we can utilize aircraft observations and satellite data to understand three-dimensional space-time variation in greenhouse gases.

For observation of short-lived gases, clouds, and aerosols at bases where long-term monitoring is performed, it is desirable to maintain continued observations; it would also be useful to provide a monitoring center by establishing an observation base in areas for which long-term observation data has not been obtained (Arctic Ocean, Siberia). Since short-lived gases, clouds, and aerosols have intense spatio-temporal variation, it is also important to periodically deploy observations using ships, aircraft, and other flight craft, and to verify the physical and chemical properties of clouds and aerosols in each area (optical properties, number concentrations, size distribution, composition, etc.) and spatio-temporal variations and trends in short-lived gases. Furthermore, we can also use satellite data to track spatial variation in distribution of clouds and aerosols.

Terrestrial monitoring

a. Long-term and continuous observation of the terrestrial environment using the same satellite for more than a few decades

Data from AVHRR sensors onboard the NOAA satellites is amongst the most widely used long-term data (more than 30 years) for vegetation change analysis at continental and global scales. These data sets enable us to analyze and detect extension of vegetation growing seasons and changes in vegetation photosynthetic activities responding to climate changes (e.g. Suzuki, 2013). The NOAA AVHRR data contains large uncertainties in terrestrial signals due to effects such as replacement of sensors and satellites, orbital drift, and difficulties in atmospheric correction. On the other hand, the improved atmospheric correction and observation wavelength bands of recent satellite observations such as SPOT / VEGETATION (observation period: 1998 to present) and Terra / MODIS (observation period: 2000 to present) provide better quality data compared with NOAA AVHRR. This observation data covers a 10–15 year period, and through continuous future observation, it is expected to be possible to detect changes and trends in vegetation amount and activity.

In recent years, there has also been frequent vegetation monitoring using a spaceborne L-band microwave synthetic aperture radar such as ALOS PALSAR (SAR). SAR data are quite useful for estimating aboveground biomass in the boreal forest and have been widely applied. This is because aboveground biomass in the boreal forest is much smaller than in tropical forests and the backscatter intensity from SAR is not saturated in the boreal forests. Long-term observations by the L-band microwave SAR are expected in future.

In terms of the importance of change detection over longer time scales, it is important to construct satellite observation networks aiming at long-term observation of more than ten years at a minimum. For example, the observation satellites planned in Japan need to be developed from the perspective of needing long-term observation, including by planning successors.

In recent years, we have not only seen the development of data products of surface biogeophysical parameters as satellite projects, but it has also become possible to provide various biogeophysical parameter products at each individual study group level. In addition, integration of multiple satellite data provide the possibility of producing better products, by maximizing the advantages of data from each individual satellite. It is important to construct a base for building these biogeophysical parameters in individual groups, even without participating in satellite product development projects.

b. Long-term continuous observation of meteorology, flux and vegetation phenology

In the past, various meteorological stations have been deployed, and development of wide-area grid data has been advanced by using these in several institutions (e.g., CRU data and APHRODITE precipitation datasets). However, the area where meteorological data etc. can be widely used is limited; in Siberia, for example, the network of observation stations is sparse compared to other regions. Development of meteorological observation networks and observation data in these areas is important.

Ground tower observations of heat, water, and carbon fluxes are the most directly relevant monitoring aspects for understanding spatio-temporal variations in heat, water, and carbon balances. To measure global water, heat, and carbon fluxes, a ground observation network called FLUXNET has been in use since the 1990s. Although more than 500 sites in the world are currently registered in FLUXNET, there are 10 sites (each) in Alaska and in the Nordic area, and only about 5 sites in Siberia, notwithstanding the latter's vast area. Even though the Arctic is an important area for the Earth's carbon cycle and heat balance, given the severity of its natural conditions and low population, observation point density is sparse at present. An observation site in east Siberia (Yakutsk suburbs) was established through the GAME project in 1997 and is one of few sites jointly maintained by Japan, Russia, and the Netherlands. Flux data is necessary and essential for validating land-surface models; from this perspective, so-called super site specific ground-based observations, where observations of meteorology, snow and ice, hydrology, vegetation, and soil are carried out at the same point, are important. Moreover, it is critical to have river basin discharge observations (including at the observation site); these are important for verification of water balance. Long-term variations in the land surface and vegetation environment have been considered to be strongly influenced by soil temperature and soil moisture, and continual observation of these parameters is also important. There are presently only few super sites, such as Yakutsk and Fairbanks in the Arctic, and there are challenges in terms of development and maintenance of long-term comprehensive observation sites (see also Theme 4).

For observation of fluxes, previous studies have focused on relatively short-term fluctuations, such as seasonal variation. In recent years, there has been more emphasis on detecting inter-annual variability, and sites with an observation period of more than ten years have increased. We are now attempting detection of trends of ten or more years duration. These long-term observations allow for detection of, for example, the carbon balance change due to climate (Ueyama et al., 2014). In future, it is expected that the number of observation sites where long-term observation is possible also increases by continuing current observations, allowing for continued improvement of the reliability of trend detection. Furthermore, in areas where large variations in the carbon balance are expected, such as where variation tendencies are accelerated by future climate change, it will be necessary to develop a monitoring network for early detection of these variations.

For vegetation phenology, observation networks are being deployed, such as those of PEN[56], performing fixed point photography of forest landscapes by fisheye lens cameras. However, there are only very few observation sites at present, and more sites across a wider range are needed. Further, by carrying out trend analysis on the timing of variation, such as by using leaf indicators, it will be possible to detect variation signals at more sites. Moreover, through fusion with satellite data, we expect to be able to scale up results to discuss the phenology information of a wider area.

c. Increase in ecosystem forest plots and tree census and long-term maintenance over 100 years

With climatic changes, signs of changes in vegetation have been reported. In North Slope, Alaska, by comparing recent photos with photos from 1950, it was noted that shrubs have increased in the tundra (Tape et al., 2006). In addition, the dynamic global vegetation model has predicted that deciduous forests that currently exist in Eastern Siberia will disappear by 2300, with northward expansion of the distribution area of evergreen forests in their stead (Kawamiya et al., 2012). To capture changes in vegetation over a 10-year, and furthermore, a 100-year scale, it is expected that data measurement at vegetation survey plots in various places continues over a 100-year period at intervals of several years; relevant data includes, for example, species composition, number of trees, diameter at breast height, and tree height. It will be essential to establish a strong human mechanism for maintaining vegetation survey plots over this time scale. In addition, it would be ideal for such plots to form part of networks of long-term ecosystem research, such as the domestic network JaLTER and the international network iLTER, allowing for survey data to be a global asset. It would also be very useful for such plots to play a role as ground validation sites for satellite observations.

d. Long-term monitoring of vegetation ecosystems, especially around ecotones

Due to large differences in the state of taiga and tundra vegetation, there are differences in the albedo of the ground surface, roughness, soil conditions, state of snow, and snow accretion. There are also differences, in that the leading greenhouse gas is carbon dioxide in the taiga, but methane in the tundra. For this reason, the respective heat, water, and carbon balances are different, and the distribution of taiga and tundra greatly affect the climate. To elucidate the state of vegetation, water cycle information concerning stable isotope ratios (such as of water, carbon, and nitrogen) is very useful. Despite the importance of the shift in the taiga-tundra ecotone, present information is largely insufficient. For understanding ecotone shifts, we need accurate monitoring in the field and using satellites, also focusing on isotopes.

e. Accumulation amount of carbon (biomass, soil organic matter)

Monitoring of carbon stocks is also important, together with flux measurement. In particular, carbon content in soil is likely to be released with future climate change, making it important to estimate the size of such potential carbon emissions through a more reliable estimate of biomass. As pointed out in the section on cryospheric monitoring, thawing of permafrost has been strongly involved in processes such as methane release. Since changes in frozen ground vary greatly by region, detailed monitoring is required. In addition, the release of methane is also affected by differences in soil moisture with microtopography. Spatial differences in this narrow area must be monitored continuously, not only through automatic observation, but also through long-term on-site observations.

[56] PEN: Phenological Eyes Network

Theme B: Earth system-modeling for inter-disciplinary research

Abstract

If we try to understand the Arctic area, in which various complex processes interact with each other, we need an earth system model to deal with the entire system. Here, the current state and challenges of modeling are discussed, from the aspect of individual fields, such as the atmosphere, ocean and land, and also system modeling of integrated fields. The key questions are as follows:

Q1: What are the development challenges for earth system modeling?

Q2: What are the development challenges for atmospheric modeling?

Q3: What are the development challenges for ocean-sea ice modeling?

Q4: What are the development challenges for land-cryosphere modeling?

For research using the earth system model, we can be more efficient by selecting the one suitable for the time scale of the subject concerned. If the models are used to predict outcomes for several years or less, they must be precise and reliable. Hence, we need to achieve a higher resolution in regional models. The models for studying the longer time scales need to provide a secure representation of paleoenvironmental experiments and future projection. For this purpose, it is desirable to develop models that replicate the heat and water balances and represent the geochemical cycles, ecosystems, snow and ice processes accurately. Of primary importance for both cases is the correct selection of parameters, and also the evaluation of the effect caused by an error generated in one of the other elements.

Each field, which forms the earth system model, has its own subject. The central subject for the atmospheric models is verification of a non-hydrostatic, high-resolution model which explicitly describes the behaviors of clouds, and also a hydrostatic normal-resolution model with the cloud parameterization by using cloud data. The subjects for the ocean models are improvement of water mass formation modified by the inflows to the Arctic Ocean and vertical mixing, and also parameterization of the ecosystem processes. The sea ice models have the subject to improve dynamic and thermodynamic processes at the pack ice scale and also mixed-layer processes under sea ice cover. The subjects for the land surface models include verification by use of paleoenvironmental indices, application of data assimilation techniques, improvement of duplication of interactions with the other elements, and then, development of the framework within the system model for long-term integration or off-line experiments. Our preference would be to use the earth system model as a basis for linking various fields of the Arctic area, through the initiatives described for the individual fields.

Structure of this theme

The global climate system is a complex one, with interactions between elementary processes occurring in the atmosphere, ocean, and land surface. The Arctic is much more complex than other areas, because, in addition to these processes that are present also in areas other than the polar region, the Arctic has cryosphere and ice sheet processes also. To understand the various phenomena occurring in the complex Arctic and also to accurately project the future state of the Arctic (including uncertainty), experimental equipment needs to be developed and used, so that the sophisticated climate system may be dealt with as is. However, it is actually very difficult to prepare such a device in the real world. The substitute is a computer numerical model, developed on the basis of scientific principles and insights into natural phenomena. The earth system model, which is expected to reproduce the climate-environment system, plays an important role in climate and environmental research. In this theme, we describe the present state, development challenges, and verification methods of earth system modeling from the perspective of Arctic research.

Numerical models are widely used as research devices in the field of earth science, also beyond climate studies. In this theme, we describe numerical models for the primary purpose of understanding climate variability in the earth surface layer. Elementary processes that are objects of climate studies are distributed over atmospheric (physics, chemistry, and material cycles in the troposphere and stratosphere), ocean-sea ice (physics, chemistry, material cycles, and ecosystems) and land-cryosphere (ground ice, snow cover, soil, rivers, vegetation, and ecosystems) components. Here, the material cycle usually denotes the biogeochemical cycle for the ocean and land but is also used as more general terminology. First, we describe the current state and challenges of earth system modeling, with these fields integrated in Q1, and then focus individually on atmospheric modeling (Q2), ocean-sea ice modeling (Q3), and land-cryosphere modeling (Q4).

Q1: What are the development challenges for earth system modeling?

a. Introduction

We describe development challenges for earth system modeling through numerical models from the viewpoint of Arctic research. In general, earth system modeling is used to denote a coupled model which includes the carbon cycle and related elementary processes (IPCC/AR5); here it is defined as a model to integrate multiple elementary processes, taking the entire earth or a specific region into account; if the latter, principles are extended to the entire earth. Purely physical models are also dealt with. Please refer to other sections of this theme or to other themes for models dealing with only individual elementary processes.

Earth system models are developed on computers having finite capacities or computational resources. It is impossible to perform simulations for periods of several thousands of years with models handling precise processes or spatially fine phenomena. If we need to explain climate variability spanning several thousands to several tens of thousands of years, we have to compromise, with coarse spatial expression or low resolution models. It is therefore necessary to choose models appropriate for the phenomena and targets being addressed. In Figure 60,

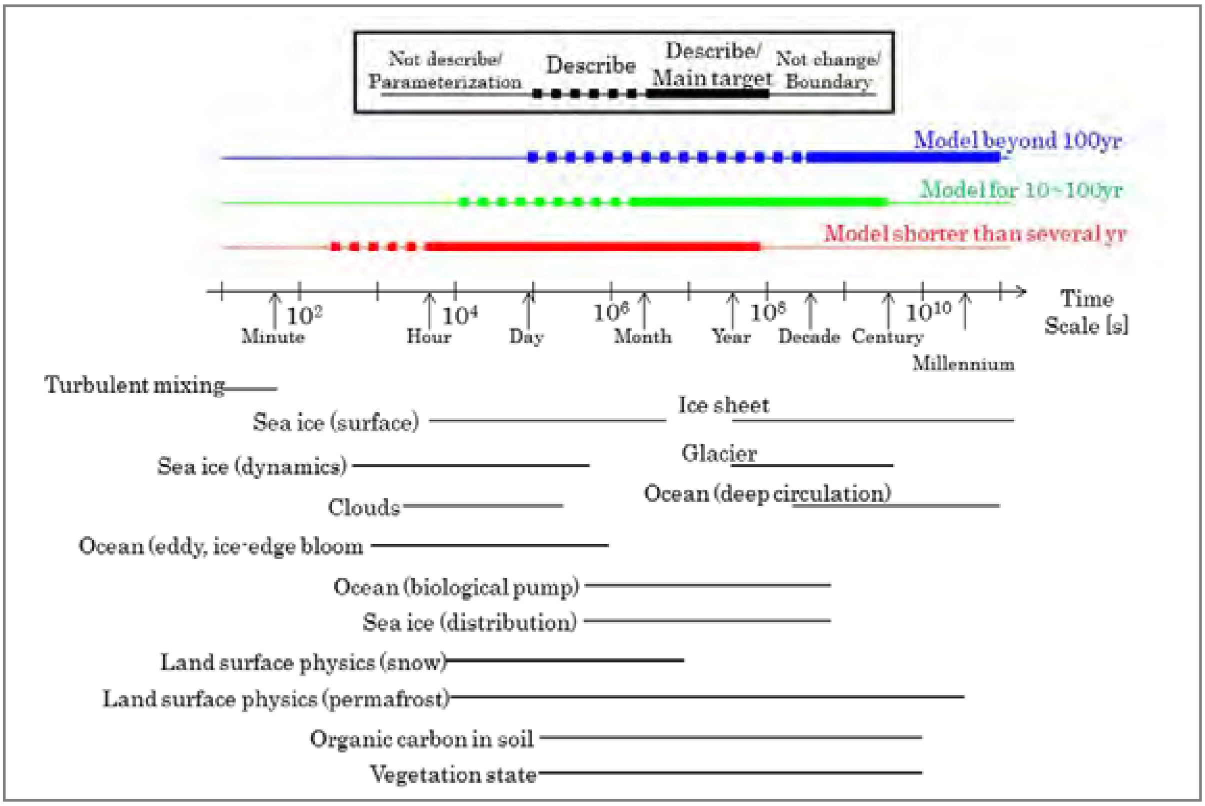

Figure 60: The time scales of the representative models (upper part) and the time scales of individual processes related to the Arctic. If both time scales agree with each other between the models and processes, the models are suitable for dealing with the processes.

we show the time scales of targets handled in typical models and also time scales of the main elementary processes involved in the Arctic area. Here, time scales denote the time lengths for which targets and phenomena may range. We describe the current state and future development issues for each of the models suited to different time scales, and then outline issues with these models, focusing on the evaluation of uncertainty.

b. Earth system model issues with time scales shorter than several years

Models suited to this time scale are those with the highest resolution; these are currently possible using available computational resources. By increasing resolution, it is possible for models to express flow fields on steep topography, eddies, vortices, and convection. Repeating the same type of experiments is effective for a sensitivity study, as well as to separate random errors and statistically robust results, allowing for more reliable predictions. Examples of problems to be solved with this type of model include predictions for the Arctic for periods ranging from a season to a few years, as well as quantitative estimates of anthropogenic impacts on extreme weather events. A particularly relevant problem in the Arctic is prediction of navigation through the Arctic Sea Route, which is expected to become possible more regularly as a result of the rapid decline in sea ice in recent years. If we try to predict navigation over one year, we need to improve atmospheric prediction by predicting amplitudes and phases of natural variations. It is important for this purpose to start predictions from initial conditions consistent with model physics and observation data by using data assimilation methods (see Theme C). It is further desirable to advance collaboration with engineering techniques for social application of these prediction results to marine state forecasts. The results of high resolution models can be more easily compared with observation data because topography and spatial structures are precisely described, providing for spatial correspondence with data. For this reason, such models are useful as a basis for various research aspects related to specialized field observations.

High resolution models require significant computational resources for experiments and for analyses of results. We should consider wise use of computational resources for problems that require high resolution in the Arctic. In practical terms, effective methods are regional models focusing on the Arctic area, using nesting techniques to embed high resolution Arctic models within global models having relatively lower resolutions. In the United States, several research centers have collaborated to develop and improve a regional model (RASM13) that reflects elementary processes in the atmosphere, the ocean, sea ice, and terrestrial hydrology. However, no such initiative has yet taken place in Japan. Nesting of earth system models has just started, while atmospheric and ocean models are independently nested within corresponding global models. The research community in Japan should focus more on developing earth system models using nesting techniques.

Below, we list individual issues related to high-resolution earth system modeling. In connection with Northern Sea Route predictions, we should promote the development of a sea ice model that precisely describes mechanical processes in the ice edge zone. We need to integrate material cycle and ecosystem models with high resolution physical models, so that we may understand both localized phenomena and effects on large-scale climate fields. However, in order to efficiently use limited computational resources, we need to develop model structures within which elementary processes can be easily added or removed, in accordance with the simulation aim.

c. Earth system model issues with time scales of between ten and hundred years

The models used for problems with this time scale (referred to as c-models) provide options for studying recent and future climate variability in the Arctic area from various perspectives. "c-models" usually have lower resolution than models for problems with time scales shorter than several years (referred to as b-models), and often deal equally with the entire earth, not limited to the Arctic area. As experimental devices, c-models can be used with less computational resources than b-models and are hence used more easily for discussing interactions between many systems, including material cycles and ecosystems. Global c-models can be used to discuss interactions between the Arctic and other areas, for example, with respect to the effects of variations in sea ice and land surface on weather statistics in Japan.

Let us look at the future predictions of the IPCC assessment reports as a specific example. Japan contributed significantly to the IPCC assessment reports through "the Human-Nature-Earth Symbiosis Project", which commenced in 2002 for AR4, and through the "Innovative Program of Climate Change Projection for the 21st Century", which commenced in 2007 for AR5. "c-models" played a significant role in these IPCC reports. A global model that includes the Arctic area is currently also being developed through the "Program for Risk Information on Climate Change", which commenced in 2012. However, in terms of models dealing with the Arctic, where climate is changing more rapidly and extensively than in other areas, it is not sufficient to reproduce the present state. We should continue model development as presented below, so that various states that could occur may be reproduced with statistical stability. The evaluation of model reproduction is discussed in Section e.

Heat and water budgets are important elements for representing climate variability in earth system models. Cryosphere processes in the ocean and on the land surface, such as sea ice, land ice, permafrost, and snow cover, are particularly important in the Arctic. These processes significantly affect heat and water balances through albedo variations, possibly inducing climate variations at the decadal time scale. The reliability of climate variability projections could be improved by incorporating components that are not yet sufficiently represented in earth system models, e.g., reductions in the albedo of snow and ice due to dust and micro-organisms, and the thermodynamic effects of melt ponds on the upper surface of sea ice. In addition, it is important for earth system models to ensure consistency across these element models, which are often developed individually. We need to deepen understanding through collaboration between researchers working in various fields, such as the ocean, land surface, etc.

In the case of c-models with relatively low resolution, there are many elementary processes that are important but difficult to express due to insufficient resolution. For heat and water balances, examples include clouds in the atmosphere and eddies and vertical mixing in the ocean. For improved reproducibility, it would be indispensable to incorporate these effects with expressible forms in low resolution models (parameterization). We need to promote the development of parameterization in close cooperation with elementary process models and b-models.

Another important point to be considered for c-models is related to variations in material cycles and ecosystems and their effects on climate variability. Earth system models should express responses of vegetation and ecosystems to climate variability. Forest fires and permafrost melting are remarkable phenomena in the Arctic. As a result, ground organic carbon decomposes, emitting carbon dioxide and methane, which accelerate global warming. It is necessary to express the feedback mechanisms related to the carbon cycle to improve terrestrial ecosystem models, so that we may accurately estimate carbon fluxes from photosynthesis and respiration, and also carbon stocks from plant biomass and soil organic carbon under conditions of climate variability. Vegetation variability is also important because of the effect on albedo. Modeling of material cycles and ecosystems is insufficient in Japan relative to some foreign countries; this is not ideal for Arctic research. We expect further development of these element process models, which can be directly linked to earth system models.

d. Earth system model issues with time scales beyond hundred years

When problems with this time scale are dealt with, we use earth system models (referred to as d-models) with similar structures but that can be operated with fewer computational resources than c-models. The concrete strategy is to lower resolution and to express elementary processes more simply, including through more parameterization, allowing us to carry out experiments spanning longer periods of time. Examples of problems include simulation of paleoclimates and experiments for understanding ice sheets and the deep ocean over long time scales. "d-models" can be operated for individual experiments with smaller computer resources and can therefore be useful for a large number of experiments; examples are sensitivity studies to examine results by varying model settings from one case to another. To be used for these various purposes, d-models are thus expected to contain a number of elementary processes and parameterization, which can be easily added or removed in accordance with the simulation aim.

The other purpose of d-models is to develop "All-in models" by adding ice sheets, vegetation dynamics, and crust isostasy to those composed of physical, material cycle, and ecosystem components. Models with more processes lend significance to Arctic research, since there are more processes here than in other areas. Most newly-implemented processes have a wider variety of time scales and spatial sizes than processes that are already included. Examples of additional components are ice sheets, which are located at limited locations but that have time scales longer than one thousand years, and also vegetation dynamics, which act on interactions of vegetation types and sizes with climate variations over time scales of several decades to several centuries. The combination of these new elementary process models is a major scientific challenge by itself. We should actively contribute to projects to implement new elementary process models in earth system models.

The earth system model, once built as described above, could express large-scale transitions specific to terrestrial ecosystems, such as advances of the taiga forest into the tundra region due to global warming, and regime shifts of the vast amounts of organic carbon accumulated in Arctic peat lands (Ise et al., 2008). Here, we focus on interactions between the ecosystem and climate variability through the material cycle. Since such interactions often occur with a long time lag from impact, we need to develop the model that reproduces long time scale processes.

It is difficult to verify experimental results of d-models against observation data, because observation data have not been continuously obtained for more than 100 years. The results of paleoenvironmental experiments are therefore often verified in comparison with proxy indices, which are considered to reflect certain aspects of the past environment recorded in core samples taken from seabed sediments and ice sheets, or temperature and precipitation recovered from the proxy indices. Attempts to reproduce the paleoenvironment in earth system models are important for improving model reproducibility. Furthermore, if proxy values can be produced in the models and compared with data, the reliability of earth system models, including the Arctic area, would be improved. It will be indispensable to improve various model aspects, such as sea ice distribution, changes in vegetation distribution, the production processes of dust and micro-organisms, transport of various aerosols in the atmosphere, isotope ratio changes in the atmosphere, isotope ratios and acidity of seawater, and ocean circulation in and around the Arctic Ocean, including deep water formation. It would be ideal for researchers in various fields to collaborate with each other, including with researchers specialized in observations.

e. Issues relating to earth system models: evaluation of uncertainty and collaboration with monitoring

The current states and development issues of earth system models have been described in previous sections by separating these into several time scales. The other important issue relates to verification and evaluation of uncertainty included in model results by comparing model results with observation data, with uncertainty often related to model errors and also to shortage of scientific understanding. Here, we outline issues and related proposals concerning verification of uncertainty in Arctic earth system models.

During discussions, we need to take note of the importance of uncertainty in earth system models, i.e., we cannot understand uncertainty by simply superimposing uncertainties of the individual elementary process models of which the earth system models are composed. In most cases, individual elementary process models are verified with experiments under the “right” boundary conditions. However, the elementary process models built into earth system models are driven by information comprising errors from the models, thus conveying additional errors to other models. These errors are sometimes amplified due to interactions between elementary process models, while in some cases, errors do not significantly affect other components. Research on elementary processes cannot solely explain what interactions will occur. To reduce uncertainties in earth system models with such characteristics, it is of course necessary to improve low-performance components by understanding individual processes and developing more reliable models. Simultaneously, it is extremely important to evaluate error amplitudes relative to others by verification of earth system models as a whole.

With regard to methods of evaluation and verification of model uncertainty, we may refer to existing inter-comparison projects of numerical models. Examples include CMIP5, one of the groups promoting prediction research in IPCC-AR5, and AOMIP, the Arctic Ocean Model Inter-comparison Project. It is important for the research community in Japan to actively participate in these projects, so that researchers understand the uncertainty of their own models by transmitting their information and making comparisons with other earth system models. Three additional proposals are given below.

The first point is the necessity of monitoring and standard metrics for evaluation specific to the Arctic area. For earth system models covering the Arctic area or the entire earth, observation information covering a wide area is very important. Observation data are not sufficient when compared with other areas, due to the difficulty of observation. For this reason, monitoring is expected to be enhanced in future (refer to Theme A). In addition, standard metrics for evaluation should also be established to evaluate the uncertainty of certain processes in the models. One example is ocean current intensity along the shelf edge in the Arctic Ocean, as defined in AOMIP. Another example is sea ice cover: i.e., although the ice-covered area has been widely used, net metrics would be required to comprehensively evaluate the analysis outputs of dynamic fields.

The second proposal is for mutual enlightenment of modeling and monitoring from the viewpoint of system modeling. It is difficult for monitoring to directly measure specific elementary processes. It is also difficult to directly observe parameters that specify the intensity of processes expressed by parameterization in the models. We hence propose comparison in the following way. From the modeling side, we examine the effects of parameters on variables, such as temperature, salinity, and velocity, using sensitivity studies and data assimilation (see Theme C). From the monitoring side, observation accuracies are presented for these variables. If model errors are larger than observation errors, we assume that models are not sufficiently comprehensive, or that they have large uncertainties. This method is useful for verification of earth system models, and also indicates observation parameters and monitoring methods as significant outcomes.

The third proposal is for a method to evaluate the responses of the earth system model to main factors of climate variability. For example, if we consider air temperature, we compare the contributions of individual processes, taking the energy balance as a medium (see Q5 in Theme 1). Using this type of method, we can evaluate the relative importance of individual processes in earth system models. We can also compare evaluations across different models, and investigate dependence on various parameterization methods so that we may reduce uncertainty ranges. Once this method is combined with data assimilation, the responses of the actual earth may be evaluated.

In Q1 here, we have described issues related to the uncertainty of earth system models, along with proposals to address the challenges involved. The issues and proposals are common to all areas, even if they are particularly important for the Arctic. The reason for the latter is that so many processes interact in sophisticated ways and that Arctic models have larger error than models for other areas. Furthermore, there can be significant demand for information given recent rapid changes in the Arctic. From the reversal point of view, by posing challenges to develop and reduce uncertainty of earth system models, with a focus on the Arctic, we will improve reproducibility and reliability of the models, not only for the Arctic but also for the entire earth. Further, we can contribute to connections between various academic fields and also with society. Fortunately, Japan has researchers working on both modeling and observation in many fields. It is therefore desirable for researchers familiar with various methods in various fields to continuously and cooperatively pursue development and verification of earth system models.

Q2: What are the development challenges for atmospheric modeling?

a. The present status of research and related issues

First, we review the history of atmospheric model development with respect to problems specific to the Arctic. During the early stages of model development, gridding and process parameterization were common to the entire earth, rather than paying specific attention to the polar region. Representative parameterization is cloud formation, which has a very small horizontal scale. A numerical model usually has variables specified at grid points that are uniformly distributed along each coordinate axis. However, atmospheric models have been formalized to a spectral model, in which variables are expanded into horizontal Fourier modes, so that numerical errors may be removed in model calculations. The grid model on the conventional latitude-longitude system suffers from the problem of a very small time step with high longitudinal resolution (referred to as the polar problem). On the other hand, the spectral model has a problem of significant computation time for communication between many modes. To solve these problems, the numerical model based on icosahedrons, NICAM, has been proposed, together with non-hydrostatic dynamics and high resolution (Satoh et al., 2008).

A widely used method for focusing on a certain region is to connect a regional model with a larger-scale model through boundary conditions for both, referred to as “nesting”. This method has been used for detailed weather forecasts of a certain region, and has also been applied to Arctic regional models, which are connected with global models along boundaries in certain latitudes. Such projects have been promoted by international collaborations, such as MM5, and its successor, WRF. The models developed in Japan, JMA-NHM and CReSS, could also be applied to polar regional models. A regional model facilitates parameterization specific to a certain region. Some projects using Arctic regional models are currently underway, in which storm tracks are being predicted and verified in comparison with the actual phenomenon through a focus on increased low-pressure disturbances in recent years.

The Arctic area is usually covered by more clouds in summer and by fewer in winter. In spring and autumn, cloud amounts increase (decrease) responding to larger (smaller) open water areas, significantly affecting energy balances through the sea surface (see Theme 2). A study of note was carried out, verifying cloud distributions in a global atmospheric model; and reanalysis fields were also produced by assimilating observation data within the same model (deBore et al., 2014). Even though the study was based on substantial summer data, it is more difficult to reproduce cloud distribution and sea surface energy balances, compared with highly reproducible temperature and wind data.

b. Future research

We should improve the reproducibility of climate in the polar region by effective use of various hierarchical models, from global to regional, and from conventional coarse grid models to high resolution LES (large eddy simulation) models. To achieve this, model improvement is necessary based on verification against observation data for appropriate expression of polar clouds in numerical models. The processes involved are aerosol-cloud microphysical processes, boundary layer mixing, and radiation processes; and these could be expressed in the model, once it is verified against accurate observation data, and also equipped with improved numerical schemes (techniques used for numerical calculations).

The fundamental solution for exploring physical processes is to express phenomena explicitly with high accuracy, rather than through parameterization. Using the high resolution LES model, we should attempt to explicitly resolve turbulent flow in the land surface boundary layer, and also to precisely reproduce clouds, including cloud microphysical processes, by use of the bin method, in which cloud particle sizes evolve, shifting from one bin to the next. In particular, it is a challenge to reproduce cloud physics, including ice crystals and multiphase states. To correctly express the height of the boundary layer, cloud bottom height, and cloud thickness, we have to improve the boundary layer and cloud microphysics processes, and also consider reproducibility of large-scale fields. To understand the relationship between large-scale synoptic fields at high and low pressure scales and clouds and weather in the polar region, we expect usefulness not only of conventional global models with hydrostatic dynamics but also of regional models (WRF, JMA-NIM, etc.) and global non-hydrostatic models (NICAM, etc.). NICAM has features to explicitly express cloud physical processes and has been applied to research relatively small scale phenomena, such as typhoons, for which we expect to reproduce cloud formation through non-hydrostatic processes. In terms of applications to the Arctic, we have started analyzing Arctic low pressures and verifying storm tracks, while verification of cloud formation may also be significant.

By reference to objective verification, in which the results of several global models are compared with reanalysis fields, we propose a study to compare a common variable between observation data and the results of several different types of models. This comparison project should be performed with a focus on cloud distribution, which is important but difficult to reproduce. Model members include the global non-hydrostatic model, and also regional models nested within global models. With respect to dynamics in comparison with non-hydrostatic models, members need to include hydrostatic models with cloud formation parameterization. In the case of several models being used, several researchers or institutes would need to form a collaborative team.

Q3: What are the development challenges for ocean-sea ice modeling?

a. The present status of research and related ocean model issues

The Atlantic Water flows into the Arctic Ocean through the Fram Strait and the Barents Sea, forming the Fram Strait branch water and the Barents Sea branch water. The Barents Sea branch water increases its density due to sea surface cooling in the Barents Sea and penetrates underneath the Fram Strait branch water (Figure 61). These water masses flow as a cyclonic boundary current along the Siberian shelf slope and affect stratification in the basins due to shelf-basin interactions. On the other hand, the Pacific Water, which flows through the Bering Strait, interacts with Siberian shelf water, the Atlantic Water, and saline water rejected from sea ice formation, contributing to sophisticated stratification in the Canada Basin. The stratification produced from the surface mixed layer, eddy motion, and water mass transport from the shelf edge to the basin area are crucial processes for ocean models to reproduce ocean circulation in the upper layer and the basins.

With regard to modeling status, we first describe the current state of reproducibility of the Arctic Ocean using earth system models, by referring to CCSM4 used for a climate study as a typical example (Jahn et al., 2012). The ocean model, POP2, implemented in CCSM4, has horizontal resolution of 1 deg and 60 vertical levels, along with parameterizations for mixing processes, in which temperature and salinity fluxes are included in terms as functions of the isopycnic layer thicknesses for eddy-induced mixing. Mixed-layer development is controlled by turbulent mixing.

CCSM4 has reproduced representative water structures in the Arctic Ocean, even if there are a few problems to be resolved, including the location and strength of the Beaufort Gyre, the depth of the temperature maximum in the Atlantic Water layer, volume and heat transport through the Fram Strait, and temperature in the deep Arctic Ocean. These problems are partly related to the low horizontal resolution and poor reproducibility of deep water supply caused by vertical mixing. For horizontal resolution, it is therefore necessary to partly increase the resolution in the main straits and bottom topography, or instead to adjust topography so that fluxes may be fitted with observations. As for vertical mixing, we need to reconsider whether the parameterizations of breaking internal waves and deep dense water flow are appropriate for the Arctic Ocean.

Although uncertainty still remains, due to a lack of observation data and quantitative discussion, we need to note the following important processes. For variability of the heat flux, which starts in the Atlantic Water layer, crosses the halocline, and reaches the sea ice cover,

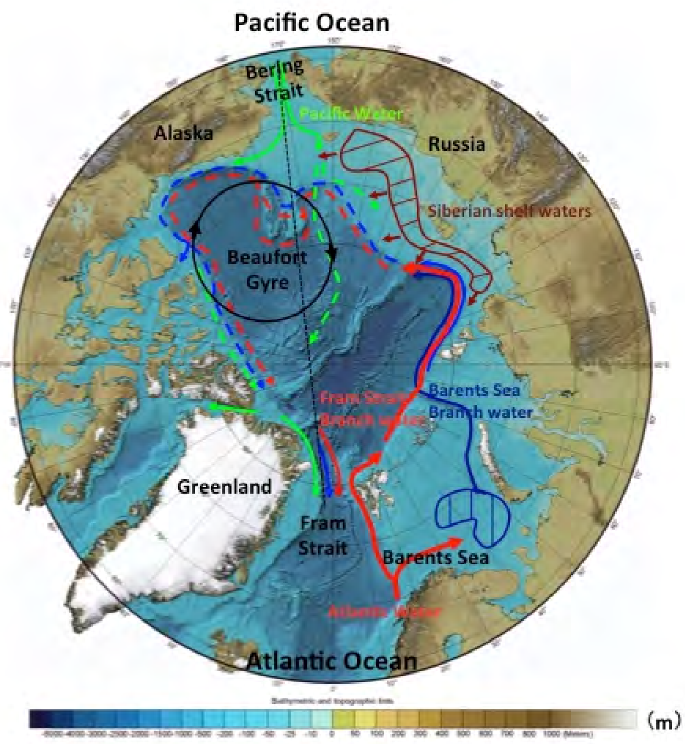

Figure 61: Schematic of near-surface circulation of the Arctic Ocean (solid arrows known flows; dashed arrows, presumed flows). Vertical section from Bering Strait to Fram Strait indicated by a black dotted line connecting is shown in Figure 62. Bathymetry is from IBCAO.

important processes include vertical mixing caused by winds and tides, upwelling Atlantic Water along the basin rim, and vertical circulation due to eddies (Figure 62). Further observation data and process studies are indispensable for understanding the spatio-temporal variability in these processes (refer to Theme 2 for detailed process studies). The steady state in the middle and deep layers of the Arctic Ocean is maintained by deep water, which is supplied by an overflow from the Greenland Sea, rises slowly and mixes with even a small amount of water penetrating from the middle layer. In cases when there is no realistic supply of deep water, an extremely small vertical mixing coefficient could help vertical stratification, whereas the steady state is different from the real field. Both intrusion of deep water and mixing with the middle layer are therefore necessary for having a realistic vertical profile in middle and lower layers. These deep water formation and transport processes are particularly crucial for long-term integration of the century scale (refer to Q2 in Theme 5 for middle and deep layer circulation).

When incorporating marine ecosystem processes into earth system models, we should consider the number of nutrients and biological species. As long as the governing equations are not extremely complicated, the related computational load is not high. However, advection and diffusion calculations increase in proportion to the number of variables, with the computational load then becoming higher for schemes with high accuracy. We should therefore select only nutrients and plankton species that are definitely necessary. Another option is compromise, by using a scheme with lower accuracy for biological and chemical variables. It is not easy to determine what is responsible for a mismatch with observation data, whether uncertainty of ecosystem processes, or reproducibility of background physical fields. In Japan, although the target area was not the Arctic, comparison of model results was performed by coupling a common ecosystem model with various physical models. We need to establish an effective evaluation method.

As sea ice cover declines in the Arctic Ocean, biological productivity may become more active in the basin area, and it will then be necessary to express appropriately iron-limitation processes and transport processes of shelf waters rich in iron. At the stage of discussing differences between ocean areas, we might need to incorporate denitrification and nitrogen fixation processes. These issues are central, even for ocean-only models; and we should hence consider, on the basis of obtained knowledge, the extent to which these should be dealt with in earth system models. The verification of marine ecosystem variables is usually carried out by comparing chlorophyll concentrations estimated from satellite measurements and nutrient concentrations based on in situ measurements. However, significant errors associated with subsurface chlorophyll maxima are included in the satellite data algorithm, by which a vertically integrated amount of primary production is estimated from information collected at the sea surface. As for nutrients, it is only the World Ocean Atlas that covers a large area. This data set retains only climatic information and hence is not usable for discussion of inter-annual variability. The problem is thus that observation data for the marine ecosystem are too limited compared with physical data.

b. The present status of the sea ice model and related issues

We need to focus on sea ice variability at time scales from several days to several decades, with consideration of variability in the earth system at time scales shorter than

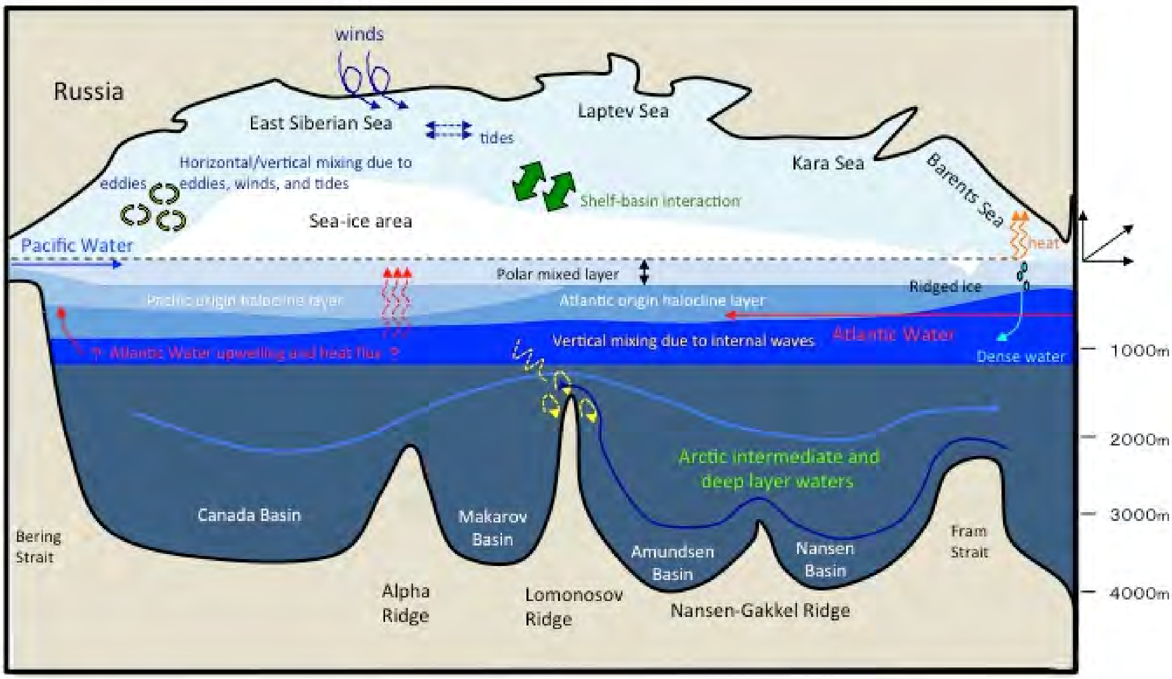

Figure 62: Schematic of vertical structures and sea ice-ocean processes in the Arctic Ocean (see Figure 18 of Theme 5).

several years, and also from a decade to a century. At present, coupled sea ice-ocean models with atmospheric forcing reproduce well seasonal and inter-annual variations larger than several tens of kilometers in the sea ice area: e.g., AOMIP. However, coupled atmosphere-sea ice-ocean models (such as CCSM4) underestimate the rapid decline trend of sea ice cover. Even though this discrepancy is not attributable only to sea ice models, we discuss the dynamic and thermodynamic processes of sea ice, to be considered for future earth system models. Since some points have already been discussed in Theme 2, we focus here on three problems.

(1) Two fundamental processes for dynamic growth of ice thickness are ridging and rafting in ice cover composed of ice floes. Ridging means a thickness increase by deformation due to collision of ice floes, and rafting describes one ice floe running above another. Both processes are crucial to changes in the spatial distribution of sea ice thickness. Since there are inadequate observations to understand the extent to which sea ice experiences ridging and rafting, it is still difficult to express ridging and rafting of relatively thin ice in gaps between thick ice floes, even if this may be an important deformation process for ice floes smaller than 10 km.

(2) In mixed layer processes underneath sea ice, brine (high salinity water) rejected due to sea ice formation tends to mix with surrounding sea water and contributes to deepening of the surface mixed layer, resulting in a heat flux from the subsurface layer to the sea surface. In addition, heat release also occurs due to turbulent mixing driven by winds and breaking internal waves. It is thus crucial, in terms of the thermodynamic processes of sea ice, to understand the extent to which the mixed layer depth changes below sea ice and how much heat is transported to the sea surface or to the bottom surface of sea ice.

(3) With respect to the effects of fast ice, AOMIP model results have suggested the need for parameterization of fast ice formation and growth, so that the reproducibility of sea ice cover may be improved along coastlines with fast ice. In addition, the seaward extension of fast ice provides crucial information for the safety of vessel navigation along the Northern Sea Route and hence should be noted as a future issue for route prediction.

The three problems described above have been noted to be important, even if quantitative discussion based on observation data is not yet sufficient, requiring further refinement. First of all, we need to understand physical processes and quantitative estimates using observation data and process models. Using the technologies and data of satellite observations, where Japan's achievements are highly valued, we expect to develop new schemes and parameterization to be used in earth system models. The concentration and area of sea ice are widely used for verification of sea ice models, although ice thickness data remain insufficient (e.g., Jahn et al., 2012). Given the fact that sea ice is changing from multi-year to seasonal in the Arctic Ocean, we should enrich ice thickness data through continuous observations in time and space, as an important element of this long-term plan. The scale dependence of ice deformation rates is expected to be useful for examining the reproducibility of the sea ice field, through comparisons between observations and models.

c. Contribution and roles of the research community in Japan and relationship with main projects

Two climate models are well recognized in Japan as a basis for earth system models; MIROC was developed by UT-AORI, NIES, and JAMSTEC for MIROCESM, and MRI-CGCM was developed by JMA-MRI for MPI-ESM1. These two climate models participated in CMIP organized by WCRP, and contributed to the future projections of global warming included in IPCC-AR5. From now on, we should develop earth system models based on the latest

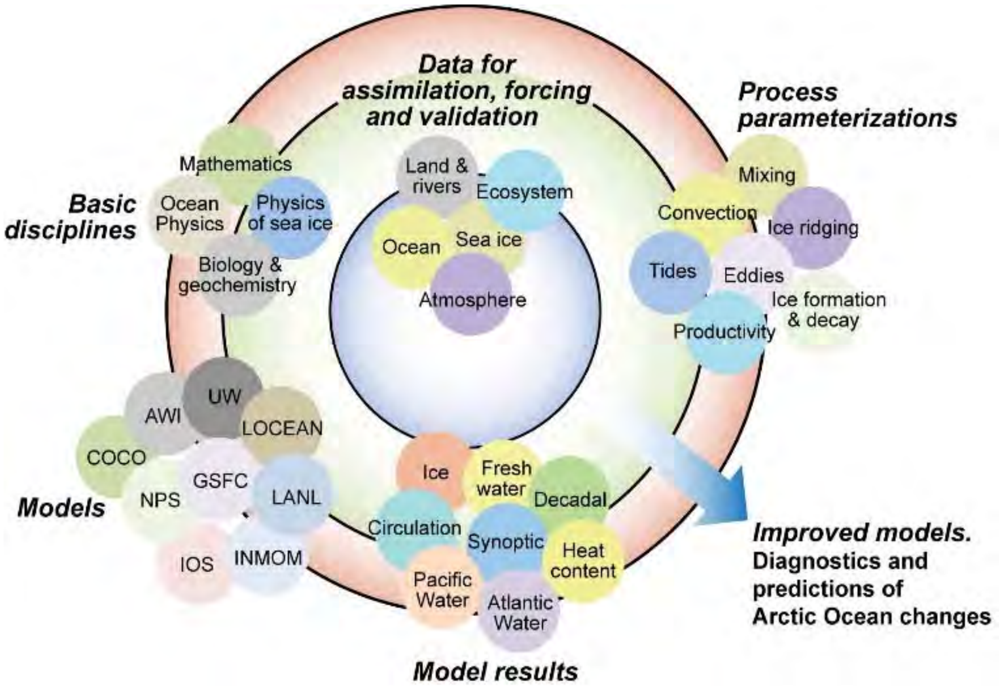

Figure 63: Schematic figure of approaches by AOMIP/FAMOS, taken from Proshutinsky et al. (2011).

climate models (e.g., MIROC5, Watanabe et al., 2010), and contribute to research for CMIP6 and IPCC-AR6, in which we will attempt to understand the processes listed as issues for ocean and sea ice modeling (see also Theme 2) and to reduce uncertainty in projections by implementing ocean and sea ice models in earth system models.

Research using the sea ice-ocean component of MIROC has contributed to AOMIP specifically through coupled sea ice-ocean models of the Arctic Ocean (Figure 63, and see Theme 2); our roles will be increasingly important also for FAMOS, the successor of AOMIP. Sea Ice Outlook is an international project forming part of SEARCH, aiming to provide predictions of the summer sea ice areas in early spring; Japan supplies these predictions, using satellite data. Since observation data are indispensable for improvement of earth system models and climate models, our contribution to this type of project will be more valuable through use of satellite data, Japan's specialty.

Q4: What are the development challenges for land-cryosphere modeling?

In some cases, it is possible to reduce uncertainty of phenomena for the land surface element in earth system models at decadal to century time scales, by improving the phenomena at time scales from 1000 years to 10000 years. This element model could thus be verified and then improved by using dust aerosols and atmospheric methane concentrations, which have been reconstructed from paleoclimatic indices and shown to be different in different eras. Dust aerosols are dependent on vegetation cover, soil moisture, and wind speeds, and methane emissions are dependent on wetland distribution and organic carbon stocks. These parameters can therefore be used for verification of land surface models, even if present-day data samples are too limited and cannot be used for quantitative comparison with models. As a result, we expect a reduction in the uncertainty of global warming predictions focusing on the century scale. In addition, dust accumulation is influenced by atmospheric circulation transport and dust data could thus contribute to verification of global atmospheric circulation. Since dust and methane affect climate through radiative forcing, reducing their uncertainty is important for future predictions.

It is important in the land-surface and cryosphere models to accurately reproduce variability in permafrost on a decadal scale and longer. In contrast to snow cover, which usually melts away in a year, permafrost is dependent on small heat fluxes, then acting as a memory and influencing heat fluxes, soil moisture, and vegetation for a long time. In addition to improving elementary process models such as water permeability to the permafrost, an important issue is how to reasonably determine the hydraulic and thermal parameters of soil at the global scale. Since vegetation cover on the land surface and the thickness of the withered material layer also significantly affect permafrost behavior (Yi et al., 2007), vegetation variability is crucial for permafrost variability predictions. Please refer to Q4 in Theme 12 for issues relating to individual elements, such as the permafrost, the atmosphere, snow cover, and vegetation.

Here, we focus on model development of ice sheets and glaciers, the processes for which have been described in Theme 4. Ice sheet processes are unique in the sense that topography is usually fixed in atmospheric and ocean models but changes in the ice sheet models. Ice sheet and glacier models are ultimately common, although they often have different configurations, depending on application to typical problems and for different purposes. Individual glaciers are small, but so many of them have a significant impact on sea level over a shorter time scale. Simplification and parameterization need to be developed so that several glaciers can be treated in the expression of integrated impacts. At the level of individual glaciers, detailed process models are required to understand variation mechanisms and to make predictions. The problems of ice sheet modeling have a wide temporal range, from a century to 100 thousand years. When we consider shorter time scale problems, such as variability in the Greenland ice sheet's response to global warming over 100 years or so, reproducing the present state is important. For this, we need to express the basal sliding process, using data assimilation techniques for ice sheet models. For model verification of these processes having time scales too long for monitoring, as in the case of land surface models, we need to attempt verification through comparisons with paleoclimatic information. Although conventional ice sheet models cannot express localized fast motion, which is dynamically important, we should improve models to reproduce ice sheet variability at long time scales, on the basis of understanding localized motion variations and their impacts on large scale motion.

From the perspective of long-term research and development, earth system models may have to be run asynchronously, with ice-sheet models integrated continuously for long periods and climate models integrated intermittently for short periods. Technological inventions are critical for managing very large computational resources. To understand ice sheet variability, in the past, present, and future on a common basis, asynchronous coupled ice sheet-climate models are indispensable, requiring careful selection of processes. The additional requirement is to appropriately introduce interactions between the atmosphere, the ocean, and the solid earth. As for coupling with the atmosphere, both ice sheets and glaciers require high horizontal resolutions to calculate melting. Typical coupled models now fill resolution gaps by introducing empirical mass balance models between the two models, although we also expect improvement of coupled models using physical models to explicitly include ice sheet topography and other small scale features. As for coupling with the ocean, ice sheets may receive impacts from basal melting of ice shelves and separation of icebergs (calving). Modeling of these processes is still immature, with large uncertainties, and requires high-priority development.

Researchers in Japan have participated in inter-comparison projects of ice sheet models and climate models related to ice sheet variability (Bindschadler, 2013; Sueyoshi, 2013, etc.). In particular, it is noteworthy that ice sheet and paleoclimate modeling researchers in Japan played a central role in determining boundary conditions during the last glacier maximum experiments of PMIP3. An important challenge for us is to stay at the forefront of model development, with a clear presence in the ice sheet-climate modeling community.

Theme C: Data assimilation to connect monitoring and modeling

Abstract

Here, we describe the techniques of data assimilation and the application to the Arctic environmental research, along with a survey of the present status. It has been confirmed that advanced techniques are in place for the operational forecast and the reanalysis system to be applied to the atmosphere-sea ice-ocean system. In the fields where data assimilation techniques have not been applied extensively, such as state estimation of the ice sheet, some applied examples are introduced. The current situation, as described above, has been built on the knowledge that long-term monitoring is important, the reinforcement by the improvement of observation techniques and the recognition of rapid climate change. On this basis, the future direction is proposed to combine observational techniques, and networks as well as numerical modeling techniques. For practical reasons, data assimilation research for the Arctic has to be selected according to the handicaps of the area: i.e., atmospheric measurements have limited coverage, sea ice thickness is not measured in situ, and remote sensing data are not available for the sea water. The long-term future direction is likely to be challenging for data assimilation to the multi-disciplinary system and aiming at the operational objective to implement forecast of the Arctic Ocean state for the safe sea routes. Considering the limited resources for Arctic research in Japan, an appropriate path is presented here, with regard to data assimilation research proposal. This report has touched on the necessary terminology for data assimilation literature and information on the discussed technology.

Introduction

Data assimilation is a general term for a technique to produce useful information by combining a model solution with data collected from a common system. Data assimilation has two objectives: state estimate and time-series control. The state estimation technique combines observed data with model variables and estimates a reasonable state of a system that contains large uncertainty due to no direct observations or highly uncertain data. The time series control technique guides progression in model variables through sequential matching with data. These two kinds of techniques are usually used in optimal combination for individual data assimilation systems: for example, in the weather forecast system, the state estimate technique provides an initial condition of an atmospheric circulation model, with the time series control technique then putting forecast error growth under control.

In global environmental research, data assimilation is a powerful tool for understanding various phenomena occurring in the climate system composed of the atmosphere, sea ice, and ocean, by combining observations, data analysis, modeling, and theoretical studies. Data assimilation is a basic technology for integration of these research methods, with potential for its outcomes to feed back into methods, through optimization of observation networks, production of reanalysis data, and estimation of model parameters. Once a physical model is coupled with chemical and biological components, the data assimilation technique is capable of integrating different research fields. Data assimilation studies in Japan for the Arctic lag significantly behind the rest of the world, and we hence need to consider work in this field with a top priority.

Here, we propose applying data assimilation techniques to explore individual processes related to environmental variability in the Arctic region. The international Arctic research community has projects to carry out observations in the Arctic Ocean (e.g., WWRP-PPP*, * is explained later), aiming at improvement of numerical models and forecast capability along with state estimates through data assimilation techniques. Following this trend, this long-term plan also proposes a research direction to bridge observational and modeling communities. In addition, we survey the current status of this work and propose applying data assimilation techniques to research fields to which these have not yet been applied, such as to ice sheets and the carbon cycle.

This theme has the following structure, with many technical terms. The representative techniques, variational method*, and Kalman filter method* are explained in Box 10. Table 3 lists data assimilation techniques, along with project names. The terms explained in Box 10 and Table 3 are identified with *. In the first part of the text, examples of data assimilation used for Arctic environmental issues are analyzed, followed by proposed future research directions. The second part presents practical proposals for data assimilation research. In the last part, we list problems for the Japanese research community of the Arctic environment to address, by carrying out the data assimilation research, and countermeasures are also proposed.

The present state of data assimilation research in the Arctic area

Data assimilation techniques have been implemented to produce estimates and forecasts of the troposphere and sea ice cover in the Arctic, for which data are collected regularly with satellites and instruments deployed on sea ice. These techniques are not extensively applied to the ocean interior because of the difficulties of continuous monitoring due to sea ice cover. However, observations of temperature and salinity under sea ice cover have come to be more representative of reality, following development and improvement of under-ice instruments such as ITP* (see Theme A for details). Hence, data assimilation for the ice-ocean component is progressing, along with development of observation networks. A main focus of this section is the review of research and operational activities for the atmosphere, sea ice, and ocean in the Arctic area. We then also provide an additional report on state estimates of atmospheric chemical compositions and of the Greenland ice sheet, for which satellite observation systems have been greatly improved.

a. Reanalysis of atmospheric data

In various countries, operational divisions produce atmospheric reanalysis data using data assimilation techniques from observed data and numerical modeling. However, it is widely known that reanalysis data contain some problems. For example, all global reanalysis data sets show significant deviations from fields observed with radiosondes in the Arctic atmosphere (Jakobson et al., 2012). In particular, significant mismatches were found in the inversion layer of air temperature and moisture profiles near the land/ice surface, suggesting problems in the boundary layer scheme on the land surface or the boundary condition at the sea ice surface. As presented by other studies, the boundary layer at the sea ice surface of the representative reanalysis fields commonly has larger mismatches in temperature and humidity than wind direction and speed. Our urgent task is to identify the cause of these mismatches and to improve physical processes.

One of the reasons for these mismatches in Arctic reanalysis data is thought to be the fact that many parameterization schemes have been determined on the basis of mid- and low-latitude data. One solution to address this problem is to construct reanalysis data using a regional model suitable for the Arctic region. The pioneering work in this respect was carried out by a research group at the University of Ohio, producing Arctic atmosphere reanalysis data, ASR*, from Polar-WRF* optimized for the Arctic atmosphere, where the data assimilation technique used was the three-dimensional

Box 10 Explanation of data assimilation techniques

There are now two main groups of data assimilation techniques used in the fields of atmospheric science and oceanography: i.e., the variational method and the Kalman filter method, which are briefly explained here. The detailed techniques and applications, including other technical information, are described in the textbook edited by the Japanese data assimilation research community (Awaji et al., 2009).

a. Variational method (Adjoint method): 4DVar/3DVar

By correcting the variables that determine model behaviors (control variables), the functions to measure distances between observation data and model outputs (cost functions) are minimized. The model variables that are determined from optimized control variables are defined as the analysis values. The control variables are usually selected from initial conditions, boundary conditions, and model parameters. The analysis values strictly satisfy the governing equations of the model (Figure 64a). The method is called the four-dimensional variational method (4DVar) in cases where time is included in the governing law, while it is called the three-dimensional variational method (3DVar) in cases where time is not included.

b. Kalman Filter method

The Kalman Filter method has the characteristic that the model governing equations retain the temporal evolution and explicitly produce the error covariance matrix of forecast values from initial and boundary values, including errors. The optimal solution (analysis values) is obtained by linearly adding forecast values and observation data. The optimal solution therefore does not satisfy the governing equations at the times of analysis or assimilation, although it is easier than in the case of the 4DVar to obtain analysis time sequences that follow the observation data (Figure 64b).141

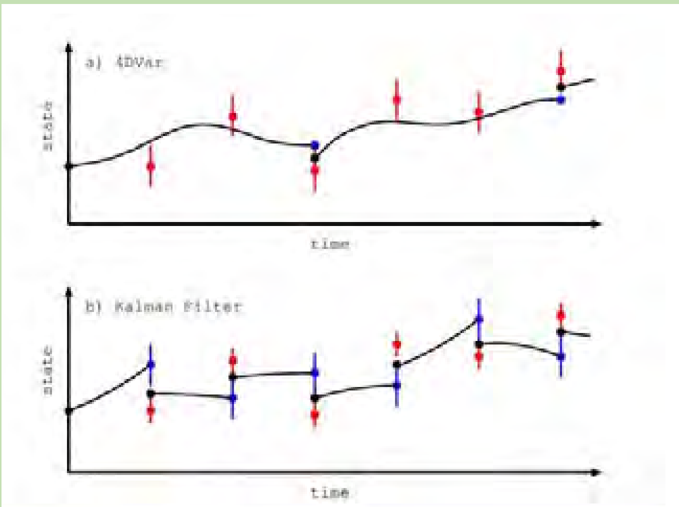

Figure 64: 4 - dimensional variational (4DVar) method and Kalman filter method. Red circles denote observed data, black circles and lines denote analysis values, and blue circles denote model prediction values. State variables can be temperature, velocity and others.

variational method. Another attempt involved preparation of reanalysis data, CBHAR*, specified for the atmosphere over the Beaufort Sea and the Chukchi Sea, using the regional data assimilation system WRFDA* on the basis of Polar WRF.

In the field of the atmospheric sciences, it is possible for an individual research group to construct a regional reanalysis product from global observation data sets; hence, data assimilation experiments are now carried out to examine the influences of additional data on reanalysis results over the Arctic Ocean. The results of the data assimilation system, ALERA2* developed by JAMSTEC, indicate that stratospheric data over the low pressure center are useful for reconstruction of low pressure in the Arctic, and also that the data may have impacts on reconstructions in the upper portion of the mid-latitude troposphere (Inoue et al., 2013). The international research community has recognized the leading role of these results and the impacts of barometers deployed on sea ice, as well as of radiosonde observations over the Arctic Ocean. Research groups in Japan can pursue observations and manage data assimilation systems independently of operational weather centers, which is noted by the IASC atmospheric working group as a rare case with respect to global standards.

b. Ocean-sea ice data assimilation systems

Operational reanalysis of ocean-sea ice states using data assimilation techniques is now carried out at a few institutes. One typical example is the Nansen Environmental and Remote Sensing Center, at which a regional ocean-sea ice data assimilation system, TOPAZ*, produces reanalysis fields in the North Atlantic and Arctic Ocean using the ensemble Kalman filter method. The other example is FOAM*, a global ocean-sea ice data assimilation system based on the optimal interpolation method*, developed by the United Kingdom meteorological station, the UK Met Office. Both of these have been developed on coupled ocean-sea ice models and have the common objective of providing medium- to long-term forecast and reanalysis data, even though they opted for different data assimilation methods. Their products, reanalysis fields, and forecasts are publicized every day through the portal site, MyOcean.

More research-oriented attempts at ocean-sea ice data assimilation are NAOSIMDAS* of the project, DAMOCLES*, and the Arctic Ocean analysis system of the project, ECCO2*. Both of these adopt the 4-dimensional variational method*, and are only two successful attempts of the adjoint codes* for the coupled ocean-sea ice model at this stage. At the University of Washington, the Arctic Ocean sea ice-ocean reanalysis system, PIOMAS*, has been developed using the optimal interpolation method, and is considered a semi-operational tool. These ocean-sea ice data assimilation systems have strength in simultaneous assimilation of observation data from the ocean and sea ice. An interesting outcome of these analyses is the possibility that sea ice data significantly affect state estimates of the ocean interior.

Sea ice data assimilation systems have been implemented in coupled atmosphere-sea ice-ocean forecast systems. At Environment Canada, the sea ice data assimilation system was implemented experimentally using the optimal interpolation method. The Meteorological Research Institute in Japan has estimated sea ice concentrations in the Sea of Okhotsk using the nudging method* (Usui et al., 2010). In addition, reanalysis fields of sea ice concentration have been estimated using the three-dimensional variational method and assimilated with global atmosphere-sea ice-ocean models using IAU* (Toyoda et al., 2011). We are interested in this trend of assimilation of sea ice data to improve forecast accuracy of the atmosphere (and the ocean in the case of Environment Canada).

Let us look at operational data assimilation, with a focus on analysis of sea ice fields. As a typical example, Environment Canada has developed RIPS*, the system for regional sea ice analysis and forecast. This system is built on a model of sea ice movement, with the aim of automatically estimating sea ice states, the latter prepared manually by forecast operators. Sea ice concentration fields are produced four times a day, matching with weather forecasts, and provide information for sea ice charts and bottom boundary conditions in numerical weather forecasts. With regard to ocean circulation data assimilation, there has been very limited application to date due to the lack of observation data for the ocean interior. Research results by the University of Alaska have reported that the four-dimensional variational method* was applied to estimation of climatic ocean circulation in the Bering-Chukchi sea area.

c. Sea ice seasonal forecast

We focus on seasonal prediction of sea ice states during the melting season, in which initial and final denote late spring and late summer, respectively. The correction of initial sea ice thickness, which is reconstructed from assimilation of thickness data, improves final ice thickness distribution (Lindsay et al., 2012). A similar but more detailed suggestion was provided through the coupled atmosphere-sea ice-ocean model, CNRM-CM3.3*; here, the initial sea ice thickness distribution at a sub-grid scale contributes most significantly to the final ice covered area. The reason for this sensitivity lies in the tendency for common volume but different thickness distributions, with thicker ice over a smaller area persisting longer than thinner ice over a larger area during the melting season. If this mechanism to extend sea ice presence is really effective, initial state correction by thickness data is expected to play an important role for improving seasonal forecasts of sea ice.

d. Estimates of atmospheric chemistry components

Ozone in the Arctic stratosphere has been observed for half a century, with accumulation of sonde data for 45 years, and of satellite data for 35 years. Analyses of these data sets show active inter-annual variability in winter-to-spring and also a long-term trend, indicating a relationship with atmospheric circulation variability, such as the Brewer-Dobson circulation. As we understand that an atmospheric chemistry composition varies dynamically in conjunction with atmospheric circulation, research is advancing on the basis of coupled physical-chemical systems. Chemistry-climate models, composed of atmospheric circulation models of the troposphere and stratosphere, along with chemical transport models, therefore play an important role in understanding this coupled system (Dameris and Jöckel, 2013). Since chemical data sometimes provide useful constraints for circulation and mixing, ongoing research and development are focused on simultaneous data assimilation systems combining both physical and chemical models, and on production of reanalysis fields from the system.

e. State estimates of ice sheets

Since the measurements of surface elevation and ice flow velocities of the Greenland ice sheet have advanced, mainly through the use of satellites over the last ten years, monitoring conditions have improved dramatically. A quantitative estimate of ice sheet variability is crucial to climate change research, although an important task is how to estimate parameters that cannot be observed directly, such as bottom boundary conditions of the ice sheet. Data assimilation research was initiated through a twin experiment* using a standard dynamical ice sheet model (e.g., SICOPOLIS*) and its adjoint equation model (Heimbach and Bugnion, 2009). It is now possible to attempt estimates of forcing terms and model parameters from observation data, using the variational method or the Kalman filter method.

The data assimilation experiments with altitude data show that corrections of both surface mass balance (SMB) at the top boundary and friction coefficient at the bottom boundary are effective for reproducing variability of surface elevation changes over the last ten years or so. Sensitivity experiments indicate that ice velocity is sensitive to the basal friction coefficient and topography, and hence, we expect that bottom boundary conditions may be accurately determined from simultaneous assimilation of surface elevation and velocity data. From a different perspective, because SMB is usually specified through outputs of an atmospheric model or reanalysis fields, an attempt to estimate SMB has been made using data assimilation in a regional atmospheric model.

Direction of data assimilation research for the Arctic environment

The Arctic is one of the most difficult areas for monitoring of the climate system, due to its special climate and geography. The applications of data assimilation technology and successful cases introduced in Section 2 indicate the possibility of overcoming this difficulty, through integration of observation data sets and governing laws for targeted systems. In this section, we propose the further development of data assimilation techniques presented in Section 2 for monitoring the atmosphere-sea ice-ocean system. We then propose the extension of data assimilation techniques to the multi-sphere climate system including the marine ecosystem, ice sheets, and terrestrial vegetation. The other item to discuss here is establishing operational weather and oceanic forecast systems, which are required for safe and secure economic activities in the Arctic under conditions of rapid climate change, and the implications of the latter (such as a decrease in the sea ice area).

a. Data assimilation for the ocean

As explored in AOMIP* and other research, the Arctic ocean circulation and sea ice state produced in coupled ice-ocean models suffers from large deviations from observations; and there are also wide variations between models as compared with mid-latitude models. Coupled ice-ocean models therefore need to be improved to provide accurate reanalysis fields for the Arctic Ocean. Although it is impossible to list here all causes of model error due to combinations of complex factors, some of these have been well identified, along with their treatments, as follows: (1) low model resolutions, (2) representativeness of temperature and salinity data under sea ice, (3) errors and biases in ice-ocean heat fluxes, and (4) errors and biases in external forcing data.

Item (1) will be resolved through continuous improvement in the ability of computers. A necessary component to resolve (2) is implementation of Argo*-type floating buoys with mobility and data transmission capabilities even under sea ice cover. In addition to developing observation systems, as proposed in Theme A, data assimilation research should also take place for the oceans and sea ice. The data assimilation community should play its role to establish an optimal observation network, through sensitivity analyses of observation systems using a coupled ice-ocean model with high resolution. Since (3) and (4) are related to external forcing errors, correction of external forcing with data assimilation techniques is effective, along with improvement of the accuracy of atmospheric reanalysis data.

In the process of improving ocean models and observation systems of the Arctic Ocean, the ocean data assimilation groups will examine detailed techniques for production of ocean reanalysis data. In addition to sea ice cover, bottom topography is specific to the Arctic Ocean, with circulation dominated by flows trapped on the topography and filled with eddies. To reproduce this circulation, high horizontal resolution of numerical models is necessary, although there is no hope of increasing observation networks in the near future. It is therefore obviously impossible to reproduce oceanic states to the eddy-resolving scale from observation data, even if we use data assimilation techniques as an inversion problem. In this situation, the data assimilation approach, with a basis in regional models, may be useful by implementing an eddy-resolving observation network with a focus on eddy-rich regions such as the Barrow Canyon. Once we attempt state estimates over the entire Arctic Ocean, a probably useful method will be parameterization of eddy-driven transport of momentum, salinity, and temperature, with another being reduction in the order of model state using EOF mode expansion.

Following significant achievements in the physical environment, we are going to implement material circulation (i.e., biogeochemical) models and marine ecosystem models. We will then sequentially tackle production of reanalysis data and initial conditions for forecast, suggestion of optimal observation networks, and state estimates of material circulation and marine ecosystems. Collaboration with specialists in material circulation and marine ecosystems seems promising for producing significant scientific outcomes in multi-field data assimilation; this is because, these specialists in Japan are considered to be world-class. The four-dimensional variational method is suitable for material circulation, which is expected to satisfy tracer conservation (whereas nonlinear behaviors often create problems in parameter estimates). It has been suggested that the genetics algorithm* and the Green function method* are useful as auxiliary techniques for parameter estimation in the case of strong nonlinearity.

b. Data assimilation for sea ice

The purposes of sea ice data assimilation are categorized as follows: (i) providing lower boundary conditions to atmospheric models, (ii) providing upper boundary conditions to ocean models, and (iii) short- and medium-term predictions and long-term reanalysis data of sea ice itself. To improve predictions and reanalysis data of sea ice, the optimization of initial conditions and boundary conditions plus external forcing is required, along with higher quality of basic numerical models. Data assimilation techniques can play a major role in these tasks.

Most sea ice models have internal dynamics or rheology in the form of viscous-plastic or elastic-viscous-plastic, the latter more appropriate in the case of high sea ice concentration. For the marginal ice zone with concentration less than 90%, more appropriate laws have been suggested. One of these is a pack ice model, the internal dynamics of which are represented by loose collisions between ice floes, with a model variable being the distribution function of an ice floe size. A newly developed model often has parameters to be determined from observation data, and data assimilation can contribute to optimization of parameter values. This combination of observations and data assimilation techniques is expected to work on optimization of parameters included in momentum and heat fluxes within the air-ice and ice-ocean systems, and then, leads to improving sea ice models and resultant prediction skills.

Observation data that will contribute most significantly to the sea ice data assimilation system are sea ice thickness and concentration, which are estimated from data collected with spaceborne sensors. The algorithms for sea ice state estimates will be improved using ground truthing with field data, as introduced in Theme A. The polar research community in Japan has a reputation for developing algorithms for translating satellite data to sea ice states in the Arctic Ocean and in marginal seas with seasonal sea ice zones (Okhotsk Sea and Bering Sea). Taking advantage of this, the data assimilation researchers should actively collaborate with satellite observation researchers, making significant contributions to the technology of sea ice state estimates. As the outcome of this technological advancement, more accurate initial conditions will contribute to short-term and seasonal forecasts of sea ice cover.

c. Data assimilation for the coupled atmosphere-sea ice-ocean-ice sheet system

For forecast of the Arctic atmosphere-sea ice-ocean states, an important research theme is developing operational data assimilation and short-term forecast systems with a focus on the Arctic area, by establishing a basis in numerical models with initial and boundary conditions consistent with observation data. The basic model is selected from regional coupled atmosphere-sea ice-ocean models, the configurations of which have been optimized for the Arctic, as shown by Polar-WRF. Here, the parameterization schemes should be suitable for physical processes in the polar region; it is then also crucial to adjust parameters consistent with observation data, using data assimilation techniques. Since accuracy of initial conditions is a key to a precise short-term forecasts, the Kalman filter method may be useful. The most suitable data assimilation procedure for forecasts is achieved through the regional coupled atmosphere-sea ice-ocean model, by examining what data are suitable for the forecast.

Large errors exist in estimated heat and freshwater fluxes between the atmosphere, sea ice, and ocean in the Arctic (Bourassa et al., 2013). These fluxes determine the boundary conditions in coupled ice-ocean and atmospheric models, and hence, biases and errors in fluxes directly limit the simulation and forecast abilities of the models. The lack of observation data is one error source, but cannot be immediately resolved by better observation techniques, because the gap is related to climate conditions and the geographic environment. The necessary approach to solve this problem is production of reanalysis flux data that maintains physical consistency, which is guaranteed by the atmosphere-sea ice-ocean data assimilation system. We hope to initiate a research project, taking advantage of the dominant position of Japan, based on an atmospheric model and a coupled ice-ocean model, as well as corresponding data assimilation systems.

When the time scale of analysis exceeds a decade, the prediction of mass loss from the Greenland ice sheet becomes important. To estimate surface mass balance of the ice sheet as a result of snowfall, refreezing, and melting on the surface, we propose using surface elevation data of the ice sheet and also assimilating the data to an ice sheet model, along with improving the base atmospheric model. We should design a data assimilation procedure with extreme caution with regard to the characteristics of the basal friction coefficient, which reduces under a melting bed condition and has a nonlinear relationship with basal sliding speed. In addition to fast ice flow over a melting bed, we should also look at significantly large ice sheet mass loss near the boundary with the ocean. Data assimilation is hence supposed to take into account the coupled ice sheet-ocean model, which is just starting to be developed. We expect many obstacles to data assimilation for these coupled models, caused by the variety of model accuracies and data amounts; however, undertaking this challenge constitutes a worthy long-term plan.

d. State estimate for marine primary ecosystem

It is expected that marine ecosystems will be under higher stress due to a sharp decline in summer sea ice cover, urging us to establish a monitoring system and to explain the variability mechanisms (see Theme 9 for details). Coupled ocean-sea ice-ecosystem modeling has to be used to supplement sparse monitoring of the marine primary ecosystem over a wide area. For the state estimate of Arctic ecosystem responses, which are controlled by the seasonality of sea ice, model ice cover is required to agree with retreat timing of the observed ice edge. Improvement of physical models is necessary, while one of the approaches is to use assimilation of sea ice data. However, in cases when oceanic stratification is crucial, a freshwater flux from ice melting has to be correctly represented in addition to shortwave radiation. We have to remember that the freshwater flux tends to include a substantial bias caused by the nudging method for data assimilation. Even if the physical field is absolutely correct, model results of biological variables are dependent on the reliability of ecosystem models. More accurate states are achieved by improvement of both physical and ecosystem models and also by optimization of model parameters using data assimilation techniques. As an example, in Japan, the optimal parameters of the primary ecosystem model, NEMURO*, are estimated globally by taking chlorophyll data of SeaWiFS* and nutrient data in World Ocean Atlas (WOA) (Toyoda et al., 2013). The tasks to be carried out for applying data assimilation technology to marine ecosystem models are listed below.

First, we list tasks for improving reproducibility of base models. AOMIP for Arctic ecosystem models pointed out that the variety in mixed-layer depths is responsible for differences in primary productivity among the models (Popova et al., 2012). Main plankton species and nutrient components are expressed in most Arctic ecosystem models, including ice algae unique to the polar ocean; however, important elements such as denitrification, nitrogen fixation, and iron-restriction, which constitute crucial differences between regions, have not been properly included in ecosystem models. Since this issue is not relevant only to the Arctic Ocean, the necessary elements should be developed by referring to the knowledge provided by mid- and low-latitude model studies. Please see Theme B for various elements to produce this bias.

The next issue is validity of the data set to be used for data assimilation. Observation data sets usually have various acquisition periods: e.g., chlorophyll data by SeaWiFS are prepared over the time series 1997–2010, while WOA retains only climatic values; cost functions hence have to be carefully designed to utilize different types of information. Spaceborne chlorophyll data have large biases in the polar ocean, and need to be dealt with using caution for data assimilation. Enhancement and accuracy of observation data directly contribute to the utility of data assimilation products; we hence require collaboration with field research scientists.

Since ecosystem models have much more variables and parameters than physical models, an important work is to select and prioritize parameters to be optimized so that computer resources may be spent efficiently. Optimized parameters include not only a maximum photosynthesis rate and a half-saturation constant of nutrients, but also a re-suspended nutrient flux from bottom sediments. A meaningful data assimilation product requires evaluation of whether estimated parameters are within realistic ranges.

e. State estimate for carbon cycle in the Arctic

As the ice-free area expands, observation results show an increase in carbon absorption in the Arctic Ocean. A temperature rise over the land surface enhances vegetation products in high-latitude areas, and the vegetation area is reported to expand northward in some regions. The carbon cycle is hence predicted to strengthen over the coming several decades in the Arctic area. To understand the background principle of climate change, a carbon cycle monitoring system is expected to be established as soon as possible. We need optimal integration of a limited number of observations with numerical models using data assimilation techniques, so that the carbon cycle may be estimated quantitatively, in the same way as state estimates of the coupled atmosphere-sea ice-ocean system.

State estimates of the air-sea carbon dioxide flux have been carried out successfully using data assimilation techniques. For example, Valsala and Maksyutov (2010) constructed a data assimilation system with a four-dimensional variational method based on a time-varying equation for dissolved inorganic carbon (DIC) in the euphotic layer, and estimated spatio-temporal distributions of the air-sea CO_2 flux by assimilating carbon dioxide partial pressure (pCO_2) data in the ocean surface layer. In this experiment, they used reanalysis fields of temperature and salinity, which are needed for ocean circulation and parameterization of the air-sea DIC flux formulae, and the control variable was an initial condition. For application to the Arctic Ocean, we have to carefully examine the assumption of unifying governing equations for a DIC model. The other issue is related to pCO_2 data, which is limited to summer ice-free areas in the Chukchi and Barents seas. To solve this problem, we expect year-round monitoring of pCO_2 under sea ice cover, which has now been experimentally attempted using ITP.

Large-scale monitoring of the air-land carbon flux in the Arctic has been carried out, relying on spaceborne data along with a land carbon flux model (Kimbell et al., 2009). The carbon flux model is composed of the production efficiency model (PEM), which is a diagnostic model, and estimates carbon dioxide uptake by vegetation from spaceborne data. The resultant air-land carbon flux is verified against in situ data collected at flux towers, so that model parameters may be optimized. This procedure requires that weather elements are supplied from atmospheric reanalysis data, along with spaceborne data. Even over land, reanalysis data contains non-negligible uncertainty, affecting uncertainty in the carbon flux. Since atmospheric reanalysis data can be corrected sequentially with flux tower data using data assimilation techniques (such as the Kalman filter method), these techniques could improve the accuracy of carbon flux estimates.

f. Data assimilation for Arctic terrestrial vegetation

In the Arctic area, as air temperature rises due to global warming, vegetation becomes more active in some cases, while it declines in other cases because soil moisture is reduced by permafrost melting (see Theme 8). As a result, there are impacts on wildlife and then on the lives of residents (see Theme 7). To assess the regional effects of vegetation variability under climate change, we need to predict the distribution variability of individual plant species, which are dependent on terrain and soil conditions. Growth and mortality of terrestrial vegetation are dependent on atmospheric conditions, solar radiation, and soil moisture, and the dependency is described as a different function for each species. The functions are constructed by empirical laws induced from observation data and include many uncertain parameters. The uncertainty should be minimized for future prediction.

In cases when many parameters are simultaneously estimated using data assimilation techniques, insufficient observation data may lead to some parameters being ill-posed: i.e., optimization falls into a local minimum, and hence some parameters are not determined. Given the current state of data assimilation studies for terrestrial vegetation, seasonal variability in vegetation is reproduced as a spatial average, by assimilating net carbon dioxide exchange, gross primary production, daily mean total respiration, and carbon stocks to an ecosystem Box model, with a reduced number of parameters. For cases when spatial distribution of vegetation is predicted under climate change conditions, we need to reproduce decline and growth of multiple species in an ecosystem model, and hence the way should be paved to simultaneous optimization of many parameters.

A database on responses of various plant species to the environment has been built, based on field investigations in Hokkaido, Alaska, and Siberia (see Theme 8), providing conditions for applying data assimilation techniques to vegetation models. Next, we will start to confirm that the techniques are useful for optimization of model parameters associated with a particular species. Then, once this utility is confirmed, we will challenge data assimilation with a coupled ecosystem-soil-atmosphere model, which is specific to optimization of fluctuation processes of various plant species and the atmospheric boundary layer. This plan requires a complete observation network, dataset arrangement, adjustment of appropriate complexity in an ecosystem model, and selection of parameter estimate techniques, and hence an indispensable condition is collaboration between specialists in data assimilation techniques and specialists in field investigation and ecosystem modeling.

g. Data assimilation for the atmosphere

Numerical weather forecast demands over the Arctic Ocean will increase in response to sea ice decline, because the forecasts of cyclone paths and sea ice motion play a major role in keeping safety of ship navigation for growing traffic along the Arctic Shipping Route. In addition, extreme weather events in mid-latitude areas have large socio-economic impacts, increasing associated with polar amplification of the global warming. A necessary element for more accurate predictions lies in research on the location and frequency of data collection contributing to improvement of initial conditions based on data assimilation. A research group in Germany is keen to carry out observing system experiments by combining radiosonde data collected from a German ice breaker and the Japanese data assimilation system, ALERA2 to the Arctic cyclone that contributed to sea ice reduction in 2012. The group in Japan has thus started to be at the forefront of atmospheric data assimilation in the Arctic. This activity is considered a pilot study for MOSAiC*, which is planned for 2018–19 and will definitely form a basis for Arctic research in the near future.

The development of a data assimilation system which ties with the Arctic regional atmosphere model will become important, in response to arrangement of observation networks in polar regions. In this approach, the regional model has boundary conditions taken from a global atmospheric reanalysis system, while it is desirable to include sea ice as a part of a coupled atmosphere-ice model. In addition, by following the suggestion given by Inoue et al. (2013), it is important to examine an optimal observation system for estimates of atmospheric states, through inclusion of sea ice.

Triggered by data accumulation due to intensive observation campaigns, we need to reconsider a parameterization scheme for air-ice fluxes, with crucial effects on the lower boundary layer of the Arctic atmosphere. An example is found in the roughness of the atmosphere being dependent on sea ice concentrations, as the ice surface state is influenced by ridges and freeboard. Considering that melt ponds spread due to global warming and modify radiation fluxes, the albedo scheme is also being re-examined. Since data are widely collected with spaceborne sensors for physical conditions from the ice surface, data assimilation systems are expected to contribute significantly to optimization of surface parameters and hence improvement of atmospheric circulation models.

h. Short-term forecast of sea ice and surface layer currents along the Arctic Sea Route

The Arctic Shipping Route, composed of the Northeast route on the Russian side and the Northwest route on the Canadian side, is now partly operational. To secure safety of ships through the Arctic Shipping Route, it is necessary to accurately predict cyclone paths, wind waves, and sea ice states for up to a week, and also to deliver the information to ships. A coupled sea ice-surface ocean model with high spatial resolution is needed for accurate prediction of the Arctic Shipping Route. The model that can provide a basis for data assimilation and short-term prediction is a coupled atmosphere-sea ice-ocean regional model with high resolution, which is specific to the Arctic Shipping Route, using a dynamic downscaling method for boundary conditions constructed from reanalysis data of the Arctic atmosphere-sea ice-ocean model. If reanalysis fields do not exist or are not usable, we have to start with development of a large-area analysis system. Considering the need for an operational forecast system to deliver forecast results within a certain time limit (e.g., six hours), the analysis system has to use a data assimilation method with light computational load, such as the nudging method and the optimal interpolation method. In addition, along the Arctic Shipping Route, we need to be aware of fast ice typical of coastal regions and the effects of wind waves generated by cyclones. It is hence important for a long-term plan to prepare to introduce these aspects into data assimilation systems, along with investigation of data acquisition.

i. Wind wave forecast in the Arctic coastal area

As ice cover declines and cyclones become stronger, more active wind waves are observed along the coastal region in the Arctic Ocean. Accurate wave information must be provided for safe navigation along the Northern Sea Route, which is expected to be used for commercial voyages. Wind waves are important factors controlling ice edge distribution, and hence, an ice cover forecast needs a wave forecast. The Norwegian Mohn-Sverdrup Center is actually carrying out WIFAR*, a project of wave forecasting for improving ice edge detection skill. An operational wave forecast system is indispensable also for providing forecast information of coastal erosion caused by wind waves to residents who suffer from this problem. Wave forecast systems have been operated for a long time in low- and mid-latitude areas. It is therefore considered to be useful and reasonable to extend these systems to the Arctic Ocean.

The wind wave research group is relatively small in Japan and is not fully experienced in data assimilation. Given this situation, we will start modeling research and verification of model results for the Chukchi Sea and the coastal region in the Canada Basin, where we have been performing intense observations. We will concentrate on examination of the necessary items for wave forecast: i.e., model accuracy, observation datasets to be used for initial condition estimates, etc. After this step, we need to proceed toward development of a forecast system based on data assimilation technology, step-by-step.

Arrangement of basic conditions for Arctic data assimilation research

To carry out the data assimilation research described in the previous section, it is also important to arrange basic conditions within Japan. We focus on three points: how to make active use of limited human resources, how to provide observation data as a basis of data assimilation research, and how to respond to expected technical issues.

The Arctic research community in Japan, having limited experience in data assimilation research, needs to develop close cooperation with and receive timely advice from agencies that are developing assimilation technology. It then needs to implement models for the Arctic area to assimilation systems. Having a view of various future applications, it is desirable to concurrently implement multiple assimilation techniques, although this is a difficult task when considering domestic human resource constraints. It is therefore necessary to select an appropriate technique for each application so that we may concentrate available human resources. It is also important for the atmospheric and oceanographic assimilation research communities, who have made adequate progress in assimilation research, to support the dissemination of this technology to other disciplines through workshops and summer schools.

Since a wide variety of observation data are available for data assimilation in the Arctic, it is not realistic to accumulate and archive data only for data assimilation purpose. We therefore adopt the strategy of using existing data archiving systems for data accumulation and proactively make recommendations with respect to observation data storage among the data assimilation research community. In practice, we will clearly convey the requests of the assimilation community regarding the types of data to be stored, the file formats, and the implementation methods of interfaces for application, calling for active participation from the observation community. On the other hand, field observation data are often managed by institutes and researchers as their own research assets, and it is hence critical to build individual relationships for application to data assimilation. By keeping this point in mind, we need to develop a framework of mutual cooperation between data assimilation and observation communities.

We discuss errors in observation data as a problem common to data assimilation research. Although the errors strongly affect assimilation system behaviors, error estimates have not yet been sufficiently performed. This situation may be related to the fact that uncertainty estimates of data have to be examined for respective data sets separately, because of no merits of multi-disciplinary collaboration. However, we should actively challenge uncertainty estimates, which constitute an important technical problem forming a core element of data assimilation. In particular, in the case of assimilating multiple kinds of observed values, we need the relative uncertainty estimate of each value. Here, errors are categorized into measurement errors caused by instruments, and representative errors due to sparse observations and numerical model capabilities. In practice, since representative errors are harder to estimate than measurement errors, it is necessary to propose an observation plan to provide statistical information on representative errors, through verification of model outputs against observation data.

Table 3 Explanation of terms

Term	Explanation
ALERA2: AFES–LETKF experimental ensemble reanalysis	The data set from experimental ensemble reanalysis of atmosphere during the period of January 1, 2008 to January 5, 2013, made public by Earth Simulator Center
AOMIP: Arctic Ocean Model Intercomparison Project	The model intercomparison project of the Arctic Ocean models carried out in the period from 1999 to 2011, aiming at exploration of problems and improvement of reproducibility by making model setting as common as possible
Argo	Automated floating buoys to monitor oceanic fields, measuring temperature, salinity and others along trajectories of sea water and communicating at near real time
ASR: Arctic System Reanalysis	Atmosphere reanalysis data produced from the high resolution version of Polar-WRF using data assimilation system optimized for the Arctic
CBHAR: Chukchi-Beaufort Seas High-Resolution Atmosphere Reanalysis	Atmospheric reanalysis data with high resolution specified for the Chukchi Sea and the Beaufort Sea in the period of 1979 to 2009, using the data assimilation system WRFDA on the basis of Polar WRF
CNRM-CM: Centre National de Recherches Me´te´orologiques-Climate Model	Climate system model developed for CMIP mainly by National Centre for Meteorological Research, Meteo-France

Term	Explanation
DAMOCLES: Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies	Project led by Europe for understanding Arctic climate variability, including SEARCH which manages Sea Ice Outlook, project for seasonal sea ice forecast
ECCO2 : Estimating the Circulation and Climate of the Ocean Phase 2	Ocean research project established in 1998 as part of WOCE, with a purpose of coupling modeling and observation, participated by JPL, NOAA, MIT and Scripps Institution of Oceanography
FOAM: Forecasting Ocean Assimilation Model	Ocean-sea ice data assimilation system developed by the United Kingdom meteorological station, the UK Met Office, with operational components for global, North Atlantic, Mediterranean and Indian Ocean
IAU: incremental analysis updating	The technique to incorporate increments into model integration in a gradual manner, using analysis increments as constant forcing in a prognostic equations of the model, along with estimation of initial conditions
ITP : Ice Tethered Profiler	Automated censors deployed on sea ice with wire hanging down to measure water temperature, salinity and others, communicating at near real time
MITGCM: MIT General Circulation Model	Numerical model of atmosphere, ocean and climate, developed by MIT
MOSAiC: Multidisciplinary drifting Observatory for the Study of Arctic Climate	Research plan prepared by IASC, the atmosphere working group to operate drifting observatory in the middle of the Arctic Ocean, aiming to start in 2018-2019
NAOSIMDAS: North Atlantic/Arctic Ocean Sea Ice Model Data Assimilation System	4-dimensional variational data assimilation system as part of DAMOCLES, on the basis of coupled ice-ocean model developed by Alfred Wegener Institute
NEMURO: North Pacific Ecosystem Model Used for Regional Oceanography	Low-level ecosystem model developed by the North Pacific Marine Science Organization (PICES), originally for the North Pacific but now also for the global and Arctic Ocean
PIOMAS: Pan-arctic Ice-Ocean Modeling and Assimilation System	Coupled ice-ocean model developed by University of Washington, with optional data assimilation system of nudging sea ice concentration toward satellite data
Polar-WRF: Polar Weather Forecast Model	Version of WRF specified to the polar region developed by Byrd Polar Research Center, Ohio State University
RIPS: Regional Ice Prediction System	System developed by Environment Canada for regional sea ice analysis and forecast, used for operational analysis of sea ice concentration with 3-dimensional variational data assimilation method
SeaWiFS: Sea-Viewing Wide Field-of-View Sensor	Satellite sensor for ocean color to estimate amount of chlorophyll
SICOPOLIS: Simulation COde for POLythermal Ice Sheets	Three-dimensional dynamic-thermodynamic model for simulation of large-scale progression of ice sheet
TOPAZ: Towards an Operational Prediction system for the north Atlantic european coastal Zones	Operational prediction system of regional ice-ocean in the North Atlantic and Arctic Ocean developed by Nansen Environmental and Remote Sensing Center using ensemble Kalman filter method
WIFAR: Waves-in-Ice Forecasting for Arctic Operators	Project to assess the effects of waves on ice-ocean fields near the ice edge conducted by Mohn-Sverdrup Center
WRF: Weather Research and Forecasting model	Next generation mesoscale weather forecast system for atmospheric research and weather forecast
WRFDA: WRF Data Assimilation system	Data assimilation system for atmosphere based on WRF
WWRP-PPP: World Weather Research Programme-Polar Prediction Projects	Project led by WMO for assessment of prediction capability of the Arctic area

Term	Explanation
Adjoint code	Model code formulating the gradients of the cost function necessary in a variational data assimilation method, being derived as the adjoint operator associated with the model operator in a linearized governing equation
Ensemble Kalman filter (smoother)	Method to replace time dependent equation of error covariance matrix with ensemble average of model variables in Kalman Filter (Smoother)
Genetics algorithm	One of the optimal search techniques, using the process similar to evolution for a search process, being capable of search with strongly nonlinear phenomena
Kalman Filter (KF)	One of the data assimilation techniques, proceeding with prediction of both numerical model variables and their error covariance matrix, used for initialization of a numerical prediction system
Kalman Smoother (KS)	One of the data assimilation techniques, with the principle common to KF which includes previous data, but including both previous and later data for analysis, used mainly for production of reanalysis fields
Green function method	One of the optimal search techniques for a cost function, using finite difference approximation instead of adjoint code to formulate the gradients of the cost function
Optimal interpolation method	One of the data assimilation techniques, adding model prediction and observation data, with the relative weights determined from observation operators and error covariance matrix
Nudging	One of the data assimilation techniques, nudging model variables toward observation data and producing analysis fields
Twin experiment	One of the evaluation methods for data assimilation system, taking data from the output of the same model as the evaluated model

Chapter 9: Improvement of Research foundation

There are various frameworks and equipment required to follow through with the research themes we have described above, and we provide a description of these requirements for each theme in prior to this chapter. We have re-organized the following to represent the research infrastructure which has the greatest cross-cutting utility, and which we believe is appropriate for our domestic community of researchers to be ready for our use.

Ice-Breaking Observation Vessel

There are a plethora of anticipated uses for an ice breaker: from shipping materials to undersea resource exploration. In this section, we will outline the necessity of the observation infrastructure rightly referred to as a 'Research-Specialized Ice-Breaking Vessel', which is deeply-rooted in polar atmospheric and oceanic research, including seafloor exploration (As a matter of convenience, we will refer to these vessels simply as icebreakers in this document.).

Explaining the mechanism behind sea ice fluctuation in the Arctic Ocean is an urgent issue to understanding the global climate system, and is indispensable to improving the accuracy of forecasting the future of Arctic sea ice. A dramatic reduction of sea ice up to this point has been observed primarily on the Pacific Ocean-side of the Arctic Ocean, which has shown marked ocean warming; however, the phenomenon of seasonally-variant sea ice continues to advance throughout the Arctic Ocean. Generally, the regions with seasonally-variant sea ice, including the marginal ice zone, contain numerous fascinating physical and biogeochemical phenomena, such as atmospheric-oceanic heat exchange, the transportation of substances via sea ice and high-density water, invigorated biological activity through phytoplankton, the effects of inflow on rivers etc. Without understanding the mechanisms behind these phenomena, it will not be possible to predict the effects on atmospheric/oceanic cycles and climate change that accompanies a reduction in sea ice, nor the responses of material cycles and marine ecosystems. To understand these phenomena at their locations, process research is required that takes a perspective on atmospheric/sea ice/oceanic heat budgets, as well as ecosystems and material cycles; thus, it is indispensable to having data gathering on location that spans all seasons. Additionally, in predicting the state of the Arctic Ocean and the ice sheet as warming continues, it is important to reconstruct the distribution of sea ice and the terminal position of the ice sheet in the Arctic Ocean as it is currently versus conditions of radically different climate conditions and to understand the various mechanisms behind these changes.

To carry out the above, it is absolutely essential to assess the status of erosion and sedimentation on the seafloor through topographical analysis of the Arctic Ocean bottom and to extract sediment samples from a wide area. Additionally, to further understand long-term

Table 4: The concrete objectives of having its own icebreaker for various observational activities

Atmosphere	Improvement of weather forecast accuracy in the mid and high latitude area by aerological observations over the sea ice cover
	Supply of meteorological information for shipping on Arctic sea routes
	Flagship to build big international projects such as MOSAiC
Ocean and ice	Drastic improvement of the degree of freedom (flexibility) for selection of observation periods and regions
	Implementation of sea ice observations all year-round (importance of observations over the ice-covered area during winter)
	Realization of field observations of physical and geochemical processes in the sea ice growing and decaying periods (including wintering observations on sea ice)
	Realization of observations synchronizing with no-ice area observations (in cooperation with existing ice-class vessels)
	Improvement of reproducibility of coupled ice-ocean models (essential for shipping route prediction)
Ecosystem	Realization of biological observations from the sea surface to bottom without effects of sea ice presence
	Establishment of all year-round observation systems of marine ecosystem (impossible under carpool systems of icebreakers between countries)
	Establishment of observation sites of marine ecosystem
Solid earth Paleoenvironment Paleoclimate	Improvement of reconstruction accuracy of the distributions of sea ice and ice sheets in past
	Improvement of accuracy of bathymetric maps
	Exploration of hydrothermal systems along seafloor spreading centers under sea ice cover
	Estimation of internal structures below the seafloor of the Arctic Ocean
	Preliminary survey for progress in paleoenvironmental and paleoclimate research and large-scale excavation in future
	Estimation of the formation process of the Arctic Ocean

changes, it will be necessary to investigate the tectonics of the Gakkel Ridge, which is currently expanding the ocean bottom, as well as the formation process of the Arctic Ocean and the inner structure of the Earth; and, there will also be a need to understand the interaction of solid Earth dynamics with the uppermost stratum environment in conjunction with the paleoenvironmental / paleoclimatic research on deposits. In sum, the procurement of observational infrastructure - specifically, an icebreaker - to obtain data and samples on location is of the utmost importance to advance Arctic research.

Japanese research expeditions to the Arctic Ocean have, up to this point, been carried out using Japanese ice-resistance ships or icebreakers from other countries, and these operations have been constrained by expedition timing, operating area, the number of participants and budget. There are problems associated with the use of icebreakers from other countries in particular that cannot be overlooked; for example, not only is there the constant risk of interference with the Japanese research agenda via the political tendencies of other countries, but there is also the issue of transporting (exporting/importing) samples, research equipment and materials. This has become a particularly large hindrance in limiting the types of research materials and data amounts for chemical and biological research needed in on-site analyses and experimentation. In contrast, countries that possess icebreakers already have research regimes in place, and have been vigorously carrying out their research programs. If nothing is done, Japan will fall behind in promoting research of the critical area where we need to understand changes of the Earth's systems in recent years. For Japan to further develop its own Arctic research, we must have our own icebreaker which can be flexibly adjusted to match the research expedition timing and region; and, Japan must have in place our own trans-seasonal (including overwintering) regime that utilizes an icebreaker as a platform to engage in on-site research (including on ice), as a manned-observation station, and as a base to carry out unmanned observation (including with AUVs).

There has been little accomplished by other countries with serious observation in the seasonal sea ice areas, including along the marginal ice zone. Japan, which has already carried out much research, in not only the Arctic and Antarctic Oceans, but also in the seasonally-variant sea ice regions of the Sea of Okhotsk and the Bering Sea, possesses significant potential for further process investigation by deploying our own icebreaker to carry out our own original observational research. Moreover, the combined use of our existing ice-strengthened vessel with an icebreaker would allow for observations to have a surface-based understanding of the ice-forming preconditions in the sea-ice zones, the marginal ice zones and the open water zones, along with year-round observation of atmospheric/sea ice/oceanic heat balance. There is also great significance to Japan possessing its own icebreaker since we will be expected to take a large role in the preliminary survey and drilling research for the international research drilling in the Arctic Ocean currently under discussion towards being carried out by the IODP (Integrated Ocean Drilling Program), among others. It is clear that the acquisition of an icebreaker by Japan will dramatically expand the potential of Japanese Arctic research. The specific implications of possessing our own icebreaker for various observational research activities have been summarized in table 4.

Should Japan build our own icebreaker the Arctic Ocean, the Antarctic Ocean, and the Sea of Okhotsk will all become available to serve as potential operating regions. However, to actually sail through ice zones for many years, the icebreaker must be outfitted with the appropriate specifications. To carry out Japan's own Arctic research, an icebreaker must ultimately be specialized for academic research purposes; however, an operational regime must be built that also allows it to flexibly respond to various societal demands. Other factors to continuously operate an icebreaker must also be kept in mind, such as a crew, equipment and assembly of an operating system. Sea ice has been predicted to disappear completely during the summer season in the Arctic Ocean by the 2030s at the earliest; however, there is an extremely low possibility that there will be no sea ice in the Arctic Ocean throughout the year, including during the winter, and we do not anticipate future conditions where an icebreaker would not be required. To go beyond being simply an icebreaker and actually function as a Research-Specialized Ice-Breaking Vessel, the following equipment will be required: a moon pool, a satellite data receiver system for the Sailing Plan, CTD observation system and storage racks, A-frames, winch with multipurpose cable, automatic radio sonde launcher, laboratory for chemical, biological and geological analysis (including refrigerator), a low/wide/long vertically-opening observation gunwale on the same level as the laboratory, a workshop to handle maintenance of all shipboard equipment, an AUV with multiple sensors and the ability to operate for extended periods underneath sea ice, an ROV with the ability to take samples, a long, large-diameter piston corer, a large crane to lower the corer from the gunwale, a multi-beam depth sounder to be used in surveys of seafloor topography, sub bottom profiler for stratum exploration, equipment to estimate tectonics and the inner structure of the Earth, such as a gravimeter and a magnetometer. Additionally, the icebreaker would be ideally equipped with seafloor-based drilling equipment that can take longer deposit samples from the moon pool and either reflection or refraction seismic survey equipment, should the need arise for such.

By possessing our own icebreaker, Japan will be able to conduct original mission-oriented research. For example, observational research will be enabled that aims at understanding specific processes in important marine regions. Additionally, by basing projects on a platform, there will be further involvement and advancement expected from Japanese researchers in numerous polar research fields (atmospheric sciences / sea ice / oceanography / paleooceanography / paleoclimatology / paleoenvironmental sciences / solid Earth physics; biology/physics/chemistry). Proposals for international research projects will also be possible without suffering from the constraints of national borders. If a system is put in place that accepts foreign crew members, such as with existing research vessels, then this not only promotes transnational collaborative research, but also allows for the development of research on a par with the rest of the world. Major expectations can also be placed in the widespread training of new talent, which not only involves researchers and technicians, but also includes improved sea-ice navigational skills by mariners.

Satellite Observation

Satellite observations have been made with various purposes other than environmental monitoring, and also many kinds of satellite missions have been carried out for environmental research, as well as are scheduled in near future. In this section, the satellite missions only for the lower portion of the stratosphere are described.

Environmental change at the polar regions, which are keenly vulnerable to the effects of climate change, is occurring on various spatiotemporal scales -from the reduction of sea ice, snow and glaciers to changes to ecosystems; and, those changes are having an effect on global climate systems. It goes without saying that a satellite observational network is invaluable if it can conduct concurrent and continuous surface observation in the remote and inaccessible Arctic region, where the spatiotemporal scales of phenomena are immense. The scaled-up site observational capacity and the compatibility with back-up and modelling research will make a satellite observational network the required infrastructure for the evolutionary development of polar environmental research into the future. A satellite observational network will be a tremendous resource to creating long-term data, which may be rightly called a 'Climate Record', to elucidate the changes of the Earth's environment -a duty that Japan has taken on through our leading research on global warming and its effects on climate change. In the following, we will describe the role that a satellite observational network infrastructure provided by Japan will play in not only research on global climate systems in the Arctic, but also in helping to resolve the societal problems outlined in the Future Earth plan.

Japan has contributed greatly in the realm of satellite observational networks up to this point, with the representative contribution being the AMSR series. Japan's microwave scanning radiometer boasts the world's most advanced performance (AMSR, AMSR-E, AMSR2) and has taken the place of the United States' SMMR and SSMI series in currently monitoring the sea ice, snow, glaciers and ice sheet of the Arctic region. The monitoring of ice on the surface of the Earth not only involves research on the characteristics of the ice (surface area, volume, velocity), but also indispensably involves research on the changes to the heat balance/water balance between the surface of the Earth and atmosphere as well as changes to the ecosystem. Currently, no other countries are involved in the development of microwave scanning radiometer technology, and Japan's role in continuing this observation is exceptionally large. Additionally, in comparison with the SSMI series, the AMSR series has dramatically improved spatial resolution, and has made a significant impact on polar research. To accurately analyze changes to the polar region, higher spatial resolution is still needed; and, the continuous improvement of resolution and sensors through technological innovation, such as with the doubling (3 to 5km at 89GHz) of the current resolution of the AMSR2 is desirable to carry out monitoring of polar routes on a daily basis.

To monitor mass fluctuations in the ice, Japan will require our own laser radar altimeter. In addition to the CryoSat-2 currently carrying out observations, the US is planning to launch its own ICESat-2; however, the largest drawback with their altimeter is relatively low spatial resolution and this disallows analysis of small-scale fluctuations in ice mass. The acquisition of seamless and high-resolution composite altitude data through collaborative altimeter readings from a Japanese altimeter and the altimeters of other countries will contribute greatly to research on global-level fluctuations in the water cycle through the monitoring of mass fluctuations in glaciers, ice sheets, sea ice and snow. Additionally, the outfitting of optical/synthetic-aperture radar (SAR) is indispensable to monitoring fluctuations in glaciers and ice sheets. For example, with high-resolution visual stereo pair images we can expect significant results in measuring ice volume changes based on detailed digital elevation model (DEM). Therefore, the development and launch of a successor to the ALOS/PRISM is an urgent task. Moreover, measurement of ice flow velocity through optical sensors/SAR is necessary for the monitoring of changes in glaciers/ice sheets.

The PALSAR-2 (L-band SAR), which was to be carried aboard the ALOS-2 due for launch in 2014, is uniquely different from the SAR satellites of other countries insofar as it is extremely useful for monitoring glaciers and ice sheets. ALOS/PALSAR plays the primary role in obtaining data on the ice flow velocity distribution on the Antarctic ice sheet, and glaciologists around the world anticipate the same of the data from ALOS-2. Obtaining high-resolution spatiotemporal data using a Japanese satellite would be desirable going into the future. Also, measurement of the physical quantity and albedo of snow by using optical sensors (wavelength: 19 channels from visible to infrared) able to observe the entire Earth at a high frequency and resolution scale of 250 m would be incredibly important to elucidating the processes of snow accumulation/reduction in both polar regions and the Himalayas as they rapidly change accompanying global warming. The GCOM-C1/SGLI, due to be launched by Japan in 2016, will monitor the fluctuating surface and quality of snowy regions around the world and is expected to contribute to the improvement of land surface processes for numerical climate models. Furthermore, we should advance our efforts to evaluate the potential of the domestic development of satellite gravity measurement capacity, which has already produced significant results in recent years with the GRACE satellites.

The high-precision observation of clouds and aerosols which are largely involved in the Earth's radiation budget and the water cycle are crucial to explicate climate system formation in the Arctic region. Certain results in verifying and improving climate models have been produced through global observations, carried out both by ISCCP, which primarily uses geostationary satellites, and the passive satellites of AQUA with MODIS sensors.

However, there are limits to the precision of cloud observation with objects of macroscopic physical quantity, such as cloud cover, owing to the issues inherent to passive sensors, such as ground surface albedo problems in the polar regions. To overcome these limitations, observations began in 2006 with CloudSat, a primarily US-operated cloud-observing satellite equipped with radar, and the lidar-equipped CALIPSO. These satellites, along with the Aqua satellite, form the so-called 'A-Train' and follow the same orbital path mere minutes away from each other carrying out observations; this kind of satellite observation makes it easier to carry out analysis using a combination of multiple satellites. The CloudSat satellite is equipped with 94GHz cloud radar and allows radar reflectivity factor observation; and, it provides data on vertically-distributed cloud and precipitation every 1.1km in the horizontal direction and every 240m in the vertical direction. The lidar-equipped CALIPSO, can observe in two wavelengths –visible and near-infrared light—and can acquire polarized light in the visible spectrum; the horizontal and vertical differ by upper layers and lower layers, however, at its finest setting, it provides data every 330m in the horizontal direction and every 30m in the vertical direction. Cloud observation is possible with both sensors, and analysis of the data they have provided has allowed for the acquisition of comprehensive information on multiple layers of clouds not previously available, as well as information on the relative conditions of ice and water for each vertical layer. Additionally, through the combined use of CloudSat and CALIPSO, it has become possible to investigate cloud microphysical properties, knowledge of which is indispensable to having a quantitative understanding in the evaluation of influences on the radiation budget and water budget of clouds.

The dual wavelength backscatter profile and depolarization rate of the lidar on the CALIPSO has allowed the calculation of the extinction coefficient for each type of aerosol, and the lidar's non-albedo-reliant observational characteristics have been utilized to enable the extraction of aerosol properties at a high precision on both land and in the ocean. These satellites are on a polar orbit and their observation times are fixed. To acquire day changes and more detailed information, it is important to observe clouds and aerosols with ground-based active instruments. The National Institute of Polar Research has conducted lidar observations at Ny-Alesund, and began observations there last year after adding cloud radar with a 95GHz band Doppler function. The GRENE Project is also planning to carry out intensive observations in the summer of 2014 involving ground-based observation.

The EarthCARE satellite, scheduled to be launched in a joint Japanese-European mission in 2016, will have a total of four sensors aboard: the very first Doppler cloud profiling radar (CPR), high-spectral resolution atmospheric lidar (ATLID), a multi-spectral imager (MSI), and a broadband radiometer (BBR). The EarthCARE cloud profiling radar, through its radar reflectivity factor, has heightened sensitivity of 7dB greater than CloudSat as well as a Doppler function, and working with the high-spectral resolution lidar function of ATLID, is expected to open up a path to retrieving new physical quantities, such as cloud microphysical features, vertical dynamics and cloud particle vertical velocity. The ground-based observation network at the National Institute of Polar Research's Ny-Alesund Base is anticipated to play an important role as the crucial ground-based verification site for the EarthCARE satellite.

Concomitantly, the monitoring of the carbon cycle and ecosystem changes accompanying global warming are critical. This monitoring is being undertaken most notably by the US visible-range (near-infrared/thermal infrared) sensors MODIS, SPOT Vegetation and VIIRS. These sensors observe the properties of the atmosphere (clouds, aerosols etc.), and are used not only for research into radiation flux and radiative forcing, but are also important products for determining the sensitivity of visible-range sensors. These sensors also permit estimates the geographic distribution and changes of the leaf area index (the one-sided leaf area per unit ground surface area) and the length of the growing season from the spring to the autumn, and can assess the annual output, which is important for understanding the carbon cycle. Moreover, from the estimated plant seasonality, the formation of vegetation and distribution of vegetation functional types in each region can also be estimated. Additionally, AVNIR-2 and PALSAR aboard the above-mentioned ALOS have advanced research on changes to land cover, beginning with deforested areas, and estimation research in forest biomass, one of the carbon stocks in the carbon cycle. Similarly, in the ocean, while restrictions to depth observations do exist, visible-range (ocean color) sensors are the only satellite sensors that allow gathering of the biological information required for ecosystem monitoring, and contribute greatly to research not only on fluctuations in chlorophyll *a* biomass and net primary production output, but also fluctuations in oceanic phytoplankton group composition. Further, the development of seawater optical models has promoted research on the estimation of colored dissolved organic matter (CDOM), an important carbon pool that exists in high concentrations in the Arctic Ocean. However, as it now stands, we are reliant on US sensors, and we have fallen behind in immediacy and originality. To construct and strengthen a cross-disciplinary cooperative regime in Japanese Arctic research, we must make use of the skills we gained in the past ADEOS series, develop Japan's own visible-range/thermal infrared sensors and continue our monitoring. Japan is planning to launch the aforementioned GCOM-C1/SGLI, and this is anticipated to contribute to research on the ecosystem changes on land and in the oceans (particularly along coastlines and the marginal ice zone).

The groundwork has already been built in Japanese Arctic research for the variegated use of satellite observation; it would be ideal, going into the future, to upgrade sensor functionality, in short, heightened sensitivity, finer spatial resolution, hyperspectral sensor is needed. However, to allow for a discussion accompanying statistical significances, we must continue satellite observation over the long term based on the same design ideals. Additionally, aside from the above-mentioned global observation satellites, communication satellites, such as tracking/monitoring satellites (most notably the ARGOS) and the Iridium satellite constellation, are infrastructural necessities to Arctic expeditions, remote observation by buoys, as well as information collection and transmission in real-time. Yet, researchers and others who actually use these must endure the various costs associated with their use, such as going through the contracting procedures and paying high use fees. It would be desirable to consolidate this into a single process in the future to reduce economic and time-consuming burdens. In addition, reducing these burdens would be the same as purchasing data from commercial satellites, such as RADARSAT, for Earth observation purposes.

Aircraft Observation

Airborne observation is an extremely effective means of observation across a wide area of Earth sciences. Remote sensing observation is an essential means of observation for the atmospheric sciences as well as in the fields researching vegetation, ice thickness, gravity fields and topography, in particular.

In the atmospheric sciences, ground-based observation is observation from a fixed point, and in contrast to horizontally-confined ship-bound observation, aircraft can make observations in the three spatial dimensions, thus advantaging aerial observation for three-dimensional detailed observations of atmospheric structure. Aerial observation is primarily performed by fixed-wing aircraft, however, rotary-wing aircraft, namely helicopters, can also carry out aerial observation. But, helicopters pose the problem of interfering with the atmospheric region that they are tasked to observe, so they are often limited to remote observation. Broadly considering aircraft, observation can also be effectively carried out using airships, free balloons and tethered balloons -each being deployed according to purpose. The use of gliders (unpowered aircraft) has also been promoted in recent years.

The latest in equipment is also required for research using aircraft-based observation. In terms of atmospheric observation equipment, the development of direct measurement equipment and sampling techniques for trace gases, aerosols and cloud particles, as well as the development and equipping of remote measurement instruments centered on radar and lidar are most desirable, and the outfitting of drop sonde systems capable of spatially-dense atmospheric observation is also important. In all of these cases, it is a continually-important task to make this equipment as compact, light-weight and energy-efficient as possible.

As for sea ice observation equipments, measurement using a towed electromagnetic induction ice thickness meter (EM-Bird) is expected for ice thickness measurement surface roughness measurement. These instruments can be boarded on rotary-wing and fixed-wing aircraft. The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research possesses two long-distance Basler Turbo BT-67 aircraft -the Polar 5 and Polar 6-. They operate for wide-range observations using EM-Bird boarded on the two aircrafts in the Arctic Ocean during the spring.

The internal three-dimensional structure and bedrock topography of ice sheets can provide valuable information to investigating the mechanism of ice sheet dynamics. Since the radio-echo sounding using ice radar cannot be carried out by satellite remote sensing, it must be performed by the instrument boarded on an aircraft.

In addition, observations related to solid Earth science, such as airborne magnetic and gravity measurements as well as laser topographic surveying in the Arctic region, are currently being carried out by countries like Germany, Canada and Denmark. These observations can be carried out by using instruments boarded on both rotary-wing and fixed-wing aircraft, but future high spatial resolution data acquisition would be required using rotary-wing aircraft. Further, there are few field data in the Arctic region owing to the accessing difficulty as is the case with Antarctica. It is expected to enable us on-site geomorphological, geological investigations and geodetic measurements by introducing rotary-wing aircraft.

European and US institutions, such as universities and publicly-funded research institutes, generally own and operate their own dedicated observation aircraft; however, Japan has yet to reach that status. The National Institute of Polar Research previously owned a single-engine aircraft which they used for atmospheric observation in Antarctica; however, the use of that aircraft finished long time ago. The atmospheric observations have been carried out by Japanese research institutes always with rented civilian aircrafts. This is likely a factor for the lack of progress in Japanese aerial observation, and the significant delay in the domestic development of airborne observation instruments in comparison to Europe and the US. Therefore, the establishment of a system for Japan to own and operate our own observation-dedicated aircraft is strongly desirable heading into the future. In addition, since the aircraft is used for various applications at different altitude, speed and range, deployment will be required of multiple aircraft with differing flight performances. To construct a system such as this, transnational cooperation, with multiple countries in Europe and North America that possess abundant experience in airborne observation, will be essential. An aircraft network will play an important role in covering a wide area of the polar region. Additionally, since the Arctic region is a remote area from Japan, the use of aircraft will require operating bases in the Arctic region or nearby.

The use of unmanned drones in the Arctic region is also regarded as an effective measure. Unmanned drones are extremely useful from a safety point of view owing to the increased danger of the formation of ice from supercooled water droplets while flying through clouds during aerial observations targeting mixed cloud formations characteristic of the polar regions. Unmanned drones have come to be used widely in atmospheric observations in recent years, and with Japan's accumulating technical know-how, we look forward to further advancement in this field.

Oversea Bases for Research / Observation

a. Introduction

The Arctic region is a complex environment which comprises elements that react rapidly to the climate (for example, vegetation, sea ice and glaciers) and elements that react slower to the climate (for example, permafrost and ice sheets). Understanding the Arctic regional environment requires not only long-term separate observations of each of these elements, but also process research to unravel the interacting systems between these elements along with empirical observation to evaluate their influences. Additionally, to understand the regional-wide environmental changes, an international cooperative regime must be built.

These various observational activities are an important infrastructural component to environmental research in the Arctic region. To build this infrastructure, the Japanese research community should be strongly conscientious of the direction the international community is taking as well as our role in that, and we must establish, equip and continuously maintain them. Additionally, considering that Japanese observations almost always take place in other countries, it is crucial to not only respond appropriately towards international trends, but to have the interests and intents of these countries in mind when carrying out our observations.

The Japanese research community has carried out various kinds of observations in the Arctic region up to this point, and has, for those purposes, built bases there. However, the scale of the space and time of the observed phenomena was various according to the phenomena each researchers want to investigate. In the below, we organize and categorize information on our needed infrastructure from the standpoint of the management systems, functions, scales of time and space, and we describe future developments while we take into consideration the trends of the internationally-collaborative research of recent years.

b. Categories of Observation / Research Facilities

The bases for research was categorized as either research bases or observation sites. In addition, we will also describe the observational functions and observed phenomena across a wide region.

(1) Observation Sites

These are facilities that carry out collaborative research regarding observations and they have the following characteristics.

① This category of base comprises two (or more) countries working collaboratively; it is managed based on an agreement; equipment can be brought in based on the agreement; samples, observation materials and data can be secured or brought out.

② This site has a work space established along with on-site managers and researchers posted; workers stay on site and cooperate with the research and observations carried out by Japanese researchers.

Observation sites can be further broken down into the two following categories.

(a) Integrated sites: Continuous observations in a variety of fields can be carried out at this base, and there is equipment fulfilling certain observational standard. These sites are effective for satellite or model calibration and verification. They require long-term maintenance and management systems that include the training of personnel.

(b) Reference sites: These are sites that carry out continuous observation based on set observational standards for research of a specific field and in localities (regions) specific for that field of research. They require long-term maintenance and management systems.

(2) Research Bases

In addition to the characteristics of the above Observation Bases, these facilities also have the additional characteristics which follows.

① These bases are fora for the training of Japanese and local personnel, for the mutual sharing of research and for collaborative analysis.

② They are located nearby to observation bases and wide-area observation networks.

(3) Wide-Area Observation

① Periodic Observation

This is observation of elements in particular fields of research that is repeatedly carried out in specific regions and at specific times. It primarily refers to observation over the long term. This not only involves observation on land, but also involves oceanic observation along coastlines around the land observation base.

② Network Observation

This is observation that is carried out over the long term in a given region for a specific field of research across multiple bases (generally 10 or more). The observation takes a variety of forms, with both manual observation and automatic observation being carried out successively with instruments. Examples of this include the frozen ground observation network and the glacial seismic observation network.

It is possible that there are many cases where wide-area observations are carried out from a research or observation bases. We would also like to point out that there is an Arctic-wide network such as the International Arctic Systems for Observing the Atmosphere (IASOA).

c. Management of and Candidates for Observation Bases

(1) Candidates for observation sites and research bases

Table 5 indicates the observation site candidates organized by field of research, categorizes the above sites and observations, and describes the current observational status in the remarks section. Moreover, research theme for each sites and bases is indicated. In figure 65, the area indicated by a shaded square on the map showing the position is the candidate area for expansion in the coming future. Table 6 shows the observed phenomena among other information organized by field of research. Upon considering international trends and the role expected of

Table 5: Observation sites and Research base (Existing and candidate)

	Atmo-sphere	Terrestri-al(Ecology, water)	Cryosphere (Permafrost, glacier, ice sheet	Ocean (coastal)	Upper atmo-sphere	Type of site (present)	Type of site (potential)	Related Theme No.	Remarks
①Ny-Ålesund (Svalbard)	○	○	●		○	B-1	A,B-1, D	1, 3, 4, 6, 8, 10, A	Many foreign station exists. Potential research base.
①Longyearbyen (Svalbard)					○	B-2		10	EISCAT exist. Svalbard Univ. (UNIS) exist.
①Ice station	●		●	●			B-1	1, 2, 3, 9,	Russia terminated ice station. Reopened Baranova St. , and this is a candidate.
②Tromsø (Norway)					○	B-2		10	EISCAT exist.
②Tiksi (Russia)	●	○	○	●		B-2,C,D	B-2,C,D	1,2,3,4, 8,10,12	US-Russia Station, German-Russia St, also exist. GCW candidate. Coastal Obs. Possible
②Yakutsk (Russia)	○	○	○			B-1, C,D	A,B-1, C,D	3, 4, 8, 12	Japan-Russia Station exist. GCW candidate. Research Base candidate
③Fairbanks (USA)	○	○	○		○	A,B-2, C,D	A,B-2, C,D	3, 4, 8, 12	JAMSTEC-IARC obs. Site exist Research base candidate.
③Barrow (USA)	●			●		B-2		1	Many USA observation sites exist
③Eureka (Canada)	●	○			●		B-2	1, 3, 8, 10	
③Cambridge Bay (Canada)		●	●	●	●		B-2,C	2, 9	New Canadian station. Marine obs. Possible.
④Summit and others (Greenland)	●	○	○			B-2,C	B-2	4, 6, 11	

Region: ①: Arctic Ocean, ②Eurasia, ③North America, ④: Greenland.
Condition of Japanese observation activity: ○: Presently exist. ●: Request exist.
Type of sites: A: Research base, B-1: Obs. site (Supersite), B-2: Obs. site (Reference site), C: Traverse observation. D: Network
Theme No.: Corresponds to Research theme no. 1 to 12 , A to C.

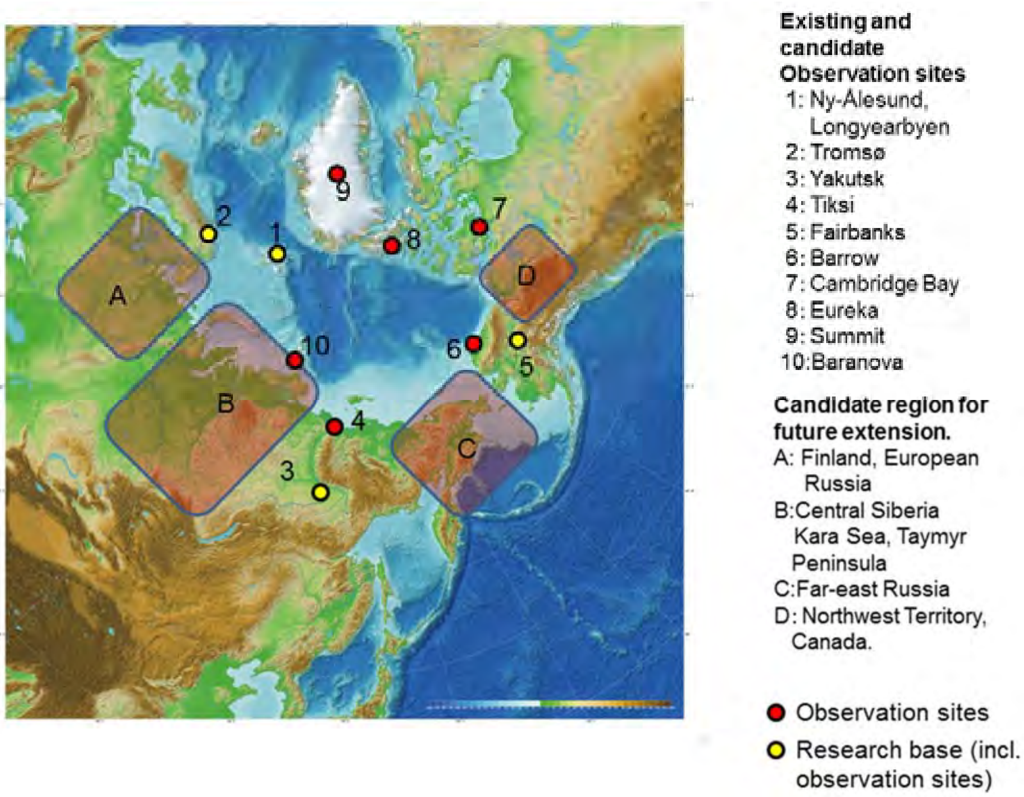

Figure 65: Position of observation sites and research bases.

Table 6: Observation items, equipment and infrastructure needed at the observation sites for variou

	Atmosphere	Terrestrial (Ecology, Water)	Cryosphere (Permafrost, Glacier, Ice Sheet)	Ocean (incl. coastal)	Upper atmosphere
Items	Water vapor Precipitation Radiation GHG Short-lived Climate Pollutants Aerosol Basic meteorological elements	Meteorological elements Snow-ice elements Ground temp. Soil moisture Organic substance Vegetation parameters Various surface fluxes Tracking system of animals	Snow-ice distribution SWE Density Snow texture Impurities Precipitation(Snowfall) amounts Various meteorological and radiation elements	Carbon dioxide Methane Pollution substance Ocean temp. and Salinity Dissolved oxygen Nutrients Minor elements Phyto- and Zooplankton Microbes Marine mammals Seabirds	Activity of solar wave Temp. fluctuation Minor elements
Equipments	Surface meteorological equipments Radiosonde system Mooring system Radiation sensors Various analyzer Lidar, Radar Computer Unmanned aircraft	Super-sites Storage facility Sample analyzing facility Snow mobile Boat Various sensors Data storage device Observation tower	Drilling device Transmission device Various sensors Data storage device Automatic obs. Systems.	Research and experiment facility Lodging facility Small ships Water pumping device Automatic sampler Mooring system Ice-resistance Ship Autonomous underwater vehicles (AUV)	Na Lidar Rayleigh Lidar Optical devices HF· VHF Radar Meteor Radar Magnetometer GNSS Receiver Electromagnetic wave receiver
Infrastructure	Satellite-surface validation Long-term monitoring Sampling Equipment maintenance	Liaison office Instrument development for remote region. Information integration facility Interrelation with indigenous people	Information integration facility Glacierquake network Coordination with GTN-P	Domestic ice-resistance ship Coordination with IARC International usage of ice-breaker and ice-resistance ships.	Participation/Usage of EISCAT Radar Network

us on the international stage, we have set out the order of priority for outfitting/developing these sites and bases

according to the important projects Japan will pursue.

Among these, the following bases are either locations that currently come close to fir the condition as research bases or are locations that we desire to be so.

① Ny-Ålesund, Svalbard

This is an international collaborative observation area hosted by the Norwegian Polar Institute with numerous participating countries, and the National Institute of Polar Research has had a station established here since 1991. Research in numerous fields has been conducted here; however, currently there is monitoring of greenhouse gases, observation of clouds and aerosols, snow and ice sampling, long-term observation of the tundra ecosystem, fixed observation of circumpolar atmospheric cycles, and upper atmospheric observation. This base functions as a collaborative international base, and to maintain and develop it, we must increase our presence to meet Japan's obligations there. There are plans to also strengthen the international collaborative research there through the Svalbard Integrated Arctic Earth Observing System (SIOS), and the full functionality of Japan's station will be an important presence in this.

②Yakutsk, Eastern Siberia

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Hokkaido University, and Nagoya University, among others, have been focused here engaged in ground-based observations of vegetation, frozen soil, greenhouse gases, hydrology, and snow and ice since 1990. They have used this base as their starting point to expand their observations out to the coastline of the Arctic Ocean and a wider area. They have been carrying out tower-based observations there since 1997, with the Netherlands currently being involved. There are also new researchers participating through the GRENE Project. This is the initial reference site for the World Metereological Organization's Global Cryosphere Watch (WMO/GCW), and it has also become a site for INTERACT. This will also be the base for the multiple combined-use field stations spreading along the coastline of the Arctic Ocean, such as at Tiksi.

③Fairbanks, Alaska

JAXA and JAMSTEC have been engaged in collaborative research at this base with the International Arctic Research Center (IARC) at the University of Alaska Fairbanks since 1997. Currently, the involvement of both of these Japanese institutions is waning; however, this base can be characterized as an observation site and a research base with numerous achievements in training personnel, including in periodic wide-area observation, and should continue to be maintained as a research base into the future.

Among other bases that can be expected to be used in the future are the Canadian High Arctic Research Station (CHARS) in Cambridge Bay, Nunavat, and the Baranova base in Severnaya Zemiya, Russia. These bases are not only useful for observations of the atmosphere, tundra, snow and ice, but they are also highly accessible to marine observation.

(2) Management of Observation Bases

Among the research and observation bases, the basic areas of the long-term, large-scale bases are handled by the appropriate domestic core institutions, and it is best for each project to handle its own share of everything else.

Additionally, should there be land observation sites of other countries or the host country in close proximity to the base, there must also be the notion of a 'designated observation zone' at the international level for a certain area centered on the research bases and observation sites in which Japan is involved.

The following points of caution must be observed in managing research and observation bases.

1) With respect to the efficiency of research and the convenience of the base occupants, it is ideal for a single organization to be charged with the maintenance and management of a base.
2) Since long-term observations are important, a stable management funding system covered not by competitive funding, but through a grant system from a designated institution is desirable.
3) There must be observation standards put in place for each field at observation sites, and data must be refined.
4) A mechanism should be introduced to allow for the smoother transition of new researchers.

Archive System for Data and Samples

a. Background

There are various changes occurring in the Arctic region due to global warming. Research up to now has revealed a reduction in the sea ice of the Arctic Ocean, an increase in ground temperatures in Siberia, melting of the permafrost, an increase in arctic river discharge, and a reduction in the amount of snow cover area, among other changes. Additionally, there are concerns about the effect that such changes may have on ecosystems and human activities. Among the environmental changes in the Arctic region and the mechanisms that drive them there are still numerous areas that have yet to be explained, and the actual conditions and mechanisms need to be explained. Research efforts up to now have pursued their own separate fields for the atmosphere, ocean and land; however, the Arctic region is a system comprising the atmosphere, the ocean, the land and the snow and ice, and each system therein includes its own phenomena that differ along scales of time and space. To elucidate the changes along these different scales of time and space as well as the complexly-integrated changes in different fields making up the environmental changes in the Arctic region, there must be a new understanding of processes and explanation of mechanisms that use integrated data sets with accumulated observational data and research results that span multiple fields. The establishment of an archive system for data and samples is a important research infrastructural component that is neglected in almost all research projects, and is of conceivably great priority. Retaining all digital data and samples in common, establishing an archive system and managing the data, promoting the sharing of data among researchers and having a system that links to new research will likely lead to research with increased potential.

b. Data Archive

In the following we provide suggestions for a Japanese data archive that we regard as important based on the current situation.

(1) Data Archive Stability

Data archiving, it is a stable system are conditions required minimum. Here by 'stability' is not only redundancy archiving (having back ups), but an archive that can be maintained for the long term. It is particularly important for a data archive to have reliability regardless of the time limit of a research project, and for the archive to be maintained, as a principle, by a permanent research institution, and not a short-term project with a specific life-span.

(2) Data Archive Accessibility

A data archive system must be as user-friendly as possible for both the data provider and the data user. A data archive system exists to not just have data input into it, but also to be widely used by researchers, and ease of access to browse data by users is essential. Setting up a search service and a data quick-look tool can likely be called the lifelines of an archive system. For example, with the Arctic Data archive System (ADS) that is undergoing trials at the National Institute of Polar Research, we believe the development of a data-saving/search function and a data-browsing system that allows minimal analysis is important, and that development of these must be continued into the future.

From the data providers perspective, there is a strong need to reduce the burden of and ease the access to register data. Enhancement of metadata to the contrary parts at this point, but an environment must be established that allows for the smooth registration of data through the construction of a support structure from the perspective of the data archive system.

(3) Data Flexibility

Arctic environmental sciences is a broad academic field, and data formats naturally have wide-scope. Humanities and social science data have also grown in importance in the realm of environmental research in recent years, and a system that goes beyond the current digital data formats and can handle a multiplicity of data formats is desirable. Additionally, there has been increased acquisition of high resolution temporal and spatial data, and data volume for observation data and model output has grown extremely large in comparison with the past. Handling this kind of complex, multifarious and voluminous data would require a considerable amount of effort by a general researcher, and would not be regarded as useful. A data archive system should be constructed in the future that can both handle complex, multifarious and voluminous amounts of data, and be convenient.

(4) Promoting Data Rescue

The Arctic region is behind the rest of the world in data maintenance, and data that are not disseminated globally must be collected and managed. Further, data rescue (the digitizing and saving of data that have been written down in paper form and are in danger of being lost forever if not stored appropriately) must be urgently done in this region.

(5) The Publication and Distribution of Data

The assignment of digital object identifiers (DOI) for data sets to guarantee permanent data set links has been advancing in the past several years at data centers. A DOI is a character string to identify digitized contents and are necessary components to improving the distribution and utility of data, as well as in guaranteeing the permanency of links. In Japan, they are currently used only for academic papers and books. Japan must assign DOIs to data that we have acquired ourselves and we must promote the distribution of this data.

Many academic journals that aim to list and publish data are put out by major publishing companies. Some of the primary examples include Earth System Science Data (EGU), Geoscience Data Journal (Wiley) and Scientific Data (Nature). These media are not only effective for promoting the publication of observation data, but also for undertaking data rescue. There should be serious consideration made in regards to the publication of data journals domestically or the establishing of similar media through the expansion of existing journals.

(6) International Coordination

There are various regions and countries in the Arctic region, and international coordination in the usage of data is a must to understand the Arctic environment. A data base on Arctic research is operated by a number of countries, primarily focused on the Arctic countries, and various data centers and data portals exist (NSIDC, CADIS, GCMD, GEO-Portal, GCW etc.). It is not realistic to integrate these into one system. However, it is extremely important to coordinate these systems; a function should be introduced that enables mutual use of metadata and searches from other databases and a distributed database should be built through international coordination. Data management has currently just begun to be discussed by the Data Management Working Group of the International Arctic Science Committee and the Sustainable Arctic Observation Network (SAON), and international coordination must be actively advanced going into the future.

(7) The Necessity of an Arctic Data Center

Data sets are managed by the accompanying metadata. As IT advances and information sharing expands, there is a tendency to integrate the format of metadata, and there is less of a need to collect and accumulate observational data in international data centers. However, there is no emphasis placed on the data management duties to construct and release data sets for field observations made by Japanese domestic research institutes and universities;.They rely on the data centers of other countries. Yet, the data that has been acquired through research observations carried out by national funding are precious, and must be released by Japanese institutions and be made more accessible for Japanese researchers. There are barriers for the research institutes and universities to carry out this for the field observation data by themselves, and there is a need for Japan to have its own integrated data center and release data in the field of Arctic region environmental research. Additionally, for the above data to be published and disseminated and international coordination to advance Arctic environmental research, Japan must carry out these efforts in an integrated manner, and should introduce a data center function.

c. Archive System for Samples

Arctic environmental research includes a lot of sample acquisition and analysis-based research, and a mechanism for the long-term and stable archiving of samples is extremely important. In consideration of the fact that samples obtained during research have been and will continue to be valuable assets, and that there is a need to pass these samples down to allow successive and long-term research, we believe it would be advisable to establish an institution, independent of the institutions to which researchers belong, that can maintain a sample storage and distribution system to allow for new analysis. In the above case, there is a possibility that it would be necessary to devise a system where, if possible, the sample is divided and part of it is managed by an institution, such as a science museum, and the other part is managed by the researcher who obtained the sample. It goes without saying that this independent institution or science museum will require stable funding and staffing, and for not merely 10 years, but with a long-term perspective in mind.

What will be simultaneously important is the metadata for the sample. To inform researchers of samples and to promote analysis and research, sample metadata must be created, and sufficient information should be released and access made easier to samples that have or will be taken.

The archive sample systems required differ largely by sample type and properties; but, there is adequate flexibility in data format for metadata that the collection and release by the aforementioned data system is possible. We believe that serious consideration should also be given to the role of the data center as a collector and manager of sample information (and not just numerical observation data).

Personnel Training

a. The Current Status of Personnel Training in Japan for Arctic Environmental Research

Japan has fundamental problems in personnel training in general, and not just limited to Arctic environmental research. Owing to the fact that many PhD graduates cannot find indeterminate research positions, and many take post-doctoral positions, the number of students who aim to enter PhD programs has decreased dramatically. We aim to suggest measures to overcome this state of affairs. We will train talent to fit a variety of paths, and tie this training to industry, which will use it as fuel for growth. There is also a need to train not just experts in the natural sciences, but also in the humanities and social sciences, and to develop education plans that particularly allow for an integrated approach between the two. It is also important to cultivate knowledge on Arctic societies affected by environmental changes. Since Japan does not possess any territories in the Arctic, we must conduct observations and field research outside of the country to carry out on-site observations and field surveys for Arctic environmental research. As many Japanese undergraduate and graduate students do not opt to go overseas, the Arctic seems like a far place; however, we propose measures to reduce the barriers for them.

b. International Efforts to Train Personnel

The following three organizations are engaged in international cooperation on Arctic environmental research.

(1) APECS (Association of Polar Early Career Scientists)

This is an organization run by students and young researchers carrying out research on both polar regions; i.e., it is supported by funding from numerous organizations, such as IASC and SCAR, and it engages in various activities. Becoming involved in APECS and participating in activities is effective to building careers for youth aspiring to be researchers. JCAR has supported the start-up of a Japanese domestic offshoot organization of APECS, and has begun the preparations to do so. Support in the form of funding activities for APECS and the domestic offshoot organization should be carried out in the future.

(2) University of the Arctic

The University of the Arctic is a university network comprising over 130 universities with member schools being primarily from the Arctic countries, along with associate member schools. The University of the Arctic offers numerous courses (lectures and seminars). In 2011, Hokkaido University was registered as an associate member school, and began activities in partnership with schools like the University of Alaska.

(3) The University Centre in Svalbard (UNIS)

The University is located at Longyearbyen on the Svalbard Archipelago, and the National Institute of Polar Research has an office there. It is the world's northernmost university, and it was established in 1993 by a federation of universities in Norway. There are nearly 20 faculty members, and students there can experience fieldwork. Almost 300 students from around the world select courses there each year, while there are only several students from Japan.

c. Future Issues to Consider for Training Personnel

We propose that instruction and general literacy of specialized knowledge be firmly established in addition to a support regime aimed at training researchers. The efforts we expound on below must not just be carried out by individual researchers and research institutions alone, but must be promoted through coordination among domestic universities along with coordination between Japanese universities and the universities of the Arctic countries. The entire spectrum of Arctic-oriented research affiliates in Japan must use JCAR as a mediator with these coordinating networks to promote these efforts so that more effective personnel training is carried out.

(1) The Training of Researchers

The following programs will be carried out through coordination among universities in Japan and coordination between Japanese universities and the universities of the Arctic countries.

- An internship program will be established that allows for the participation of graduate and undergraduate students in research activities.
- Carry out a summer school, and administer education as a community for undergraduates and graduates who have started research.
- Choices for career paths will be increased after earning Ph.D, by development, introduction and training offered for post-graduates.
- A job-seeker bank will be created, and PIs and students will be matched beyond the limits of just universities and acquaintances.
- Support activities for young GRENE researchers dispatched to the field, and a dispatch system that aims for research at foreign research institutes and universities shall be established as a follow-up effort.
- Establish a support system to assist fieldwork in the Arctic region.

(2) International Coordination

Exchange activities will be smoothly promoted through not only the cooperation of JCAR in the activities of APECS, but also the strengthening of ties of Japanese universities with the University of the Arctic, UNIS and other universities in Arctic countries. We also believe that use of the IARC is effective. The safety of students who are dispatched and stay at IARC is paramount, and the IARC has a system in place to ensure this. Additionally, English is the common language, so communication is comparatively easy.

The actions taken by ARCUS to train personnel would likely be a good reference for future efforts. For example, TREC is an initiative for school teachers to experience the field and the research involved there. If this can be carried out in Japan, it would be an effective means of disseminating research activities.

One international effort that Japan should give priority to promoting is contributing to the training of personnel by setting up an invitation system targeting young indigenous researchers. The results of this will also be fruitful for international coordination to provide overseas training for young Japanese researchers. Further, by inviting young researchers from non-Arctic countries, particularly in East Asia, this builds a foundation for transnational coordination and international collaborative research over the long term.

(3) The Succession and Development of Specialist Technical Knowledge

There have been reductions in technicians in research institutions, including universities, through administrative orders for the efficient placement of personnel. Yet, technological innovation plays a major role in supporting the development of cutting-edge research, and there is a need in Arctic environmental research for both high technological capacity and new developments in modelling, observation techniques, satellite data analysis, chemical analysis, and DNA analysis, among others. We must secure the infrastructure to improve technologies like the further development and sophistication of predictive models, the precise analysis of parameters, the sophistication of ship-bound observation, and the diversification of observation parameters. The most basic condition for the succession and development of technical expertise is the cultivation and employment of technicians. Additionally, to reduce the barriers between technicians and researchers, it is likely effective to propose various axes of evaluation.

The information exchange among different fields of research cannot keep pace with the rapid development of technology, and some fields cannot make use of the incredible technology available. Coordination across various fields of research will be helpful in allowing for the quick exchange of information. Even with coordination among specialists who use different research techniques, such as with coordination between on-site observation specialists and modelling specialists, it is the training of researchers and technicians who can link up with each other that we must devote our efforts.

(4) Establishing Literacy and Conducting Outreach

There has always been emphasis placed on the importance of the Earth's environment in the science curriculum of elementary and junior high schools. The average citizen's ability of comprehension is the foundation for the dissemination of knowledge, and there is reason to require JCAR members who are affiliated with elementary and junior high education. By sharing knowledge and information with members associated with school education, the importance and appeal of Arctic environmental research can be accurately and efficiently communicated to younger generations. We should also put our best efforts into activities, such as public lectures and science cafes, that communicate the appeal of cutting-edge research to elementary, junior high and high school students. Public outreach activities will be linked to the training of personnel to communicate the importance of Arctic environmental research, and will increase the number of students interested in the field. The Arctic region is a far place in the minds of the students, but it has cities and towns where people live, and it is possible to develop programs for the students to experience the region. By providing opportunities for this kind of experience, students will gain an education by experiencing activities in the field.

Promotional System for Research

a. Background and Objectives for Setting Up this Promotional System

Arctic environmental research is growing in complexity and size, and it is important to construct a system that allows it to be carried out smoothly, efficiently and productively. To these ends, there must be a system established that can promote research inside Japan.

The complexification process refers to the spread of the social fields required of scientific knowledge to not only the scientific community, but to industry and resources as well; it also refers to the invigoration of policy by the various government organs that relate to this; and, it is also the rise of indispensable international frameworks. These are international trends seen in numerous countries, and the effects of these trends have also been felt in Japan to the extent that they are altering our system here. This kind of situation regarding the Arctic region differs from the situation of the Antarctic region, and these complexifying conditions require research to be promoted efficiently and effectively. This implies that relations outside of the domestic community are strongly needed, even in cases of pursuing scientific truth, and this is a new chance for us. However, to carry this out in a smooth manner, we need to review our system of research.

b. International Trends

Research on the Arctic environment must be promoted through the cooperation of both Arctic and non-Arctic countries. There are international organizations that exist to determine or advise on the direction of research and activities in the polar region, like the International Arctic Science Committee (IASC) at the center as a union of scientists, the Arctic Council (AC), comprising mainly the governments of Arctic countries, and other related groups, as well as international organizations that take a partial interest in the Arctic region, such as the World Climate Research Programme (WCRP) and the Global Earth Observation System of Systems (GEOSS). Since research in Japan is placed in circumstances where it cannot possibly survive being unaffiliated with these groups, this means that Japan must becoming strongly involved in the activities of international organizations, by offering the input of the Japanese perspective into and cooperation towards the policies of these international organizations.

Further, as part of this, there are numerous requests for bilateral cooperation received, and the opportunities to adapt to these frameworks and evaluate the implementation of research through them are on the rise. There are also international frameworks regarding funding that are beginning to appear, such as the Belmont Forum, and the climate for promoting research is growing in complexity.

We must devise a Japanese domestic system to rapidly and suitably accommodate these international trends as a group.

c. Envisioning a Japanese Domestic Promotional System for Research

In terms of a domestic system, the following basics must be given due consideration and design must be implemented based on them.

- Researchers can implement new research based on unencumbered and novel ideas on the basis of a common infrastructure arranged for them as they require it. To these ends, a system must be erected to allow for the common use of as much research infrastructure as is possible.
- Japanese researchers and institutions will smoothly

carry out their research, and Japan can execute our international duties as a whole, amidst the international framework and its constraints.

・ Japan will be able to facilitate an interchange between disparate societal levels and fields of research domestically, and return results in their entirety to society at large.

d. System Specifics

Strengthening of the following system specifics is desired.

(1) We aim to strengthen the core institution which will lead the effort to advance the system of domestic promotion and implementation of research. It would be ideal to have a Promotion Committee, comprising primary organs and related groups, established in the core institution that serves the function of promoting general research, cooperation with funding institutions and the setting up of infrastructure. The core institution called for the establishment of an 'Arctic Environmental System Research Base' in a “Large Research Project” proposal in 2013 to the Science Council of Japan; such a proposal would be welcome.

(2) The arrangement of the research infrastructure (observation platforms, overseas bases, equipment, models, data) shall be handled by the primary organ, and infrastructure shall be allotted to institutions to be provided to researchers and research groups. To accomplish this, we should envision the setting up of a new organization. In arranging for observation platforms, some equipment and models must be considered in view of the entire condition of global science research.

(3) Role-sharing must be determined to promote each field of research domestically and research made more efficient based on the requirements for infrastructure. Considering the current status of global science research promotion in Japan, it is appropriate to have separate institutions handling the promotion of marine research that uses ships to conduct research and land-based snow and ice research carried out primarily on the land of other countries. The primary institutions handling other fields of research must be made clear to an extent for them to promote their research. Also, while satellite observation is a crucial means of conducting research, improvements must be made to the Japanese domestic data-use system, as there are numerous problematic issues associated with its use by researchers.

(4) The environmental changes of the Arctic region are occurring as a result of interacting factors, and it is important to treat them as a system. It is, therefore, necessary to consider a system that can allow for the arrival at an accurate understanding of these phenomena through academic research that comprises frequently-exchanged knowledge across differing fields.

(5) Since environmental changes in the Arctic region will have major societal effects, a system must be established that promotes the spread and the improvement of scientific knowledge in society. Japanese domestic Arctic research must be made available and maintained in a place where it can be easily accessed by both the general public and experts (perhaps on a Web site).

(6) It has been three years since the Japan Consortium for Arctic Environmental Research (JCAR) was established, and JCAR has fulfilled an important role in the promotion of Arctic environmental research. It has been a short period, but considering the status of the core institution and the primary organs, and the situation surrounding the promotion of research at both the domestic and international levels, there must be an examination of the future roles and existence of those bodies with a long-term perspective in mind.

e. Preparation / Development / Maintenance of Research Infrastructure

We have so far described the necessity and development of the infrastructure, including equipment; however, these remain behind schedule for the Arctic region. The Arctic region is similar to Antarctica in that it is a cold region; however, it largely differs from Antarctica in that the Arctic Ocean is surrounded by land on its peripheries, that land is expansive, and there are various restrictions that come with that land because it is the territory of specific countries.

Numerous suggestions have been put forward so far, but, the need for funding is obvious, and priorities for it must be assigned, development must occur along those priorities and it must be put to practical use. Also, it must be studied whether it is appropriate to develop this ourselves from the standpoint of efficiency, or if we should obtain something similar to that being used overseas and rapidly apply it to observations.

The case of the data archive, one facet of the research infrastructure, is an international issue; from the perspective of going past Japan and making global research more efficient, it is a field that we must promptly act on, and a system is needed now more than ever.

f. The Promotion of International Cooperation

We have described previously how, in the realm of Arctic environmental research, international cooperation, and for that reason, the push for internationalization of Japanese researchers and the researcher environment has grown in importance over the past. However, the aforementioned core institution, related organs and government bodies must be aware of the following points.

(1) Secure preparation and distribution of information regarding international institutions, foreign countries and projects: Secure suitable information through the distribution of information in Japanese and the formation of specialist groups.

(2) Establish a consultation function, and specifically and individually support international research planning.

(3) Prepare accords and cooperative methods for Japanese researchers with highly-similar foreign countries.

(4) Promote cooperative activities at high levels (bi-national science and technology accords, AC, IASC).

(5) Promote efforts regarding the internationalization of researchers and the research environment.

-Support the participation of researchers at the earliest stages in planning conferences and such.

-Dispatch office and research personnel to offices in international organizations and projects.

(6) We believe that international funding, such as the Belmont Forum, is effective, and that including continuous observations of natural phenomena in the Arctic region, and not only the 'Natural and Social Themes' presented at the 2014 stage, is an important forum for promoting international cooperation.

Research Equipment by Field

a. Atmosphere

An atmospheric observation strategy in the Arctic region will likely take the form of long-term continuous observation infrastructure that comprises the organization of a ground-based observation system, wide-area observation using satellites, ship-based ocean observation, and three-dimensional structurally-detailed observations by aircraft. Moreover, these observations complement each other, and would ideally take the form of comprehensive observations integrating all methods.

The instruments used in atmospheric observation can be broken down into the categories of remote sensing and in situ measurement. Remote sensing is generally measurements that use electromagnetic waves (primarily in the range of ultraviolet to microwave). There are two categories of sensors—passive sensors, which receive (detect) one-way electromagnetic waves from the object being observed; and, active sensors, which transmit electromagnetic waves and then receive (detect) the reflected energy from the object being observed. Additionally, in situ measurements are not just limited to on-site measurements using measuring probes or analyzers, there are times when a sample is taken at the site and brought back to the laboratory for analysis. The most appropriate methods can be selected from these various methods according to the object being observed or the purpose of the observation.

Thinking in terms of a ground-based observation system that observes meteorological phenomena such as clouds, aerosols, trace gases, atmospheric components, such as rainfall or snow, temperature, humidity and wind, then a system is needed that combines active and passive remote sensing as well as in situ measurements. Radar, which uses radio wave frequencies, and lidar, which uses visible-range laser light, have been often employed as active sensors; and, multi-wavelength, Doppler volume-scanning instruments are extremely useful for measuring physical volumes and knowing volumetric changes to high precision. Simultaneous measurement using Doppler cloud radar and multi-wavelength polarized lidar have been indispensable tools for research into cloud microphysical radiating. For passive sensors, instruments (spectroradiometers for microwave, visible light, and infrared bands) are needed that can measure a high-resolution wider spectral band to more accurately quantify physical volumes through remote sensing.

In the continuous observations of CO_2 and other greenhouse gases of recent years, CRD spectroscopy has become widely used as a new technology for the accurate detection of trace gases. This method has also been applied to direct measurements of the absorption properties of aerosols, and its use will likely become quite popular in the field of atmospheric chemistry.

There have been significant advances in the development of probes for use in direct aerial observations of cloud and aerosol particulates, and many of these instruments have been improved for use in ground-based observations and are effective for long-term continuous observations on the ground.

Precise radiation observations will be the foundation for research into the climatological effects of atmospheric content, such as greenhouse gases, clouds, aerosols and water vapor. BSRN is being developed as a global network of radiation observation. The measurement standards determined by BSRN are positioned as the world standards of radiation measurement, and making these the standards for radiation observation in the Arctic region is desirable. However, owing to the difficult environmental conditions, not only radiation measurement, but also atmospheric observations in the Arctic region will require significant effort to maintain the measurement instruments on site to retain their precision.

The observation sites that monitor water, energy and CO_2 exchange between the atmosphere and the land surface must be increased. Construction has been undertaken on an observation network known as FLUXNET , and the density of observations in the polar regions is extremely low (as of April 2013, in contrast to the 40 sites between Japan and Korea, there are a total of 3 for Siberia) in comparison to Asia (Asiaflux), the US (Ameriflux), and Europe (Euroflux). Observation data from flux towers can, apart from monitoring a site, be used as the lower boundary conditions for climate models. Further, in recent years, attempts have been made to merge the data with climate models through data assimilation techniques. It will likely become increasingly important in the future to have an increase in the observation spatial density of flux towers so that the water, energy and carbon cycles can be understood between the lower atmosphere and the land surface in the polar regions. Observation data in a plot scale is applicable as a validation data for satellite observations (known as “ground truth”). The few Arctic observation sites will serve an important role as ground-based verification sites.

Observation data of the meteorological conditions necessary to drive many land surface models, such as surface air temperature, precipitation and wind speed, are collected and maintained by research institutions both inside and outside Japan (for example, there is the Baseline Meteorological Data in Siberia through JAMSTEC). We must continue site observations to monitor the signals of the polar regions, which will likely display more serious impacts of warming in the future. Regular maintenance of instruments is essential for high-quality observations. Inspections and maintenance to check if there are any contaminants in rain gauges, or if the surrounding environment is appropriate to the observations, are necessary once every half year.

There must be technological development to improve the trap efficiency of rain gauges to observe precipitation.

Figure 66: (Top) Current EISCAT radar system and (left) schematic image of EISCAT_3D radar system (http://eiscat.nipr.ac.jp/eiscat3d/)

In the polar regions, snow is frequently observed as precipitation, and a large portion of falling snow does not enter the rain gauge due to wind. The rain gauge ought to be improved and a statistical method developed for correcting the observed value to accurately understand the amount of rainfall and snowfall.

b. Middle and Upper Atmosphere

(1) European Incoherent Scatter Radar (EISCAT Radar)

A large radar system (EISCAT radar) has been established and is managed through international cooperation in Northern Europe to monitor the geospace environments: e.g., the lower, middle and upper atmosphere, as well as the ionosphere. The EISCAT radar has monitored the geospace environments over 30 years up to now. As the next step, a large-scale overhaul plan (EISCAT_3D Project) is being advanced. Japan is also participating in this Project which involves the monitoring and 3D observations of changes in the atmosphere and ionosphere (at altitudes of 1-30 km and 60-1000 km). By building and maintaining a radar network with Japan's own large atmospheric MU radar (Shigaraki, Japan), the Equatorial Atmosphere Radar (Indonesia), and the

Figure 67: (Left) The ERG (Exploration of energization and Radiation in Geospace) satellite (http://www.jaxa.jp/projects/sat/erg/index_j.html) and (right) airglow observation with IMAP/VISI on the international space station (http://www.iss-imap.org/)

PANSY radar (Syowa Station, Antarctica) and the ESCAT_3D radar systems, we will have an exceptionally powerful infrastructure for the Earth's environmental research.

(2) Satellite/Rocket/Balloon-based Observations and Development of On-board Instruments

By launching the magnetosphere observation satellite ERG in 2015, we can monitor details of the geospace environments around the Earth, such as high-energy particles and the propagation of plasma waves. Some geospace explorations have been also planned by various countries: e.g., the Van Allen Probes (US: launched in 2012), which explores the inner magnetosphere, Resonance (Russia: 2016 launch), VSX (US: 2016 launch), Swarm (Europe: 2013 launch), which observes the ionosphere. Additionally, some imaging observations from the International Space Station (ISS_KIBO module) are made to monitor atmospheric changes in the vicinity of the altitudes of 100 km and 250 km. Observations of the same sort must be continued in the future, and, as the next step, simultaneous, multiple observations must be realized by multiple satellites. Through developments of satellite-borne instruments in the Japanese science society with the newest technology, such as photometers, accelerometers, mass spectrometers, particle counters and plasma measuring instruments, a variety of satellite missions will be possible. Rocket/balloon observations are indispensable in areas where satellites cannot go (from the stratosphere to the lower thermosphere). Rocket experiments in conjunction with the ground-based and satellite-based observations with international collaborations must be carried out (for example, collaborative observations with Norway have proven fruitful for many years).

(3) Installation and Maintenance of Instruments for Wide-Area Multipoint Observations

To understand features and roles of the atmospheric gravity waves and planetary waves in the middle and upper atmosphere in the Arctic region, MF/meteor radar, which measures wind speed and temperature at altitudes of 70-100 km, lidar, and airglow observations are necessary in the wide area in the Arctic region. Additionally, to understand the fluctuations in the ionosphere and the acceleration and heating processes of high-energy particles near the Earth, GNSS/GPS receivers, airglow/aurora cameras, and VLF/ELF/ULF wave receivers must be developed and deployed widely in the area surrounding the Arctic. This observation network will have contributions to obtaining a general picture of the longitudinal generation/propagation/dissipation of atmospheric waves and the longitudinal motion of high-energy plasmas around the Earth. Establishments of international and domestic collaboration regimes are necessary for building up and maintenance of the above mentioned observation system.

(4) Installation and Maintenance of Instruments for Integrated Observations at Specific Sites

It is also important to set up instruments mentioned above at specific observation sites with large and high performance instruments such as the EISCAT radar system. The integrated observations with them will enable us to understand effects of energy and momentum injections from the lower atmosphere and space on changes in the middle and upper atmosphere.

(5) Data Analysis, Modelling and Simulations

It is crucial to link the aforementioned satellite-based and ground-based observations with modeling and simulation studies. We should continuously develop new techniques for modeling, simulation, and data analysis: e.g., modeling of complex chemical and physical processes and developing methods of high performance computing. In order to handle vast amounts of data, research environments such as hardware and software systems should be also updated continuously.

c. Snow and Ice

It is extremely important to conduct in situ observations and samples collections in Arctic cryospheric research. They are not only important for elucidating the fluctuations and mechanisms of changes in the cryospheric environment at the observed sites, but they also play a large role in providing input and verification data for numerical models and calibration of satellite data for wide-area monitoring. Therefore, their long-term continuations are essential. There are physical properties and samples in the interior and bottom of glaciers that can only be obtained on site.

(1) Observation of Ice Sheets and Glaciers

There must be long-use observation sites in place to observe ice sheet and glacier mass balances and to evaluate the effects of biological activity on snow and ice. Specifically required are research facilities to act as the base for observations, means of transportation required for field observations, such as snowmobiles and small watercraft, and observation equipment, such as automatic weather surveying instruments and GPS receivers. Ice core drilling and ice sheet radar observations must be able to be flexible enough to be performed in a wide area, and not limited to a fixed observation site. The instruments needed for this are ice radar and laser altimeters used on airplanes and helicopters, hot water drilling system and ice core drilling equipment for use with observations and sampling the interior of ice sheets, and borehole measurement devices. It is crucial to newly develop or overhaul existing equipment. Seismometers and seismological observation systems are required for monitoring seismological activities in glaciers. The representative instruments of these are shown in Figure 69. Additionally, to carry out in situ observations to understand the formation process of proxies for environmental changes (see Theme 6), a portable analyzer for water vapor isotopes and aerosol density is essential. It is also important to construct and maintain a system (personnel and organization) to be able to carry out continuous development of instrumentation, on-site observations and sample collections.

(2) Ice Core Analysis

To reconstruct the fluctuations of past climate and cryosphere, laboratory analyses of ice core samples are needed. Targets for the analyses include water isotopes,

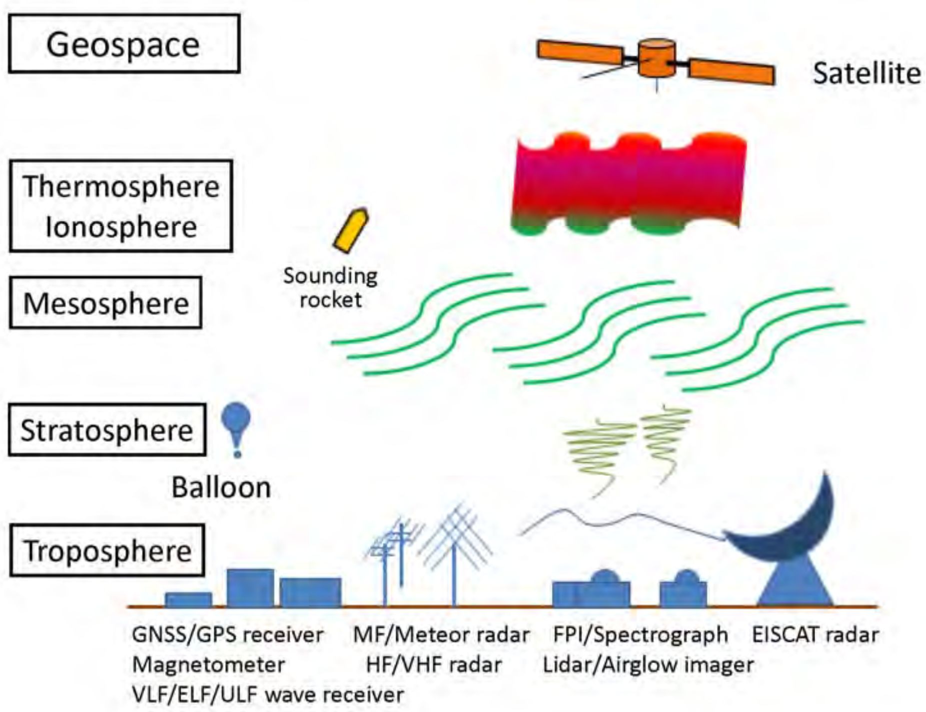

Figure 68: Instruments constituting Arctic Observation Network

aerosols, solid particles and gas composition, and it is necessary to establish and maintain measurement devices, analytical techniques and analytical systems in order to conduct high resolution analyses. In addition to the existing analytical devices (mass spectrometer, liquid chromatograph, gas chromatograph, particle analyzer, black carbon analyzer, etc.), new instruments are required to enable estimation of origin and transport routes of gases (greenhouse gases, noble gases, etc.) and aerosols (sulphur, calcium, strontium, lead, etc.) through high-precision isotopic analyses, as well as quantitative estimations through combinations of multiple proxies. A continuous melting technique has become operational to obtain a large amount of high-resolution environmental data from ice cores; however, it only has a short history of usage, and thus its further development is crucial. Innovations must also continue on analytical techniques that are used in combination with a continuous melting device, such as laser absorption or scattering applied for snow and ice sample analyses and air extraction.

(3) Permafrost

What's required for research into the ice that makes up permafrost are, similar to research on glaciers and ice sheet, long-use observation bases, means of transport and meteorological survey equipment for basic data. Stably maintaining the observation base for the long term is particularly necessary for the long-time constants in temperature monitoring at depth; and, the means of transportation must be available to allow for multipoint surveying to cover a large expanse in the observations of the shallow depths, such as the active layers. There is room for improvement in the current state of permafrost drilling technology. Also, with the idea in mind that drilling must be done in multiple spots, there must also be development of a highly-mobile permafrost drilling system of a size that can be operated by a researcher as well as a sample collecting system from a ship that does not disturb the permafrost that exists on the seafloor and the bed of lakes. To understand the permafrost ice-melting process and to reconstruct the ancient climate from the permafrost temperature, the required equipment development includes a ground temperature sensor with precision up to two decimal places, to heighten the precision of temperature measurement near the melting point, a logging system, and observation technology to perform on-site measurements of the amount of nonfreezing water. In addition, improvement is needed on the measuring instrument for thermal parameters applied to the ice lenses, organic distribution and structure of soil in the active layer.

(4) Measuring Precipitation and Snow Accumulation

The most important aspect of measuring precipitation in the Arctic region is the highly-precise measurement of winter-time precipitation amounts. There must be advancement of observation precision through comparative observations with the development of a variety of winter precipitation (snow fall) sensors, such as gravimetric systems and optical systems, in addition to the WMO standard measurements—Double Fenced Intercomparison Reference—used in calibrating trap rates of fixed rainfall. It is important to also improve the precision of the spatial precipitation observations by using observations taken by precipitation radar of changes over time and space of water vapor (clouds) and fallen snow particles, and by comparing this with precipitation satellite data (GPM/DPR and successive machine data).

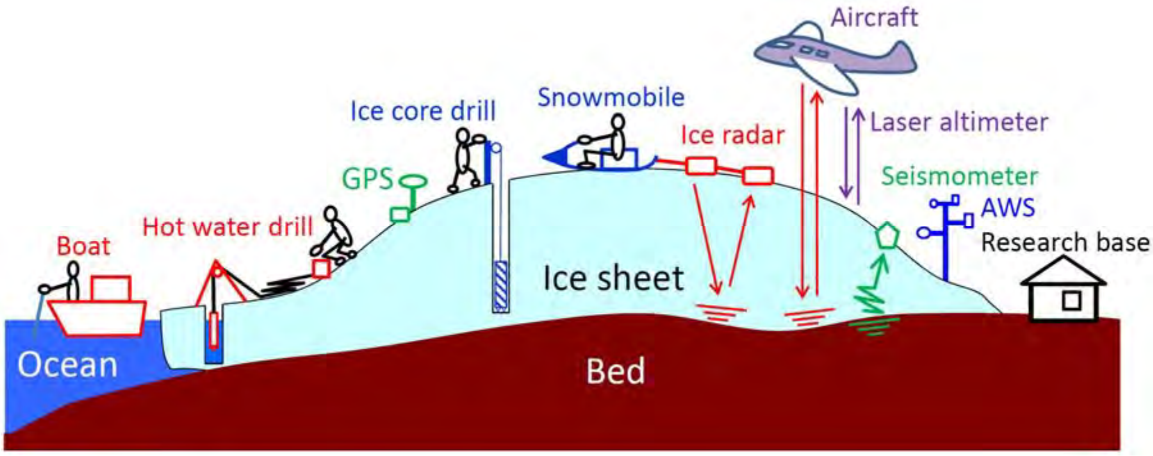

Figure 69: Field equipment and facilities for glacier and ice sheet research.

We must develop and improve observation technology for ground-based correction and verification of data for snow accumulation, such as surface snow cover, water equivalent of snow cover, snow quality, snow impurities, snow amount on tree canopies in Boreal forests, sublimation amounts etc. To improve the development of an algorithm for satellite optical sensors and microwave sensors.

(5) Land Hydrological Processes

To understand land hydrological processes detailed on-site observations are required of soil moisture, evapotranspiration amount and runoff, in addition to observations of precipitation and accumulated snow. Observations of snow melting in the spring and snow accumulation in autumn is particularly important in regards to the seasonal advancement predicted with the large changes of the future. Observations of vegetation must occur simultaneously with water/thermal Flux tower observations of evapotranspiration. Soil moisture is related to the depth of permafrost melting and ground temperature, and the on-site observations of these phenomena is not easy; however, a spatial understanding gained through multi-point observation is required. In being able to carry out observation with Doppler radar in conjunction with these observations, we can expect to understand the local water cycle, including clouds and precipitation systems. A technique is being developed and deployed for the laser measurement of stable water isotopes as a water cycle tracer for soil moisture amounts; however, field sampling and an analytical technique must be established to allow for the whole-scale measurement of precipitation, fallen snow, water moisture, plant moisture and water vapor.

d. Terrestrial ecosystems/Material Cycles

Since terrestrial ecosystems have a strong effect on carbon, nitrogen and water, among other materials, there is a need to focus efforts on future monitoring. As we described in the section on the atmosphere, enhancing Flux tower observation and establishing a system that can carry out stable observations over the long term is important. In addition to enhanced remote-sensing satellite-based observations, aircraft-based observations with next-generation sensors (lidar and high-precision hyperspectral cameras) that can precisely observe terrestrial ecosystems are also desirable. In understanding the structure of forests trees using lidar observations, the analysis of spectral reflected image data taken with a high-precision hyperspectral camera enables analysis of the chemical composition of leaves, and such (including chlorophyll, lignin and cellulose), and research is enabled into not only material cycles, but also biological diversity in terms of species composition. We also propose the setting up of a large-scale device network by placing interval cameras in numerous locations around the Arctic circle to gather data by observing changes to vegetation and seasonal characteristics.

Furthermore, to increase the efficiency of observations in the vast and pristine landscape of the Arctic region, we propose the following. Hovercraft, which have already been used to make ocean observations, would prove to be a formidable tool for observations in the tundra, from the marshes and wetlands, unclear in their separation from the sea due to snow, to the continent interior. Since accessing the regions with both water surfaces and wetlands is difficult by foot, vehicle or boat, we should envision observations around the Siberian coastline using hovercraft. The development and deployment of data transmission devices to Japan from observation equipment installed in remote locations is also sorely needed. Currently, data transmission is done using satellites, but the transmission of large amounts of Flux tower observation and image data is not widespread. Further advancement of large-volume data transmission systems and transmission satellites would make data collection, which currently requires massive amounts of labor and travel costs, drastically easier. Setting up transmission satellites to be used for data transmission is effective for developing animal pattern research to track animal migration and not only land research, but is also important for atmosphere and ocean observations.

e. Ocean

The Arctic region clearly exhibits the effects of global environmental changes. The changes in the Arctic also, at the same time, likely have a major effect on the global climate system through changes in the atmosphere and ocean circulations and in the cryosphere. Explaining Arctic systems is indispensable to understanding climate and other global systems, and observational data are the necessary foundation for this. Central to the Arctic region is the expansive Arctic Ocean, and thus marine observation is the cornerstone to this; observation and long-term monitoring from the sea floor to the atmosphere, across the expanse of the ocean are required. It is desirable to have surveys that can assess changes over, at least the same amount of time and space, as have been observed by research vessels in mid and low-latitude oceans. In particular, we need observations of seasonal and long-term variations in the Arctic Ocean for better understanding of the earth system as well for a development of exhaustive atmosphere-sea ice-ocean models.

However, observations in the Arctic Ocean are still lagging behind due to sea ice, and there are observational blank spots. To further develop observations in the Arctic Ocean in the future, we must have an ice breaker that can perform a variety of observations and have high ice-breaking capacity. Also, the development of observation devices that can perform well in areas with sea ice will also be necessary. In the following, we will describe the technical issues involved in operating in sea ice areas and the observation instruments requiring development.

(1) Ship-Bound Observation Instruments

Here we refer to ship-bound observation instruments as the instruments installed on a ship and used to carry out atmosphere and ocean observations. Since most of the observation instruments are for observing from aboard a vessel, we believe there are no major obstacles even in a sea ice zone. However, for the observation instruments that use sound, noise from the ship and noise generated by ice-breaking should be minimal. Some of the observation instruments that use sound are the strata prober operating in a low-frequency band, a multi-narrow beam echosounder, and multi-frequency profiling sonar, operating at a high-frequency in the ultrasonic range. The frequency range is broad; however, we must consider the fact that surveys can be conducted in the same frequency ranges as ice-breaking and how we might counter this phenomenon. Additionally, since the deeper the draft of an observation vessel, the farther away from the origin of noise one can get, we believe that this point should be considered when a new observation vessel is constructed.

(2) Submersible Robots

Submersible robot activity, such as with ROVs and AUVs, is expected in exploration under the sea ice. An AUV is an autonomous underwater vehicle for unmanned exploration that is an unmanned robot that can recognize its surroundings and autonomously determine its course; it is an exploratory vehicle appropriate for vertical-direction surveys under sea ice and over a wide area. In contrast, an ROV is a remotely-operated submersible vehicle for manned exploration that is controlled from aboard the ship, and can perform detailed observations under the sea ice or on the seafloor, and can also take samples. Additionally, ROVs can be used for undersea construction or recovery of mooring systems in sea ice areas, and for emergency recoveries of AUVs.

For the use of submersible robots in sea ice areas, several factors must be given consideration: outfitting it against cold temperatures, locating it using sonar navigation system from a ship, and when operating an AUV, in particular, if it can be securely recovered. The average depth of the Arctic Ocean is 1,330 meters; however, since there are deep basins that with a depth of ~4,000 meters, having a submersible that can withstand pressures of over 4,000 meters would allow it to venture throughout almost the entire region of the ocean. Yet, since a small and easier-to-use submersible robot is ideal, thought must be given to developing a submersible that can withstand the pressures, handle a payload of observation instruments and be launchable from a moon pool.

(3) Moored Ocean Observation Arrays

What is also required is continuous moored observation at a fixed point in the sea ice zone using ice profiling sonar (IPS), an ultrasonic Doppler flowmeter, a salinity, temperature and depth sensors to observe the sea ice dynamics and changes, as well as physical and chemical changes in seawater. Additionally, results can be expected from observations by instruments installed on the seafloor through seafloor seismometers, seafloor pressure gauges and various chemical sensors to estimate sub-seafloor structure and the material exchanges between sediment and sea water. These instruments and systems must be developed appropriate to observations under sea ice; and, in order to enable them to carry out continuous operations, in particular, it should be kept in mind that the devices may be installed and recovered by ROVs and other such submersibles, and certain design factors must be considered, such as underwater acoustic data transmission, tidal electricity generation and fuel cells for underwater use. The question of powering a submersed observation device, is not a problem particular to the polar region; however, the difficulties of installing and recovering of instruments in Arctic Ocean is a problem that ought to be resolved. Moreover, it would also be ideal to develop an ice-strengthened profiling float, loaded with physical, biological and chemical sensors that can observe from a certain depth to right under sea ice. In developing a profiling float, there is difficulty in positioning in the sea ice zone with GPS and sending and receiving data through satellite, therefore, a solution must be devised to build a sonar navigation system and a data transmission network under the sea ice.

(4) Coring etc.

Regarding the taking of sediment samples for paleoenvironmental and paleoclimatic research, in addition to a normal piston and gravity corer, a giant corer capable of taking sediment samples of over 60 meters, and a seafloor-stabilized drilling apparatus should be developed. The seafloor-stabilized drilling apparatus, in particular, is a rotary-style drilling machine, so it can drill into the rock bed.

(5) Sea Ice Observation Instruments

To understand the climate system in the Arctic region, the observation of not only the atmosphere and ocean, but also sea ice characteristics is required. Of particular importance is the monitoring of the mass balance and morphology of sea ice.

The mass balance of sea ice is crucial for having a correct understanding of the current status of the sea ice in the Arctic Ocean as it is rapidly decreasing. For this purpose, the estimation of the thermodynamic growth or decay amount of sea ice and the outflow amount of sea ice from the Arctic Ocean is needed. To accurately estimate the former, on-site meteorological observations and ice thickness distribution data are required. To do this, if possible unmanned observation buoys are desirable in addition to the ship-based observation. For a long time, meteorological observations in the Arctic Ocean has been carried out under the auspices of the International Arctic Buoy Programme with instruments installed on the sea ice; however, with the significant reduction of sea ice in the Arctic Ocean this method is facing a difficult problem. Since ice thickness distribution can be estimated to some degrees from aerial observation and satellite data, efforts must be made to preserve the areal density of the meteorological observations by manufacturing strong buoys that can stand for the measurements in the ocean with the sufficiently lasting power. For the quantitative estimation of the latter, it is required to monitor the thickness distribution and drifting speed of sea ice flowing out from the Fram Straight with such instruments as ice profiling sonars.

Regarding the morphology of sea ice, as the fraction of seasonal sea ice area increases in the Arctic Ocean, there is a possibility that the deformation processes of sea ice may be changing. Therefore a reexamination must be done of the physical processes used in numerical sea ice models. The characteristics of the spatial distribution of ridges and the melt ponds on the sea ice surface are particularly important. Further on-site observations with an aircraft-based 2D laser scanner and video cameras are now strongly desired to clarify the real situation in the Arctic Ocean.

(6) Other (Observations on the coastline)

Aside from ship-bound observations, the development of observation instruments for the coastal area is necessary. With moored observations in shallow areas, consideration must be given towards a structure where the system will not be dragged by the sea ice in the winter. The development of a strong platform is necessary, such as the Monbetsu Okhotsk Tower, which allows for samples to be taken under the sea ice even during the winter. Moreover, consideration must be given to aircraft-bound electromagnetic sea ice thickness measurement and terrestrial magnetism/gravity measurement in the sea region.

f. Numerical Modeling

Numerical modeling is an indispensable research tool to have a comprehensive understanding of the swiftly-changing Arctic environment and the Arctic role in global climate and Japan, and to further predict the future of the Arctic climate. To these ends, resources for massive calculations and large-volume storage to save input/output data and validation data for models are necessary, and the establishment of an infrastructural organizing system to handle them is important.

This organizing system should not be a term-limited one under specific projects, but must be managed for a long term. Currently, GRENE is advancing research related to numerical modeling in the field of Arctic climate change; however, all the goals would not be achieved within the limited project period. The development of more sophisticated models and corresponding research should be promoted. There is an international program (APPOSITE) regarding the predictability of Arctic region changes over the seasonal to interannual timescales; however, the Japanese research community lacks organizational support for this program and depends on individual efforts. Moreover, whereas the Arctic regional climate modeling is currently under development at the Naval Postgraduate School in the US, no specific activities on it have not started, partly owing to the lack of an infrastructural organization in Japan as yet. There exist large-scale, continuous modeling centers (NCAR, ECMWF, UKMO etc.) and data centers (NSIDC etc.) as research infrastructures. Without similar modeling research infrastructure in Japan, we may fall behind the world in cutting-edge research.

Regarding the computational resources, we can utilize high-performance computers at domestic universities or research institutions through a public project or paid use; however, it would be generally difficult to gain enough resources due to competition with other users. To guarantee stable resources for model experiments, it would be ideal for an individual organization to possess its own supercomputer. The management and operation of high-performance computers and data server system, and the development of sophisticated models that integrate each component of atmosphere, ocean, land and ice sheet, and the improvement for the efficient execution require highly specialized knowledge. Additionally, we certainly need supporting staffs managing observational and reanalysis data for initial/boundary conditions and validation. Coordinators will also be required to lead the unification of the coding rules (programming method) and the input/output data format, as well as the development of analysis techniques and software. In an infrastructural organization, not only technicians with a high degree of specialized knowledge, but also personnel working as an intermediary position between researchers and the technicians should be hired for a long period.

As it appears in the above, the infrastructural organization is desired to take the lead in participating in international research projects, to implement and manage various sensitivity/ensemble experiments using numerical models, and to carry out operational works, such as Arctic sea ice prediction.

Chapter 10: Directions and challenges exceeding 10 years

This long-term plan report is not limited to research projects already undertaken; it goes so far as to suggest a policy of establishing a challenge on a time scale exceeding 10 years. We have attempted to establish a hypothetical theory that will be useful in conducting the research, and to boldly propose a system in which pioneering achievements can be accomplished. The following is a brief outline of 15 themes and infrastructure improvements.

Elucidation of abrupt environmental change in the Arctic associated with the on-going global warming

"Arctic amplification of global warming (Theme 1)" will focus on energy transport centered around the Arctic region to clarify the interactions of various elements, including the upper atmosphere, clouds and aerosol, snow accumulation, sea ice, and even the mid-level depths of the ocean. To develop and use a global system model for this purpose, it is necessary to systematically obtain not only the cooperation of modelers in various fields, but also the data used for model verification. For Japan's contribution, we will approach responsible bodies to continue sensor development and satellite launching in order to expand satellite observations of various levels from the upper atmosphere to sea ice. We must also maintain a system in which field observations of the sea are performed regularly.

"Mechanisms and influence of sea ice decline (Theme 2)" is intended to facilitate the understanding of (and quantify the processes of) oceanic heat transport in the range from directly under the sea ice to the mid-level depths. In addition, the interaction between the atmosphere—sea ice—and the ocean, through clouds and low pressure, will be elucidated. With regard to the properties of the sea ice itself, the formation of melt ponds and the impact between ice floes will be clarified in detail. To perform these field observations, it will be necessary to operate ice-breaker ships. It will also be essential to perform microwave satellite observations, which are not affected by the weather. Additionally, a sea-ice/ocean coupled model that can positively handle individual ice floes or high-density water downwelling will be built. This model will be used to provide ships with highly reliable information about Arctic shipping routes.

"Biogeochemical cycles and ecosystem changes (Theme 3)" will focus on continuing observations of the atmosphere, soil, and rivers. To date, these observations have been conducted mainly in the summer, over long periods, or throughout the year. The focus of this theme will also include the expansion of land ecosystem observation points using satellite data, etc., to obtain representative areal data. At sea, environmental changes that impact ecosystems will be monitored, including coastal erosion or permanent melting of permafrost. In addition, the transport of carbon or nutrients, etc., will be linked to oceanic circulation or vortices. The most advanced chemical and biological sensors and sample collection devices will be installed along with substance sensors at camps on top of the ice and in data gaps to perform year-round observations in order to quantitatively understand biogeochemical transport and ecosystem change.

"Ice sheet/glaciers, permafrost, snowfall/snow cover and hydrological cycle (Theme 4)" will substantially improve satellite observations of ice sheet surfaces and total weight, and it will verify the observations using field data. At the same time, sufficient information will be gathered about the interior of the ice sheets. This theme will also link experts in physical oceanography to study interactions with the ocean. Building a permafrost observation system requires international cooperation, and the aim of this theme as well as Theme 3 will be to operate a super-site. This effort will contribute to clarifying the effects of the water cycle on the atmosphere, land surface, and soil over a wide area. Objective analysis performed regularly by the meteorological agency will be expanded to include the land water cycle.

"Interactions between the Arctic and the entire earth (Theme 5)" will focus on learning how fluctuations over time of the atmosphere, sea ice, and the ocean (which are now apparent as natural fluctuations) change as global warming progresses. A repeat analysis will be carried out based on observation and modeling and on data assimilation over a wide range extending from interaction with the upper atmosphere above to the formation of the weakening North Atlantic deep water layers below. Fluctuations of the atmospheric and water cycles based on land and sea distribution even impact the substance cycle as well as the Arctic Ocean through feedback with the ocean circulation. Important information regarding wide-area changes in permafrost will be obtained from Theme 4.

"Predicting future environmental conditions of the Arctic based on paleoenvironmental records (Theme 6)" will examine past cases of warming or sudden climate change that could reoccur in the future. The focus will be on their mechanisms with data and models. Efforts will be made to sample and analyze the polar region's characteristic ice cores and the Arctic seabed cores, and to perform long-term numerical experiments by developing new indirect indices and using combined climate and ice sheet models. It will be important also to identify the rise and fall of short-term fluctuations such as Arctic oscillations. Restoring and clarifying fluctuations in ice sheets, the ocean or sea ice, land areas, the atmosphere, etc., including various time scales, will contribute to a quantification of the past amplification of warming and to research on climate change.

"Effects of the Arctic environment on human society (Theme 7)" will be an attempt to expand links between the natural sciences and the humanities and social sciences in the Arctic. Its aim will be to prepare proposals for national and regional governments based on cooperation between indigenous peoples and immigrants. The proposals will involve areas such as information about natural disasters in emergency situations, reducing damage due to global warming, etc., and introducing carbon credits. Collaboration with beyond the environmental science community are essential.

Elucidation of environmental change concerning biodiversity

"Effects on terrestrial ecosystems and biodiversity (Theme 8)" will feature observations and monitoring to clarify the impact of global warming and other environmental change on ecosystems. Through this process, as much data as possible will be gathered by installing more automatic observation instruments. The diversity of species in cold regions is relatively low, but the diversity of the ecological response may be higher. Therefore, it is vital to perform a close examination of vulnerability under conditions of environmental change. Toward that end, spot surveys will be done over wider areas, and at the same time, the ecosystem of Hokkaido will be used to study the impact on the ecosystem inside the Arctic Circle.

"Influence on marine ecosystem and biodiversity (Theme 9)" will clarify the impact on ecosystems of changes in the marine environment. The central point of this long-term concept is the shift northward of the habitat range accompanying the spread of seasonal sea ice in the Arctic Ocean. It is easy to imagine the extinction of certain extant species, and it must be taken seriously that once a species is extinct, it is not recoverable. To clarify the mechanisms of ocean ecosystems, efforts will be made to fully use ice-breaking observation vessels to monitor various impacts that occur in conjunction with the progression of acidification.

Broad and important subjects on the Arctic environment

"Geospace environment (Theme 10)" will attempt to clarify the atmospheric coupling processes characteristic of polar regions, including the impact of high-energy particles precipitating from geospace into the middle and upper atmosphere of the Arctic region. At the same time, it will focus on the latitudinal coupling of the polar upper atmosphere with mid- and low-latitude regions. To clarify these processes observationally, and to proceed to predictive research on space weather, it will be necessary to organize a system to develop observation bases centered on large atmospheric radars, terrestrial multipoint network observations, satellite observations, and comprehensive atmospheric models.

"Interaction of surface environment change with solid earth (Theme 11)" will clarify the interrelationships of ice sheet melting, crustal uplift, and mantle viscosity. Field topography and geological surveys as well as surveying and observations done for this purpose are difficult and time-consuming, but they are worth tackling in order to predict future changes in the ocean surface on a global scale. Applying geological and geophysical methods to clarify the interactions of fluctuations that originate inside the solid earth (e.g., the formation and division of supercontinents) with surface environmental change will make a great contribution to understanding Earth's evolution.

"Basic understanding on formation and transition process of permafrost (Theme 12)" is intended to establish basic information about the present state of permafrost over a wide area. It is particularly necessary to obtain higher-resolution information about the horizontal distribution, thickness distribution, and active layer thickness of the permafrost and the ice, as well as the carbon content of the permafrost, in order to obtain multi-point data. A conspicuous example of a change in permafrost appears as ground settlement caused by a thermokarst. It is also necessary to observe ground surface changes caused by forest fires, and other factors unrelated to air temperature change. To collect information about permafrost, it is essential to have a cooperative system linked to international observation networks.

Development of methods enabling breakthroughs in environmental research

To perform "Sustainable seamless monitoring (Theme A)," it is important to continuously gather representative data in order to survey and clarify various changes in the environment. Valuable data can be obtained from the internal structure of ice floes and deep parts of the permafrost. It is necessary to manage boreholes in permafrost as well. To gather data in the ocean, it is essential to employ ice-breakers, mooring systems, and remotely operated sensors. On land, it is useful to collect meteorological, frozen snow, hydrological, vegetation, and soil data at super-sites.

"Earth system-modeling for inter-disciplinary research (Theme B)" focuses on building and testing an earth system model that includes constituent elements of the global environment. Among the elements, there are variations in the atmosphere, sea ice, the ocean, permafrost, and terrestrial vegetation, as well as the precision of the key processes and of their impacts on other elements. It is fundamental to explicitly represent a process in individual element models. For coupled models, however, it is necessary to use a different parameterization depending on the purpose of the model. Sensitivity test results that indicate how an error in the process of a certain element impacts other elements will be objectively evaluated.

The aim of "Data assimilation to connect monitoring and modeling (Theme C)" is to challenge the assimilation of data for multi-sphere systems. The difficulty with this lies in differences in time scale, degree of completeness of the numerical model, the number of uncertain parameters, and the amount of data for each element. To overcome this barrier, it is necessary to make investments from the observation and model perspectives. The purposes of the present project are to improve the reliability of meteorological information from inside the Arctic Circle and to realize practical predictions of the state of the Arctic Ocean. An international cooperative system is an essential condition to achieve these goals.

Building the research infrastructure

a. Ships

Ice-breakers for use in research will be newly constructed with functions far more advanced than those of previous ice-breakers. Noteworthy machines and equipment will include moon pools; chemical, biological, and geological laboratories (including low-temperature rooms); autonomous underwater vehicles (AUVs) that can travel under the sea ice for long periods and can be equipped with many types of sensors; remotely operated vehicles (ROVs) capable of obtaining specimens; long big-bore piston corers; multi-beam depth sounders to perform seabed topographic surveys; and sub-bottom profilers to perform stratigraphic investigations.

b. Satellites

An observation system combining synthetic aperture radar to monitor changes in the mass of glaciers, ice sheet, sea ice, and frozen snow with laser radar altimeters will be operated. A satellite to measure gravity will be developed. A visible light sensor to monitor land and marine ecosystems will be installed on the GCOM-C1/SGLI, which is scheduled to launch in 2016, and related organizations will be approached to continue efforts in this direction.

c. Aircraft

A system permitting the ownership of airplanes and incorporating the development of instruments for Arctic observations will be organized. Efforts will also be made to use drones for atmospheric observations.

d. Network of bases

To continue collecting diverse parameters at the super-site, bases will be maintained through bilateral links on the Svalbard Islands, in Eastern Siberia, and in Alaska. Furthermore, the use of observation equipment in Canada's high-latitude Arctic region, on the Arctic Ocean coastline of Russia, and elsewhere will be explored.

e. Data archives

We aim to establish a data center that will facilitate an even broader use of archives through links between international databases.

f. Capacity development

To train young Japanese researchers, JCAR will create links between universities in Japan and universities in Arctic countries. Besides developing an internship program, summer schools, and a career path, it will expand the GRENE young researcher dispatch support program. We will support the development of young researchers from indigenous peoples.

g. Research organizations (domestic, international)

A top-down type system of national government agencies and incorporated administrative agencies will be established along with an integrated system of bottom-up type autonomous organizations such as JCAR that will provide mutual support. Internationally, efforts will be made so that the status of Japan, which is non-Arctic country, will be recognized as legitimate.

h. Instruments (atmosphere, upper atmosphere, frozen snow, land, ocean)

The development of a network of radar that will monitor the upper atmosphere over a wide area, and of instruments to analyze aerosol, etc., in frozen snow will continue. To observe land vegetation, hyperspectral cameras capable of clarifying the constituent trees in forests will be operated. Underwater robots will be used as mobile equipment to deploy instruments in order to efficiently obtain data from under the sea ice.

i. Numerical modeling

In addition to hardware such as large-scale calculation resources and high-volume storage, it will also be essential to install personnel specializing in model development and operating hardware. A system will be put in place to assign research technologists to provide data, source codes, etc.

Chapter 11: Reference

Citation

Theme 1

Baldwin, M. P., and T. J. Dunkerton (1999), Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res.*, *104*, 30937-30946.

Curry, J. A., W. B. Rossow, D. Randall, and J. L. Schramm (1996), Overview of Arctic cloud and radiation characteristics, *J. Climate*, *9*, 1731-1764.

Derksen, C., and R. Brown(2012), Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections, *Geophys. Res. Let.*, *39*, L19504, doi:10.1029/2012GL053387.

Graversen, R. G., T. Mauritsen, M. Tjernström, E. Källén, and G. Svensson (2008), Vertical structure of recent Arctic warming, *Nature*, *451*, 53-56.

Hall, A., and X. Qu (2006), Using the current seasonal cycle to constrain snow albedo feedback in future climate change, *Geophys. Res. Lett.*, *33*, doi:10.1029/2005GL025127.

Hwang, Y.-T., D. M. W. Frierson, and J. E. Kay (2011), Coupling between Arctic feedback and changes in poleward energy transport, *Geophys. Res. Lett.*, *38*, L17704, doi: 10.1029/2011GL048546.

Liu, Y., J. R. Key, Z. Liu, X. Wang, and S. J. Vavrus(2012), A cloudier Arctic expected with diminishing sea ice, *Geophys. Res. Lett.*, *39*, L050705, doi: 10.1029/ 2012GL051251.

Manney, G. L., et al. (2011), Unprecedented Arctic ozone loss in 2011, *Nature*, *478*, 469-475.

O'ishi, R. and A. Abe-Ouchi (2011), Polar amplification in the mid‐Holocene derived from dynamical vegetation change with a GCM, *Geophys. Res. Let.*, *38*, L14702.

Oort, A. H. (1971), The Observed Annual Cycle in the Meridional Transport of Atmospheric Energy. *J. Atmos. Sci.*, *28*, 325–339.

Perovich, D.K., B. Light, H. Eicken, K.F. Jones, K. Runciman, and S.V. Nghiem (2007), Increasing solar heating of the Arctic Ocean and adjacent seas, 1979-2005: Attribution and role in the ice-albedo feedback, *Geophys. Res. Lett.*, *34*, doi:10.1029/2007GL031480.

Trenberth, K. E., and D. P. Stepaniak (2003a), Covariability of components of poleward atmospheric energy transports on seasonal and interannual timescales, *J. Clim.*, *16*, 3691–3705.

Tucker, C. J., D. A. Slayback, J. E. Pinzon, S. O. Los, R. B. Myneni, and M. G. Taylor (2001), Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999, *Int. J. Biometeorol.*, *45*, 184-190.

Yoshimori, M., A. Abe-Ouchi, M. Watanabe, A. Oka, and T. Ogura (2014), Robust seasonality of Arctic warming processes in two different versions of MIROC GCM. *J. Climate*, accepted.

Theme 2

Inoue, J., and M. Hori (2011), Arctic cyclogenesis at the marginal ice zone: A contributory mechanism for the temperature amplification?, *Geophys. Res. Lett.*, *38*, doi:10.1029/2011GL047696.

Jackson, J. M., E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram (2010), Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993–2008, *J. Geophys. Res.*, *115*, C05021, doi:10.1029/2009JC005265

McPhee, M. G. (2013), Intensification of geostrophic currents in the Canada Basin, Arctic Ocean, *J. Clim.*, *26*, 3130-3138.

Overland, J. E., and M. Wang (2013), When will the summer Arctic be nearly sea ice free?, *Geophys. Res. Lett.*, *40*, 2097-2101, doi:10/1002/grl.50316.

Rampal, P., J. Weiss, C. Dubois, and J.-M Campin (2011), IPCC climate models do not capture Arctic sea ice drift acceleration: Consequences in terms of projected sea ice thinning and decline, *J. Geophys. Res.*, *116*, doi:10.1029/2011JC007110.

Theme 3

Bates, N. R., and J. T. Mathis (2009), The Arctic Ocean marine carbon cycle: evaluation of air-sea CO_2 exchanges, ocean acidification impacts and potential feedbacks, *Biogeosciences*, *6*, 2433–2459.

Frey, K. E., and J. W. McClelland (2009), Impacts of permafrost degradation on arctic river biogeochemistry, Hydrol. Process., 23, 169–182, doi: 10.1002/hyp.7196.

Holmes, R. M., J. W. McClelland, B. J. Peterson, S. E. Tank, E. Bulygina, T. I. Eglinton, V. V. Gordeev, T. Y. Gurtovaya, P. A. Raymond, D. J. Repeta, R. Staples, R. G. Striegl, A. V. Zhulidov, and S. A. Zimov (2012), Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas, *Estuaries and Coasts*, *35*, 369-382, doi: 10.1007/s12237-011-9386-6.

Intergovernmental Panel on Climate Change (IPCC) (2013a), *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Cambridge Univ. Press, Cambridge, U. K. and New York, NY, USA, 1535 pp.

Intergovernmental Panel on Climate Change (IPCC) (2013b), Summary for Policymakers. In *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Cambridge Univ. Press, Cambridge, U. K. and New York, NY, USA.

Ise, T., A. L. Dunn, S. C. Wofsy, and P. R. Moorcroft (2008), High sensitivity of peat decomposition to climate change through water-table feedback, *Nature Geoscience, 1,* 763-766.

Kirchman, D. L., X. A. G. Morán, and H. Ducklow (2009), Microbial growth in the polar oceans — role of temperature and potential impact of climate change, *Nature Reviews in Microbiology*, *7,* 451- 459.

Lubin and Vogelmann (2010), Observational quantification of a total aerosol indirect effect in the Arctic, *Tellus B*, *62,* 181–189.

Morimoto, S., S. Ishidoya, K.Ishijima, H.Yashiro, T.Umezawa, G. Hashida, S. Sugawara, S. Aoki, T. Nakazawa, and T. Yamanouchi (2010), Temporal variations of atmospheric greenhouse gases and their related gases at Syowa Station, Antarctica and Ny-Ålesund, Svalbard. *Nankyoku Shiryo (Antarctic Records), 54,* 374-409. (in Japanese).

Quinn, P. K., G. Shaw, E. Andrew, E. G. Dutton, T. Ruoho-Airola, and S. L. Going (2007), Arctic haze: current trends and knowledge gaps, *Tellus Series B-chemical and Physical Meteorology*, *59B,* 99–114.

Shakhova, N., I. Semiletov, A. Salyuk, V. Joussupov, D. Kosmach, and Ö. Gustafssonet (2010), Extensive Methane Venting to the Atmosphere from Sediments of the East Siberian Arctic Shelf, *Science*, *327*, 1246-1250, doi: 10.1126/science.1182221.

Suzuki, R., Y. Kim, R. Ishii (2013), Sensitivity of the backscatter intensity of ALOS/PALSAR to the above-ground biomass and other biophysical parameters of boreal forest in Alaska, *Polar Science, 7,* 100-112.

Yamamoto-Kawai, M., F. McLaughlin, E. Carmack, S. Nishino, and K. Shimada (2009), Aragonite undersaturation in the Arctic Ocean: Effects of ocean acidification and sea ice melt, *Science*, *326,* 1098-1100.

Theme 4

Abe-Ouchi, A., et al. (2013), Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume, *Nature, 500,* 190-193.

Brown, R.D. and P.W. Mote (2009), The response of northern hemisphere snow cover to a changing climate, *Journal of Climate, 22*, 2124-2145.

Brutsaert, W., and T. Hiyama (2012), The determination of permafrost thawing trends from long-term streamflow measurements with an application in eastern Siberia, *J. Geophys. Res., 117,* D22110, doi:10.1029/2012JD018344.

Ekström, G., M. Nettles, and V. C. Tsai (2006), Seasonality and increasing frequency of Greenland glacial earthquakes. *Science, 311,* 1756–1758.

Gardner, A. S., et al. (2013), A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009, *Science, 340(6134),* 852–857, doi: 10.1126/science.1234532

Goodison, B. E., P. Y. T. Louie, and D. Yang (1998), WMO Solid Precipitation Measurement Intercomparison Final Report, *Word Meteorological Organization Instruments and Observing Methods Report No. 67,* 212.

Hiyama T., K. Asai, A. B. Kolesnikov, L. A. Gagarin, and V. V. Shepelev (2013), Estimation of the residence time of permafrost groundwater in the middle of the Lena River basin, eastern Siberia, *Environmental Research Letters, 8,* 035034.

Iijima, Y., A.N. Fedorov, H. Park, K. Suzuki, H. Yabuki, T.C. Maximov, and T. Ohata (2010), Abrupt increase in soil temperature under conditions of increased precipitation in a permafrost region, the central Lena River basin. P*ermafrost and Periglacial Processes, 21,* 30–41.

Iijima, Y., T. Ohta, A. Kotani, A. N. Fedorov, Y. Kodama, and T. C. Maximov (2014), Sap flow changes in relation to permafrost degradation under increasing precipitation in an eastern Siberian larch forest, *Ecohydrology, 7,* doi: 10.1002/eco.1366

Jorgenson, M. T., Y. L. Shur, and E. R. Pullman (2006), Abrupt increase in permafrost degradation in Arctic Alaska, *Geophysical Research Letters, 33,* L02503. doi: 1029/2005GL024960

Landerer, F.W., J.O. Dickey, and A Guentner (2010), Terrestrial water budget of the Eurasian pan‐Arctic from GRACE satellite measurements during 2003–2009. *Journal of Geophysical Research: Atmospheres (1984–2012) 115* (D23).

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas, and T. Zhang (2007), Observations: Changes in Snow, Ice and Frozen Ground. In: *Climate Change 2007: The Physical Science Basis,* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H.L. Miller, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Matsumura, S., K. Yamazaki, and T. Tokioka (2010), Summertime land-atmosphere interactions in response to anomalous springtime snow cover in northern Eurasia, *J. Geophys. Res., 115,* D20107.

Nitu R. (2013), Cold as SPICE, *Meteorological Technology International,* 148–150.

Ogawa, R., B.F. Chao, and K. Heki (2010), Seasonal and inter-annual gravity changes in the Siberian permafrost region. *Chikyu Monthly, 32,* 234-238. (in Japanese).

Ohta, T., A. Kotani, Y. Iijima, T. C. Maximov, S. Ito, M. Hanamura, A. V. Kononov, and A. P. Maximov (2014), Effects of waterlogging on water and carbon dioxide fluxes and environmental variables in a Siberian larch forest, 1998 – 2011, *Agric. For. Meteorol., 188,* 64-75.

Park H., J. Walsh, A. N. Fedorov, A. B. Sherstiukov, Y. Iijima, and T. Ohata (2013), The influence of climate and hydrological variables on opposite anomaly in active-layer thickness between Eurasian and North American watersheds, *Cryosphere, 7,* 631-645, doi:10.5194/tc-7-631-2013.

Rasmussen, R., and Coauthors (2012), How well are we measuring snow: The NOAA/FAA/NCAR winter precipitation test Bed. Bull, *Amer. Meteor. Soc., 93,* 811–829. doi: http://dx.doi.org/10.1175/BAMS-D-11-00052.1

Romanovsky, V. E., D. S. Drozdov, N. G. Oberman, et al. (2010), Thermal state of permafrost in Russia, *Permafrost Periglac. Process., 21(2),* 136–155, doi:10.1002/ppp.683.

Shepherd, A., et al. (2012), A reconciled estimate of ice-sheet mass balance. *Science, 338 (6111),* 1183–1189, doi:10.1126/science.1228102

Shur, Y., K. M. Hinkel, and F. E. Nelson (2005), The Transient Layer: Implication for Geocryology and Climate-Change Science, *Permafrost and Periglacial Processes, 16,* 5-17.

Sugiura, K., and T. Ohata (2008), Large-scale characteristics of the distribution of blowing snow sublimation, *Annals of Glaciology, 49,* 11-16.

Suzuki, K., J. Kubota, Y. Zhang, T. Kadota, T. Ohata, and V. Vuglinsky (2006), Snow ablation in an open field and larch forest of the southern mountainous region of eastern Siberia, *Hydrol. Sci. J., 51(3),* 465–480, doi:10.1623/hysj.51.3.465.

Takeuchi, N., S. Kohshima, and K. Seko (2001), Structure, formation, and darkening process of albedo-reducing material (cryoconite) on a Himalayan glacier: a granular algal mat growing on the glacier, *Arctic, Antarctic, and Alpine Research, 33,* 115–122.

Toyokuni, G., M. Kanao, Y. Tono, T. Himeno, S. Tsuboi, D. Childs, K. Anderson, and H. Takenaka (2014), Japanese Contribution to the Greenland Ice Sheet Monitoring Network (GLISN), *Antarctic Report,* in press.

Yallop, M. L., A. M. Anesio, R. G. Perkins, J.Cook, J. Telling, D. Fagan, J. MacFarlane, M. Stibal, G. Barker, C. Bellas, A. Hodson, M. Tranter, J. Whadhan, and N. W. Roberts (2012), Photophysiology and albedo-changing potential of the ice algal community on the surface of the Greenland ice sheet, *The ISME journal, 6(12),* 2302–2313.

Yoshimori, M., and A. Abe-Ouchi (2012), Sources of spread in multi-model projections of the Greenland ice-sheet surface mass balance, *J. Climate, 25(4),* 1157–1175.

Zhang K., J. Kimball, Q. Mu, L. A. Jones, S. J. Goetz, and S. W. Running (2009), Satellite based analysis of northern ET trends and associated changes in the regional water balance from 1983 to 2005. *J. Hydrol., 379,* 92–110, doi:10.1016/j.jhydrol.2009.09.047.

Zhang, X., J. He, J. Zhang, I. Polaykov, R. Gerdes, J. Inoue, and P. Wu (2013), Enhanced poleward moisture transport and amplified northern high-latitude wetting trend, *Nature Climate Change, 3,* 47-51, doi:10.1038/NCLIMATE1631.

Theme 5

Beare, R.J., M. K .Macvean, A. A. M. Holtslag, J. Cuxart, I. Esau, J.-C. Golatz, M. A. Jimenez, M. Khairoutidinov, B. Kosovic, D. Lewellen, T. S. Lund, J. K. Lundquist, A. Mccabe, A. F. Moene, Y. Noh, S. Raasch, and P. Sullivan (2006), An intercomparison of large-eddy simulations of the stable boundary layer, *Boundary-Layer Meteor., 118*, 247-272.

Brown, R., C. Derksen, and L. Wang (2010), A multi-data set Analysis of Variability and Change in Arctic Spring snow Cover Extent, 1967-2008, *J. Geophys. Res., 115,* D16111, doi:10.1029/JD013975.

Chapman, W.L., and J. E. Walsh (2007), Simulations of Arctic temperature and pressure by global coupled models, *J. Clim.*, *20,* 609-632, doi:10.1175/JCLI4026.1.

Dickson, B., I. Yashayaev, J. Meincke, B. Turrel, S. Dye, and J. Holfort (2002), Rapid freshening of the deep North Atlantic Ocean over the past four decades. *Nature*, *416,* 832-837.

Fereday, D., J. R. Knight, A. A. Scaife, C. K. Folland, and A. Philipp (2008), Cluster analysis of North Atlantic European weather types, *J. Clim.*, *21,* 3687-3703.

Groisman P. Y., and T. D. Davies (2001), Snow cover and the Climate System, In *Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems*, edited by H. G. Jones, et al., pp. 1-44, Cambridge University Press.

Honda, M., J. Inoue, and S. Yamane (2009), Influence of low Arctic sea-ice minima on anomalously cold Eurasian winters, *Geophys. Res. Lett.*, *36*, L08707, doi:10.1029/2008GL037079.

Hu, A., G. A. Meehl, W. Han, A. Timmermann, B. Otto-Bliesner, Z. Liu, W. M. Washington, W. Large, A. Abe-Ouchi, M. Kimoto, K. Lambeck, and B. Wu (2012), Role of the Bering Strait on the hysteresis of the ocean conveyor belt circulation and glacial climate stability, *PNAS*, *109(17),* 6417-6422.

Ineson, S., and A. A. Scaife (2009), The role of the stratosphere in the European climate response to El Niño, *Nature Geoscience*, *2*, 32-36.

Inoue, J., M. E. Hori, and K. Takaya (2012), The Role of Barents Sea Ice in the Wintertime Cyclone Track and Emergence of a Warm-Arctic Cold-Siberian Anomaly, *J. Climate*, *25*, 2561–2568. doi:http://dx.doi.org/10.1175/JCLI-D-11-00449.1.

Liston, G.E. (2004), Representing Subgrid Snow Cover Heterogeneities in Regional and Global Models, *J. Clim., 17,* 1381-1397.

Steele, M., and W. Ermold (2007), Steric sea level change in the Northern Seas, *J. Clim*, *20(3),* 403–417.

Tape, K., M. Sturm, and C. Racine (2006), The evidence for shrub expansion in Northern Alaska and the Pan-Arctic, *Global Change Biology, 12,* 686-702.

Zhang, T. (2005), Influence of the Seasonal Snow Cover on the Ground Thermal Regime: An Overview, *Rev. Geophys., 43*, RG4002. doi: 10.1029/2004RG000157.

Theme 6

Abe-Ouchi, A., F. Saito, K. Kawamura, M. E. Raymo, J. Okuno, K. Takahashi, and H. Blatter (2013), Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume, *Nature, 500(7461),* 190–193, doi:10.1038/nature12374.

Bindschadler, R. A., S. Nowicki, A. Abe-Ouchi, A. Aschwanden, H. Choi, J. Fastook, G. Granzow, R. Greve, G. Gutowski, U. Herzfeld, C. Jackson, J. Johnson, C. Khroulev, A. Levermann, W. H. Lipscomb, M. A. Martin, M. Morlighem, B. R. Parizek, D. Pollard, S. F. Price, D. Ren, F. Saito, T. Sato, H. Seddik, H. Seroussi, K. Takahashi, R. Walker, and W. L. Wang (2013), Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project), *J. Glaciol., 59(214)*, 195–224, doi:10.3189/2013JoG12J125.

de Vernal, A., C. Hillaire-Marcel, A. Rochon, B. Fréchette, M. Henry, S. Solignac, and S. Bonnet (2013), Dinocyst-based reconstructions of sea ice cover concentration during the Holocene in the Arctic Ocean, the northern North Atlantic Ocean and its adjacent seas, *Quat. Sci. Rev., 79,* 111–121, doi:10.1016/j.quascirev.2013.07.006.

Harrison, S. P., and C. I. Prentice (2003), Climate and CO_2 controls on global vegetation distribution at the last glacial maximum: analysis based on palaeovegetation data, biome modelling and palaeoclimate simulations, *Global Change Biology, 9(7),* 983–1004, doi:10.1046/j.1365-2486.2003.00640.x.

Iizuka, Y., R. Uemura, H. Motoyama, T. Suzuki, T. Miyake, M. Hirabayashi, and T. Hondoh (2012), Sulphate–climate coupling over the past 300,000 years in inland Antarctica, *Nature, 490(7418),* 81–84, doi:10.1038/nature11359.

Intergovernmental Panel on Climate Change (IPCC) (2013), Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the IPCC, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Cambridge Univ. Press, Cambridge, U. K. and New York, NY, USA, 1535 pp.

Joussaume, S., K. E. Taylor, P. Braconnot, J. F. B. Mitchell, J. E. Kutzbach, S. P. Harrison, I. C. Prentice, A. J. Broccoli, A. Abe-Ouchi, P. J. Bartlein, C. Bonfils, B. Dong, J. Guiot, K. Herterich, C. D. Hewitt, D. Jolly, J. W. Kim, A. Kislov, A. Kitoh, M. F. Loutre, V. Masson, B. McAvaney, N. McFarlane, N. de Noblet, W. R. Peltier, J. Y. Peterschmitt, D. Pollard, D. Rind, J. F. Royer, M. E. Schlesinger, J. Syktus, S. Thompson, P. Valdes, G. Vettoretti, R. S. Webb, and U. Wyputta (1999), Monsoon changes for 6000 years ago: Results of 18 simulations from the Paleoclimate Modeling Intercomparison Project (PMIP), *Geophys Res Lett, 26(7),* 859–862, doi:10.1029/1999GL900126.

Kobashi, T., D. T. Shindell, K. Kodera, J. E. Box, T. Nakaegawa, and K. Kawamura (2013), On the origin of multidecadal to centennial Greenland temperature anomalies over the past 800 yr, *Clim. Past, 9(2),* 583–596, doi:10.5194/cp-9-583-2013.

Lambert, F., J.-S. Kug, R. J. Park, N. Mahowald, G. Winckler, A. Abe-Ouchi, R. O'ishi, T. Takemura, and J.-H. Lee (2013), The role of mineral-dust aerosols in polar temperature amplification, *Nature Climate Change, 3(5),* 487–491, doi:10.1038/nclimate1785.

Meyer, H., L. Schirrmeister, A. Andreev, D. Wagner, H.-W. Hubberten, K. Yoshikawa, A. Bobrov, S. Wetterich, T. Opel, E. Kandiano, and J. Brown (2010), Lateglacial and Holocene isotopic and environmental history of northern coastal Alaska – Results from a buried ice-wedge system at Barrow, *Quat. Sci. Rev., 29(27-28),* 3720–3735, doi:10.1016/j.quascirev.2010.08.005.

Moran, K., J. Backman, H. Brinkhuis, S. C. Clemens, T. Cronin, G. R. Dickens, F. Eynaud, J. Gattacceca, M. Jakobsson, R. W. Jordan, M. Kaminski, J. King, N. Koç, A. Krylov, N. Martinez, J. Matthiessen, D. McInroy, T. C. Moore, J. Onodera, M. O'Regan, H. Palike, B. Rea, D. Rio, T. Sakamoto, D. C. Smith, R. Stein, K. St John, I. Suto, N. Suzuki, K. Takahashi, M. Watanabe, M. Yamamoto, J. Farrell, M. Frank, P. Kubik, W. Jokat, and Y. Kristoffersen (2006), The Cenozoic palaeoenvironment of the Arctic Ocean, *Nature, 441(7093)*, 601–605.

NEEM community members (2013), Eemian interglacial reconstructed from a Greenland folded ice core, *Nature, 493(7433),* 489–494, doi:10.1038/nature11789.

O'ishi, R. and A. Abe-Ouchi (2011), Polar amplification in the mid-Holocene derived from dynamical vegetation change with a GCM, *Geophys Res Lett, 38,* L14702, doi:10.1029/2011GL048001.

PALAEOSENS Project Members (2012), Making sense of palaeoclimate sensitivity, *Nature, 491(7426),* 683–691, doi:doi:10.1038/nature11574.

Pollack, H. N. (2003), Surface temperature trends in Russia over the past five centuries reconstructed from borehole temperatures, *J. Geophys. Res., 108(B4),* 2180, doi:10.1029/2002JB002154.

Sigl. M., J. R. McConnell, M. Toohey, M. Curran, S.B. Das, R. Edwards, E. Isaksson, K. Kawamura, J. Kipfstuhl, K. Krüger, L. Layman, O.Maselli, Y. Motizuki, H. Motoyama, D. Pasteris, and M. Severi (2014), New insights from Antarctica on volcanic forcing during the Common Era, *Nature Clim. Change*, in press.

Sueyoshi, T., R. Ohgaito, A. Yamamoto, M. O. Chikamoto, T. Hajima, H. Okajima, M. Yoshimori, M. Abe, R. O'ishi, F. Saito, S. Watanabe, M. Kawamiya, and A. Abe-Ouchi (2013), Set-up of the PMIP3 paleoclimate experiments conducted using an Earth system model, MIROC-ESM, *Geoscientific Model Development, 6(3),* 819–836, doi:10.5194/gmd-6-819-2013.

Uemura, R., V. Masson-Delmotte, J. Jouzel, A. Landais, H. Motoyama, and B. Stenni (2012), Ranges of moisture-source temperature estimated from Antarctic ice cores stable isotope records over glacial–interglacial cycles, *Clim. Past, 8(3),* 1109–1125, doi:10.5194/cp-8-1109-2012.

Yoshimura, K., T. Miyoshi, M. Kanamitsu (2014), Observation System Simulation Experiments using Water Vapor Isotope Information, *J. Geophys. Res. Atmos.*, in press, doi:10.1029/2014JD021662.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups (2001), Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present, *Science, 292(5),* 686–693, doi:10.1126/science.1059412.

Theme 7

SGEPSS (2013), Current status and future plan of Geomagnetism and Earth, Planetary and Space Sciences. SGEPSS, p291. (in Japanese).

Kaeriyama, M., H. Seo, H. Kudo, and M. Nagata (2012), Perspectives on wild and hatchery salmon interactions at sea, potential climate effects on Japanese chum salmon, and the need for sustainable salmon fishery management reform in Japan, *Environ. Biol. Fish., 94,* 165-177.

Kelly, R., M. L. Chipman, P. E. Higuera, I. Stefanova, L. B. Brubaker, and F. S. Hu (2013), Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years, *PNAS, 110-32,* 13055–13060.

Kitagawa H., N. Ono, H. Yamaguchi, K. Izumiyama, K. Kamesaki (2000), Northern Sea Route. Ship and Ocean Foundation. P242 (in Japanese).

Koshino, Y., H. Kudo, and M. Kaeriyama (2013), Stable isotope evidence indicates the incorporation of marine-derived nutrients transported by spawning Pacific salmon to Japanese catchments. *Freshwater Biology, 58,* 1864-1877.

Post, E., U. S. Bhatt, C.M. Bitz, J. F. Brodie, T. L. Fulton, M. Hebblewhite, J. Kerby, S. J. Kutz, I. Stirling, D. A. Walker (2013), Ecological Consequences of Sea-Ice Decline, *Science, 341(6145),* 519-524, doi:10.1126/science.1235225.

SATREPS Project. http://www.jst.go.jp/global/kadai/h2004_indonesia.html.

Steppuhn, H. (1981), Snow and Agriculture, *Handbook of Snow*, 60-125, Pergamon Press.

Symon C., L. Arris, and B. Heal (Eds.) (2005), *Arctic climate impact assessment*, Cambridge Univ. Press, New York.

Tanaka, H. L. (2008),
Relationship between the abnormal weather in Japan and the Arctic Oscillation. Proceeding of Heavy Snow Disaster Prevention, 2008. Snow and Ice Research Center, National Research Institute for Earth Science and Disaster Prevention. 1-6, 2008. (in Japanese).

Tsuboi, S., D. Komatitsch, C. Ji, and J. Tromp (2003), Broadband modeling of the 2002 Denali fault earthquake on the Earth Simulator, *Physics of The Earth and Planetary Interiors*, doi:10.1016/j.pepi.2003.09.012.

Yamaguchi, H. (2013), Sea ice prediction and construction of an ice navigation support system for the Arctic sea routes, *Proc. 22nd Intern. Conf. on Port and Ocean Eng. under Arctic Conditions (POAC'13)*, Espoo, Finland, June 9-13, 2013.

Theme 8

Cardinale B. (2012), Impacts of Biodiversity Loss, *Science, 336*, 552-553.

Clymo R.S. (1983), Peat, In *Ecosystems of the world, 4A Mires: swamp bog, fen and moor, general studies,* edited by A. J. P. Gore, 159-224R, Elsevier, Amsterdam.

Clymo, S., and P. M. Hayward (1982), The ecology of Sphagnum, In *Bryophyte Ecology,* edited by A. J. E. Smith, 229-289, Chapman and Hall, London, England.

Elmqvist, T., C. Folke, M. Nyström, G. Peterson, J. Bengtsson, B. Walker, J. Norberg (2003), Response diversity, ecosystem change, and resilience, *Frontiers in Ecology and the Environment, 1,* 488-494.

Ganter, B., A. J. Gaston (2013), Birds, In *Arctic Biodiversity Assessment*, edited by H. Meltofte, 142-181, The Conservation of Arctic Flora and Fauna (CAFF), Akureyri, Iceland.

Ise, T., H. Sato (2008), Representing subgrid-scale edaphic heterogeneity in a large-scale ecosystem model: A case study in the circumpolar boreal regions, *Geophysical Research Letters, 35*, L20407, doi:10.1029/2008GL035701.

Loreau, M., S. Naeem, P. Inchausti, J. Bengtsson, J. P. Grime, A. Hector, D. U. Hooper, M. A. Huston, D. Raffaelli, B. Schmid, D. Tilman, D. A. Wardle (2001), Biodiversity and Ecosystem Functioning: Current Knowledge and Future Challenges, *Science, 294,* 804-808.

Mäkilä, M., M. Saarnisto, T. Kankainen (2001), Aapa mires as a carbon sink and source during the Holocene, *Journal of Ecology, 89,* 589-599.

Mori, A. S., T. Furukawa, T. Sasaki (2013), Response diversity determines the resilience of ecosystems to environmental change, *Biological Reviews, 88*, 349-364.

Post, E., U. S. Bhatt, C. M. Bitz, J. F. Brodie, T. L. Fulton, M. Hebblewhite, J. Kerby, S. J. Kutz, I. Stirling, D. A. Walker (2013), Ecological Consequences of Sea-Ice Decline, S*cience, 341,* 519-524.

Purves, D., J. P. W. Scharlemann, M. Harfoot, T. Newbold, D. P. Tittensor, J. Hutton, S. Emmott (2013), Ecosystems: Time to model all life on Earth, *Nature, 493,* 295-297.

Tsuyuzaki, S., K. Kushida, Y. Kodama (2009), Recovery of surface albedo and plant cover after wildfire in a *Picea mariana* forest in interior Alaska, *Climate Change, 93,* 517-525.

Theme 9

Abdul-Aziz, O. I., N. J. Mantua, and K. W. Myers (2011), Potential climate change impacts on thermal habitats of Pacific salmon (*Oncorhynchus* spp.) in the North Pacific Ocean and adjacent seas, *Can. J. Fish. Aquat. Sci.*, *68,* 1660-1680.

AMAP(2009), *Arctic Pollution 2009*, Arctic Monitoring and Assessment Programme, Oslo. xi+83pp.

AMAP (2013), *AMAP Assessment 2013,* Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. viii + 99 pp.

Bluhm, B. A., A. V. Gebruk, R. Gradinger, R. R. Hopcroft, F. Huettmann, K. N. Kosobokova,B. I. Sirenko, and J. M. Weslawski

(2011), Arctic marine biodiversity: An update of species richness and examples of biodiversity change, *Oceanography, 24,* 232–248.
Boetius, A., S. Albrecht, K. Bakker, C. Bienhold, J. Felden, and others (2013), Export of algal biomass from the melting Arctic sea ice, *Science, 339,* 1430-1432.
Buchholz, et al. (2012), First observation of krill spawning in the high Arctic Kongsfjorden, west Spitsbergen. *Polar Biol., 35,* 1273-1279.
CAFF (2013), *Life Linked to Ice: A guide to sea-ice-associated biodiversity in this time of rapid change*, CAFF Assessment Series 10, p. 115.
CoML (2010), *First Census of Marine Life 2010*, Highlights of a decade of discovery, edited by J. H. Ausubel, p. 64.
Cooper et al. (2013), Linkages between sea-ice coverage, pelagic–benthic coupling, and the distribution of spectacled eiders: Observations in March 2008, 2009 and 2010, northern Bering Sea. *Deep-Sea Res. II, 94,* 31-43.
Grebmeier, J.M. et al. (2006) Ecosystem dynamics of the Pacific-influenced Northern Bering and Chukchi Seas, *Prog. Oceanogr., 71*, 331-361.
Honjo, S., R. A. Krishfield, T. I. Eglinton, S. J. Manganini, J. N. Kemp, K. Doherty, J. Hwang, T. K. McKee, T. Takizawa (2010), Biological pump processes I the cryopelagic and hemipelagic Arctic Ocean: Canada Basin and Chukchi Rise, *Progress in Oceanography, 85,* 137-170.
Kaeriyama, M. (2008), Ecosystem-based sustainable conservation and management of Pacific salmon, In *Fisheries for Global Welfare and Environment*, edited by K. Tsukamoto, T. Kawamura, T. Takeuchi, T. D. Beard, Jr., and M. J. Kaiser, 371-380, TERRAPUB, Tokyo.
Kaeriyama, M., H. Seo, H. Kudo, and M. Nagata (2012), Perspectives on wild and hatchery salmon interactions at sea, potential climate effects on Japanese chum salmon, and the need for sustainable salmon fishery management reform in Japan, *Environ. Biol. Fish., 94,* 165-177.
Kaeriyama, M., H. Seo, and Y. Qin (2014), Effect of global warming on the life history and population dynamics of Japanese chum salmon, *Fisheries Sci., 80 (2),* 251-260.
Koshino, Y., H. Kudo, and M. Kaeriyama (2013), Stable isotope evidence indicates the incorporation of marine-derived nutrients transported by spawning Pacific salmon to Japanese catchments, *Freshwater Biology, 58,* 1864-1877.
McClelland, J. W., R. M. Holmes, K. H. Dunton, and R. W. Macdonald (2012), The Arctic Ocean Estuary, *Estuaries and Coasts, 35,* 353-368.
Mallory, and Braune (2012), Tracking contaminants in seabirds of Arctic Canada: temporal and spatial insights. *Mar. Pollut. Bull., 64,* 1475-1484.
Matsuno, et al. (2011), Year-to-year changes of the mesozooplankton community in the Chukchi Sea during summers of 1991, 1992 and 2007, 2008. *Polar Biol., 34,* 1349-1360.
Michelutti et al. (2009), Seabird-driven shifts in Arctic pond ecosystems. *Proc. R. Soc. B, 276,* 591-596.
Orr, J.C., et al. (2005), Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, *437,* 681-686.
Pabi, et al. (2008), Primary production in the Arctic Ocean, 1998–2006. *J. Geophys. Res., D*oi:10.1029/2007JC004578.
Tremblay, J.-É., and J. Gagnon (2009), The effects of irradiance and nutrient supply on the productivity of Arctic waters: a perspective on climate change, 73-92, In *Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions*, edited by J. C. J. Nihoul, and A. G. Kostianoy, Springer, Dordrecht, Netherlands.
Uchimiya, M., H. Fukuda, S. Nishino, T. Kikuchi, H. Ogawa, T. Nagata (2011), Does freshening of surface water enhance heterotrophic prokaryote production in the western Arctic? Empirical evidence from the Canada Basin during September 2009, *Journal of Oceanography, 67,* 589–599.
Wassmann, P.(1998), Retention versus export food chains: processes controlling sinking loss from marine pelagic systems, *Hydrobiologia, 36,* 29-57.
Wassmann, P. (2011), Arctic marine ecosystems in an era of rapid climate change, *Progress in Oceanography, 90,* 1-17

Theme 10

Baldwin, M. P., and T. J. Dunkerton (1999), Propagation of the Arctic Oscillation from the stratosphere to the troposphere, *J. Geophys. Res., 104,* 30937-30946.
Chau, J. L., L. P. Goncharenko, B. G. Fejer, and H.L. Liu (2012), Equatorial and low latitude ionospheric effects during sudden stratospheric warming events, *Space Sci Rev, 168,* 385–417, DOI 10.1007/s11214-011-9797-5.
SGEPSS (2013), Current status and future plan of Geomagnetism and Earth, Planetary and Space Sciences. SGEPSS, p291. (in Japanese).
Gray, L. J., J. Beer, M. Geller, J. D. Haigh, M. Lockwood, K. Matthes, U. Cubasch, D. Fleitmann, G. Harrison, L. Hood, J. Luterbacher, G. A. Meehl, D. Shindell, B. van Geel, and W. White (2010), Solar Influences on Climate, *Reviews of Geophysics, 48,* 1209/10/2009RG000282, 2010.
Jackman, C. H., et al. (2001), Northern Hemisphere atmospheric effects due to the July 2000 solar proton event, *Geophys. Res. Lett., 28,* 2883-2886.
Jin, H., Y. Miyoshi, H. Fujiwara, H. Shinagawa, K. Terada, N. Terada, M. Ishii, Y. Otsuka, and A. Saito (2011), Vertical connection from the tropospheric activities to the ionospheric longitudinal structure simulated by a new Earth's whole atmosphere -

ionosphere coupled model, *J. Geophys. Res., 116,* A01316, doi:10.1029/2010JA015925.
Makela J. J., and Y. Otsuka (2012), Overview of Nighttime Ionospheric Instabilities at Low- and Mid-Latitudes: Coupling Aspects Resulting in Structuring at the Mesoscale, *Space Science Reviews, 168,* 419-440.
Manney, G. L., et al. (2011), Unprecedented Arctic ozone loss in 2011, *Nature, 478,* 469-475.
Plumb, R. A., and K. Semeniuk (2003), Downward migration of extratropical zonal wind anomalies, *J. Geophys. Res., 108,* 4223, doi:10.1029/2002JD002773.
Randall, C. E., V. L. Harvey, C. S. Singleton, S. M. Bailey, P. F. Bernath, M. Codrescu, H. Nakajima, and J. M. Russell (2007), Energetic particle precipitation effects on the Southern Hemisphere stratosphere in 1992-2005, *J. Geophys. Res., 112,* D08308, doi:10.1029/2006JD007696.
Rishbeth, H., and O. K. Garriott (1969), Introduction to ionospheric physics, *International Geophysics Series, 14,* Academic Press, New York.
Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?, *Geophys. Res. Lett., 16,* 1441-1444.
Rozanov, E., et al. (2005), Atmospheric response to NOy source due to energetic electron precipitation, *Geophys. Res. Lett., 32,* L14811, doi:10.1029/2005GL023041.
Shiota, D., S. Tsuneta, M. Shimojo, N. Sako, D. Orozco Suarez, and R. Ishikawa (2012), Polar Field Reversal as observed with Hinode, *The Astrophysical Journal*, arXiv:1205.2154 [astro-ph.SR].
Schunk, R. W., and A. F. Nagy (2000), *Ionospheres: Physics, plasma physics, and chemistry*, Cambridge University Press.
Tsugawa, T., et al. (2011), Ionospheric disturbances detected by GPS total electron content observation after the 2011 off the Pacific coast of Tohoku Earthquake, *Earth, Planets and Space, 63,* 875-879.
Turner, J., J. E. Overland, and J. E. Walsh (2007), An Arctic and Antarctic perspective on recent climate change, *Int. J. Climatol., 27,* 277-293.
Vadas, S. L., and G. Crowley (2010), Sources of the traveling ionospheric disturbances observed by the ionospheric TIDDBIT sounder near Wallops Island on 30 October 2007, *J. Geophys. Res., 115,* A07324, doi:10.1029/2009JA015053.

Theme 11

Alvey, A., C. Gaina, N. J. Kusznir, T. H. Torsvik (2008), Integrated crustal thickness mapping and plate reconstructions for the high Arctic, *Earth Planet Sci. Lett., 274,* 310–321.
Backman, J., K. Moran, L. A. Mayer, D. B. McInroy, and the Expedition 302 Scientists (2006), Proceedings IODP, 302, College Station TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.302.104.
Barletta, V., and A. Bordoni (2009), Clearing observed PGR in GRACE data aimed at global viscosity inversion: Weighted Mass Trends technique, *Geophys. Res. Lett., 36,* L02305, doi:10.1029/2008GL036429.
Barnett, T. P. (1984), The Estimation of "Global" Sea Level Change' A Problem of Uniqueness, *J. Geophys. Res., 89, C5,* 7980-7988.
Bowring, S. A., I. S. Williams, W. Compston (1989), 3.96 Ga gneisses from the Slave province, Northwest Territories, Canada, *Geology, 17,* 971-975.
Carson, C. J., S. McLaren, A. L. Roberts, S. D. Boger, D. D. Blankenship (2014), Hot rocks in a cold place: high sub-glacial heat flow in East Antarctica, *Journal of Geological Society of London, 171,* doi.org/10.1144/jgs2013-030.
Edmonds, H. N. et al. (2003), Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel ridge in the Arctic Ocean, *Nature, 421,* 252-256.
Ekman, M., and J. Mäkinen (1996), Recent postglacial rebound, gravity change and mantle flow in Fennoscandia, *Geophys. J. Int., 126,* 229–234.
Glebovsky, V. Y. , L. C. Kovacs, S. P. Maschenkov, J. M. Brozena (1998), Joint compilation of Russian and US Navy aeromagnetic data in the central Arctic seas, Roland, N., F. Tessesnsons (Eds.), ICAM III; Third International Conference on Arctic Margins, Polarforshungpp, 35–40.
Jakobsson, M., R. Macnab, L. Mayer, R. Anderson, M. Edwards, J. Hatzky, H. W. Schenke, and P. Johnson (2008), An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses, *Geophysical Research Letters,* doi:10.1029/2008GL033520.
Jokat, W. (2003), Seismic investigations along the western sector of Alpha Ridge, Central Arctic Ocean, *Geophysical Journal International, 152 (1),* 185-201.
Lebedeva-Ivanova, N. N., Y. Ya. Zamansky, A. E. Langinen, and M. Yu. Sorokin (2006), Seismic profiling across the Mendeleev Ridge at 82°N: evidence of continental crust, *Geophysical Journal International, 165,* 527–544. doi: 10.1111/j.1365-246X.2006.02859.x
Lorenz, H., D. G. Gee, A. N. Larionov, J. Majka (2012), The Grenville–Sveconorwegian orogen in the high Arctic, *Geological Magazine, 149,* 875-891.
Michael, P. J. et al. (2003), Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean, *Nature, 423,* 956-961.
Moran, K. et al. (2006), The Cenozoic palaeoenvironment of the Arctic Ocean, *Nature, 441(7093),* 601–605.
Nutman, A. P., V. C. Bennett, C. R. L. Friend, K. Horie, H. Hidaka (2007), ~3850 Ma tonalites in the Nuuk region, Greenland: geochemistry and their reworking within an Eoarchaean gneiss complex, *Contributions to Mineralogy and Petrology, 154,* 385-408.

Pedersen, R. B. et al. (2010), Discovery of a black smoker vent field and vent fauna at the Arctic mid-ocean ridge, *Nature Communications, 1,* http://dx.doi .org/10.1038/ncomms1124.

Peltier, W. R.(2004), Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE, *Annu. Rev. Earth Planet. Sci., 32,* 111-149.

Sella, G., S. Stein, T. Dixon, M. Craymer, T. James, S. Mazzotti, and R. Dokka (2007), Observation of glacial isostatic adjustment in "stable" North America with GPS, *Geophys. Res. Lett., 34,* L02306, doi:10.1029/2006GL027081.

Seton, M., R. D. Muller, S. Zahirovic, C. Gaina, T. Torsvik, G. Shephard, A. Talsma, M. Gurnis, M. Turner, S. Maus, M. Chandler (2012), Global continental and ocean basin reconstructions since 200 Ma, *Earth-Science Reviews, 113,* 212-270.

Shank, T., J. Bailey, H. Edmonds, P. Forte, E. Helmke, et al. (2007), Biological and geological characteristics of the Gakkel Ridge, *Eos Trans. AGU Fall Meeting Supplement*, OS41C-08, 88.

Sohn, R.A., et al. (2008), Explosive volcanism on the ultraslow-spreading Gakkel ridge, Arctic Ocean, *Nature, 453,* 1236-1238.

Vernikovsky, V. A., N. L.Dobretsov, D. V. Metelkin, N.Yu. Matushkin, I.Yu. Koukakov (2013), Concerning tectonics and the tectonic evolution of the Arctic, *Russian Geology and Geophysics, 54,* 838-858.

Verhoef, J., W. R. Roest, R. Macnab, J. Arkani-Hamed (1996), Magnetic anomalies of the Arctic and North Atlantic oceans and adjacent land areas.

Vogt, P. R., P. T. Taylor, L.C. Kovacs, and G. L. Johnson (1982), The Canada Basin; aeromagnetic constraints on structure and evolution, *Tectonophysics, 89,* 295–336.

Theme 12

Brown, J., O. J. Ferrians, Jr, J. A. Heginbottom, and E. S. Melnikov (1997), Circum-arctic map of permafrost and ground ice conditions. United States Geological Survey, published for the International Permafrost Association, Circum-Pacific Map Series, Map CP-45, scale 1:10,000,000.

Brown, J., O. J. Ferrians, Jr., J. A. Heginbottom, and E. S. Melnikov (2002), *Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2,* National Snow and Ice Data Center, Boulder, Colorado USA.

Francis, J. A., D. M. White, J. J. Cassano, W. J. Gutowski, Jr., L. D. Hinzman, M. M. Holland, M. A. Steele, and C. J. Vörösmarty (2009), An Arctic hydrologic system in transition: feedbacks and impacts on terrestrial, marine, and human life. *Journal of Geophysical Research, 114,* G04019.

Harris, C. et al. (2009), Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses, *Earth-Science Reviews, 92 (3-4),* 117-171

Ishikawa, M. and K. Saito (2006), Frozen ground sciences influencing climate and water cycle -Reviews and perspectives-. *Journal of the Japanese Society of Snow and Ice, 68,* 639-656. (in Japanese).

Ishikawa, M., N. Sharkhuu, Y. Jambaljav, G. Davaa, K. Yoshikawa, and T. Ohata (2012), Thermal states of Mongolian permafrost, 173-178, Proc, 10th Int. Conf. Permafrost, Salehard.

Koven, C. D., B. Ringeval, P. Friedlingstein, P. Ciais, P. Cadule, D. Khvorostyanov, G. Krinner, and C. Tarnocai (2011), Permafrost carbon-climate feedbacks accelerate global warming, *Proc. Natl Acad. Sci., 108,* 14769–74.

Lachenbruch, A. H., and B. V. Marshall (1986), Changing climate: geothermal evidence from permafrost in the Alaskan Arctic, *Science, 234,* 689-696.

Matsuoka, N. and A. Ikeda (2012), Research Frontier in Periglacial Processes. *Journal of Geography (Chigaku Zasshi), 121(2),* 269–305. (in Japanese).

Romanovsky, V. E. et al. (2010), Thermal state of permafrost in Russia, *Permafrost and Periglacial Processes*, 21 (2), 136-155

Saito, K., T. Zhang, D. Yang, S. Marchenko, R. G. Barry, V. Romanovsky, and L. Hinzman (2013), Influence of the physical terrestrial Arctic in the eco-climate system, *Ecological Applications, 23,* 1778–1797.

Schaefer, K., H. Lantuit, V. E. Romanovsky, and E. A. G. Schuur (2012), Policy Implications of Warming Permafrost, 31 pp., UNEP.

Schirrmeister, L., D. Froese, V. Tumskoy, G. Grosse, and S. Wetterich (2013), Yedoma: Late Pleistocene Ice-Rich Syngenetic Permafrost of Beringia, in *Encyclopedia of Quaternary Science (Second Edition)*, edited by S. A. Elias, pp. 542–552, Elsevier.

Schuur, E.A.G., and B. Abbott (2011), High risk of permafrost thaw, *Nature, 480(7375),* 32-33.

Shur, Y. L., and M. T. Jorgenson (2007), Patterns of permafrost formation and degradation in relation to climate and ecosystems, *Permafrost and Periglacial Processes 18*, 7–19.

Singh, V. P., P. Singh and U. K. Haritashya (Eds.) (2011), Encyclopedia of Snow, Ice and Glaciers, 844, *Springer*, doi: 10.1007/978-90-481-2642-2.

Slater and Lawrence (2013), Diagnosing Present and Future Permafrost from Climate Models, *J. Clim., 26(15),* 5608-5623, doi: 10.1175/JCLI-D-12-00341.1.

Tarnocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova and S. Zimov (2009), Soil organic carbon pools in the northern circumpolar permafrost region, *Global Biogeochemical Cycles, 23,* GB2023, doi:10.1029/2008GB003327.

United Nations Environment Programme (2012), Policy implications of warming permafrost.

Vonk, J. E., P. J. Mann, K. L. Dowdy, A. Davydova, S. P. Davydov, N. Zimov, R. G. M. Spencer, E. B. Bulygina, T. I. Eglinton, and R. M. Holmes (2013), Dissolved organic carbon loss from Yedoma permafrost amplified by ice wedge thaw, *Environ. Res. Lett., 8,* 035023, doi:10.1088/1748-9326/8/3/035023.

Zhang, T., R. G. Barry, K. Knowles, J. A. Heginbottom, and J. Brown (1999), Statistical and characteristics of permafrost and

ground-ice distribution in the Northern Hemisphere, *Polar Geogr., 23,* 132-154.
Zimov, S. A., E. A. G. Schuur, and F. S. Chapin III (2006), Permafrost and the global carbon budget, *Science, 312,* 1612-1613.

Theme A

Bolch, T. et al. (2013), Mass loss of Greenland's glaciers and ice caps 2003–2008 revealed from ICESat data, *Geophysical. Research Letters, 40,* 875–881, doi:10.1002/grl.50270.

Comiso, J. C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res., 113*, C02S07, doi:10.1029/2007JC004257.

Fukuda, M. (1993), Genesis and occurrence of ice complex (Edoma) in lowland area along Arctic coast of east Siberia near Tiksi, In *Proceedings of the First Symposium on Joint Siberian Permafrost Studies between Japan and Russia in 1992*, 101-103.

Grebmeier, J. M., Moore, S. E., Overland, J. E., Frey, K. E., and Gradinger, R. (2010), Biological Response to Recent Pacific Arctic Sea Ice Retreats, *EOS Trans. AGU, 91(18),* doi:10.1029/2010EO180001.

Hori, M., T. Aoki, K. Stamnes, and W. Li (2007), ADEOS-II/GLI snow/ice products - part III: Retrieved results, *Remote Sens. Environ., 111,* 274−319, doi:10.1016/j.rse.2007.01.025.

Kawamiya, M., T. Hajima, and T. Tokioka (2012), Foreseeing the forests: vegetation dynamics in an Earth system model, In *Forest for people,* Tudor Rose, Leicester, England, 291-294.

Keeling, C. D., R. B. Bacastow, A. E. Bainbridge, C. A. Ekdahl, Jr., P. R. Guenther, L. S. Waterman, and J. F. S. Chin (1976), Atmospheric Carbon Dioxide Variations at Mauna Loa Observatory, Hawaii, *Tellus, 28,* 538-551.

Key, J., M. Drinkwater, and J. Ukita (2007), Integrated Global Observing Strategy - Partnership (IGOS-P) Cryosphere Theme Report, *World Meteorological Organization, 132 pp,* Geneva.

Moon T. et al. (2012), 21st-century evolution of Greenalnd outlet glacier velocities, *Science 336(6081),* 576–578, doi: 10.1126/science.1219985.

Morimoto, S., S. Aoki, T. Nakazawa and T. Yamanouchi (2006), Temporal variations of the carbon isotopic ratio of atmospheric methane observed at Ny Ålesund, Svalbard from 1996 to 2004, *Geophys. Res. Lett., 33,* L01807, doi:10.1029/2005GL024648.

Quinn, P. et al. (2007), Arctic haze: current trends and knowledge gaps, *Tellus Series B-chemical and Physical Meteorology,* doi:10.1111/j.1600-0889.2006.00238.x

Serreze, M. C., A. P. Barrett, A. G. Slater, M. Steele, J. Zhang, and K. E. Trenberth (2007), The large-scale energy budget of the Arctic, *J. Geophys. Res., 112,* D11122, doi:10.1029/2006JD008230.

Steffen, K., and J. E. Box (2001), Surface climatology of the Greenland ice sheet: Greenland climate network 1995-1999, *J. Geophys. Res., 106 (D24),* 33,951-33,964, doi:10.1029/2001JD900161.

Suzuki, R. (2013), A review of recent studies on vegetation in boreal regions by remote sensing. *Journal of The Remote Sensing Society of Japan33,* 48-55. (in Japanese).

Tape, K., M. Sturm, and C. Racine (2006), The evidence for shrub expansion in Northern Alaska and the Pan-Arctic, *Global Change Biology, 12,* 686-702.

Ueyama, M., H. Iwata, and Y. Harazono (2014), Autumn warming reduces the CO_2 sink of a black spruce forest in interior Alaska based on a nine-year eddy covariance measurement, *Global Change Biology, 20,* 1161-1173.

Vaughan, D. G., J. C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen, and T. Zhang (2013), Observations: Cryosphere, In *Climate Change 2013: The Physical Sci- ence Basis,* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F.Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley,. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Viereck, L. A., N. R. Werdin-Pfisterer, P. C. Adams, and K. Yoshikawa (2008), Effect of Wildfire and Fireline Construction on the Annual Depth of Thaw in a Black Spruce Permafrost Forest in Interior Alaska: A 36-Year Record of Recovery, In *Proceedings of the Ninth International Conference on Permafrost*, 1845-1850, Fairbanks, Alaska.

Wang, X., and J. Key (2005), Arctic Surface, Cloud, and Radiation Properties Based on the AVHRR Polar Pathfinder Dataset, Part II: Recent Trends, *Journal of Climate, 18(14),* 2575-2593.

Wientjes, I. G. M., R. S. W. Van de Wal, G. J. Reichart, A. Sluijs, and J. Oerlemans (2007), Dust from the dark region in the western ablation zone of the Greenland ice sheet, *The Cryosphere, 5,* 589-601, doi:10.5194/tc-5-589-2011.

Yamanouchi, T. (2011), Early 20th century warming in the Arctic: A review, *Polar Science*, doi:10.1016/j.polar.2010.10.002.

Theme B

Bindschadler, R., S. Nowicki, A. Abe-Ouchi, A. Aschwanden, H. Choi, J. Fastook, G. Granzow, R. Greve, G. Gutowski, U. Herzfeld, C. Jackson, J. Johnson, C. Khroulev, A. Levermann, W. Lipscomb, M. Martin, M. Morlighem, B. Parizek, D. Pollard, S. Price, D. Ren, F. Saito, T. Sato, H. Seddik, H. Seroussi, K. Takahashi, R. Walker and W. L. Wang (2013), Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the {SeaRISE} project), *J. Glaciol., 59,* 195-224.

De Boer, G., M. D. Shupe, P. M. Caldwell, S. E. Bauer, O. Persson, J. S., Boyle, M. Kelley, S. A. Klein, and M. Tjernstrom (2014), Near-surface meteorology during the Arctic Summer Cloud Ocean Study (ASCOS): evaluation of reanalysis and global climate models, *Atmos. Chem Phys., 14,* 427-445,

www.atmos-chem-phys.net/14/427/2014/ , doi:10.5194/acp-14-427-2014.
Ise, T., A. L. Dunn, S. C. Wofsy, and P. R. Moorcroft (2008), High sensitivity of peat decomposition to climate change through water-table feedback, *Nature Geoscience*, *1*, 763-766.
Jahn et al. (2012), Late-twentieth-century simulation of Arctic sea ice and ocean properties in the CCSM4, *J. Climate*, *25*, 1431-1452.
Jakobsson, M., L. A. Mayer, B. Coakley, J. A. Dowdeswell, S. Forbes, B. Fridman, H. Hodnesdal, R. Noormets, R. Pedersen, M. Rebesco, H.-W. Schenke, Y. Zarayskaya A, D. Accettella, A. Armstrong, R. M. Anderson, P. Bienhoff, A. Camerlenghi, I. Church, M. Edwards, J. V. Gardner, J. K. Hall, B. Hell, O. B. Hestvik, Y. Kristoffersen, C. Marcussen, R. Mohammad, D. Mosher, S. V. Nghiem, M. T. Pedrosa, P. G. Travaglini, and P. Weatherall,(2012) The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0, *Geophysical Research Letters,* doi: 10.1029/2012GL052219.
O'ishi, R. and A. Abe-Ouchi (2009), Influence of dynamic vegetation on climate change arising from increasing CO_2, *Climate Dynamics*, *33*, 645-663.
Proshutinsky, A., and Coauthors (2011), Recent advances in Arctic ocean studies employing models from the Arctic Ocean Model Intercomparison Project, *Oceanography, 24(3),* 102-113.
Proshutinsky, A., and Z. Kowalik (2007), Preface to special section on Arctic Ocean Model Intercomparison Project (AOMIP) Studies and Results, *J. Geophys. Res., 112,* C04S01, doi:10.1029/2006JC004017.
Satoh, M., T. Matsuno, H. Tomita, H. Miura, and T. Nasuno (2008), Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulation. *J. Comp. Phys., 227,* 3486-3514.
Sueyoshi, T., R. Ohgaito, A. Yamamoto, M. O. Chikamoto, T. Hajima, H. Okajima, M. Yoshimori, M. Abe, R. O'ishi, F. Saito, S. Watanabe, M. Kawamiya and A. Abe-Ouchi (2013), Set-up of the PMIP3 paleoclimate experiments conducted using an Earth system model, MIROC-ESM, *Geosci. Model Dev.*, *6*, 819-836.
Taylor, K. E., R. J. Stouffer, and G. a. Meehl (2012), An Overview of CMIP5 and the Experiment Design, *Bull. Am. Meteorol. Soc., 93,* 485–498.
Watanabe, M., and Coauthors (2010), Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity, *J. Climate*, *23,* 6312-6355.
Yi, S. H., M. K. Woo and M. A. Arain (2007), Impacts of peat and vegetation on permafrost degradation under climate warming. *Geophys. Res. Lett.*, *34(16),* L16504.

Theme C

Awaji, T., M. Kamachi, M. Ikeda and Y. Ishikawa (2009), Ocean data assimilation: innovation to combine observation, experiment and modeling. Kyoto Univ. Press, pp.284. (in Japanese).
Bourassa,et al. (2013), High-latitude ocean and sea-ice surface fluxes: Challenges for climate research, *Bull. Amer. Meteor. Soc.*, *94(3),* 403–423, doi:10.1175/BAMS-D-11-00244.1.
Dameris, M. and P. Jöckel (2013), Numerical modelling of climate-chemistry connections: Recent developments and future challenges, *Atmosphere*, *4,* 132-156, doi: 10.3390/atmos4020132.
Goldberg, D. N., and P. Heimbach (2013), Parameter and state estimation with a time-dependent adjoint marine ice sheet model, *The Cryosphere Discuss*., *7*, 2845-2890, doi:10.5194/tcd-7-2845-2013.
Heimbach, P., and V. Bugnion (2009), Greenland ice-sheet volume sensitivity to basal, surface and initial conditions derived from an adjoint model, *Ann. Glaciol.*, *50*, 67–80, doi:10.3189/172756409789624256.
Inoue, J., T. Enomoto, and M. E. Hori (2013), The impact of radiosonde data over the ice-free Arctic Ocean on the atmosphere circulation in the Northern Hemisphere, *Geophys. Res. Let.*, *40*, 864-869.
Jakobson, E., T. Vihma, T. Palo, L. Jakobson, H. Keernik, and J. Jaagus (2012), Validation of atmospheric reanalyses over the central Arctic Ocean, *Geophys. Res. Lett.*, *39*, L10802, doi:10.1029/2012GL051591.
Kimball, J. S., L. A. Jones, K. Zhang, F. A. Heinsch, K. C. McDonald, and W. C. Oechel (2009), A satellite approach to estimate land-atmosphere CO_2 exchange for Boreal and Arctic biomes using MODIS and AMSR-E, *IEEE Transactions on Geoscience and Remote Sensing*, *47*(2), 569-587, 10.1109/TGRS.2008.2003248.
Lindsay, R., C. Haas, S. Hendricks, P. Hunkeler, N. Kurtz, J. Paden, B. Panzer, J. Sonntag, J. Yungel, and J. Zhang (2012), Seasonal forecasts of Arctic sea ice initialized with observations of ice thickness, *Geophys. Res. Lett.*, *39*, L21502, doi:10.1029/2012GL053576.
Popova et al. (2012), What controls primary production in the Arctic Ocean? Results from an intercomparison of five general circulation models with biogeochemistry, *J. Geophys. Res.*, *117*, doi:10.1029/2011JC007112.
Toyoda et al. (2011), Impact of the assimilation of sea ice concentration data on an atmosphere-ocean-sea ice coupled simulation of the Arctic ocean climate, *SOLA*, *7*, 37-40, doi:10.2151/sola.2011-010.
Toyoda et al. (2013). Improved state estimations of lower trophic ecosystems in the global ocean based on a Green's function approach, *Prog. Oceanogr.*, *119*, 90-107.
Usui, N, T. Imaizumi, H. Tsujino (2010), Toward introduction of assimilation of ice concentration into MOVE/MRI.COM: A model validation and a simple assimilation experiment in the Sea of Okhotsk. *Weather service bulletin 77, Special issue*, S71-S82. (in Japanese).
Valsala, K. V. and S. Maksyutov (2010), Simulation and assimilation of global ocean pCO_2 and air-sea CO_2 fluxes using ship observations of surface ocean pCO_2 in a simplified biogeochemical offline model, *Tellus*, *62B*, 821–840, doi:10.1111/j.1600-0889.2010.00495.x.

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<Theme 4: Ice sheet / glaciers, permafrost, snowfall / snow cover and hydrological cycle >

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<Theme 5: Interactions between the Arctic and the entire earth >

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<Theme 6: Predicting future environmental conditions of the Arctic based on paleoenvironmental records >

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<Theme 7: Effects of the Arctic environment on human society >

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<Theme 8: Effects on terrestrial ecosystems and biodiversity >

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<Theme 9: Influence on marine ecosystem and biodiversity >

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<Theme 10: Geospace Environment >

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<Theme 11: Interaction of surface environment change with solid earth >

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<Theme 12: Basic understanding on formation and transition process of permafrost >

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< Theme B: Earth system-modeling for inter-disciplinary research >

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< Theme C: Data assimilation to connect mentoring and modeling >

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