Towards a seasonally ice covered Arctic Ocean

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Report compiled by

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Introduction

In October 2014 IASC, with support of Woods Hole Oceanographic Institute, the Finnish Meteorological Institute and the EU program NACLIM, arranged an ICARPIII workshop in connection with the annual FAMOS meeting in Woods Hole. The workshop was held in the Carriage House at WHOI and the theme (appendix a)of the workshop “Towards a seasonally ice covered Arctic Ocean” grew out of a previous IASC workshop on “Internal mixing processes in the Arctic Ocean” also held in the Carriage House in 2013 just before the FAMOS meeting that year. Due to logistical constraints the workshop was semi-closed and limited to about 40 participants (appendix b). The workshop was arranged by topics (see workshop program in appendix c). Each topic was introduced by an invited speaker (25-30 minutes) and followed by questions and discussion (15-20 minutes). The topics were collected into four different themes and after each themes a summary discussion (45 minutes) was held, led by two or three moderators.

Theme 1: “Processes in the Arctic Ocean”

This theme was introduced with the questions “**Why do we have an ice cover in the Arctic Ocean, and what would a change to a seasonal ice cover imply**?” asked by **Bert Rudels**. In the 19th century the idea of an ice free Polar Ocean was seriously discussed. This in spite of all failed attempts to sail the Northeast and Northwest passages and the fact that the mean air temperature north of 70^{o}N was below zero and ice should form. The argument for an ice free ocean was that the warm ocean currents, especially the Gulf Stream, would carry enough heat to prevent sea ice to form in the ocean away from the coastal areas. When Nansen on Fram eventually penetrated into the Arctic Ocean he found no ice free ocean, but he observed a warm subsurface layer, the remnants of the Gulf Stream, overlaid by low salinity surface water, which prevented the heat from the warm, Atlantic, layer from reaching and melting the ice.

The first question to ask is: How much heat could be carried by the ocean currents, and how does this compare with the heat loss to space and with the atmospheric heat transport? If saturated air is cooled from 10^{o}C to $-$25^{o}C the energy release would be ~54000Jkg^{-1}. Cooling 1 kg of water by 4.5^{o}C, the average cooling of water entering the Arctic Ocean through Fram Strait and the Barents Sea, would release 18000Jkg^{-1}, which is of the same order. The yearly average heat loss north of 70^{o}N is ~100Wm^{-2} implying a total loss of 1.5$\times$10^{15}W north of 70^{o}N. This corresponds to a northward transport of 28.5$\times$10^{9}kgs^{-1} of air, including 0.15$\times$10^{9}kgs^{-1} of water vapor, or a mean wind velocity of 0.4 ms^{-1} through 70^{o}N. The corresponding ocean transport, 3Sv through Fram Strait and 3Sv through the Barents Sea, only amounts to 0.11$\times$10^{15}W, less than 10% of the required heat transport. The main northward heat transport is carried by the atmosphere. However, the heat carried by the Fram Strait inflow branch would be enough to melt 70% of the ice formed by the water vapor, if all heat went to ice melt. The oceanic heat transport, although being a small part in the meridional heat transport, is thus large enough to affect the ice cover in the Arctic Ocean.

The upper low salinity layer is in most parts of the Arctic Ocean supplied by river runoff and by the Pacific inflow and effectively isolates the Atlantic water below. The Nansen Basin is different. Here no river water is present and the Atlantic water entering through Fram Strait encounters and melts sea ice. This leads to the formation of a less saline upper layer comprising cooled Atlantic water and sea ice melt water. The observed salinity of this upper layer is higher than it would be, if all oceanic heat went to melting ice. Part of the heat is released to the atmosphere, and the hypothesis that the heat loss is distributed in such a way that sea ice melting is a minimum appears to well represent the observed upper salinity. A higher temperature of the Atlantic water leads to a less saline upper layer and a heat loss of about 60Wm^{-2} is needed for the upper layer to reach the freezing point. This corresponds to the cooling of a 60-100m thick Atlantic layer and the melting of 2-3 m of ice. A higher Atlantic water temperature leads to a thinner and less saline upper layer

To create the upper layer by ice melt and also supply the heat to the atmosphere the thickness of the ice cover should be ~0.5m. This implies that ice must continuously drift over the Atlantic water and melt. In a seasonally ice covered Arctic Ocean, would there be enough ice create the upper layer or will the ice disappear before the upper layer reaches the freezing point? If this happens, the buoyancy input from ice melt disappears and the upper layer only cools and becomes denser. This could lead to an overturning of the upper layer and deep convection in the Nansen Basin. The Nansen Basin will not produce less dense Polar surface water but instead modify the overflow water already formed in the Norwegian Sea. It will also create an area of open water, where heat is lost directly to the atmosphere that could seriously influence the atmospheric circulation.

This topic was followed by an overview of the impacts and changes of the freshwater in the Arctic Ocean **"Freshwater sources and the Mechanisms of Polar Surface Water and their prospects with loss of Summer Ice Cover"** given by **Tom Haine**. Several aspects were examined: First, the different sources and their expected change in a warmer climate scenario. Secondly, the outflows to the North Atlantic, how they are driven, by wind or by stratification and geostrophy, and how they might change in the future. Thirdly, the observed increased storage of freshwater in the Arctic Ocean, especially in the Beaufort Gyre, and its causes. Fourthly, the ice extent and the ice volume in the Arctic Ocean and how they have changed over the last decades. This led to a definition of a seasonal ice cover using the ratio of the seasonal ice thickness change to the perennial ice thickness. If this ratio is above one, we are in a seasonal ice cover regime. This change occurred already 5-10 years ago.

River runoff and net precipitation have been observed to increase, as is expected with a warmer climate, while no trend can be seen in the freshwater input through Bering Strait. An additional source of freshwater in the Arctic Ocean is the reduction of the ice cover suggesting more freshwater being stored and exported in liquid form. However, no clear deceasing trend in ice export has been reported. Furthermore, there is also no documented trend in the export of freshwater. The observed increased storage of freshwater should, if the outflow is controlled by stratification and geostrophy, lead to a larger freshwater export. This could either mean that stratification is not important for the freshwater export or that the atmospheric circulation collects the freshwater in the Beaufort Gyre and prevents it from reaching the outflow passages and increase the thickness of the freshwater layer there. Model studies indicate that the large scale wind fields and especially the different phases of the Arctic Oscillation could force increased and reduced outflows from the Arctic Ocean to the North Atlantic on time scales much shorter than the 10-15 years required for the geostrophic outflow to adjust to changes in the stratification and freshwater content.

John Toole addressed the **"Mixing and entrainment into the surface layer".** His introduction was done as a dialogue with the participants around the question: "Why do we care about mixing and entrainment into the surface layer?" Mixing is important for the ice-ocean heat flux and the sea ice balance. By controlling the depth and strength of the nutricline, it also affects the biological productivity. The response of the surface layer to wind stress depends on the layer thickness as well as on the presence of open water and the compactness of the ice cover. Spatial variations in forcing and thickness can lead to instabilities (eddies) and possibly to increased mixing.

One fundamental question was how the high latitude upper layer differs from those found at lower latitudes. The main difference is the presence of sea ice. This eliminates surface waves and wave generated mixing. The stress will be controlled by form drag and the movement of sea ice relative to water, which will depend upon the compactness of the ice cover. The buoyancy fluxes across the sea surface will be dominated by freshwater fluxes caused by freezing and melting rather than heating and cooling. The seasonal stability variations will be stronger and the stable upper layer in summer will be shallower. The presence of sea ice affects the penetration of light and through this the biological production. The closest parallel would be the barrier layers found in the equatorial latitudes. The absence of surface waves and the presence of sea ice will prevent Langmuir circulation, perhaps leading to less efficient vertical mixing close to the surface. The mesoscales will be closer to the sub-mesoscale at high latitudes. Density compensating temperature and salinity anomalies are also less frequently observed in high latitudes than in extra-polar latitudes. Nonlinearities in the equation of state are, by contrast, stronger at low temperatures and the heat expansion coefficient changes sign above the freezing point for $S<24.7$. New technological developments to study the mixing in the upper layer were also addressed. ITPs with velocity sensors (travel time), in addition to pressure, conductivity and temperature, have been introduced. The velocity relative to ice can then be determined, allowing for estimates of dissipation in the surface layer.

“The impact of sea ice retreat on shelf and shelf break mixing and exchange processes” was described by **Tom Rippeth**. He started by reviewing the coastal regions at temperate latitudes, where a balance often exists between the input of freshwater from runoff, heating and cooling at the surface, and wind as well as tidal mixing. Since diapycnal mixing raises the potential energy in the water column, a kinetic energy source is needed. Wind and tides are the two main energy sources, but only a fraction of the energy can be converted to potential energy, the rest is lost to dissipation. The canonical value is 20% but internal tides only convert 5.6% of the energy to potential energy, hydraulic jets <1% and the tidal bottom boundary layer only 0.004%.

How does sea ice affect the transfer of energy and momentum from tides and wind? What is the impact of sea ice on the energy cascade from large to small scales and how does this affect the mixing efficiency? Diapycnal mixing occurs at marginal stability, which can be estimated from the gradient Richardson number (Ri). Ri<0.25 for onset and Ri<1 for maintenance of turbulence. Within regions of strong vertical velocity gradients Ri~1 and close to mixing. Wind might generate inertial oscillation and the mixing level rises. The shear generated by inertia waves may be enhanced when the shear vector is aligned with the wind as is observed over the Laptev Sea. Mixing is also enhanced over rough topography. This could be due to formation and breaking of internal tides. The internal tides generated north of the critical latitud cannot propagate but have to dissipate close to their formation area. An ice free Arctic Ocean could lead to stronger generation of lee waves, but a new parameterization of wave propagation beyond the critical latitude (where the wave frequency is smaller than the inertia frequency) is needed.

Summary discussion of theme 1: “Processes in the Arctic Ocean”

Ice extent, thickness and volume have declined. The ice motion is speeding up and deformation has increased.

What else is changing?

Surface fluxes? Evaporation? (does it matter?) Increased precipitation (snow accumulation on ice)

Increasing cloudiness, which can affect albedo and the radiation balance?

Snow and melt ponds?

Wind and increased storminess?

Impacts of surface waves on sea ice cover?

T**heme 2: “The effects on biological processes and ecosystem”**

was introduce with the question: **“Will the Arctic Ocean primary production go up, stay the same or go down?”** posed by **Meibing Jin**. The overall hypothesis is that a declining will lead to more light reaching the ocean, increasing ocean temperature, and increasing the period of open water. All these changes favor an increased growth rate and growth area, earlier blooms and a prolonged growth season and thus act to increase the primary production. But they also open possibilities for changes in the species composition. The question was addressed using a coupled ice-ocean-ecosystem model (POP-CICE) forced with NCEP reanalysis data 1960-2009, and with primary production separated into ice algae production and open ocean production. The model indicated that while the ice area has diminished not just the open ocean but also the under ice (ice algae) primary production have increased. The timing of the ice algae production was, as expected, in April when the light returned, and the ice extent remained unaffected or showed a slight decrease. As the ice extent diminished the ice algae production decreased, being positive correlated with the ice extent. The open ocean production, by contrast, was negatively correlated to the ice extent and increased, while the ice cover became more reduced. The open ocean production was about 50 times larger than the sea ice production. Additional factors that may affect the productions are changes in nutrient supply, river input, and ocean mixing and circulation. The possible changes in these factors should also be taken into account when describing productivity changes in a warming Arctic.

The situation in the **“Marginal Ice Zone”** was addressed by **Ekaterina Popova**. The presentation focused on three questions: 1) Why are the marginal ice zones more productive? 2) Will a seasonal ice cover lead to a productive marginal ice zone propagating across the Arctic Ocean or is the initial nutrient storage too low?

3) How important are the existing regional differences in the upper layer for the production and will these differences remain? The questions were approached by examining the runs of a fully coupled ocean-ecosystem-carbon cycle model for the period 1860-2099 (RCP8.5). The model showed that the ice was almost gone by 2100.

The Marginal Ice Zone is defined as the area with 15-80% ice cover, and the maximum primary production is found in the upper layer of the Marginal Ice Zone extending to the sea surface, while under the more compact ice cover the maximum production is attached to the ice. In the open ocean beyond the Marginal Ice Zone the maximum production is located in a sub-surface layer. This situation is dependent upon the nutrient supply. With less nutrients available the productive layer is thinner and loses contact with the sea surface also in the Marginal Ice Zone and under the ice. With more nutrients the productive layer extends to the surface also beyond the Marginal Ice Zone. This indicates that the upper low salinity layer will be more rapidly nutrient depleted in the low nutrient case, less rapidly in the high nutrient case. The Marginal Ice Zone will with present nutrient supply remain more productive than the open ocean almost to the end of this century, when the productivities in open ocean and the in marginal Ice Zone converge. The answers to the second question will depend upon what happens to the Arctic Ocean nutrients, stratification and circulation. The answer to the third question is that the regional differences will remain because they are determined by the proximity to the inflows, which are generally more nutrient rich than the interior Arctic shelves and the Arctic deep basins.

"What will be the effects on the energy flow in the upper trophic levels?" was asked and described by **Carin Ashjian**. The effects are multifaceted and involve: 1) Loss of substrate, loss of ice algae, loss of habitats for ice obligate animals. 2) Changes in seasonality and growth season length. Changes in the range of organisms, advection and colonization. 3) Change in water column primary production. 4) Changes in the marine food web, dominant organisms, food web linkages, allocation of carbon, changes from benthos dominated to pelagic dominated eco systems and vice versa.

Decreasing sea ice might see increase in seasonally migrant species and depletion in ice-obligate species. Changes in seasonality might create a mismatch between the reproduction of Arctic species and the availability of food. Some species might adapt, other have to reduce their geographic distribution, or worse. Increased advection of species from lower latitudes, plankton (krill) as well as whales, could affect the ecosystem. For a species to become endemic it must survive and reproduce. A two degree temperature increase would largely increase the distribution of Arctic species from the shelves to the interior of the Arctic Ocean, while subarctic species could not make it into the Arctic with a 2 degrees temperature increase and/or a season lengthened by two weeks.

If the ecosystem is benthic or pelagic depends largely upon if the zooplankton in the water column can consume most of the primary production. In shallow areas with extensive ice cover like the Chukchi Sea or the northern Bering Sea much of the primary production sinks to the bottom, creating a benthic dominating ecosystem, feeding e.g. diving ducks and walruses. In the deeper and less ice covered southern Bering Sea and in the Barents Sea the zooplankton consume most of the primary production and can support e.g. a larger fish stock. In the deep Arctic Basins the zooplankton abundance is presently dominated by small species, while the zooplankton mass is dominated by large species. Will this change with changing ice conditions?

Summary discussion theme 2: "The effects of biological processes and ecosystems"

Deformation of sea ice as well as changes in snow cover increase changes in ice algae community. Ice algae will not affect albedo unless the ice is turned upside down.

Release of condensation nuclei to the atmosphere could change, and aerosol particles can lead to clouds and fog. Gas fluxes through the ice take place in winter, but the gas exchange would increase with more open water.

Sea salt might act as a cloud condensation nuclei and sea ice might emit more salt into the air than open water.

There is a seasonal cycle in aerosols. Arctic haze is the largest aerosol. It is man-made and accumulates during the polar night and then burns off. Unclear how much long-range transport dominates over locally formed aerosols.

Theme 3: "Connections with lower latitudes"

The second day started with the question: **"Why do we have Arctic (Polar) amplification?"** asked by **Klaus Dethloff**. The Polar amplifiers of climate change are: ice and snow albedo, clouds and water vapor, carbon and methane, aerosols and black carbon, and stratospheric ozone. Polar amplification also appears to be linked with cooling in the interior of the mid-latitude continents, especially in Siberia. In summer the major change is associated with the net incoming short-wave radiation, which has increased by 12 Wm^{-2}/decade. This is primarily connected with the reduction of the ice cover and the surface albedo. In winter, when no solar radiation is present, the main increase is due to less outgoing long-wave radiation, which is mainly caused by higher humidity, more clouds and inversion layers. The heating trend is, however, significantly less, 4 Wm^{-2}/decade, and not really significant.

There is an increased poleward heat and moisture transport by the atmosphere in winter. The Arctic amplification in winter is also associated with cold mid-latitude winters. Low sea ice condition in autumn, due to the additional heat stored in the ocean, leads to higher surface temperature the following seasons, causing reduced atmospheric vertical stability and amplified baroclinic weather systems. This baroclinic Arctic response can impact the planetary wave propagation in winter and initiate negative NAO/AO phases and weaken the stratospheric Polar vortex. This large-scale barotropic response can enhance the probability of cold winters over Eurasia. The vertical heat flux into the stratosphere occurs through Eliasen-Palm fluxes initiated by the low ice conditions. This also leads to changes in the stratospheric vortex, which becomes less confined and large amplitude waves can penetrate to lower latitudes and create blocking situations. Finally also coupled atmosphere-ice-ocean feedbacks and decadal changes were examined using model runs, and additional drivers such ENSO, aerosols and vegetation effects were discussed.

The **"Driving mechanisms and constraints for the exchange flow through Fram Strait"** were examined by **Larry Pratt**. The presentation focused on two questions: 1) "Does the Fram Strait constrain the exchanges between the Arctic Ocean and the Nordic Seas in some manner?" with the tentative answer: Yes and No. and 2) "What drives the flow of Atlantic water through Fram Strait: wind or buoyancy?" and the answer is: We don't know.

Fram Strait has the largest exchange flow in the world and the passage is wide enough not to constrict the exchanges. The inflow takes place in the West Spitsbergen current and is ~6.5Sv of which 50% is warmer than 2^{o}C. There are two cores, one inner core close to Svalbard that is more or less steady throughout the year carrying 1.3Sv warmer than 2^{o}C. The outer core is more seasonally variable but transports about the same amount of warm Atlantic water. The strait is also filled with quasibarotropic eddies with a horizontal scale of ~10km. Simple models of the Fram Strait exchanges have been examined using lock exchange theory and laboratory experiments. The flow can then be described by geostrophy and be determined by the depth of the upper layer and the density difference between the layers. This leads to exchanges between 1.6Sv and 4.2Sv. Fram Strait is too wide to choke any baroclinic flow but a barotropic component could be reflected and propagate back to the strait.

Topographic steering is probably important, with the flow following the f/H contours. A geostrophic flow in the Arctic Ocean can be based on circulation integrals along closed bathymetric contours. The area integrated wind forcing has to balance the bottom dissipation along the circulation path. An extension of this approach is to use the Island Rule, which in the context of the Arctic Ocean says that to conserve potential vorticity and under the assumption that the relative vorticity is small, the advected vorticity is determined by the latitudes of the inflow and outflow passages. If these latitudes are different either bottom friction or the wind field has to change the vorticity to balance the difference. An overall cyclonic flow is found for the average wind stress, but there are large differences in how the flows are distributed for high and low Arctic Oscillation indexes. Since the Atlantic water cools and becomes denser in the Nordic Seas as well as in the Arctic Ocean buoyancy forcing may also affect the exchanges through Fram Strait as well as the overflow of the Greenland-Scotland Ridge further to the south. This might add to the wind driven exchanges.

No conclusions were reached but some outstanding questions were identified: 1) Why is the inshore core of the West Spitsbergen Current less variable than the offshore core? 2) Implications of the disappearance of sea ice for the circulation integral? 3) More complete formulations of circulation integrals as diagnostics. 4) Comparison with the Gulf of Mexico Loop Current might be informative.

The **"Fate of the Atlantic water in the Arctic Ocean"** was explored by **Mike Spall**, who showed the distribution of the Atlantic water as well as the Polar mixed layer, halocline waters and deep water in the different basins of the Arctic Ocean. The Atlantic water enters trough Fram Strait (~3Sv) and the Barents Sea (~2Sv) and circulates as a boundary current around the Arctic Ocean. Individual gyres are formed in the different basins, which become filled with Atlantic water. One stream of the Fram Strait inflow circulates around the Yermak Plateau and one stream follows the shelf break directly north of Svalbard. The two streams meet east of Svalbard and flow together as a boundary current along the slope. The deep isopycnals slope upwards, away from the slope, the shallow isopycnals downwards, indicating the weaker stratification in the Atlantic core compared to the interior of the Nansen Basin. Anticyclonic eddies are observed separating from the boundary current.

East of St. Anna Trough the Barents Sea inflow branch enters the Arctic Oceana and flows along but higher up on the slope than the Fram Strait branch. The Barents Sea branch is generally colder and less saline and spans a larger density range than the Fram Strait branch. Inversions and interleaving indicate strong mixing between the branches north of Severnaya Zemlya. Mooring data from the continental slope in the Eurasian Basin also show strong mesoscale variability with both shallow and deep eddies with azimuthal velocities of about 20 cm/s. Direct current observations also indicate a branching of the Atlantic water near the Lomonosov Ridge with half, ~3Sv, of mainly Barents Sea branch water moving into the Amerasian Basin and the rest, mostly Fram Strait branch water, remaining in the Eurasian Basin. In the Nansen Basin the Atlantic water loses heat to the atmosphere and to ice melt close to Fram Strait. After the low salinity upper layer is formed, the mechanisms driving the heat flux from the Atlantic water to the mixed layer and eventually to the ice and atmosphere are more difficult to determine, but a combination of double-diffusive fluxes through diffusive interfaces and haline convection in the mixed layer is conceivable.

The Atlantic water continues cyclonically around the Amerasian Basin following a complex pathway along the topography. Spatial variability arises from a combination of advected transients and local mixing. The presence of inversions in the Atlantic core suggests that double-diffusively driven interleaving might be active. Mooring observations also show that eddies are present, enhancing the mixing. Eddies are observed both in the upper and lower halocline and in the deep layers. No estimates of the life time of eddies are, however, available. Warm Atlantic water eddies could lose heat upwards through double-diffusion but the implied fluxes ~$0.2Wm^{-2}$ are an order of magnitude less than the heat flux to the ice and it would take >50 years to remove a $0.5^{o}C$ anomaly, suggesting that lateral mixing is a more likely processes to remove eddies. As the Atlantic water moves along the slope the isopycnals slope down, into the basin, indicating that the Atlantic water located higher in the water column at the slope is denser than the water s in the basin interior. Observations also show that the Atlantic water upwells onto the Chukchi shelf at strong wind events. This and subsequent mixing could be an important process in modifying the Atlantic water.

Observations of heat and salt fluxes into and out of the Arctic Ocean show that the Atlantic water gets colder and fresher. Immediately downstream of Fram Strait there is no halocline and most heat is lost directly to the atmosphere and to sea ice melt. The Atlantic water loses heat and becomes fresher in the Barents Sea. Beyond the Laptev Sea low salinity shelf water input isolates the Atlantic water from the ice and the atmosphere and the properties of the Atlantic water change more slowly. Eddies or interleaving intrusions spread Atlantic water from the boundary into the interior and wind-driven upwelling can bring Atlantic water onto the slope and shelf, leading to mixing, ice melt and heat loss.

Is the Atlantic water pushed or pulled into the Arctic Ocean? The mixing and the circulation of Atlantic water are likely not independent of each other. The circulation of the Atlantic water in the Canada and the inflow through Fram Strait might thus depend on the strength of the diapycnal mixing. Another possibility is

that the Potential Vorticity of the inflow and outflow determines the path of the Atlantic water so that the Potential Vorticity balance is maintained. A further scheme would be a balance between interior diapycnal mixing and lateral eddy fluxes from the boundary into the interior. In the last case the transport of the Atlantic water in the boundary current is driven by a deepening of the halocline from the boundary to the interior via the thermal wind equation. The balance between eddies and diffusion then controls both the halocline and the circulation of the Atlantic water. *In this case the Atlantic water is pulled into the Arctic Ocean*.
Major open questions for the current state of the Arctic
We do not have a (good) theory for the general circulation of the Arctic Ocean.
What determines the transports through Fram Strait and Barents Sea?
Why does the Atlantic water recirculate in the Eurasian Basin?
What controls the circulation of the Atlantic water in the Canada Basin?
Where is the heat lost from the Atlantic water? To ice melt? To the atmosphere? Through mixing with other water masses?
Where and how does the Atlantic water get mixed?
Major open questions for an ice free Arctic Ocean
Will the flux of Atlantic water increase or decrease?
Will there be an enhanced heat flux to the atmosphere and potential for positive feedback (warmer atmosphere, less ice)?
Will there be an increase in mixing between Atlantic water and the halocline as a result of less ice cover and more penetration of wind-driven energy for mixing? less because of ice melt?

Summary discussion Theme 3: "Connections with lower latitudes"
"Will exchanges with lower latitudes become different?" and "Will the impact on lower latitudes change?"
Atmosphere: Mid-latitude impacts; reduced temperature gradients → reduced Rossby wave propagation speed → more persistent weather situations (blocking high) → floods and droughts.
Ocean & ice: Warming implies a faster hydrological cycle → larger freshwater input to the Arctic → increased river runoff → cannot be stored in the Arctic Ocean forever → increased freshwater export → possible impacts on the Atlantic meridional circulation. Removal of sea ice could change the circulation. Could the Arctic Ocean become saltier? An additional freshwater source exists due to increased melting of the Greenland ice sheet.
Biogeochemical and ecological impacts: Freshwater impact on timing of the spring bloom. Invasion of species from the North Pacific to the North Atlantic?

Theme four: "How to proceed"
was first addressed by **Andrey Proshutinsky**, who examined : **"What observational strategies are needed to answer these questions?"**. He concentrated on two major topics: 1) Climate studies. In a time of rapid change in the Arctic Ocean a sustained environmental Arctic monitoring system targeted to address specific questions about climate and its changes is required. The traditional approach of acquiring observation when and where the Arctic is accessible (e.g. ice breaker expeditions in summer and aircrafts in spring) has to be enhanced automatic systems operating around the year, providing observations to shore in real time. 2) The data collection by the traditional expeditions designed for specific process studies are still essential but should be complemented by the automated observing systems. It is necessary to maximize observational capabilities both in the marginal/seasonal ice zones and in the year-round pack ice for studies under, in and over the ice. Many new tools are now available, ice tethered platforms, bottom moored profiling ctds and current meters, pressure gauges and sea level recorders, the possibility to extend the ARGO system into the Arctic Ocean, satellite altimetry and satellite gravity (GRACE). Finally a hierarchy of models must be developed to understand the processes over a wide range of time and space scales.

"Modelling requirements for studying Arctic physical and biogeochemical states and interaction" were discussed by **Wieslaw Maslowski**. He started by identifying the physical processes that are critical for the

Arctic marine biogeochemical states. The major factors are nutrient transports, light availability and ocean stratification, which depend upon: – mesoscale eddies, upwelling/downwelling – surface/bottom mixed layer dynamics – ocean coastal and boundary currents – sea ice cover with snow and meltponds – marginal ice zone including ice edge upwelling – river runoff (buoyancy and biogeochemical fluxes) – upper ocean (above halocline) stratification – upper ocean heat and freshwater content.

The coastal currents are important but climate models cannot resolve them. The upper ocean heat content is important. Climate models do not reproduce the subsurface maximum in temperature. Better resolution is needed. The Regional Arctic System Model (RASM) has either 9 km or 2.4 km resolution and provides sufficient structure both of both velocity and eddy kinetic energy content. However, there is a need to close the volume transport budget. The models do so (they have to) but the observations do not. Still, the models need to be constrained by observations, e.g. ice extent, ice volume.

Possible evaluation metrics for Polar models should consider: 1) Observations currently do not close surface energy/ lateral volume budgets of the Arctic. 2) State variable may be "correct", though different terms in the model energy budget have opposing errors. 3) Fully coupled polar models are strongly dependent upon variability and sensitivities deriving from feedbacks (e.g. surface radiative feedbacks). 4) There is a need for evaluating metrics that target constraining sign and magnitude of key feedbacks in the Arctic system. 5) This requires constraining energy terms rather than state variables.

Discussion: "Future observational and modelling efforts"

Classical hydrography is still valuable. There is a need to look into the overturning circulation in temperature and salinity space both to identify processes and to evaluate the process parameterizations in the models.

Three ways to observe the Arctic: 1) Expeditions, one or repeated. 2) Process studies. 3) Sustained large-scale observations. These are related but independent approaches.

How is the Arctic Ocean working today? More information is needed about: 1) mixing, 2) stirring, 3) atmospheric radiation, 4) clouds, 6) biological and chemical parameters, 7) ice thickness, 8) flux divergences (in both atmosphere and ocean), 9) heat uptake and storage by the ocean should be measured.

Observational requirements: Need for another SHEBA? MOSAiC effort should provide this. The existing network should be maintained and multiple observatories be added. LIDAR on buoys and an automated radiosonde program. Autonomous aircrafts are also a possibility as is the extension of the ARGO program under ice into the Arctic Ocean.

Logistic is challenging and international cooperation and collaboration are beneficial and perhaps essential. Large scale successful technologies and cooperation are ARGO, Satellite observations, climate models.

A break in the workshop was made toallow for the participants to move to the Clark building to attend the **WHOI Physical Oceanography Seminar: "Forced transient in the Meridional Overturning Circulation"** given by **Mike Spall.**

Summary: What to do next

The summary statement was very short. The main purpose of this workshop has been to sustain old and initiate new cooperation and network, and to advertise and stimulate participation in the upcoming ICARPIII conference in Toyama 2015.

Appendix a: Rationale of the workshop

The ice cover in the Arctic Ocean has gradually diminished during recent decades. The minimum ice extent in fall has decreased and the mean thickness has been reduced. Climate models also show that the arrival of a seasonal ice cover could occur by mid-century, perhaps earlier. Whether the present trend is irreversible or not, the fact remains that an almost ice free Arctic Ocean is a real possibility in a not too distant future. How would this change the physical processes active in the Arctic Ocean and the interactions with sea ice and the atmosphere? What would be the effects of ocean acidification, caused by uptake of CO_2, on the biological communities and on the ecology of the Arctic Ocean?

Some changes have not yet happened, and may not even take place. However, when considering research priorities in the Arctic extending ten years into the future, the moment, when the climate projections indicate a possible change to a seasonal ice cover, comes uncomfortably close. It might therefore well be worth to seriously address such questions as: What will change, and how, and what will essentially remain the same? The proposal is focussed on the ocean and on ocean processes, but interaction with sea ice and the atmosphere as well as causes and consequences of a changed radiation balance will be essential parts in the analysis.

The key parameter dominating the processes in the Arctic Ocean is the stability. It is caused by the net precipitation and the excessive continental runoff occurring in the Arctic, and it is the reason why the Actic Ocean is permanently ice covered. The stratification limits the vertical mixing depth in winter and the upper layer is cooled to freezing temperature and heat advected from lower latitudes becomes isolated from the sea ice and the atmosphere in most part of the Arctic Ocean.

An open Arctic Ocean allows for more wind mixing and wave breaking in the surface layer than in an ice covered ocean. However, a looser ice cover with ice keels present could transfer a substantial amount of wind energy into the ocean and the optimal state for transferring kinetic energy from the atmosphere to the ocean is not necessarily one without sea ice. Furthermore, the melting of ice will increase the stratification and the advected heat stored in the Atlantic layer might well be as inaccessible as today.

The annual freezing and melting cycle is expected to increase, more ice is formed in the open water in winter and more is melted in summer. It is an open question, if the increased freezing might, at least locally, compensate for the larger amount of freshwater in the upper layer and allow for increased ventilation of the deeper layer, or if these layers will become even more isolated. The ice growth will involve more frazil and less columnar ice, becoming more like the Southern Ocean.

The increased open water affects the albedo, making the surface water warmer and increases the evaporation, thus raising the water vapour and freshwater contents in the atmosphere. This leads to trapping of heat radiated from the ocean and a larger long-wave back radiation from the atmosphere to the sea surface, further increasing the temperature. A more compact cloud cover could, at least in principle, increase the albedo and partly compensate for the loss of sea ice, but are the clouds high enough, or will the effect on the long-wave back radiation dominate?

The increased water content in the atmosphere is likely to cause heavier snowfall in winter, which might lead to higher albedo in spring and the early part of summer before the ice disappears. The increased sensible heat loss and evaporation and the subsequent condensation in the atmosphere will promote a more energetic, locally driven atmospheric circulation in the Arctic.

The diminished Arctic Ocean ice cover is usually considered a consequence of the present increase in greenhouse gases in the atmosphere. How will the uptake of CO_2 in the Arctic Ocean, presently a net sink for CO_2, change when the ice cover is seasonal? Will the uptake be reduced by the warmer surface water or increased by the larger area of open water? If the production of dense water in winter increases, will this be connected with a transfer of more CO_2 into the deep Arctic Ocean? The CO_2 uptake in the Arctic Ocean is double-edged. An increased CO_2 concentration in the ocean will lead to stronger acidification. A situation that already is critical for the marine life in the Arctic Ocean.

The biology and ecology of the Arctic Ocean will be seriously affected. The increased stratification in summer is likely to inhibit nutrient supply from below and thus reduce the production in spite of stronger mixing and more light being available. Will the production be concentrated to continental slopes and topographic features, where enhanced vertical mixing is present? What will be the effects on ice algae and the communities thriving in the ice, when they cannot retain their habitats over summer?

The workshop aims at identifying and evaluating the likelihood and the effects of these, and other, changes that might occur. It will also confront the issues why and when the Arctic Ocean might become ice free in summer, and if it does, under what circumstances can it revert back to an permanently ice covered ocean (multiple equilibria).

Appendix b: participants

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appendix c: program

Towards a seasonal ice covered Arctic Ocean

An IASC workshop in the Carriage House at Woods Hole Oceanographic Institution, 20/10-21/10, 2014.
Arranged by Bert Rudels, Andrey Proshutinsky, Mike Spall and Tom Haine
Co-sponsored by WHOI, FMI and NACLIM (EU programme No: 308299)

Monday 20/10
7:45 *Bus from Falmouth to the Carriage House. Coffee and refreshment available at the CH*

8:30 to 12;15 Processes in the Arctic Ocean. Chair: Mike Spall
8:30-8:45 Presentation of the workshop
Bert Rudels

8:45-9:30 Why do we have an ice cover in the Arctic Ocean and what could a change to a seasonal ice cover imply?
Introduction: Bert Rudels 15-20 minutes for questions and discussion

9:30-10:15 Freshwater Sources and Mechanisms of Polar Surface Water, and their Prospects with Loss of Summer Ice Cover
Introduction: Tom Haine 15-20 minutes for questions and discussion

10:15-10:45 *Coffee*

10:45-11:30 Mixing and entrainment into the surface layer
Introduction: John Toole 15-20 minutes for questions and discussion

11:30-1215 Impact of sea ice retreat on shelf and shelf break mixing and exchange processes.
Introduction: Tom Rippeth 15-20 minutes for questions and discussion

12:15-13:45 *Lunch provided at the Buttery. Mention IASC workshop*

13:45-14:30 Discussion Will there be changes in the dominant physical processes?
Discussion Leaders: Daniel Feltham, Laurie Padman, Benjamin Rabe

14:30 to 18:00 Effects on biological processes and ecosystems Chair: Bert Rudels
14:30-15:15 Will the Arctic primary productivity go up, stay the same or go down?
Introduction; Meibing Jin 15-20 minutes for questions and discussion

15:15-15:45 *Coffee*

15:45-16:30 Why are the marginal ice zones more productive?
Introduction: Ekaterina Popova 15-20 minutes for questions and discussion

16:30-17:15 What will be the effects of the energy flow in the upper trophic level?
Introduction: Carin Ashjian 15-20 minutes for questions and discussion

17:15-18:00 Discussion Possible Impacts on biology, productivity and ecosystems
Discussion Leaders: Patricia Matrai, Nicole Jeffery

18:00 *Bus to Falmouth*

Tuesday 21/107
7:45 *Bus from Falmouth to the Carriage House Coffee and some food available at the CH*

Connection with the lower latitudes. Chair: Benjamin Rabe
8:30-9:15 Why do we have Polar (Arctic) amplification?
Introduction: Klaus Dethloff 15-20 minutes for questions and discussion

9:15-10:00 Driving mechanisms and constraints for the exchange flow through Fram Strait.
Introduction: Larry Pratt 15-20 minutes for questions and discussion

10:00-10:30 *Coffee*

10:30-11:15 Fate of the Atlantic water in the Arctic Ocean.
Introduction: Mike Spall 15-20 minutes for questions and discussion

11:15-12:00 Discussion Will the exchanges with lower latitudes become different?
Discussion Leaders: Sheldon Bacon, Bert Rudels

12:00-13:15 *Lunch provided at the Buttery. Mention IASC workshop*

13:15 to 14:45 How to proceed? Chair Steffen Olsen
13:15-14:00 What observational strategies are needed to answer these questions?
Introduction: Andrey Proshutinsky 15-20 minutes for questions and discussion

14:00-14:45 Modeling requirements for studying Arctic physical and biogeochemical states and interaction.
Introduction: Wieslaw Maslowski 15-20 minutes for questions and discussion

15:00-16:00 WHOI Physical Oceanography seminar
Forced transients in the Meridional Overturning Circulation.
Mike Spall

16:00-16:30 *Coffee (the Carriage House)*

16:30-17:00 Discussion Future observational and modelling efforts.
Discussion Leaders: Peter Rhines, John Toole

17:00-18:00 Summary of the workshop. What to do next?

18:00 *Bus to Falmouth*