ICARP II – SCIENCE PLAN 7

TERRESTRIAL CRYOSPHERIC & HYDROLOGIC PROCESSES AND SYSTEMS

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PREFACE

The Second International Conference on Arctic Research Planning (ICARP II) was held in Copenhagen, Denmark from 10 November through 12 November 2005 and brought together over 450 scientists, policy makers, research managers, indigenous peoples, and others interested in and concerned about the future of arctic research. Through plenary sessions, breakout sessions and informal discussions, conference participants addressed long-term research planning challenges documented in twelve draft research plans. Following the conference drafting groups modified the plans to reflect input from the conference discussions and input from the ICARP II web site. This science plan is the culmination of the process.

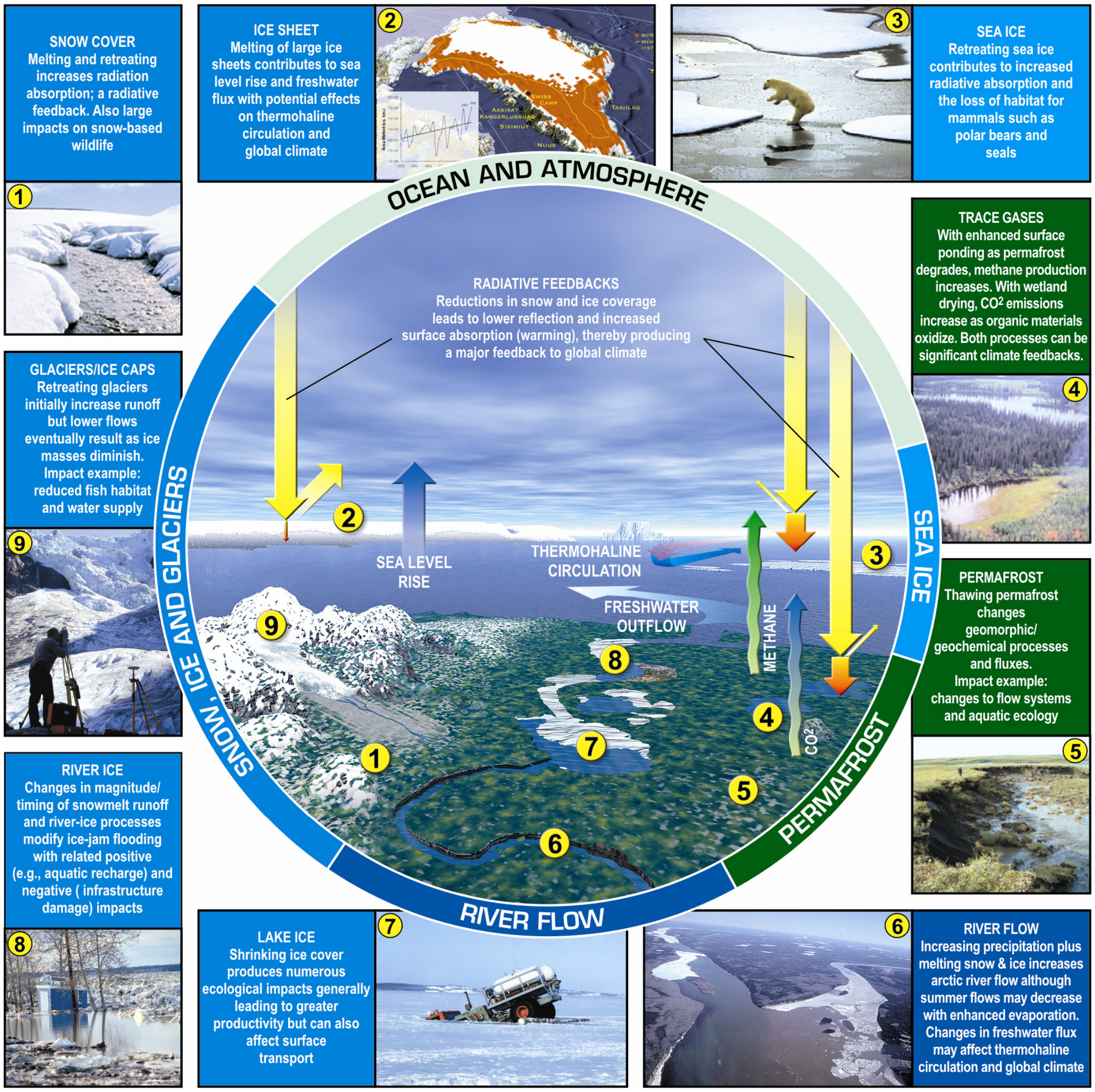
ICARP II Science Plans

Science Plan 1	Arctic Economies and Sustainable Development
Science Plan 2	Indigenous Peoples and Change in the Arctic: Adaptation, Adjustment and Empowerment
Science Plan 3	Arctic Coastal Processes
Science Plan 4	Deep Central Basin of the Arctic Ocean
Science Plan 5	Arctic Margins and Gateways
Science Plan 6	Arctic Shelf Seas
Science Plan 7	Terrestrial Cryospheric & Hydrologic Processes and Systems
Science Plan 8	Terrestrial and Freshwater Biosphere and Biodiversity
Science Plan 9	Modeling and Predicting Arctic Weather and Climate
Science Plan 10	A Research Plan for the Study of Rapid Change, Resilience and Vulnerability in Social-Ecological Systems of the Arctic
Science Plan 11	Arctic Science in the Public Interest
Background Document	Contaminants

7.1. Introduction

International scientific consensus is building that the Arctic is moving towards a new seasonally ice-free state (e.g., Overpeck et al., 2005) accompanied by major intra-arctic changes to bio-geophysical and socio-economic systems of special importance to northern residents and also producing some extra-arctic effects that will have global consequences (e.g., ACIA, 2005; AHDR, 2004; Figure 7.1). Pivotal to such changes are the terrestrial cryospheric and hydrologic processes and systems. These can play multiple and synergistic roles in the Arctic, ranging from the control of biodiversity and productivity that sustains traditional lifestyles and supports commercial production, to the generation of major feedbacks that affect arctic and global climate.

The cryosphere is an especially important part of the global climate system. It is strongly influenced by temperature, solar radiation and precipitation, and, in turn, influences each of these properties. It also has an effect on the exchange of heat and moisture between the earth's surface and the atmosphere, on clouds, hydrologic processes (e.g., river flow), and atmospheric and oceanic



SNOW COVER
Melting and retreating increases radiation absorption; a radiative feedback. Also large impacts on snow-based wildlife

ICE SHEET
Melting of large ice sheets contributes to sea level rise and freshwater flux with potential effects on thermohaline circulation and global climate

SEA ICE
Retreating sea ice contributes to increased radiative absorption and the loss of habitat for mammals such as polar bears and seals

TRACE GASES
With enhanced surface ponding as permafrost degrades, methane production increases. With wetland drying, CO^2 emissions increase as organic materials oxidize. Both processes can be significant climate feedbacks.

RADIATIVE FEEDBACKS
Reductions in snow and ice coverage leads to lower reflection and increased surface absorption (warming), thereby producing a major feedback to global climate

GLACIERS/ICE CAPS
Retreating glaciers initially increase runoff but lower flows eventually result as ice masses diminish. Impact example: reduced fish habitat and water supply

PERMAFROST
Thawing permafrost changes geomorphic/ geochemical processes and fluxes. Impact example: changes to flow systems and aquatic ecology

RIVER ICE
Changes in magnitude/ timing of snowmelt runoff and river-ice processes modify ice-jam flooding with related positive (e.g., aquatic recharge) and negative (infrastructure damage) impacts

LAKE ICE
Shrinking ice cover produces numerous ecological impacts generally leading to greater productivity but can also affect surface transport

RIVER FLOW
Increasing precipitation plus melting snow & ice increases arctic river flow although summer flows may decrease with enhanced evaporation. Changes in freshwater flux may affect thermohaline circulation and global climate

Figure 7.1. Examples of major climate feedbacks and bio-geophysical impacts resulting from major changes to cryospheric and hydrologic processes and systems in the Arctic.

circulation. Since parts of the hydrologic and cryospheric systems are strongly influenced by changes in the global climate system, they may therefore act as early indicators of both natural and human-induced climate change. Moreover, because of the explicit changes that occur in cryosphere elements when they are near the 0 °C point of phase change (freezing/melting), they are relatively easily monitored for climate-change detection. The cryosphere also responds strongly to climate change over a wide range of timescales. Components such as snow cover, freshwater ice, sea ice, and thaw depth in frozen ground respond to seasonal forcing while glaciers respond on decadal to centennial timescales and permafrost and ice sheets on centennial to millennial timescales.

Significant changes have been observed in hydrologic and cryospheric systems, particularly over the last half-century, and more pronounced changes are forecast as climate changes as a result of global greenhouse gas emissions (e.g., Arnell, 2005; Walsh et al., 2005; Wrona et al., 2005). This report details a research plan that focuses on the most significant issues about changing arctic hydrologic and cryospheric systems as determined by their potential to affect aquatic, climatic, and human systems. Moreover, the proposed plan attempts to generate synergistic benefits from the potential integration and orchestration of a number of essentially disparate scientific efforts that are ongoing or that will soon be initiated in the Arctic.

7.2. Focus

As the arctic system moves towards a new state, concern has been expressed about how changing cryospheric/hydrologic systems will affect:

i. major global climate feedbacks;
ii. biological productivity and biodiversity; and
iii. human and economic systems.

In reference to (i), the supply of freshwater to the Arctic Ocean is known to affect ocean salinity/sea-ice production and thereby radiative feedbacks, ocean circulation and biogeochemistry, and perhaps most importantly, the export of freshwater from the Arctic Ocean to the North Atlantic, where it can affect the intensity of thermohaline circulation and consequently global climate. Future major losses of cryospheric storage from arctic glaciers and ice caps, most notably from the Greenland Ice Sheet (Gregory et al., 2004), will contribute significantly to these freshwater flows and play a major role in the rise of sea level, which will have both substantial intra- and extra-arctic effects. The focus of this aspect of the research plan will be to provide an integrated assessment of freshwater fluxes to the Arctic Ocean from both rivers and melting cryospheric components. Because there is considerable ongoing work in this field from a variety of separate and somewhat unconnected research initiatives, part of the plan will be focused on achieving international collaborative integration, preferably under the auspices of an international scientific body such as the World Climate Research Programme (WCRP) Climate and Cryosphere Project (CliC; similarly for items ii and iii below).

In reference to (ii), the biological productivity and biodiversity of terrestrial and aquatic ecosystems are strongly influenced by terrestrial cryospheric and freshwater systems. For example, changes in precipitation and evaporation affect soil moisture and thereby plant succession, and changes in freshwater ice-cover thickness/composition influence water-level and radiation budgets of aquatic systems that in turn directly control productivity and biodiversity. Furthermore, geochemical processing and nutrient supplies to both fresh and marine aquatic habitats depend on freshwater fluxes that can be significantly altered by permafrost degradation. Shifts in terrestrial vegetation brought about by changes in snow cover, soil moisture and permafrost conditions will have a marked effect on radiation budgets, such as when tundra is replaced by more woody species (e.g., as currently occurring in northern Alaska and elsewhere as permafrost thins and thermokarst evolution modifies surface soil and water storage conditions). Changes to aquatic productivity will also have a major effect on northern peoples whose economy and/or culture rely on, for example, small aquatic mammals and freshwater fisheries. Two distinct research foci will be generated for this component. The first will assess the state of soil moisture conditions under changing climate and cryospheric (snow and permafrost) conditions. This part of the research plan also links to ICARP II Science Plan 8, which requires information about soil moisture conditions to assess vegetative response and succession and bio-feedbacks to the atmosphere (e.g., ACIA, 2005; Callaghan et al., 2004). The second focus will be on generating freshwater ice-growth models for arctic lakes that are able to predict changes in ice cover thickness and composition (the latter being strongly modified by changes in snow cover). This part of the research plan links strongly to the needs of ICARP II Science Plan 8 that requires information about freshwater ice cover given that it so strongly affects aquatic productivity (e.g., ACIA, 2005; Wrona et al., 2005).

In reference to (iii), terrestrial, arctic freshwater systems are characterized by extreme events, such as floods and droughts that are predicted to occur more frequently with climate change (Walsh et al., 2005; Wrona et al., 2005). Extreme flood events, driven commonly by spring snowmelt runoff and related ice jams, are of major concern in northern latitudes because of the preponderance of communities that are located along river edges and the huge economic impact such events can create on development infrastructure (the catastrophic ice-jam floods along the Lena River in spring 2001 being one recent example). Notably, however, spring floods created by ice jams have also recently been shown to be of critical importance to the ecosystem health of high-latitude rivers, particularly deltas, which are some of the most biologically productive areas in the North. The focus of this part of the research plan will be on producing river-ice break-up and ice-jam models for northern rivers that are capable of predicting conditions under different spring-runoff conditions, such as are forecast to occur with alterations to other cryospheric components (snow and permafrost), which are the focus of the river component as outlined in (i) above. Figure 7.2 shows a typical case where backwater from river ice produces extreme water levels under relatively low river discharge.

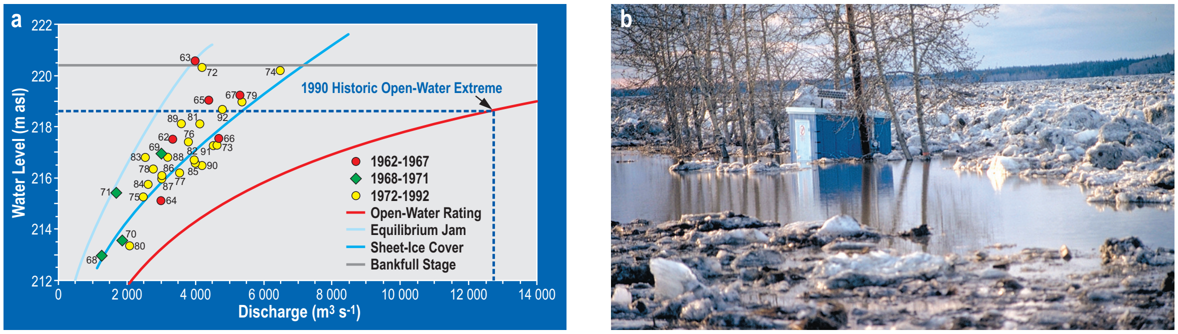


Figure 7.2. (a) Example of ice- (upper curved line) and open-water (lower-curved line) rating curves for a northern ice-covered river. (b) Dots and years indicate ice-induced extreme flood events, which produce water levels far higher than those for equivalent discharge under open-water conditions. Such spring extreme events are typical for large arctic rivers forming a major hazard to northern communities but are also essential to sustaining healthy aquatic ecosystems (from Prowse et al., 2002).

7.3. Key Scientific Questions

7.3.1. Broad Scientific Questions

How will ongoing and predicted future changes to the inter-annual variability of arctic terrestrial cryospheric and hydrologic processes affect global and regional feedbacks to the climate system (e.g., radiative feedbacks and feedbacks via the thermohaline circulation), and global sea level? This includes, for example, space-time variability in albedo of cryospheric components, snow-cover extent, thawing of ice-rich permafrost, lake/river/wetland ice-covers, glaciers/ice caps and the Greenland Ice Sheet, geomorphic processes, soil moisture, and freshwater fluxes.

How will ongoing and predicted future changes in the cryospheric and hydrologic systems affect terrestrial and freshwater aquatic ecosystem productivity and biodiversity? This includes, for example, soil moisture (especially in terms of vegetation succession), freshwater ice cover (timing, duration and composition), wetland-peatland water levels (magnitude and seasonality; especially in terms of trace gas fluxes), permafrost-controlled groundwater circulation, sediment production and transfer, and snow cover (structure and depth for mammals).

How will ongoing and predicted future changes in the hydrologic system impact humans? This includes, for example, changes in the dynamics and properties of freshwater ice (timing, duration, composition, e.g., effects on transportation), river flow and water storage components (timing, seasonality, extremes: floods and low flows; e.g., generation of hazards and limitations on water supply), rainfall and snow cover (extent, duration, depth and structure) and permafrost dynamics (active layer depth, geomorphic processes, thaw settlement-thermokarst; e.g., implications for water access and development).

7.3.2. Specific Questions

1. What are the main climatic and landscape controls on the volume and timing of arctic discharge; how do these controls vary across the pan-arctic domain, and how will they be affected by future climate change? How do hydrologic characteristics (volume, timing, and extremes) of arctic river discharge affect biogeochemical fluxes (including water temperature)? What changes in the dynamics of hydrologic processes are most likely to pose threats to the availability of water for northern residents?

2. What are the effects of climate variability and change on spatial and temporal variation in snow cover that are known to affect radiative and trace gas feedbacks to the climate system, runoff seasonality, permafrost, winter biological habitat, geomorphic changes and biogeochemical processes?

3. What are the effects of climate variability and change on permafrost properties and extent that are known to be important in affecting the variability, magnitude, and composition of trace-gas fluxes to the atmosphere? What ecological and geomorphic changes occur in association with degradation of ice-rich permafrost and how do these influence hydrologic processes?

4. How will seasonal soil moisture regimes in permafrost and seasonally frozen environments respond to variability in hydro-climatic conditions, and what will be the implications of these for terrestrial runoff, geomorphic processes, and biogeochemical fluxes?

5. How are freshwater fluxes from glacier masses in the pan-Arctic changing? To what extent do factors other than climate affect volume/geometry changes? What will be the future sensitivity of glacier masses to climate change variability? How can increased melting trigger changes in glacier dynamics? How are dynamic changes currently observed at several Greenland outlet glaciers related to climate change variability?

6. What changes in the characteristics of lake and river-ice covers result from variations in climate that are important to radiative feedbacks, aquatic productivity, geochemical fluxes during the spring freshet, surface transport conditions, and threats from extreme flooding events?

7.4. Scientific Approach

7.4.1. Background

Considerable international effort has been expended in trying to understand historical changes in arctic cryospheric and hydrologic systems, and to predict their future course. Although much progress has been made, advances in both diagnosis and prediction have been thwarted by the sparseness of data in the region. This situation has been exacerbated in recent years because of the reduction in many observing networks for budgetary reasons. Moreover, even when changes in arctic systems have been identified, knowledge gaps associated with cold-regions processes have made the problem of identifying controlling factors difficult. For example, causes for the observed increase in Eurasian discharge (Peterson et al., 2002; McClelland et al., 2004) remain elusive because of the absence of spatially detailed precipitation data and poor understanding of other cryospheric and hydrologic processes (e.g., ground ice melt) coupled with the presence of enlarging urban centers in northern environments which can modify streamflow regimes (e.g., storage/release of water-reservoirs, dams).

To improve our understanding of cold-regions hydrologic systems, two research initiatives were undertaken over the last decade on two major northern river basins, the Mackenzie River in Canada (MAGS: Mackenzie GEWEX [Global Energy and Water Cycle Experiment] Study) and the Lena River (GAME-Siberia: GEWEX Asian Monsoon Experiment). Although both studies have resulted in major advances in cold-regions hydrologic knowledge, particularly through the coupling of atmospheric and hydrologic models and detailed small-basin process studies, both programs end by 2006. Unfortunately, these studies were also to be the testing platform for subsequent phases of a WCRP/GEWEX Project for Intercomparison of Land-surface Parameterization Schemes (PILPS), a project with the objective of identifying the capabilities of models to simulate high-latitude water and energy cycles. To date, though, the only completed project is on a relatively small basin on the border of Sweden and Finland (Torne-Kalix River), which while it is a high-latitude river does not flow to the Arctic, and has a climate that is more temperate than most of the pan-arctic drainage (e.g., permafrost underlies only a small part of the Torne-Kalix basin). Many other process-based hydrologic studies have been conducted in high-latitude regions but they have never been coordinated aside from the inter-comparison of water-balance results from circumpolar basin studies (Kane and Yang, 2004; via US Freshwater Initiative (FWI)) whose researchers are affiliated with a long-standing Northern Research Basins (NRB) Working Group originally sanctioned by UNESCO's International Hydrological Programme (IHP).

Both in the case of the large GEWEX and small IHP-NRB scale studies, the focus has been on solving the water budget, although other cryospheric focused studies (e.g., permafrost, snow, lake and river-ice) have been integrated to varying degrees. In all cases, however, solution of related hydrologic effects, ranging from effects of permafrost on soil moisture and groundwater recharge to ice-affected flow routing and ice-jam flood generation remain elusive.

Hydrologic studies focused on glaciers, for instance, have been very rare with most of the information coming from programs focused on determination of glacier mass-balances, the major driver being for input to sea-level estimation. On the other hand, many small basins (10 to 100 km^2) in the Arctic are partly glacierized and the mass balances of these glaciers have an important effect on the water balance as the net balance represents the storage term that can provide a larger reduction (water storage) or surplus runoff on a yearly basis. Unfortunately, as is the case for small basin studies, mass-balance studies in the circumpolar Arctic are very limited. Less than 0.1% of the glacierized area of the Arctic (although this is regionally variable) is monitored by ground-based programs (Walsh et al., 2005). Similar to the case of non-glacierized catchments, such a small data base makes spatial extrapolation difficult particularly without a comprehensive range of representative glaciers from all major arctic hydro-climatic regimes. The value of such an approach is exemplified by the startling findings of some recent extrapolation results for Alaska that indicated meltwater production from southern Alaskan glaciers in recent years is almost double that estimated for the Greenland Ice Sheet (Arendt et al., 2002; Rignot and Thomas, 2002) and is about half the estimated loss of glacier mass worldwide (Meier and Dyurgerov, 2002). However, other studies indicate that meltwater production from Greenland might have been underestimated (Raper and Braithwaite, 2005). Evaluations of several large glaciers draining the ice sheet indicate that their velocities have recently doubled (Rignot and Kanagaratnam, 2006) and been accompanied by greater areas of surface melting (Steffen and Huff, 2005), the combined effects indicating that existing estimates of Greenland freshwater flux and contributions to sea-level rise are too low (Dowdeswell, 2006). Specific results show the northern Greenland glaciers to be close to balance yet losing mass. East Greenland glaciers are in balance and flowing steadily north of Kangerdlussuaq, but Kangerdlussuaq, Helheim and all the southeastern glaciers are thinning dramatically. In the northwest, most glaciers are largely out of balance. Jakobshavn accelerated significantly in 2002, and glaciers in its immediate vicinity accelerated more than 50% in 2000-2004. Overall, the mass balance of the Greenland Ice Sheet was about -80 ± 10 km^3 of ice per year in 2000 and -110 ±15 km^3 of ice per year in 2004, i.e. more negative than based on partial altimetry surveys of the outlet glaciers. The negative mass balance for the Greenland Ice Sheet was even larger in 2005, resulting in one of the largest terrestrial ice freshwater fluxes in the northern hemisphere. Figure 7.3 shows the extent of surface melting (not ice thickness changes) recorded in 2005 and the fluctuations since 1979. More research, however, is required to relate surface melt extent to mass-balance changes and ultimately freshwater production. In general, as climate continues to warm, more glaciers will accelerate, and the mass balance will become increasingly negative, regardless of the evolution of the ice sheet interior.

In summary, our limited monitoring and current physical understanding of high-latitude cryospheric and hydrologic processes and systems makes it difficult to answer adequately any of the scientific questions posed in section 7.3. Importantly, however, there are now a number of timely opportunities that might make it possible to meet these challenges within the timeframe of the ICARP II process:

1. A greatly improved ability to model key water-cycle variables over the arctic region that has emerged over the last decade as a result of recently completed (or soon to be completed) hydrologic regime studies noted above (MAGS and GAMES-Siberia). Major scientific advancements should be imminent through the application of this enhanced ability.
2. Although there remain critical gaps in process understanding and in the representation of physical processes in hydrological models applicable to arctic landscapes at all spatial scales, the recent assessment of IHP-NRB studies offers the additional opportunity to focus effectively research energies on these gaps.
3. The upcoming International Polar Year (IPY) and four programs – Arctic-HYDRA (an arctic hydrological observing system), GLACIODYN (a program initiated by the International Arctic Science Council-Working Group on Arctic Glaciology [IASC-WAG]), ICEMACH-GIS (ICE MAss CHange on the margins of the Greenland Ice Sheet), and TSP (Thermal State of Permafrost: an integrated set of permafrost-related projects overseen by the International Permafrost Association [IPA]) – provide unique opportunities in the near term. All four have direct links to the longer term objectives of this ICARP II science plan.

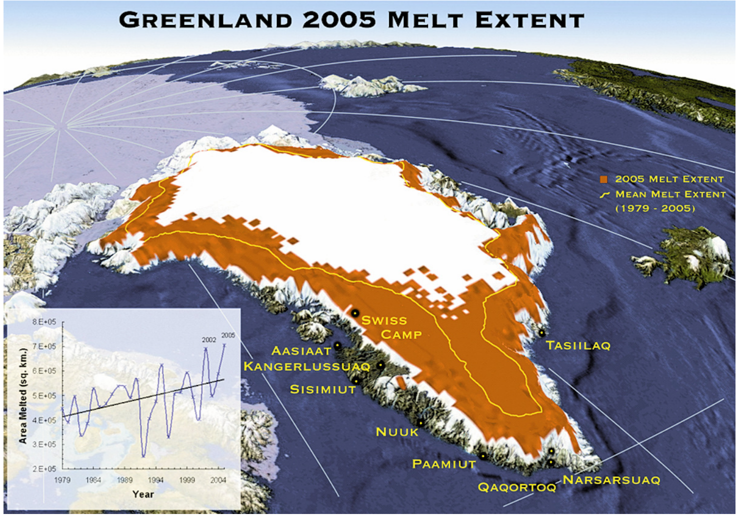


Figure 7.3. Extent of melt on the surface of the Greenland Ice Sheet. Red zone denotes 2005 melt extent; mean extent 1979-2005 is shown by yellow line. Inset shows annual variations in extent of melt (km^2) over same period (from Steffen and Huff, 2005). Note: figure shows only surfacing melting not loss of ice.

4. The emergence of new technologies will allow the science questions articulated in section 7.3. to be addressed in ways that were not previously possible. New satellites, some newly launched and others to be operational within the ICARP II timeframe, offer dramatically new opportunities to provide observations over large areas of critical quantities such as precipitation, snow-cover extent and water equivalents, glacier ice volume, surface-water extent and soil moisture, among others. Although most of these satellites are intended for global application, this ICARP II science plan has been designed to promote high-latitude basin "supersites" where integration of multiple cryospheric and hydrologic ground-based measurements will offer the ideal locations for the testing and application of such remote-sensing tools.

Given the above, this ICARP II science plan outlines a program that is based on a phased approach that includes (a) process studies, (b) modeling and prediction, and (c) long-term observations in a format that will allow short-term progress in a number of areas outlined in the science questions, while ensuring that gaps in long-term observations are addressed. The intent is that, by the end of the program, these new observations will make it possible to address aspects of the science questions that are critically dependent on long-term observations. Furthermore, the approach includes near-term actions that will permit many of the science questions to be addressed in the short term, using existing observations, and/or measurements that are currently being acquired. Figure 7.4 is a schematic outlining the ICARP II process of integrating field-based monitoring at supersites with modeling and remote-sensing applications to permit broad-scale upscaling of results.

7.4.2. Procedure

Although some of the science questions require that new information be obtained about all components of the arctic terrestrial cryospheric and hydrologic system, different research strategies need to be undertaken for the study of some components. Questions 7.3.2.1 to 7.3.2.4 will focus on various controls of the water balance that vary greatly among physiographic regions, particularly with respect to the form and quantity of the storage. Moreover, since Question 7.3.2.5 focuses explicitly on large-scale glacier masses, a different approach for water-balance determinations is required. Similarly, a specialized program will be essential to provide answers regarding the freshwater ice systems articulated in Question 7.3.2.6.

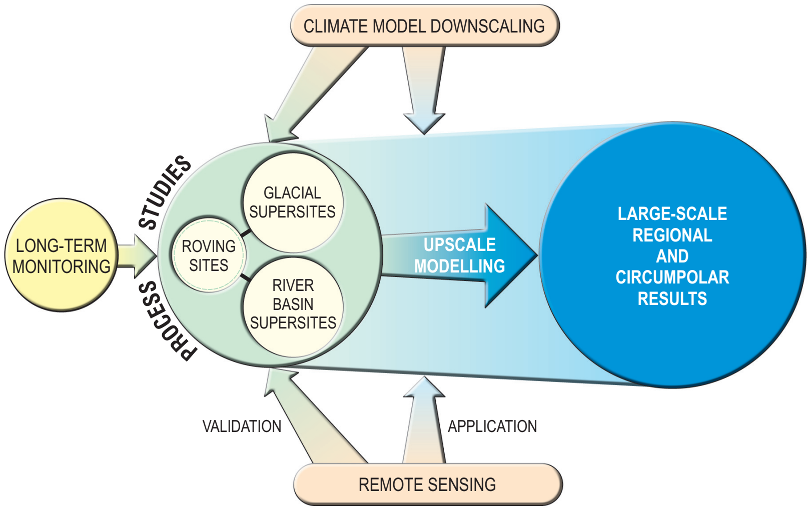


Figure 7.4. Major components of the ICARP II process.

Providing answers to all questions can best be accomplished by focusing research on watersheds and glacierized regions spanning a range of spatial scales. Given the current state of knowledge and large unstudied parts of the Arctic, a three-pronged approach is recommended:

- filling of existing knowledge gaps through process research in well-studied regions;
- initiation of new research programs in regions that are currently unrepresented by previous field programs; and
- extrapolation of understanding gained through process studies and modeling analyses throughout the pan-arctic basin. To enable such extrapolation, it is essential to conduct verification and validation studies in carefully selected sites in under-studied regions.

In the case of river-basin hydrologic studies, the strategic approach will be to link process studies at relatively small scales (e.g., research catchments typically of size <10 to 100 km^2) with modeling and observations within intermediate-scale river basins typically having drainage areas of around 50,000 km^2, both of which would be linked to observations and modeling at the scale of continental river basins (e.g., Mackenzie, Lena) with drainage areas exceeding 10^6 km^2, and eventually the entire pan-arctic land domain. The observational strategy includes enhanced measurements at the smallest scale to support detailed process studies (some of which would be conducted on a rotating basis over the 15-year study horizon), and enhanced long-term observations over the pan-arctic domain. While field studies may be conducted at all three spatial scales, of necessity they will be focused mostly at the smallest scale, for example, research catchments. A similar strategy will be used for the glacier studies and related upscaling described in subsequent sections. Lake and river ice studies will focus on specific sites of regional interest or representativeness.

Supersites

It is recommended that some field locations be designated as “supersites” at which enhanced observations and process studies would be carried out. A concentration of cryospheric and hydrologic field process studies including ancillary ground-based monitoring programs offers the enormous advantage relative to other relevant satellite-based programs for the testing/validation of new generation remote-sensing technology in high-latitude environments, as described in section 7.4.3. Development of an enhanced network of essential measurements within such supersites, including for example, precipitation, air temperature, thaw depth/subsidence, slope processes, ice thickness and soil moisture, will be necessary to permit calibration and validation of remote-sensing results. Such broad-scale spatial data will be invaluable for providing reliable answers to the science questions listed in section 7.3 such a data-sparse region of the globe. Final selection of site locations will form part of this ICARP II science plan, as outlined in section 7.7.

Nested Structure of Supersites

Detection of changes in hydrologic and other cryospheric variables in response to a changing climate and quantification of natural temporal and spatial variations will require establishment and maintenance of key observation programs. Quantifying extreme conditions must be a priority due to the consequences of their effects on human and natural systems. Additionally, the marked changes that occur as ecosystems change from conditions of frozen to thawed (e.g., snow-covered to snow-free, continuous-permafrost to discontinuous-permafrost, ice-covered to ice-free) represent drastic threshold changes with radical impacts on thermal and hydrologic properties. Accurately incorporating these threshold changes in modeling analyses is essential to correctly portraying not only annual dynamics but more broadly ecosystem evolution and quantitative changes in the linkages among system components. Such linkages are scale-dependent properties that change in level of importance from the local to regional to continental domains. To address this issue in river watersheds, research studies will be conducted using a nested-basin approach where scale-dependent variations may be detected and quantified.

Roving Sites

Ideally, regionally representative supersites should be instituted at sites that already have comprehensive water and energy-balance data sets, hopefully augmented by other supporting paleo-information. Such a network of sites will be a critical starting point to improve and enhance understanding of northern processes and to provide data which can be used to calibrate and validate both modeling strategies and state-of-the-art observation platforms. However, given that the pan-Arctic possesses a huge diversity of terrain and climatic conditions, achieving an improved understanding of hydrologic-cryospheric processes (e.g., streamflow, evaporation, storage changes, and permafrost dynamics) in large tracts of the Arctic will be unattainable with only this strategy. Other sites will be needed in regions currently lacking representative locations for the extrapolation of results and confirmation of the reliability of physically-based models that have been extrapolated from the data-rich supersites to these more data-sparse zones. Similarly, areas noted to be experiencing atypical conditions (e.g., areas experiencing warmer conditions or heightened hydrologic activities such as extreme floods/droughts or rapid shifts in glaciers mass-balance/vegetation) may also require additional observations and process studies. To deal with both of these situations, a second strategy of employing temporary roving sites (ranging from simple deployment of hydrometric/ meteorological equipment to additional research field research) will be used.

Modeling

Modeling activities will be conducted both at the small scale in support of (or to assist in interpretation of) process studies, and at the intermediate and larger scales. The question arises as to how best to integrate across the three spatial scales. It is suggested that this be done both in the observational arena, through use of remote sensing data, and in the modeling domain, through use of macro-scale models evaluated and improved through use of data collected at the smallest scales. Furthermore, at the largest (and perhaps intermediate) spatial scales, data assimilation, as in the recently completed ECMWF (European Centre for Medium-Range Weather Forecasts) ERA-40, North American Regional Reanalysis, and the planned Arctic System Reanalysis, must play a key role. Links to advancements in such reanalysis data sets and numerical weather prediction/climate models via appropriate land surface models is imperative (see section 7.4.5).

Specifically, environmental information from the selected supersites will provide the requisite data to parameterize land surface schemes (see section 7.4.5). Testing and validation of modeling capabilities will be undertaken at these sites but further validation will be required in selecting new locations prior to extrapolation to the pan-arctic domain. This approach of model development, calibration, and validation utilizing well-studied and under-represented research sites will then permit attribution of causes of currently observed changes ongoing in arctic regions and quantitative projection of future responses in the hydrologic and climatic systems. Projections of hydrologic and cryospheric responses to a changed climate will be examined through the downscaling of data from a select set of models and scenarios identified by the most recent assessments of the Intergovernmental Panel on Climate Change (see section 7.4.6).

7.4.3. Observations

Conducting the process-based and modeling studies outlined above will require large suites of observations of various cryospheric and hydrologic components. Although a rich body of observational data does exist, a major impediment to integrated cryospheric and hydrologic studies over large areas of the Arctic is the sparse and discontinuous nature of monitoring stations and data records in time and space. This section addresses how this research program will generate the requisite additional data needed to address the major science questions. Important to the success of this program is the collection of complementary data (i.e., observations collected according to some standard that enables greater ease in sharing and detecting differences) and the promotion of archiving data in relevant data centers (outlined by variable) for access by all. See section 7.7.1.

Although resource limitations might preclude directly funding augmentation of existing observation networks, this program has been designed (e.g., through the use of supersites) to present ideal opportunities for related national/international programs to operate at similar locations. With such spatial integration of activities, each program should be able to more effectively attain their individual goals (e.g., high-latitude testing and validation) and because of program synergies contribute to answering of the questions outlined in this ICARP II science plan. To this end, an assessment has been conducted of upcoming programs, especially those dealing with new remote-sensing products, to ensure that the proposed research to be conducted over the next 10 to 15 years will remain at the cutting edge of developing scientific frontiers.

Precipitation

The lack of high-quality precipitation data is one of the most commonly cited problems for the inability to close the land-surface water and energy budgets in arctic cryospheric and hydrologic studies. Although there are a number of precipitation archives (e.g., Global Precipitation Climate Center, Arctic Precipitation Data Archive, and more regionally specific data sets for research programs such as MAGS and GAME), the observed data are usually found to be too sparse and/or improperly distributed by region and altitude. There also exist a number of re-analysis gridded products, the most recent and superior product being the ERA-40, which has an approximate 1 degree latitude-longitude grid). ERA-40 has been shown to provide surprisingly good annual estimates of precipitation at the scale of the major arctic river basins, albeit with apparent biases seasonally, and at smaller spatial scales. Within the ICARP II timeframe, the international SEARCH (Study of Environmental ARCtic CHange) plans a regional reanalysis which has the potential to provide much better estimates of the time-space variations of precipitation over the Arctic. At present, however, this activity is funded only at the exploratory level and only by a single U.S. agency (NOAA: National Oceanic and Atmospheric Administration). There is also an opportunity to link with one or both of two new international satellite missions, the GPM (Global Precipitation Measurement mission led by the U.S and Japanese, and other international partners) and the EGPM (European Global Precipitation Measurement), whereby it would be possible to obtain detailed precipitation data (including solid precipitation) useful for the process studies outlined below. Both missions have high-latitude capability and will require northern validation sites. This ICARP II science plan via its supersites and possibly roving sites offers ideal locations for such validation.

Soil Moisture

Large-scale reliable archives of soil moisture information do not exist for the arctic region. Most data have been collected by small-scale projects and tend to be of relatively short-term duration (spring and summer, often missing the critical autumn-freeze-back period). Unfortunately, recent studies attempting to close the water-balance of large-scale arctic basins (e.g., MAGS) have found that soil moisture storage can be a major unknown source of error. Moreover, it is this type of information that is also crucial to other studies of arctic change (e.g., vegetation succession being addressed by ICARP II Science Plan 8). Similar to the case of precipitation, however, there are new and emerging satellite-imaging products that should soon be able to provide high-resolution soil-moisture data that have never before been possible to obtain. Such opportunities are offered by, for example, the recent U.S.-German dedicated gravity satellite GRACE (Gravity Recovery and Climate Experiment), the upcoming European (2007) Soil Moisture and Ocean Salinity Mission (SMOS) and the U.S.-Canada (2010) Hydrosphere State Mission (HYDROS). Again, the hydrologic supersites and roving sites of this ICARP II science plan offer ideal high-latitude validation locations for these missions.

Snow Cover

Although in situ measurements of snow depth and snow water equivalent (SWE) have been made throughout the Arctic ranging from single-site depth measurements at climate stations to multi-point snow survey and snow pillow observations, the most comprehensive data are collected via remote sensing. Maps of snow-cover extent are regularly (e.g., daily) produced for the northern hemisphere (e.g., NOAA NESDIS: National Environmental Satellite, Data, and Information Service). They rely on a variety of visible and infrared spectral data, such as from the Polar and Geostationary Operational Environmental Satellite (POES/GOES) programs or from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Earth Observing System (EOS) Aqua and Terra satellites.

A more critical need for model validation and hydrologic simulations is information about the spatial distribution of SWE, which is a much more difficult quantity to measure than snow extent. The need for better SWE data is especially urgent for high latitudes, where there are few in situ measurements to complement the estimates derived from remote sensing. Algorithms have been developed and tested based on SSM/I (Special Sensor Microwave/Imager) instruments on board several US DMSP (Defence Meteorological Satellites Program) satellites, and for AMSR-E (Advanced Microwave Scanning Radiometer for EOS) on the EOS Aqua satellite. A major problem that plagues all algorithms is strong sensitivity to liquid water in the snow pack. Validation programs are underway for AMSR-E environmental products and an additional satellite is being planned by the U.S. and European satellite missions that would provide SWE estimates at a spatial resolution of 5 km. Again, the proposed ICARP II science plan supersites would offer ideal validation locations for these missions. A similar opportunity exists for testing and validating remotely sensed daily snow-albedo data; a snow characteristic that is highly variable in vegetated areas and plays a critical role during the late winter and spring seasons in controlling snowmelt runoff. Data that can be derived from MODIS make it possible to provide essential information about large-scale variations in snow albedo at the supersites for model validation and to permit upscaling to the larger basins.

Seasonally Frozen Ground and Permafrost

The presence or absence of frozen ground (seasonal or perennial) in the Arctic is a major control on the movement and storage of water, both on the landscape and in aquatic environments. Moreover, it has been cited as a potential factor in recent changes in the hydrologic productivity of northern basins and even more so for projected future changes under climatic warming (e.g., Wrona et al., 2005). Of particular importance to hydrologic response is not only the presence of different types and extent (both vertically and horizontally) of frozen ground (e.g., seasonally frozen, discontinuous permafrost, continuous permafrost, ice-rich permafrost) but the thickness of the active layer (which controls the rate of runoff response), and the rate/magnitude of thaw subsidence.

Under the auspices of the IPA Global Terrestrial Network for Permafrost (GTN-P), several circumarctic initiatives are underway. The oldest and best-developed is the Circumpolar Active Layer Monitoring (CALM) program, initiated in the early 1990s to detect changes in the thickness and temperature of the active layer throughout the world's cold regions (Brown et al., 2000; Nelson et al., 2004; Figure 7.5). Sites were initially selected based on two primary criteria: (a) the existence of pre-existing data records; and (b) accessibility (effectively, association with other scientific monitoring or experimental programs). The distribution of many CALM sites is highly clustered, although in several cases (Kuparuk Alaska, Mackenzie Canada, West Siberia) their arrangement in latitudinal transects represents an effort to monitor large drainage basins with the specific intent of scaling to the regional level using the WMO Global Hierarchical Observing Strategy (GHOST; see U.S. Arctic Research Commission Permafrost Task Force, 2003). The GTN-P also operates a borehole program (Figure 7.5), TSP (Romanovsky et al., 2002), which would be invaluable for evaluating the hydrologic sensitivity of arctic hydrologic systems to future warming. Like CALM, TSP uses existing facilities (boreholes) opportunistically and, subject to this limitation, attempts to achieve extensive geographic coverage at sites that are representative of major landscape types.

The CALM, TSP and related observation programs should be expanded geographically to include the proposed supersites, thereby further increasing the comprehensiveness of their cryospheric/hydrologic observation network and hence their utility as test/validation sites for the hydrologic remote-sensing programs noted elsewhere in this ICARP II science plan. Notably, both CALM and TSP are key components of an integrated IPY-endorsed permafrost program, under the title of Thermal State of Permafrost.

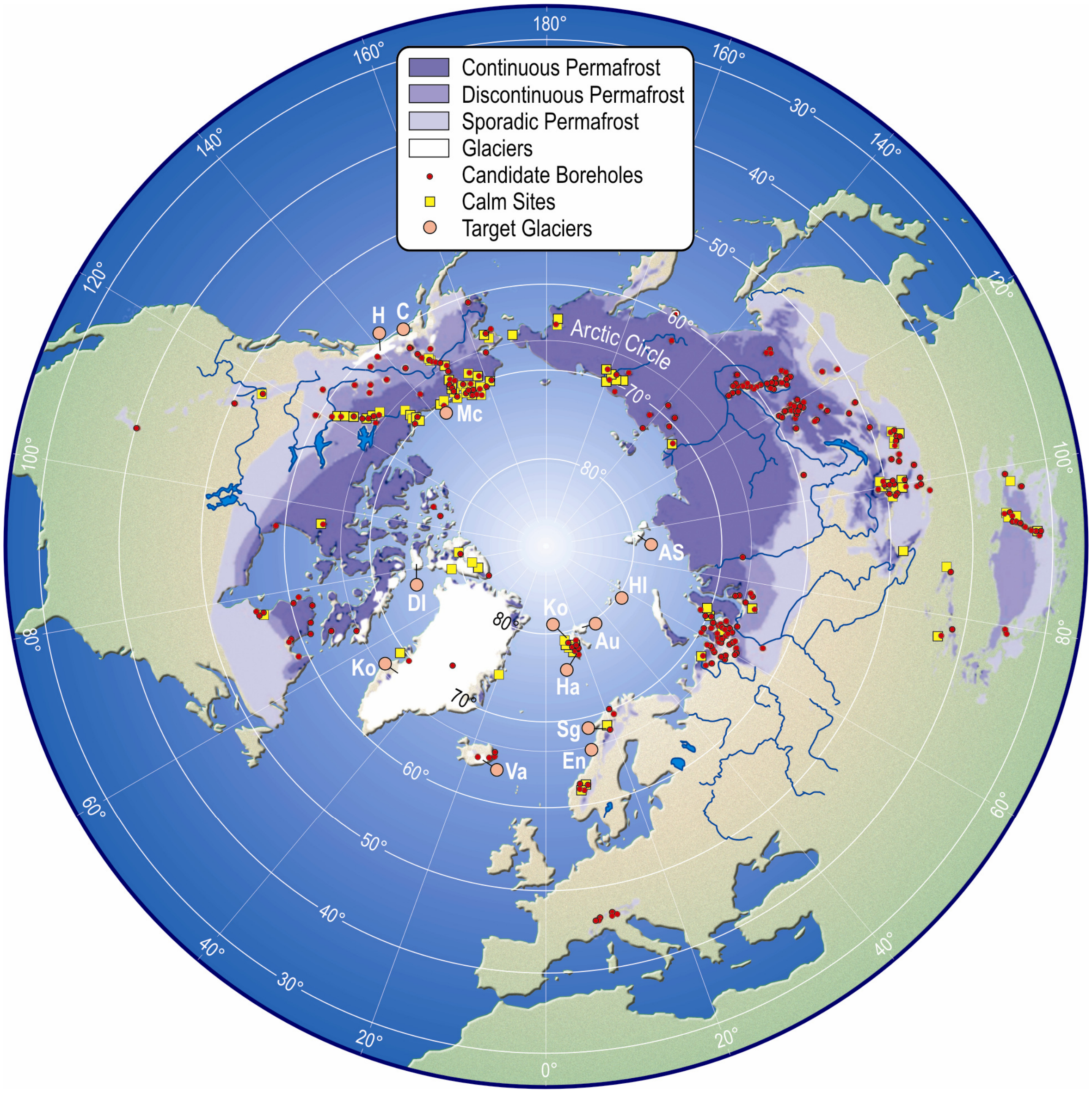


Figure 7.5. Location of permafrost candidate boreholes, active-layer monitoring sites (after International Permafrost Association) and GLACIODYN target glaciers.

Periglacial Landforms and Processes

Observations of periglacial (cold, non-glacial) geomorphic processes are critical for understanding the production, mobilization, and transport of sediments in cold-climate landscapes, and their relation to climatic fluctuations. Periglacial processes and landscape evolution are closely linked to watersheds and the large-scale hydrological system. The magnitude and frequency of geomorphic processes influence terrain stability and vegetative composition, thereby exerting an important influence over albedo and the subsurface thermal regime. Recent evidence for widespread thaw subsidence (e.g., Jorgenson et al., 2006) indicates an urgent need for a coordinated and standardized approach to monitoring periglacial processes and sediment fluxes in the circum-arctic region. The SEDIFLUX (Sedimentary Source-to-Sink-Fluxes in Cold Environments) program has made progress toward this goal in Europe under the sponsorship of the European Science Foundation. The IPA's Working Group on Periglacial Landforms, Processes, and Climate has initiated observations at several pilot sites as a precursor to building a global network of periglacial observatories, and has prepared a field manual for monitoring periglacial processes (Humlum and Matsuoka, 2004). These efforts, which are part of the IPY-endorsed TSP program, represent key steps toward developing a comprehensive network, and the observation strategies developed for periglacial processes in recent years should be integral components of monitoring conducted at both the roving and supersites proposed here.

Runoff

Besides the generation of extreme events (e.g., snowmelt and ice-jam floods), most concern in recent years about arctic river flow has been its potential influence on the freshwater budget of the Arctic Ocean and ultimately via export through Fram Strait, the rate/stability of the thermohaline circulation in the North Atlantic (e.g., Lewis et al., 2000). Importantly, however, much of the runoff to the Arctic Ocean is generated at much lower latitudes well outside the Arctic (Figure 7.6); the annual runoff volume being approximately linearly related to the defined contributing area.

There exist a number of archives of runoff in the arctic region (e.g., GRDC, Global Runoff Data Centre; ARDB, Arctic Runoff Data Base; R-ArcticNET) but runoff observation networks in the Arctic have been shrinking over the last two decades and the size of ungauged areas has correspondingly increased. Often relied on as the benchmark term in water-balance studies, declines in the availability of runoff data have made hydrologic evaluations and modeling strategies much more problematic. It has, for example, become increasingly difficult to provide direct estimates of river runoff to the Arctic Ocean – information essential to answering Question 7.3.2.1. To remedy this situation, a new international program, Arctic-HYDRA, has been initiated with a general objective of establishing networks for measuring basic hydrological components in the Arctic. The initiative took form under the WCRP Arctic Climate System Study (ACSYS) and its follow-on project CliC. A recently formed Steering Group for Arctic-HYDRA is now developing a full international plan for this core IPY project. Moreover, it was decided by the Arctic-HYDRA Steering Group (April 2005) that the IPY plan would be developed around the scientific goals of, and be directly linked to, this longer term ICARP II science plan.

New satellite remote-sensing products and methods are rapidly emerging as the future source for observations of hydrologic regimes (e.g., Alsdorf and Lettenmaier, 2003; Brakenridge et al., 2005; Harding and Jasinski, 2005). Of special value are recent radar and laser altimetry measurements of

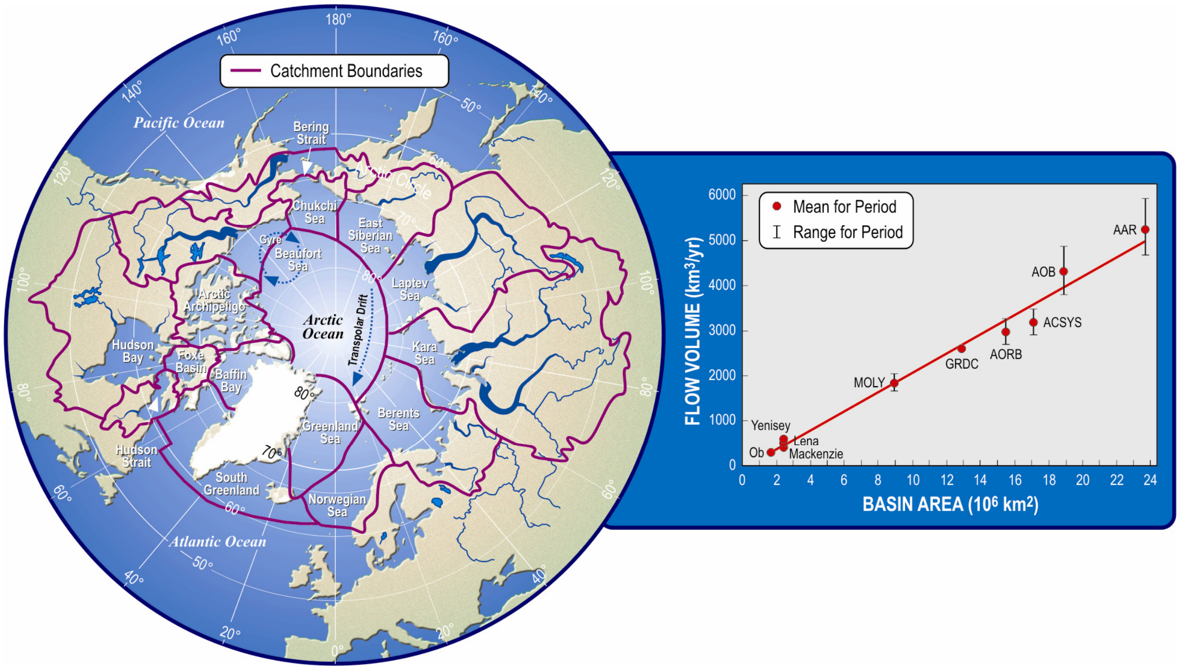


Figure 7.6. Major catchment areas and river networks draining to the Arctic Ocean and seas. Width of rivers illustrates relative discharge (after Walsh et al., 2005). Note that catchments extend well beyond the Arctic to almost 40° N. Inset shows relationship (approximately linear) of total annual flow volume to varying definitions used to define the total catchment area contributing flow to the Arctic (from Prowse and Flegg, 2000).

water-surface elevation and slopes obtained from the TOPEX/Poseidon satellite (NASA and CNES [Centre National d'Etudes Spatiales]) and ICESat (NASA's Ice, Cloud and Land Elevation Satellite). Furthermore, evolving major programs, such as the EU-U.S. proposed Water Elevation Recovery (WaTER) Satellite Mission (Alsdorf et al., 2005), would provide a unique opportunity for direct observations of lake and reservoir levels over much of the Arctic, and (via assimilation of surface slope measurements) estimation of the discharge of most rivers over the Arctic with widths greater than about 50 m. Such a program would form an ideal interface with the related Arctic-HYDRA initiative and the hydrologic supersites proposed in this ICARP II science plan.

Biogeochemical Fluxes

Most comprehensive observations of biogeochemical fluxes in the Arctic originate from site-specific research studies, although some national programs do measure select variables (e.g., sediment) on the main stems of the largest arctic rivers. One variable often overlooked, however, is water temperature, which is likely to experience dramatic changes and produce significant effects on other arctic systems as the terrestrial cryosphere shrinks.

There does exist, however, one broad-scale circumpolar program focused on measuring the biogeochemical characteristics of river waters from the six major arctic drainage basins as they flow from land into the Arctic Ocean. Conducted under the U.S. Freshwater Initiative (FWI), the PARTNERS project has the overall objective of using river-water chemistry as a means to study the origins and fates of continental runoff (Peterson, 2003). Unfortunately, the observation program for this initiative concludes in 2006. It is hoped that some of these observations can be integrated into the Arctic-HYDRA observations strategy and continued as part of this ICARP II science plan that would permit linkages of planned supersite observations to the larger river responses. The IPA is currently formulating a plan to assess carbon stocks in permafrost regions that could be integrated with these efforts through ICARP II Science Plan 8.

Lake and River Ice Cover

The only centralized archives of lake and river ice data, primarily related to timing of freeze-up/break-up and ice thickness, are held by national agencies. In general, ground-based observations of lake ice tend to be fewer in number than those for river ice, which are collected on a regular basis as part of the river hydrometric programs. In rare cases, records of freeze-up/break-up phenology exist for >100 years (Magnuson et al., 2000) but sites are extremely rare in arctic regions. The largest international archive of data is held by the Global Lake and River Ice Phenology Database at World Data Centre for Glaciology, Boulder, CO, USA. To varying degrees internationally, ice cover on freshwater bodies has been monitored from space using visible (e.g., Advanced Very High Resolution Radiometer (AVHRR)), active radar (e.g., RADARSAT) and passive microwave (e.g., SSM/I) sensors. There remains a need to integrate the in situ and satellite observations to create long-term time series of dates regarding freeze-up and break-up processes. Furthermore, there is also a need to identify a limited number of sites with high quality in situ measurements for evaluation of satellite data, and for development / validation of lake-ice models. Again, over the 10 to 15 year timeframe planned for the ICARP II process, significant improvements in satellite remote sensing products for both lake and river ice observing will be made. Of particular interest are products which should have short-interval repeat cycles necessary for the observation of dynamic changes in river ice during freeze-up and break-up. This ability combined with increased vertical measurement resolution (e.g., from laser altimetry) will permit the direct observation of ice-generated flood conditions and stream-wise variations in river slope, a critical piece of information for improving dynamic river-ice models that is extremely impractical to document from in situ observations presently.

Glaciers, Ice Caps, Greenland Ice Sheet

A critical research need in the Arctic is to compile an up-to-date global glacier inventory. For some regions, existing inventories are sparse; inventories also need to be updated where glacier areas have changed. A global satellite-derived dataset of exposed ice areas is a minimum requirement. Ideally, a complete glacier database describing individual glacier locations, areas, and geometries should be compiled, so that mass-balance measurements on individual benchmark glaciers can be extrapolated to unmeasured glaciers with greater certainty. In recognition of the lack of global information about the extent and changes in glaciers, an international program entitled GLIMS (Global Land Ice Measurements from Space) was initiated by the U.S. Geological Survey. It was designed to use primarily data from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument, flown on board the EOS Terra spacecraft, and the monitoring activities are expected to continue through the life of the Terra mission. This work will also establish a digital baseline inventory of ice extent for comparison with inventories at later times. Current observations are held by the World Glacier Monitoring Service (WGMS) and the National Snow and Ice Data Center (NSIDC). This program offers the ability to provide the much-needed arctic glacier inventory required for this ICARP II science plan.

The Program for Arctic Regional Climate Assessment (PARCA) supported by NASA cryospheric sciences has been monitoring the Greenland Ice Sheet mass balance, dynamics, and surface climate using in-situ, aircraft, and satellite observations for over a decade. Only recently has it been recognized, primarily from satellite observations that sectors of the Greenland Ice Sheet can abruptly speed and thin over periods of just a few years resulting in a reduction of the size of this frozen reservoir. Further, measuring how much water is stored in ice sheets and glaciers and its interannual variability is important in the interpretation of satellite gravity data that can be used in the estimation of ice-sheet mass balance. Estimating past contributions to local hydrology and global sea level rise is critical in predicting the response to anticipated changes in climate. Such temporal perspectives will be aided by the extensive information about Greenland paleo-climate produced by Greenland ice-core programs (e.g., the U.S.-sponsored second Greenland Ice Sheet Project, GISP2, and GRIP, its European counterpart) and from the Greenland-focused part of the arctic climate research proposed ICARP II Science Plan 9.

Although the Greenland Ice Sheet is the major ice mass in the arctic region, many other regions and catchments in the Arctic are dominated by glaciers/ice caps that can also contribute substantial amounts of water to river systems and ultimately the Arctic Ocean. As such, observations of their changes are important to a number of the science questions listed in sections 7.3, specifically including Questions 7.3.2.1 and 7.3.2.5. A first-order estimate of changes that might result from future climate change (see section 7.4.5) has also been completed for the Arctic Climate Impact Assessment (Oerlemans et al., 2005; Walsh et al., 2005). As for other arctic hydrologic processes, however, generalized assessments of glacier response in the Arctic are hampered by a lack of observations (i.e., <0.1% of glacier area with ground-based monitoring) and the fact that the measured glaciers are not sufficiently representative to be used in upscaling assessments of mass balance. Hence, there is a critical need to obtain mass-balance information from a broader set of ice sheets, ice caps and large glaciers (>25 km^2) representative of different climatic regions and altitudinal zones. In particular, areas of special focus should be the west and east Arctic Islands (Svalbard and Russian Arctic), Canadian Arctic Archipelago and Greenland small glaciers and ice caps. While field-based programs are essential to such a large-scale assessment (see section 7.4.4), recent advances in satellite-based remote sensing have markedly increased the ability to observe changes in glacier mass balance. Most notably, promising results about the mass-balance of major ice sheets have been generated using laser altimetry sensors of ICESat (Zwally et al., 2002; Zwally, 2005) that will hopefully be followed by a successor satellite in the near term. Although a major focus of this initiative in the Arctic is the Greenland Ice Sheet, such a system could provide the observations necessary to evaluate changes in other critical concentrations of glaciers and ice caps. Enhanced observations will also be made as part of the IPY-GLACIODYN (see Figure 7.5) and ICEMACH-GIS programs including the measurement of ice motion (such as through the use of InSAR; Interferometric Synthetic Aperture Radar). The broader use of these observations is described in section 7.4.5.

7.4.4. Process Studies and Modeling

At the small basin scale, field research will be required to develop process-based algorithms for inclusion in, and improvement of current state-of-the-art cold-regions cryospheric and hydrologic models – both for off-line prediction, and representation of these processes in coupled land-atmosphere-ocean models. Overall, these models should be capable of determining snowmelt evaporation, transpiration, surface and subsurface runoff, thawing and freezing of the active layer, thermal regime of the active layer, slope processes, sediment transfer, infiltration, and channel and lake routing. Moreover, the models need to explicitly couple atmospheric and terrestrial systems. Section 7.4.5 outlines the basic modeling strategy that will be used. A select number of processes requiring special attention are outlined in the following sections.

Evaporation

Although network improvements and new remote-sensing techniques are identified above that could lead to improvement of the estimates of arctic terrestrial precipitation (P), current calculations of evaporation (E) are equally problematic in solving P-E for much of the Arctic. Such problems are evidenced by the results of various General Circulation Model simulations of future climate, which do not agree even on the sign of changes in E, let alone the magnitude (e.g., Walsh et al., 2005). Unfortunately, observational data are far too scarce for regional model evaluations. Process studies at the various representative supersites (and enhancement of currently extremely sparse direct measurements of E, e.g., via eddy correlation and other flux tower measurements) will aid in refining E parameterizations. Special attention will need to be placed on the simulation of transpiration for differing vegetation types, since major vegetation shifts are forecast to occur with changing climate. Remote sensing products, used in conjunction with modeling (e.g., via data analysis) will, however, have to play a major role in upscaling direct observations, which are constrained to points or very small areas, to the river basin and larger scales.

Sublimation

Recent research has pointed to the importance of blowing snow and related sublimation in local and regional water budgets. The regional supersites will permit broad-scale evaluations of their importance so that proper algorithms can be incorporated into the next generation of climate models, which do not currently include the enhancement of sublimation of blowing snow or, in some cases, even direct sublimation from snow surfaces (e.g., Walsh et al., 2005). A key problem is associated with inaccuracies in measurements of humidity at low temperature (Bowling et al., 2004), a problem which should be resolvable in the context of supersite observations.

Snowmelt

Most versions of snowmelt models used in the Arctic were developed for application in more temperate climates. Process-based studies in higher latitude, colder climates have shown that such models are deficient because they do not adequately consider factors such as large negative soil heat flux, or infiltration into cold snow covers and frozen soils of varying soil moisture. Continued process studies are required to permit the proper parameterization, testing and validation of snowmelt models that can ultimately be used in upscaling hydrologic and geomorphic predictions. For upscaling from plot to catchment or larger scales, it is important to account for the effect of the mosaic of snow covered and snow free patches, and related variations in albedo – information at the larger scale that will be possible to obtain from remote-sensing products.

Seasonally Frozen Ground and Permafrost

Frozen ground plays a significant role in controlling the interactions between surface and groundwater flow regimes. Changes in the temporal and/or spatial regimes of frozen ground (e.g., via talik formation) can produce major changes in the relationship between precipitation and terrestrial hydrologic processes such as evaporation, surface runoff, thaw subsidence, sediment transfer, slope processes, and groundwater flow. Specific to the intra- and sub-permafrost systems, more field-based research will be required to evaluate hydrogeological properties such as permeabilities, storage capacities, flow velocities, and residence times, including groundwater recharge rates in fractured and karsitic rocks. Again, the regionally representative supersites will be the platform for studies aimed at improving the parameterizations in hydrologic flow models. The related active-layer and borehole measurements from the CALM and GTN-P programs will be especially valuable in this regard for calibration and validation.

Geochemical Fluxes

Major changes in geochemical fluxes in ground and surface water are expected to accompany changes in permafrost conditions and related vegetation shifts (e.g., Wrona et al., 2005). New generations of hydrologic models that consider land-water interactions at the catchment scale, however, are still in a state of initial development. Comprehensive data from the supersites will be of significant value to further development of these models.

Runoff and Ice Cover

Accurate runoff data are critical in process studies analyzing any of the other basic water-budget variables. Small-scale field studies will need field-based measurement programs to generate these but it is planned that the larger network will be supported and augmented via the remote-sensing approaches noted earlier. There remains, however, a need to conduct additional field-based research that will lead to development of a hydrological model that permits reasonably accurate simulation of river discharge during the transitional times of freeze-up and break-up (e.g., Prowse, 2005). Such work should also focus on the linkages with atmospheric controls (e.g., radiation induced ice decay) that are known to control the interactions with runoff and the severity of ice-jam flooding (i.e., relate to Question 7.3.2.6). Further to this end, advances are required in the state of lake-ice models, particularly with respect to their ability to model changes in cover composition as a result of increases in snowfall that are forecast to occur at higher latitudes under future climate change (e.g., Wrona et al., 2005).

Glaciers/Ice Caps

Process-based field studies, including mass-balance measurements, are needed at various representative sites to permit calibration/validation of the above noted remote sensing systems (ICESat) and further refinement of mass-balance models. Moreover, while laser and radar altimetry systems are most likely to yield an improved capacity to accurately measure changes within accumulation zones, large unknowns associated with controlling processes in the ablation zones still remain (H.J. Zwally, NASA/Goddard Space Flight Centre, pers. comm.). Here, further process work is required to aid in the development of more reliable models that can explain the observed thinning of the Greenland Ice Sheet. Of particular importance is to find explanations for the excess thinning of the margin where melt water penetration, flow history and the albedo field are likely to be controlling factors. Both GLACIODYN and ICEMACH-GIS studies will provide information on these.

7.4.5. Upscale Modeling / Synthesis

Most of the science questions posed in section 7.3 will require integration of process-study and observation/remote-sensing results. For Questions 7.3.2.1 to 7.3.2.4, macroscale land surface models will be the primary mechanism for model integration. These models typically are implemented at spatial scales utilized by numerical weather prediction and climate models – in practice usually meaning >10 km. Most land surface models use “flat earth” representations of the land surface in that they do not deal explicitly with topography, at least not in the context of explicit representation of slope and aspect effects on solar radiation, and/or moisture redistribution. For this reason, they are not applicable at spatial scales much less than about 5 km. Nonetheless, this is enough to be consistent with local field measurements of vertical fluxes (radiant and turbulent), as long as the measurements are taken in areas without significant terrain complications. Furthermore, a trend in land-surface modeling is the explicit representation of sub-grid heterogeneity effects on the larger scales (e.g., spatial variability in soil moisture, discontinuity in snow cover). Therefore, supersite observations both of variables that by their nature represent integrated effects over an area (e.g., streamflow) and variables for which high resolution networks (such as grid measurements) can be designed to capture spatial variability, are appropriate for model testing and evaluation at the local scale. The process of synthesizing data from these research catchments will proceed in two steps. The first will be upscaling to the intermediate (to ~ 50,000 km^2) scale. The strategy envisaged here will be similar to PILPS-2e, which used gridded model forcings (1/4 degree resolution) of hydrometeorological data from observing stations. A similar approach possibly using recent reanalysis products (e.g., ERA-40) will permit this intermediate-scale modeling. The availability of streamflow data, ideally for multiple locations within each nesting of sites, as well as the various satellite-derived products of other hydrologic/cryospheric variables will facilitate model evaluation and testing. A similar combination of station, reanalysis and satellite data will be used to complete modeling at the largest scales at the continental watershed to pan-arctic domain. This upscale modeling framework when instituted will also be used to link the observations of thaw penetration and geochemical fluxes observed at the large-basin scale to the measured and modeled fluxes at the supersite/research-basin scale.

In reference to the upscale modeling of glacier response, this program supports the work conducted by the IASC (International Arctic Science Committee) Working Group on Arctic Glaciology (WAG). As input to the Arctic Climate Impact Assessment, they employed a simple approach relying on seasonal sensitivity curves (i.e., sensitivity of the mass balance of glaciers within different hydro-climatic regimes to changes in temperature and precipitation) to estimate the runoff of all glaciers in the Arctic for a set of climate-change scenarios (Oerlemans et al., 2005; Walsh et al., 2005). In this static approach, calculations were made assuming constant glacier geometries and calving rates. As part of a submission to IPY under the name GLACIODYN, the IASC-WAG proposes to use more dynamic modeling approaches that will make improved use of observational techniques (e.g., as described in section 7.4.3) and to develop a hierarchy of models that can be used to aggregate data for improved regional predictions. A set of 15 target glaciers (see Figure 7.5) with extensive records of relevant environmental conditions (e.g., micro-climate, mass balance, geometry, ice flow, internal structure, temperature field, hydraulics, calving, runoff and hydrology, sediment dynamics, bathymetry) will be used, with special attention placed on calving glaciers. In a related vein, the IPY project ICEMAC-GIS will involve field campaigns, aircraft campaigns, satellite-based studies and modeling efforts to produce a comprehensive picture of mass loss (runoff, sublimation and ice discharge) from the GIS. Given the short timeframe of the IPY and the scope of GLACIODYN and ICEMAC-GIS, it is expected that additional research will be required in subsequent years to address fully the glacier-related components of Questions 7.3.2.1 and 7.3.2.5. Hence, extension of the GLACIODYN and ICEMAC-GIS programs over the full timeframe proposed by ICARP II is proposed, particularly with enhanced linkages with the new satellite-based programs described in section 7.4.3.

Significant progress has been made in the advancement of river-ice modeling that considers various factors such as frazil transport, freeze-up bridging, ice growth and ice-jamming but comprehensive models that consider both river flow and ice dynamics are still in prototype states of development (Morse and Hicks, 2005). Observations of river ice during the dynamic periods of freeze-up and break-up (particularly with detailed slope information), combined with enhanced observations and prediction of river discharge will offer the ideal opportunity to refine and validate the current set of models over a suite of river-reach scales and thereby permit answers for Question 7.3.2.6.

7.4.6. Downscale Modeling: Future Climate and Scenarios

Some of the questions posed in this ICARP II science plan involve effects of future climate change. Future scenarios of climate change to drive the various models will rely on an ensemble of global climate model output from those selected by the most recent assessment by the Intergovernmental

Panel on Climate Change, i.e., over the 10-15 year timeframe of the ICARP II process beginning with those for the IPCC Fourth Assessment Report, due in 2007. Notably, however, much of the research to be conducted by this ICARP II science plan is likely to lead to improved understanding and related algorithms that can be incorporated into future global climate models and regional climate models. Examples range from better upper-soil layer definition for resolution of the permafrost active layer, particularly in areas of thin permafrost, to improved calculations of river-flow generation from various cryospheric components (snow and glaciers/ice caps) and its routing in ice-affected systems.

The expanded measurements and research proposed in this ICARP II science plan will also lead to an improved ability to forecast future conditions via confirmation of hind-cast results. The best example is that for glaciers/ice caps in which additional/improved mass-balance modeling will permit additional hind-casting in regions where atmospheric data are available. Expanded mass-balance observations (field-based and/or via satellite) will also provide credibility and an indication of the uncertainties in future predictions.

7.4.7. Data Rescue and Archiving

Important to all aspects of existing and proposed observation programs, particularly including remote sensing (see section 7.4.3), and the process/modeling studies (see sections 7.4.4 to 7.4.6) is the need to develop an integrated program of data rescue and archiving. Although a number of international bodies/agencies already exist for storing many of the identified physical variables, they are in many cases as unconnected as the programs that they serve. Ready access to a wide range of cryospheric and hydrologic data is essential to conduct many of the modeling studies and integrated assessments and subsequently to answer the scientific questions articulated in section 7.3. Given the rapid expansion of arctic research, including that proposed under IPY and in the various ICARP II science plans, this need is not unique. Two possible options exist to achieve successful data archiving: a fully integrated central data archive, or an integrated multi-node archive network. Although determination of final solutions to achieving appropriate data archiving methods would rest with the scientific body selected to oversees this ICARP II science plan (see sections 7.5 and 7.7), it would be logical to integrate data-archive activities with a program specifically designed for this such as the newly developed COMAAR (Co-ordination of Observation and Monitoring of the Arctic for Assessment and Research; see IPY initiatives in section 7.5.4).

7.5. Linkages / Users

The major focus of this ICARP II science plan is to identify and subsequently cement a network of linkages. There exist large ranges of recently completed, ongoing, and emerging science efforts that could be brought together to more effectively achieve their individual goals and, through their synergistic efforts, answer some critical cryospheric/hydrologic questions in the terrestrial Arctic. The various types of linkages are categorized in the following sections.

7.5.1. Research Program Extensions

This ICARP II science plan has direct linkages to several programs initiated by the WCRP that are complete, or are about to conclude. These include the two GEWEX studies dealing with cold regions hydrology in the Mackenzie (MAGS) and Lena river basins (GAME-Siberia). It will have the advantage of building on the data collected and work conducted under these two programs. Originally these large basins were also to be used for test sites under the PILPS program after the initial testing on a small northern basin in PILPS-2e. This program now offers the opportunity to validate the land process schemes at a variety of basin scales within the originally defined basins. The opportunity also exists to build on work conducted on the various, hydrologic research basins as linked through the UNESCO-IHP-NRB and currently under review by the US FWI.

7.5.2. Remote Sensing Validation

Through the establishment of supersites, this ICARP II science plan offers ideal basin platforms for the testing and validation of a number of new types of remote-sensing instruments that require high-latitude, cold-regions test sites. Linkages of various observation programs mean that the supersites proposed in this ICARP II science plan will have the fullest range of ancillary observations in the arctic regions necessary for calibration/validation. Remote sensing initiatives that could profit through such linkages include: precipitation (GPM and EGPM); soil moisture (GRACE and SMOS); snow and ice characteristics (ICESat; EOS-AMSR-E), thaw subsidence (ICESat, ASTER) and the upcoming hydrologic measurement programs such as WaTER.

7.5.3. Program Advancement

This program will also have necessary linkages to some other remote sensing systems/initiatives that are either already producing information about snow (GOES; EOS-Aqua & Terra MODIS) or glacier coverage (GLIMS). In the case of permafrost, this ICARP II science plan depends on linkages with the IPA-generated CALM and GTN-P/TSP to ensure expansion of these active layer and borehole monitoring programs into the supersite locations. Through hydrologic model upscaling, this program creates a direct linkage with the objectives of the International Association of Hydrological Sciences (IAHS) program for Predictions in Ungauged Basins (PUB). It is aimed at "formulating and implementing appropriate science programmes to engage and energise the scientific community, in a coordinated manner, toward achieving major advances in the capacity to make predictions in ungauged basins."

Overall, this ICARP II science plan has a direct linkage with many of the more global objectives formulated by the CliC program including their project areas:
- CPA1: The terrestrial cryosphere and hydrometeorology of cold regions
- CPA2: Glaciers, ice caps and ice sheets, and their relation to sea level, and
- CPA4: Links between the cryosphere and global climate.

Following the presentation of this ICARP II science plan to the international Arctic science community in Copenhagen (November 2005), members of the CliC Scientific Steering Group expressed a strong interest in employing the plan to help build its international research strategy for CPA1. More formal linkages are currently being pursued. Significantly, the CliC timeframe is comparable to that envisaged by this ICARP II science plan.

7.5.4. International Polar Year

In designing this ICARP II science plan, a linkage was forged with the program Arctic-HYDRA (see section 7.4.3, Runoff), which has been selected by the IPY Joint Committee as a core project. Moreover, it was agreed by the recently formed Arctic-HYDRA Steering Group that this ICARP II science plan will provide the scientific rationale for what is being proposed to be undertaken during IPY under Arctic-HYDRA. This is significant given that most national programs related to this theme have been requested by the IPY Joint Committee to be captured under Arctic-HYDRA.

As outlined in this program, much of arctic hydrology depends on permafrost conditions and therefore the work being conducted under CALM and GTS-P for the IPY TSP program will be invaluable. Given the value of the permafrost monitoring data, it is recommended that the supersites identified in this ICARP II science plan be spatially merged with present/future TSP monitoring locations. Similarly, given the research needs for hydrologic studies to be conducted at yet-to-be determined "supersites" under the IPY core project Freshwater Biodiversity Network, such sites should also be spatially integrated. One of the goals of this ICARP II science plan is to try and integrate a number of ongoing projects, the locations of "supersites" being one necessary objective. To this end, the newly developed COMAAR project, an initiative of the Arctic Council for the IPY, might be a vehicle to aid in the coordination of "supersites" identified in this ICARP II science plan and to manage the requisite data rescue and archiving described in section 7.4.7.

Although Arctic-HYDRA has a strong terrestrial hydrologic focus, answers to many of the Arctic-HYDRA/ICARP II Science Plan 7 scientific questions requires research on glaciers, ice caps and the Greenland Ice Sheet. Much of this information should be generated by the type of research proposed under the IPY projects, GLACIODYN and ICEMACH-GIS, although extensions of these programs beyond the Internal Polar Year would be needed to generate the detailed information required to answer fully the science questions listed in section 7.3.

7.5.5. Northerners and Ecological Systems

In addition to the various programs noted above, the design of this ICARP II science plan has developed from research needs identified in the Arctic Climate Impact Assessment (ACIA, 2005), which had a strong focus on evaluating the impact of climate change on northern residents. Specifically, it focused on needs identified in Chapter 6 (Cryosphere and Hydrology) by Walsh et al. (2005) and Chapter 8 (Freshwater Ecosystems and Fisheries) by Wrona et al. (2005) and related water-resource issues identified in additional socio-economic chapters. The program has also tried to provide supporting research for other ICARP II science plans, such as ICARP II Science Plan 8 which requires information about changing hydrologic conditions to assess related changes in biological feedbacks and biodiversity.

Successful initiation, conduct and completion of this ICARP II science plan will require that northerners be involved in as many of the development stages as possible. Such opportunities need to be explored through the regional and national government infrastructures, which include the various northern research laboratories and monitoring agencies. Participation is also essential from the various regional, national and international aboriginal organizations.

7.6. Outcomes / Achievements

Because the Arctic remains an area of frontier scientific study compared to most other parts of the globe, the current lack of a coordinated scientific infrastructure and the opportunity to fill this void through an integrated coordinated approach as outlined in this ICARP II science plan creates a unique opportunity. The proper design and coordination of a broad-scale range of cryospheric and hydrologic studies in the circumpolar north will prove to be a major international achievement, possibly unequalled elsewhere.

The major outcomes of this program will be the answers to the set of six specific questions outlined in section 7.3 and the creation of an international research structure and related long-term northern sites that can be used for answering many other questions related to the more general questions of section 7.3. Because water is such a central theme to so many arctic issues, an enormous list of outcomes that will accrue from this program could be generated. This is beyond the scope of this program description but important examples include:

- the definitive accounting on freshwater fluxes from all terrestrial cryospheric and hydrologic sources (i.e., from rivers to polar ice sheets) to the Arctic Ocean that are so important in controlling global climate (e.g., sea-ice production/radiation budgets and effects on the North Atlantic thermohaline circulation) and sea level rise;
- projections of terrestrial soil moisture and ice cover conditions that are needed by modelers of changes in terrestrial biodiversity (e.g., ICARP II Science Plan 8); and
- threats to northern residents that will result from changes in flood regimes and water availability regimes, water availability, and thawing permafrost.

Even the simple compilation of observations and modeled results will fill large spatial data gaps in many global monitoring archives, such as operated by the GRDC or the WGMS. This combined with a more comprehensive understanding of terrestrial cryospheric and hydrologic systems will also permit numerous related products to be generated for the Arctic, items that normally exist for other parts of the globe with larger population bases. One illustrative example of a concrete product useful for both scientists and northern residents would be a circumpolar atlas of arctic water resources including their availability and the local hazards they create. Most broadly, this knowledge base coupled with the modeling of future climate scenarios will provide northerners with the essential information on how their cryospheric and hydrologic systems will be affected, and thereby provide a guide on how they may have to adapt. Quantifiably predicting changes in hydrology or permafrost on a very local scale remains a problematic challenge; however, local impacts of a changing climate are of greatest concern to indigenous residents and therefore must be a goal of the research community.

7.7. Implementation

Two implementation strategies are required for the initiation of this ICARP II science plan, one at the programmatic level and the other at the operational level. There will also be short-, medium- and long-term implementation phases.

7.7.1. Phase 1: Programmatic

In the initial phase and at the programmatic level, it is clear from this ICARP II science plan that many ongoing research activities operating in the Arctic are germane to the scientific questions posed. Unfortunately, they are largely disparate programs with little formal linkage. This ICARP II science plan has been designed to orchestrate a coalescence of a number of program activities, at least geographically (e.g., via supersites), so that they can all profit from synergistic activities and also produce integrated results required to answer some of the key scientific questions. Initiating and continuing to promote program integration, however, cannot be completed in an ad hoc fashion and requires the long-term involvement of a dedicated scientific body. A number of potential international scientific organizations exist which could strike a program and/or group to address such integration of cryospheric and hydrologic activities. These include, for example, WCRP-CliC that already has a related set of program activities; IASC following along the lines of its related Working Group on Arctic Glaciology; CEON (Circumarctic Environmental Observatories Network) and its developing set of circumarctic observatories; or the newly forming International Study of Arctic Change (ISAC; initiated by IASC and the Arctic Ocean Sciences Board (AOSB); Anderson, 2005)), which wishes to become the legacy of IPY and through an international project office, the “home” of ICARP II projects. Whatever the selected body, they would be the one to facilitate and/or conduct the integration of results (including overseeing complementary observation programs/data archiving) to address scientific questions posed in section 7.3.

7.7.2. Phase 1: Operational

Once a program body has been identified a number of steps are needed to operationalize the program. It is proposed that a number of dedicated workshops be conducted to initiate integration. Given the overlapping objectives of many groups, it should be relatively straightforward to achieve a successful confederation of program activities.

The first key workshop should focus on the identification of supersites. In the case of glaciers, this is already being addressed by the IASC-WAG through their selection of 15 key glaciers. Although some preliminary review work has been conducted through an evaluation of UNESCO-IHP-NRB sites (Kane and Yang, 2004), a broader evaluation needs to be conducted in recognition of the different programs that would be involved. These would include the various remote-sensing programs that require northern sites for testing and validation of hydrologic products (e.g., GRACE, SMOS, ICESat, GPM, EGPM); the programs that would involve extension of their ground-based monitoring programs (e.g., Arctic-HYDRA, CALM, GTN-P/TSP), and the groups that would be involved in the process and upscale modeling activities in and from these supersites (e.g., PUB WG on cold regions, the various circumpolar Chief Delegates from the UNESCO-IHP-NRB, and those from GEWEX-PILPS for cold regions). Subsequent workshops would be needed to initiate focused work on the basins; budget conditions being one of the primary considerations (see section 7.8).

A related workshop would also be required to initiate integration of ice-hydraulic and hydrologic models. The hydrologists measuring/modeling flow generated from the supersite and upscale basins would be the logical group to interface with the ice-hydraulic modelers. Again, there are some pent up energies related to this topic that will assist in the research moving forward. In recognition of the need to integrate cold-regions hydrologic and hydraulic research, an international working group was struck (Ferrick and Prowse, 2000) in 1999 by the IAHS-International Commission on Snow and Ice (ICSI) and the Ice Committee of the International Association for Hydraulic Research (IAHR-Ice). There has been renewed interest in this group and the requisite work to answer Question 7.3.2.6 is an ideal focus for their next phase of activities.

7.7.3. Phases 2 & 3

Striking of a governing body and completion of the two workshops forms the initial implementation phase. The medium term will include other research and workshop activities including: establishment of supersite networks; identification/implementation of roving sites; calibration/validation of remote sensing (phased as new satellite systems come on line); parameterization of hydrologic, river-ice and glacier models; model calibration and validation, and initial future climate-scenario modeling. The final implementation phase will deal with the upscaling of results from the supersites and the broad-scale modeling of future-climate scenarios.

7.8. Funding

7.8.1. Synergistic Leveraging (Ongoing Programs and Initiation of IPY Activities)

Given the broad-scale nature of the most critical questions related to terrestrial arctic cryospheric and hydrologic systems, significant long-term funding is required to answer them (see section 7.8.3). However, in light of the large number of research groups with complementary sub-objectives to this overall research plan, much of this funding can result from financial "leveraging" of existing programs and projects. Many of the projects already operating in the Arctic on issues relevant to this ICARP II science plan already have funding and will be able to "profit" from the synergies of inter-program cooperation/integration, such as through the use of supersites. This is especially the case, for example, with the remote-sensing initiatives that require well-instrumented high-latitude calibration and validation sites. Moreover, given that during the development phase of this ICARP II science plan, a number of studies have been generated with comparable objectives to those identified by this project. For example, Arctic-HYDRA, the core hydrologic project of the IPY has adopted much of the research foci of this ICARP II science plan. Moreover, most of the hydrologic studies proposed by individual countries have been clustered under Arctic-HYDRA. Hence, IPY funding should be available for a number of the objectives defined in this ICARP II science plan. The main issue will be whether such funding will be continued by participating countries after IPY. To this end, the best budget approach will be to ensure that an international scientific body assumes the responsibility of ensuring the continuation of the programs.

7.8.2. Phase 1 (Governing Scientific Bodies and Initial Workshops)

One desired outcome of the ICARP II meeting in November 2005 was the identification of a scientific body to take charge of the ICARP II Working Group 7 project. Members of the Scientific Steering Committee of the WCRP program CliC expressed a strong interest in this ICARP II program and how it could assist in the development of CPA1 (The terrestrial cryosphere and hydrometeorology of cold regions), although the program has implications for its other programs dealing with sea-level rise and global climate. However, given that this ICARP II science plan deals specifically with the Arctic, it is also recommended that a dedicated Working/ Steering Group also be established but operating under the auspices of CliC. Annual costs for the operations of such a group are estimated to be approximately US$60,000 per year. Additional costs would also be associated with the planning and undertaking of the two integrative workshops identified for Phase 1 (see section 7.7.2). These would be essential to promote the inter-program synergies that will ultimately lead to significant multi-program leveraging of resources.

Costs for planning and undertaking the initial supersite workshop would be in the order of US$50,000 and US$150,000 respectively. Costs for the ice hydrologic-hydraulics workshop for the same two activities are estimated at US$20,000 and US$80,000, respectively. Thus the first phase of this program, likely to occur in the first two years of the program and preferably to interface with the implementation of the IPY studies, could be completed at a total cost of US$420,000. Some of the workshop costs could well be partly funded through coordinated activities with the IPY programs (e.g., using COMAAR for assistance in supersite selection). No specific agency for securing Phase 1 funds has been identified here but it is recommended as a point of discussion for the ICARP II steering group, the international bodies (including the Arctic Council and the IASC) in attendance at the 2006 Arctic Science Summit Week at which this plan will be delivered, and other relevant international scientific bodies (e.g., WCRP-CliC and ISAC – see section 7.8.3).

7.8.3. Phase 2 & 3 (Long-term Program Management and International Contributions)

Some of the largest costs associated with this ICARP II science plan will be from the potential observation infrastructure that might have to be instituted at the supersite locations. Levels of funding for such, however, are difficult to estimate at this time prior to the identification of the sites and also in recognition that many will be supported by individual countries and their respective federal departments and funding agencies. The costs borne by the various circumpolar monitoring agencies involved with the establishment of Arctic-HYDRA is one such example. Notably, however, some countries (e.g., Canada) are already in the process of identifying resources that could be used for supporting the program objectives, such as through IPY and/or GEOS (Global Earth Observation System) activities.

Securing funds to ensure successful continuation of this program through Phases 2 & 3 is expected to be the responsibility of the governing scientific body identified in Phase 1. This could be aided by official program status of the governing body, such as that proposed by the Interim Science Planning Group of ISAC that envisions ISAC to be the pan-arctic focus for future funding calls. To this end, however, it is important to stress that this program builds upon many national research programs, such as the FWI in the US and MAGS in Canada that are about to conclude without any clear program successors. Extensions to these or revised/updated programs are critical to achieving the scientific synergies necessary to answer the scientific questions posed here and articulated in related international science assessments. Moreover, this ICARP II science plan also offers the vehicle by which various other non-arctic nations, which are increasingly recognizing the global importance of arctic processes, can participate in an internationally collaborative research program. More generally, direct national participation can provide concrete evidence of responding to the critical research needs expressed by international arctic assessments such as the Arctic Climate Impact Assessment (ACIA, 2005). Budget estimates are difficult but they would be in the range of five to ten million US dollars per year, or approximately an order of magnitude larger than the coordination function outlined for Phase 1.

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