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Appendix 2

Current Gaps in Understanding the Pan-Arctic Hydrological Cycle

The listing below was drawn from the set of key, unresolved scientific and technical issues that were solicited from participants of the NSF-ARCSS Arctic Hydrology Workshop, held at the National Center for Ecological Analysis and Synthesis, Santa Barbara, California, in September 2000. This listing is organized by the major domains over which the water cycle plays an integrative role: land, oceans, atmosphere, society (see Figures 1-1, 1-3, 2-1, 2-2). A subset of these issues has been identified and further articulated in the main body of this report.

Land Systems

Scientific Questions

- What would be the river response to extreme Holocene climatic events?
- How is spring meltwater partitioned into infiltration and runoff?
- What is the relative role of soil moisture dynamics in relation to other hydrological processes?
- What is the role of wind-pumping convection in arctic depth hoar and what is the importance of hard slab and snow dune formation processes?
- What determines the regional and temporal distribution of snow trends? Is it tied to the AO?
- How important is lateral transfer of heat during snowmelt?
- What are the mechanisms of vegetation-snow feedback?
- What is the role of vegetation in water budgets and how does it vary in space and time?
- What is the affect of boreal forests on pan-arctic hydrologic processes?
- Is there widespread drying of soil and ponds across the pan-Arctic in response to regional warming trends, and if so what is its impact on resident ecosystems?
- What is the distribution and importance of rock glaciers and rock fields as a source of late summer arctic discharge?
- What controls basin morphology in watersheds underlain by permafrost and how will it change with a warming climate?
- How does the fact that sediment is immobile (frozen) at the time of maximum stream power affect the sediment load in arctic rivers?
- What are the pathways of sediment discharged into the continental shelves by the arctic rivers and is the variability of this sediment delivery large enough to be represented in paleorecords?
- What is the timing and magnitude of sediment, carbon, and nutrient loads from hillslopes to large rivers and what is the effective constituent discharge of ice-affected rivers?
- How will sediment and other constituent discharges change as permafrost distribution responds to climate warming?
- What are the controls on the transfer of nutrients and organic matter from soils to streams across the pan-Arctic?

Technical Needs and Uncertainties

- Study energy, water, and carbon cycles as a linked system.
- Develop methods to quantify historic levels of soil moisture.
- Quantify the cumulative impacts of industrial and civil development on hydrologic systems.
- Improve understanding of water storage and subsurface flow processes in discontinuous permafrost and mountainous regions.
- Improve understanding of the surface heat and mass transfer processes in mountain regions.
- Better define the role of geometric patterns of permafrost degradation and its ecological and hydrological consequences.
- Develop better understanding of hydraulic routing through

glaciers; models of glacier runoff need better depiction of water dynamics at the base of the glaciers.

- Improve understanding of groundwater fluxes, including dynamics during winter.
- Sublimation needs better quantification.
- Methods need to be developed for improved mid-winter discharge measurements in high-latitude rivers.
- Wind-blown flux of snow and its redistribution is a critical unknown.
- Winter wind speed and direction often unreliable due to riming/icing of sensors; improved technology is required.
- Reliable methods to provide electrical power to remote weather stations need to be developed.
- Stratigraphy is hard to measure widely but determines critical bulk thermal and physical properties of arctic soils.
- Accurate and widespread measurement of winter precipitation not yet achieved.
- Improve upon the quality and documentation of observing techniques for making precipitation measurements.
- Link NSF arctic hydrological initiatives more closely to GEWEX/Mags, Crysys/ACSYS/CLiC.

Data Needs

- Quantify paleoclimatic forcing fields.
- Requirement for long-term observations of soil moisture at stations with climate data.
- Need for time series of discharge along the Arctic Coast that is ocean model-ready (including

gauged and ungauged, chemistry, pollutants, sediments and heat).

- Accurate digital elevation models and vegetation maps necessary for hydrological studies.
- Thermal and hydraulic properties of frozen soils need to be sampled more systematically.
- Critical need for permafrost temperatures and distribution, including active zone dynamics.
- Measure the spatial and temporal variation of P-E around the Arctic.
- Develop and apply standard methods of precipitation measurement and correction.
- Fully quantify and map current glacier-covered areas to provide baseline for change.
- Need more arctic glacier mass balance measurements.
- Data rescue of hydrology observations from former USSR.
- Assessment of hydrometeorological data across national and other administrative borders is necessary due to wide array of sampling equipment.
- Need streamflow from a wide range of watershed scales.
- Snow cover depth maps derived from remote sensing or meteorological inputs need to be harmonized and cross-validated.
- Conventional networks are under severe cost pressures and automation leads to loss of key data and data degradation.
- Develop baseline data set of chemical (nutrient, sediment, contaminant, tracer) flux from all rivers in the Arctic Basin.

Scaling-Related Issues

- Do processes in the headwater basins really matter when modeling large basins and regions?

- New methods are necessary to scale hydrologic fluxes across basin sizes, from smallest headwaters to scale of the pan-Arctic.
- Improved techniques are needed to rescale hydrologic processes from points to GCM domains.
- Creation of gridded data sets by interpolation of sparse data across space and time requires additional attention.

Modeling and Related Analysis

- Need extensive soil moisture modeling over cold regions.
- Need improved methods for remotely sensing soil moisture over large areas.
- Snow sub-grid distribution variations by modeling or remote sensing remains a need.
- Spatial variation of snow cover insulation and density (snow water equivalent) is currently poorly articulated.
- Validation of model outputs of snow cover, snow water equivalent, snow depth, and precipitation is required.
- Develop and verify models of mass transport from ungauged watersheds for water, nutrients, and sediment.
- Compare regional water balances across Siberian, North American, and Northern European domains.
- Improve representation of permafrost in regional and global climate and hydrological models.
- Improve compatibility of *in situ* measurements, remotely sensed, and modeled data.
- Need for model intercomparison from local to pan-arctic scale.

Ocean Systems

Scientific Questions

- What was the timing and extent of the Eurasian ice sheet and its impact on the coasts and ocean?
- How do terrestrial ecosystem dynamics affect freshwater fluxes to oceans?
- What are the processes and effects of stamuhki: runoff over and under fast ice?

Data Issues

- Develop time series of sea level measurements around the Arctic Basin.
- Quantify biogeochemistry and primary productivity in estuaries and shelf regions.
- Document exchange in marginal seas, mixing and vertical fluxes associated with freshwater.
- Measurement of sea ice.
- Measurement of snow thermal, optical hydraulic properties.
- Develop improved methods for incorporating sediment-tracer studies in oceanographical studies depicting the fate of freshwater.

Modeling Issues

- Develop models of near-shore and estuarine exchanges of water and constituents.

- Further current understanding of the partitioning of freshwater into sea ice and sea water as a function of space and time.
- Develop fully coupled freshwater-sea ice-atmosphere simulations.

Atmospheric Systems

Scientific Questions

- What is the moisture flux convergence between Greenland and Scandinavia?
- What is the spatial and temporal variability of precipitation minus evaporation (P-E) over arctic land mass and ocean?
- Which factors control summer circulation regime near western Siberia?
- How does global warming forcing invoke feedbacks from the pan-arctic system and from the arctic water cycle?
- How does the atmospheric boundary layer respond to snow melt?

Data Issues

- Improve rawinsonde network in Eurasia and Canada.
- Secure agreements to work with numerical weather prediction modelers to jointly process pan-arctic data sets.

Modeling Issues

- Develop coupled, fully interactive arctic process models that include vegetation and how it interacts with the land surface and the atmosphere.
- Develop subgrid land surface process representations, with tests to determine which ones are important.
- Improve representation of permafrost in regional and global climate and hydrological models.

Human Systems

Key Issues

- Identify parameters, locations, and activities where we expect that human activities in the Arctic demonstrate most sensitivity to hydrological change.
- Conduct empirical studies of how observed hydrological variations affect human settlements and activities in the Arctic.
- Integrate findings from the two steps above with physical science results to project future human impacts of likely hydrological changes.

Appendix 3

Integration of Arctic-CHAMP with NSF and Other Federal Agency Initiatives

NSF Programs

Several offices of the Foundation support arctic research and there are numerous opportunities for Arctic-CHAMP to capitalize on this shared interest in the region. NSF has already invested heavily in field campaigns, modeling, monitoring and instrumentation, database development, and paleo studies.

NSF Field-Oriented Programs

Arctic-CHAMP intensive field campaigns will be based on a rich heritage drawn from the several ARCSS field programs listed in Box 6-2. Although many of these research efforts have been fundamentally interdisciplinary—for example, the collaborative work of boundary layer physicists and ecosystem field scientists at LAIL sites—there has been little tangible movement toward an integration across all ARCSS Program elements.

Existing Synthesis Efforts

The ARCSS Synthesis, Integration and Modeling Studies (SIMS) program funds a small group of scientists who are beginning to work toward a quantitative picture of the Arctic as an interacting part of the

earth system. At the heart of SIMS is a recognition of the importance of analysis of observational records as well as modeling as a means to catalyze cross-disciplinary understanding. Arctic-CHAMP would make an obvious contribution to the overall SIMS effort, and in some sense represents a substantial expansion of SIMS. The Arctic Natural Sciences Program provides core support to disciplinary studies in atmospheric sciences, earth sciences, ecosystem analysis, glaciology, and oceanography, as well as facilitation of cross-disciplinary polar projects supported by the NSF Office of Polar Programs (OPP). Coordination of Arctic-CHAMP with the Arctic Natural Sciences Program would be beneficial.

Role of Current NSF Paleo Studies

A seasonal-to-centuries time frame is targeted for Arctic-CHAMP which will require retrospective paleo, historical, and contemporary monitoring in tandem with models describing each of these time domains. There would be obvious connections to virtually all NSF-OPP initiatives. The Paleo-environmental Arctic Sciences

(PARCS) program helps to articulate the nature of Quaternary climates over the Arctic and sub-Arctic. PARCS itself has promoted synthesis studies including development of arctic proxy data (e.g., PARCS database) and data-model comparisons (e.g., Circum-Arctic PaleoEnvironments [CAPE], Paleoclimate Modeling Inter-comparison Project [PMIP]).

NSF-Funded Monitoring and Instrumentation Efforts

OPP is active in supporting initiatives to improve the current state of the art and it is recommended that Arctic-CHAMP capitalize on progress to date. Two programs are noteworthy. The first, the Polar Instrumentation and Technology Development Program, supports research infrastructure in high-latitude environments, including development of novel techniques for harsh weather sampling. Second, the Long-Term Observatory (LTO) Program (joint between ARCSS, Division of Atmospheric Sciences, and Division of Environmental Biology) is currently supporting an array of individual projects seeking to establish arctic environmental observatories,

sample repositories, and remote/autonomous instrumentation. Long-term data sets associated with the NSF-LTER (Long-Term Ecosystem Research) Program also provide important supporting information. An integration and expansion of these NSF-supported environmental monitoring capabilities will be key to a successful Arctic-CHAMP.

Integrated Arctic Database Efforts

Another critical component of Arctic-CHAMP will be development of an integrated database of routinely collected observational data (e.g., precipitation, discharge), intensively sampled process-experiment results (e.g., from long-term watershed sites), biogeophysical forcing fields for Arctic-CHAMP models (e.g., from GCMs, weather prediction forecast/reanalysis models), and outputs from arctic system simulation models. A permanent archive for ARCSS-generated data is well established through the Arctic System Science Data Coordination Center at the National Snow and Ice Data Center (NSIDC). It is recommended that an ongoing dialogue be established with this data repository to accommodate Arctic-CHAMP data needs, with requisite funding support from ARCSS.

Interagency Issues and Opportunities

Arctic-CHAMP's Role in U.S.

Arctic Research

Because Arctic-CHAMP is envisioned to catalyze arctic and earth system synthesis activities, it could make important contributions to federally funded programs beyond NSF. The Interagency Arctic Research Policy Committee (IARPC),

a multioffice initiative chaired by NSF, could provide the appropriate multiagency context for Arctic-CHAMP. IARPC includes thirteen individual agencies and offices, setting priorities for future arctic research, preparing multiagency budget requests, and promoting cross-agency research coordination, including logistical planning and data sharing. With the Arctic Research Commission (USARC), it establishes integrated arctic research policy. Arctic-CHAMP provides an opportunity for IARPC to support its mandate of fostering integrated research and data exchange.

Arctic-CHAMP and SEARCH

Many of the issues described in this hydrology-related strategic plan are, in fact, interagency SEARCH issues. These are concerned with changes in arctic hydrology that may be related to the features of more broad-scale pan-arctic environmental change (see Box 4-1; Chapter 5 Boxes), and thus linked to the atmospheric and oceanic branches of the hydrological cycle (SEARCH SSC, 2001). In recognition of such linkages to the terrestrial domain, SEARCH evolved from ARCSS-OAII into a thematic program extending across several individual components of NSF-ARCSS. And now, SEARCH has become an interagency and international effort as well. In the U.S. it includes partners from NSF, NOAA, DOD, NASA, EPA, and DOI. Arctic-CHAMP, since it seeks to provide a long-term and pan-arctic perspective on the terrestrial water cycle, could play a prominent role in SEARCH and be NSF-ARCSS's contribution to the overall initiative.

Fostering Links to NOAA and Arctic Operational Analysis

The newly formed NOAA Arctic Research Office promotes studies into the role of the Arctic in global weather and climate variability, impacts of environmental change on marine resources, and vulnerability of human health in the Arctic to contaminant pollution. NOAA and NSF share leadership for U.S. interests in the Arctic Climate Impact Assessment (ACIA), a pan-arctic initiative of the intergovernmental Arctic Council set for completion in 2004. The NOAA National Center for Environmental Prediction (NCEP) also can provide contemporary numerical weather predictions, as well as systematic reanalysis of multiyear atmospheric dynamics to support diagnostic versions of Arctic-CHAMP models. The interaction should be two-way, with Arctic-CHAMP researchers working with NOAA staff to improve current versions of NCEP operational land surface schemes over high latitudes.

Arctic-CHAMP and NASA Satellite Missions

NASA has recently put forward a series of post-2002 mission concepts focused on land surface hydrology. These include the systematic collection of data on soil moisture, global precipitation, inland surface waters, and cold region processes (Jackson et al. 1999, Vörösmarty et al. 1999, Cline et al. 1999). The cryospheric monitoring mission, envisioned to include some combination of passive or active radiometers, will provide a pan-arctic view of freeze-thaw dynamics, critical information for activating and in-

activating the large array of physical and biological processes considered by Arctic-CHAMP. NASA Earth Observing System (EOS) sensors will measure a very large number of biogeophysical variables (Parkinson et al. 2000), which should also be exploited by Arctic-CHAMP diagnostic models of the contemporary pan-Arctic. The Global Precipitation Mission (GPM) could be enhanced by the use of Arctic-CHAMP validation products over the pan-Arctic. Work should be directed within Arctic-CHAMP to develop a means for assimilating the operational data sets to emerge from these missions.

Glacial mass balance and the associated discharges of meltwater is an important observational re-

quirement within Arctic-CHAMP. GLIMS (Global Land Ice Measurements from Space) is analyzing the world's glaciers using data from EOS-ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). NASA ICESat, scheduled to launch in July 2001, is a benchmark EOS mission to measure ice sheet mass balance, cloud and aerosol heights, vegetation, and land topography via laser altimetry. NASA's Program in Arctic Regional Climate Assessment (PARCA) is currently using airborne laser altimetry to measure ice sheet thickness changes, with an emphasis on the changing character of the Greenland ice sheet.

Appendix 4

International Collaborations

There are several major international science initiatives—both ongoing and planned—that focus on the Arctic. Many have made substantial investments in polar research and could provide a mutually beneficial synergy with Arctic-CHAMP.

Among the numerous ongoing efforts, two broad-scale scientific initiatives would provide benefit to Arctic-CHAMP. The World Meteorological Organization's World Climate Research Program and the International Geosphere-Biosphere Program (IGBP) represent major efforts at securing an improved understanding of the interactions across atmosphere-land-ocean system and their impacts on climate dynamics and the biosphere. The pan-Arctic, as a well-bounded, linked land-atmosphere-ocean system, provides a unique test bed for regional and global climate, biology, and biogeochemical feedback studies. The World Climate Research Program (WCRP) Global Energy and Water Experiment (GEWEX) and its focus on improving land-atmosphere linkage modeling has numerous activities, including large-scale river basin experiments, such as in Siberia, that will aid in the integration of water cycle dynamics into future climate models.

WCRP's Arctic Climate System Study (ACSYS) and follow-on Climate and the Cryosphere (CliC) Project provides another important programmatic link (WCRP 1998, 1999, Allison et al. 2000). Major synthesis efforts are underway in the IGBP, including analysis of paleoenvironmental dynamics across the high north. SEARCH has already integrated some of its activities with the WCRP Climate Variability and Predictability Study (CLIVAR) and provides an excellent vehicle by which to unite Arctic-CHAMP hydrology with a much larger international initiative.

Intercomparison Studies

An important component of Arctic-CHAMP is the objective assessment of algorithms and observational data sets, and there are several opportunities for linkages to ongoing intercomparison experiments. Intercomparison studies of the type envisioned for Arctic-CHAMP are already ongoing in several international fora (Box 6-3) (e.g., Goodison et al. 1998). These treat land-surface exchanges including the dynamics of vegetation and snow and consider both contemporary and paleo time domains.

Existing Field Sites

A central idea behind Arctic-CHAMP is to create a series of well-instrumented process study sites across the northern high latitudes. The program could benefit greatly by conjunctive use of existing study sites, supported by both federal and international science agencies (Box 6-3). The value of such experiments is highly evident, with the corresponding data sets typically analyzed for several years after the dedicated field experiments have ended (e.g., BOREAS). Sustaining long-term experiments will provide even more scientific value. Cost-sharing across several international agencies will be required but will provide to all the observational context by which to monitor ongoing arctic change and improve upon our current level of process understanding.

Remote Sensing

The use of remote sensing will be essential for achieving a truly pan-arctic perspective (Goodison et al. 1999). U.S.-based activities, discussed in chapter 2, are well-augmented by several international efforts. The utility of radar systems to infer water and freeze or thaw state, together with the absence of a U.S. radar satellite system, makes

collaboration with European, Japanese, and Canadian space agencies essential. Such data have traditionally been costly both in terms of their price and computer storage and processing requirements, making it difficult to assemble long and coherent time series. A funding commitment to make these data sets available would help to achieve a more complete picture of the seasonal storage and release of frozen water than is currently possible.

Major Monitoring Programs

Several multiorganizational observational frameworks for systematic change detection and improved climate prediction are also in place, exemplified by the Global Climate and Global Terrestrial Observing Systems (GCOS/GTOS). These seek to establish a global reference network of land surface observational weather/climate stations, including several of high relevance to the pan-Arctic (Cihlar et al. 2000). These activities also encompass International Perma-

frost Association activities in monitoring frozen soil condition. The immediate challenge is for individual countries to acquire the resources to implement an observational program that will meet both their own needs and contribute to those outlined for GCOS/GTOS networks. Canada, for example, plans to enhance its current GCOS surface network and its cryospheric observing system in remote northern regions as its contribution to international arctic science.

Numerical Weather Prediction and Reanalysis

The Arctic-CHAMP models will be cast in both a diagnostic and prognostic mode. Important data sets are currently being prepared by the European Center for Medium-range Weather Forecasting (ECMWF). The forthcoming ERA-40 global reanalysis will provide a nearly half-century time series (1957–present) of atmospheric variables at high spatial and temporal resolution. It is critical to assess the performance of this and

other such products from the standpoint of water and energy conservation and the production of sensible predictions with respect to the land surface hydrological cycle. ECMWF has been receptive to the inputs of Arctic researchers and a productive interaction could be further promoted through Arctic-CHAMP.

International Data Archives

Arctic-CHAMP data requirements could take advantage of several major international data collection, archiving, and distribution activities. These involve both global and arctic-wide data repositories. Given the wealth of geophysical data sets currently available, meta-data systems and search engines optimized for Arctic-CHAMP research needs should be established. An early activity of the Arctic-CHAMP Synthesis and Education Center could be the assembly of existing, hydrologically relevant arctic environmental data to provide a quantitative benchmark for assessing future change.