

Designing, Optimizing, and Implementing an Arctic Observing Network

A Report by the Arctic Observing Network
Design and Implementation Task Force



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*Study of Environmental Arctic Change (SEARCH)
Fairbanks, Alaska
2012*



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On the cover:

The “Snow Bird” looks for light making its way into the snowpack. Here Barry Lefer checks the instruments on a computer screen to ensure it is collecting valuable data as the moon watches overhead. Near the Bally Building, Summit Camp, Greenland. Photo by Craig Beals (PolarTREC 2008), courtesy of ARCUS.

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A tripod that is part of the Circumpolar Active Layer Monitoring Network (CALM) is marked so that it is more easily distinguishable for future pilots and data collectors. Toolik Field Station, Alaska. Photo by Josh Dugat (PolarTREC 2010), courtesy of ARCUS.



Executive Summary

The Arctic has become a focus of scientific research through its role as both an amplifier and driver of global climate change. Policy imperatives involving Arctic climate change range from marine shipping to resource extraction, the vulnerability of civil and private infrastructure, and the preservation of endangered biotic and cultural assets. Just as the environment and decision-making contexts are rapidly changing, so has the scope and nature of observing strategies to monitor and understand Arctic system change. The concept of an integrated Arctic observatory dates to the late 1990s with early planning of the Study of Environmental Arctic Change (SEARCH) initiative. The multidisciplinary Arctic Observing Network (AON) has been implemented with guidance from SEARCH workshop reports, the 2006 “Toward an Integrated Arctic Observing Network” report by the National Research Council, and meetings organized through the SEARCH Observing Change Panel. The International Polar Year (IPY) of 2007–2008 provided substantial resources to put in place key pieces of an AON. We are now ready to review options and approaches to guide observing system design and optimizing a sustainable system. This Arctic Observation Network Design and Implementation (ADI) Task Force report provides guidance to the National Science Foundation (NSF) and other agencies interested in the AON. This report focuses on the continued development of the AON, with the following major goals:

- assess the present state and near-term implementation plans of the AON and related efforts,
- synthesize lessons learned from other observing systems,
- identify and assess promising approaches and tools for system design and optimization,
- offer and discuss specific design options and approaches, and
- provide a summary of ADI Task Force findings and recommendations.

The ADI Task Force efforts to engage a broad set of contributors included a community survey and two workshops (in 2009 and 2012) to discuss observing systems and approaches. Outcomes of the workshops and community survey are provided in this report; these serve as the foundation for the Task Force recommendations.

Assessment of the Present State of the AON

The science goals of the AON encompass a broad range of questions that span many disciplines, as outlined in SEARCH science planning and implementation documents. While it is difficult to design and optimize a multidisciplinary observation network, the starting point is system specification—there must be design targets to optimize around. Without such targets, there is no way to assess which is the optimum configuration.

A necessary first step for network design is to identify science questions that the observational network will address. The SEARCH Understanding Change Panel

completed a preliminary and qualitative assessment of the present AON in terms of scientific gaps, needs, and priorities (Elliott et al. 2010). The panel's assessment of needs was organized into five spheres: (1) marine changes, (2) atmospheric changes, (3) terrestrial changes, (4) Arctic–global connections, and (5) the integration of information and knowledge networks. The observational needs summarized by the small SEARCH panel in each sphere are discussed in the report, and the following overarching design strategy needs were identified as a follow-up to the SEARCH panel assessment:

- address observational requirements (accuracy, frequency, locations, etc.) with quantitative rigor, and
- identify the architecture of a system-scale framework that will enable assessments of how particular observations would impact understanding and prediction issues or problems that span several components of the Arctic system.

Approaches and Tools for Observing System Design and Optimization

The ADI Task Force convened a community workshop in December 2009 to review and discuss lessons learned from other observing systems, with a focus on mature efforts outside of the polar regions. The workshop also reviewed state-of-the-art observing system design approaches that could be applied to the AON. Following the 2009 workshop, the ADI Task Force, with input from the broader research community, developed a hierarchy of approaches for observing system design and optimization. The six broad categories for design and optimization methods are:

- 1. Integration through overarching projects, including impacts of change on human activities**—an approach that integrates observation sites, methodologies, and metrics used in previous work to identify the needs for an observing network.
- 2. Retrospective analysis and review of past work**—an approach that reviews previous work to identify gaps in data collection and to describe any potential obstacles identified from existing observing systems.
- 3. Ecosystem services**—a mostly qualitative approach to identify observation parameters based on ecosystem services that are important to stakeholders at local and regional scales.
- 4. Data thinning experiments**—a model-based approach that can be used to determine the minimal observational densities and assist in identifying the protocols and frequencies for making observations.
- 5. Model-based observing system experiments (OSEs)**—a model-based approach that can be used to assess the impact of observations or observation sites for a particular application.
- 6. Observing system simulation experiments (OSSEs)**—a model-based approach to optimizing network design using different scenarios of observing network design.

Examples of key approaches for each category are summarized in Table 1. The first three methodological approaches are mostly qualitative in nature and would be most suitable for observing goals that are less well-defined. The last three approaches are quantitative and model-based and require a greater level of understanding of the observing system design goals and the local-scale expression of the processes that

are driving the observed change. The quantitative assessments may also be more applicable for optimizing or adapting existing observing systems.

A hierarchy for the elements of AON design and optimization is presented in Table 2. This provides a context for using the different methodological approaches discussed above. Using qualitative approaches such as retrospective analysis and review of past work would be most applicable at the strategy or tactics stage, whereas more quantitative approaches such as OSSEs and OSEs are more applicable at the planning stage for specific deployments and campaigns.

Table 1. Range of different approaches and specific examples for observing system design

Methodological Category	Specific Approaches and Examples of Potential Studies
<p>Qualitative and Semi-quantitative Evaluations</p> <p>Integration through overarching projects, including impacts of change on human activities</p> <p>Retrospective analysis & review of past work</p> <p>Ecosystem services</p>	<p>Synthesis of past reviews & disciplinary design studies; review of existing observation sites & methodologies of state of permafrost; retrospective analysis of forecasting efforts from the perspective of management of living marine resources; statistical modeling of environmental and human dimensions variables; pattern recognition experiments using existing biogeophysical observations to understand coordinated and/or uncoordinated signatures of change in Arctic terrestrial ecosystems; thematic and physical coherence studies among all variables tested</p> <p>Synthesis of existing approaches; gap analysis; spatial scales of variability; design of repeat sections; detection of system spatial-temporal patterns of change in Arctic terrestrial environments; sphere of influence of Arctic communities for snow measurements; statistical modeling of environmental and human dimensions variables</p> <p>Identification of ecosystem services (supporting, provisioning, cultural, or regulating services); quantifying these services in biogeophysical terms; translating the service metrics to engage stakeholders in resource management</p>
<p>Quantitative Model-based Assessments</p> <p>Data thinning experiments</p> <p>Model-based observing system experiments (OSEs)</p> <p>Observing system simulation experiments (OSSEs)</p>	<p>Spatial and temporal scales for snow observation network design; optimal sampling of leading modes of variability</p> <p>Data denial experiments; sensitivity studies of key Arctic climate indices; spatial scales of variability in ocean-ice interaction</p> <p>Assessment of hypothetical datasets collected through an observing network at specified locations, using predictive or diagnostic models to build on an observing system</p>

Table 2. Elements of AON design and optimization hierarchy

AON Design Elements	Activity	Implementation	Discussion in Report
Problem definition	Development of science goals and definition of actionable science questions	SEARCH program, agencies, stakeholders, AON Science Steering Group	Section 2 (AON science question alignment chapter)
Strategy	Feedback and uncertainty analysis, identification of metrics, model-based assessments, process studies	Working groups, funded projects, ad-hoc meetings (researchers, agencies, stakeholders)	Section 6.2 (Heuristic feedback and uncertainty analysis)
Tactics	Target quantity definition and measurement options, model-based assessments	Synthesis forums (e.g., Sea Ice Outlook, flagship site teams), funded projects and ad-hoc meetings (researchers, agencies, stakeholders)	Section 6.3 (Sea Ice Outlook section)
Deployment scale	Sampling array design	AON projects, OSSE/OSE teams	Section 4.2.6 (OSSE chapter/case study)

Synthesis of Lessons Learned From Other Observing Systems

The Arctic is not the first domain in which integrated observing challenges have been addressed. A broad suite of research and application themes have required sustained observational networks, including operational meteorology, climate change detection, carbon exchange with the biosphere, oceanography, seismology, socioeconomic surveys, and so on. Lessons learned from the Long Term Ecological Research (LTER) network, other observing networks, and feedback from 120 responses to the community survey were discussed by the ADI Task Force and were used to help determine the Task Force recommendations. A summary of these lessons suggests that networks with a distinct focus rather than broader, less clearly articulated objectives are more successful, in particular if coupled with continuous feedback from stakeholders and data users on the evolution of network requirements. Data must be comparable across individual sites, allowing for network-wide analyses and integration into an overarching network of networks. These needs are best met in a context that allows for interagency and international network contributions. Data management needs to be integrated into network design from the outset. Moreover, a scientific oversight group is critical to successful programs. A key function of such a group is to ensure that data serve the identified (and sometimes evolving) needs and are made available as soon as possible and in a form useful to the broader stakeholder community.

ADI Community Survey

The ADI Task Force launched a survey of the scientific community to obtain additional information on relevant design and optimization approaches, lessons learned from previous and existing efforts, and priorities for AON implementation. A total of 120 respondents provided input, which is reflected in the conclusions and recommendations outlined below. Analysis of survey responses, grouped into AON

principal investigators and others as well as scientists from academia or government agencies, yielded statistically significant differences in some categories and provided insights that will be helpful in AON implementation. Key challenges identified by a majority of respondents include the availability of data from the AON (including the rapid release of data), consistency in observation protocols, implementation of effective management models, sustained funding support, and technical limitations. Open-ended question responses provided guidance on how to overcome such challenges, with the need for national and international coordination seen as the most important priority.

Discussion of Design Options and Approaches

A strategy is essential for distilling the complex Arctic system into its fundamental components and the interactions among them. A strategy also allows an objective assessment of changes and uncertainties in these interactions. One example of how such a strategy might unfold is to employ a heuristic approach to determine the critical feedbacks and relationships between key components of interest for a specific science question. As one such case study, changes relevant to the Arctic hydrological system were considered (Francis et al. 2009). To help identify criteria and metrics useful in observing system design and optimization, a focus on the system components that directly affect life was chosen: marine primary productivity, terrestrial vegetation, and people living in the Arctic. This case study illustrates a strategy for distilling a complex system into its fundamental components and allows the objective assessment of uncertainties in our understanding of the interactions between those components. Alleviating those uncertainties can then guide an observing strategy such as the AON. The focus on living components also provides a framework to help prioritize key variables and interactions and greatly reduces the scope of the investigation.

A second case study considered by the ADI Task Force, centered on the SEARCH Arctic Sea Ice Outlook, is an effort to synthesize findings from different seasonal ice prediction approaches to improve the prediction of seasonal and interannual ice variations. The Sea Ice Outlook illustrates how a set of science questions and metrics (in this case related to pan-Arctic and regional ice extent prediction) can be arrived at jointly by different interests within the scientific community and key stakeholder groups. This greater level of specificity, compared to the example for the hydrologic cycle, allows for a discussion of different approaches to deploying observing assets. In the case of the Sea Ice Outlook, coupled ice-ocean models provided guidance on priorities of key variables and ideal measurement locations, similar to what an OSSE would indicate. Through the synthesis aspects of the Sea Ice Outlook effort, such findings can be linked back to required accuracies of remote sensing data that form the basis for the analysis of successful ice prediction.

ADI Task Force Conclusions and Recommendations

The conclusions and recommendations of the ADI Task Force include a synthesis of challenges, lessons learned, and relevant methodologies for observing system design. Specifically, they include the following:

1. **Key science questions:** The key science questions driving network design and optimization must be laid out in an actionable form. Actionable, in this context, indicates that questions are formulated in a way to meet at least one and ideally

both of these two requirements: (1) The question translates an overarching science question or SEARCH or Interagency Arctic Research Policy Committee (IARPC) five-year science goal such that it links directly to specific quantities that need to be determined in the context of an observing system and (2) Data and information derived from addressing this actionable question allows stakeholders or governing bodies to develop policies or inform specific decisions and actions in response to Arctic change. Once such actionable questions have been formulated, one can begin to determine the quantities (e.g., fluxes, storages) that need to be measured and define metrics to inform acceptable levels of uncertainty (e.g., associated with network density). Actionable questions regarding energy, carbon, and freshwater budgets should be a first priority since they are relevant to many disciplines. For aspects of the observing system for which understanding of design approaches is in its early stages (such as in the social sciences, as outlined by Berman 2010), network design should draw from regional pilot studies that can help determine scales of variability.

2. *Space and time scales:* The AON should have its sights set on the pan-Arctic space scale and seasonal-to-decadal time scales, laying a foundation for and tying into complementary national and international measurement programs that delve into the regional to local scales (regional downscaling). At the same time, AON should take advantage of regional measurements that are mandated or taken by other national and international organizations. Moreover, while the overarching focus is pan-Arctic, the need to address questions of societal relevance will often require AON observing activities at the local or regional scales, which are often more relevant to stakeholders. Both in integrating different components of an observing network across a range of spatial-temporal scales and in evaluating scales of variability that can inform system design, remote sensing approaches have an important role to play. Available remote-sensing data sets have substantial potential in addressing these tasks and can play an important role in the context of ADI.
3. *Prioritization:* The AON should strive for a balance that addresses the physical, biological, and human components of the Arctic system. Observations should be prioritized based on the breadth of application for different actionable science questions, with higher priority assigned to those approaches that can help address multiple questions. Some variables have well-established sampling methodologies and well-defined space and time scales of variability; such information will be central in network design. While the network can be designed initially based on past experience in sampling strategy, more rigorous evaluations should be carried out for comparison using OSSE's and other methodologies, such as data denial experiments. Pilot studies should be implemented to explore effective approaches for system design where the background science has not yet developed sophisticated design algorithms.
4. *Design and optimization approaches:* Methodologies and implementation strategies for network design vary widely between disciplines, both in approach and maturity. Hence, no single blueprint or common design exists for the components of an AON. Rather, observing system design and optimization need to be considered in a hierarchy of approaches relevant for an AON (Table 2). Therefore, the diversity of science questions that an AON must address requires an extensive strategic analysis of (1) their prioritization, (2) the variety of observational methodologies that must be implemented, and (3) the different levels of readiness in each field. An important aspect of the AON design is the ability of the network to remain

agile and able to adapt to a rapidly changing Arctic, coupled with an evolving set of actionable scientific questions.

5. **Metrics:** Network design to address specific science questions requires quantitative metrics (targets) of allowable uncertainty in the quantities being measured. Metrics should be relevant to the present and possible future states of the Arctic as opposed to the Arctic of the past. Allowable uncertainties will depend on the science question being asked, with different science questions requiring a specific analysis of allowable uncertainties. For the latter, consensus within the scientific community is important.
6. **Management structure:** An AON Scientific Steering Group (AONSSG) is recommended to provide a management structure that can respond to input from the SEARCH Science Steering Committee, the scientific community, AON stakeholders, and federal or state agencies. The SSG composition would reflect this diversity and be able to advise NSF and other agencies supporting the AON on network goals and provide input on how individual projects address these goals and how different observations may be prioritized. This structure may require the formation of ad-hoc working groups that focus on specific issues and would include establishing a project office that provides management support to AON activities.

Next Steps

Based on the conclusions and recommendations above, the ADI Task Force identifies a number of key next steps. These include (1) compiling an inventory of harmonized data from different agencies to improve data interoperability, access to data, knowledge of data holdings, and support to modeling studies; (2) planning for and implementation of an AON SSG; and (3) steps towards prioritizing existing and future observing activities as outlined in the hierarchical approach summarized in Table 2.

Elizabeth Eubanks climbed partway up this tower in Point Barrow, Alaska. Photo by Rob Eubanks, courtesy of Elizabeth Eubanks (PolarTREC 2008), courtesy of ARCUS.



I

Introduction

1.1. Background

It has been recognized for years that we need an Arctic Observing Network (AON) that tracks and fosters understanding of the suite of rapid Arctic environmental changes presently underway, thereby improving projections of and adaptation to anticipated future change (SEARCH 2003, 2005; NRC 2006; IARPC 2007; ISAC 2010). In response, the scientific community has identified a broad set of key scientific questions in the context of the Study of Environmental Arctic Change (SEARCH) Science Plan (2001) and Implementation Workshop Report (SEARCH 2005). Building an effective, scientifically robust AON requires planning, coordination, and analysis of data and model output over a range of disciplines and scales. The International Polar Year (IPY) has fostered a substantial push for intense observation campaigns and deployment of sensor networks, ushering in a phase of more coordinated observing efforts. Of these, three programs are of particular relevance: the SEARCH AON, the European DAMOCLES program (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies, now completed but with a number of follow-on efforts), and the Canadian ArcticNet Program. With U.S. agencies and others maintaining complementary observation efforts in the Arctic, there is now an urgent need for coordination, consolidation, and optimization of the existing observing system elements and to develop a broader strategy that includes more detailed design studies to enhance and sustain the observing system. There is also an unprecedented opportunity to use the wealth of available observations from the Arctic to exploit their synergies and assess their contributions to a holistic depiction of the state of the Arctic.

The AON Design and Implementation (ADI) Task Force was put in place in 2009 with guidance by the National Science Foundation (NSF) to explore and define different options and provide guidance to NSF, the scientific community, and others engaged in Arctic environmental observations on how to best achieve a well-designed, effective, and robust U.S. Arctic observing effort that complements and helps integrate activities at the national and international level towards an Arctic observing system. The Task Force comprised experts in the Arctic and broader scientific community knowledgeable in observing system design and related fields who worked with other key experts and contributors at workshops to achieve these goals and produce this report (see appendix 1 for Task Force member information).

1.2. Charge, Objectives, and Tasks for the ADI Task Force

Based on guidance from NSF, the following objectives drove the ADI Task Force activities and supporting efforts by the SEARCH panels and Science Steering

Committee and other relevant steering groups towards improvement of observing system design:

1. evaluate the current implementation status of the Arctic Observing System vis-à-vis the key science questions identified by the Arctic research community;
2. improve design and adaptation of observing system components through observing system simulation experiments and similar approaches;
3. synthesize information arriving from the existing observing system components and quantitative design studies to guide its design and refinement; and
4. coordinate between individual national and international efforts. Here, the International Study of Arctic Change can help with international aspects of coordination.

The process to advance these goals and the urgent need for guidance on AON design and implementation identified above included the following tasks:

1. *Assessing the present state and near-term implementation plans of the AON and related efforts*

Under the leadership of Understanding Change Panel Co-Chair John Walsh, SEARCH representatives (mainly members of its Science Steering Committee, Observing Change Panel, and Understanding Change Panel) with key contributors from the Arctic System Science Program (ARCSS) and the broader Arctic community prepared an assessment of the AON in its current form. The review examined how well the AON addresses the major Arctic change science questions; identified newly emergent, high-priority science questions or drivers that should augment those in the SEARCH plan; highlighted critical gaps; and made recommendations for the next steps in the integration of observing system efforts.

2. *Identify and assess effective, promising approaches and tools for observing system design and optimization*

Given the lack of a comprehensive theoretical framework for observing system design and optimization that is applicable to the AON, the Task Force considered a broad array of methods to determine the performance and options for future enhancement of the observing system. These methods include observing system simulation experiments (OSSE), evaluation of the information coming from the data assimilation community (e.g., reanalysis and forecasting projects, Bromwich and Wang 2008), or tools such as manipulation of data sets to examine the data density required to capture the processes that determine the characteristic features of the observed system components.

3. *Synthesize and discuss design options and approaches as part of a workshop*

An ADI Task Force Workshop was held in conjunction with the AON principal investigator meeting in December 2009 to review and synthesize ongoing activities reported at the level of themes or disciplines rather than individual projects. Workshop participants were from within and outside of SEARCH to provide broader scale evaluations. Participants recruited from a broader range of non-Arctic and Arctic observing programs (including agency-led activities) provided overviews and reviews of activities and methodologies relevant to the ADI charge. Specifically, the workshop goals included:

- discuss and define the scope of predictive understanding of change (i.e., what magnitude of change over what time frame?) in the AON context;

- inform task force members on the current status of AON, particularly regarding ongoing data acquisition and evolution of network components;
- review the evaluation of the current status of AON with respect to driving science questions recently developed by the SEARCH Understanding Change Panel (Elliott et al. 2010);
- review constraints on and challenges of AON design, implementation, and optimization;
- identify and evaluate other ongoing or past efforts that hold important lessons for the AON effort;
- discuss different approaches and levels of integration within and among observing system components;
- discuss methods for serving the information needs of stakeholders;
- identify promising approaches and tools for observing system design and implementation; and
- identify specific tasks or broader activities (and associated metrics) that could be completed through brief proof-of-concept, exploratory studies and that would serve to inform the Task Force recommendations and report.

4. *Summarize ADI Task Force findings and recommendations in a report*

The key product of Task Force activities and contributors is this report to the National Science Foundation, the broader scientific community, and other agencies, summarizing findings and recommendations from the ADI process.

1.3. Timeline of Activities

The ADI project activities started with the planning and organization of the Fall ADI Workshop that was held in Boulder, Colorado, in December 2009. The workshop resulted in a concrete plan with a timeline and activities to move the ADI process toward Phase II. After the workshop, the following ADI and Task Force activities were carried out:

- December 2009 to January 2010: ADI Task Force identified key proof-of-concept and exploratory design exercises.
- February 2010: Two bundled Rapid Response Research (RAPID) collaborative proposals submitted to NSF.
- March 2010: Small ADI Task Force follow up and planning meeting at the State of the Arctic Conference.
- June 2010: The ADI Task Force initiated work on revising the two bundled RAPID collaborative proposals for resubmission based on the feedback and comments received from NSF in May 2010.
- Spring and summer 2010: ADI Task Force teleconferences and subgroup meetings to develop a refined, smaller-scale set of proof-of-concept studies, focusing on ocean-ice-atmosphere proof-of-concept studies bundle.
- Summer 2011: Work on first draft of ADI report.
- May and June 2012: ADI Task Force teleconferences to assign editing roles to sections of the draft report.
- June 2012: The ADI Task Force meets in Boulder, Colorado, to discuss final conclusions and recommendations and complete writing sections for the final report.
- July 2012: Draft of the final ADI report sent out for review by SEARCH and NSF.
- October 2012: Final report released.



Kristen Mitchell measures discharge near Linne Glacier. Linne Valley, Svalbard, Norway. Photo by Missy Holzer (PolarTREC 2008), courtesy of ARCUS.

2

Evaluation of the Status of the AON in Relation to Driving Science Questions

AON science goals encompass a broad range of questions that span many disciplines, complicating network optimization efforts. Any optimization effort must begin with a system specification—we must have design targets to optimize around. Without such targets, there is no way to assess what is the optimum configuration. The following steps are required to optimize a network, first for a single science question:

1. Identify the science question that the observational network will address.
2. Identify the level of uncertainty to which the scientific question must be constrained.
3. Articulate the information that will be required to address the question, including what fluxes and state variables are needed.
4. Inventory the variables that must be measured to provide this information.
5. Consider one or more plausible scenarios of change. How will this change manifest in the measured variables? What uncertainties could be tolerated while still retaining the ability to distinguish the signals of interest?
6. Clearly articulate quantitative network design targets given the above information.

Once we have quantified the level of uncertainty that can be tolerated, a range of tools can be employed to explore the trade-offs of various designs and identify optimal approaches that meet the design targets while minimizing some measure of cost (actual cost, logistical complexity, fit with other U.S. or international efforts, etc.).

By repeating this process for a collection of high-priority science questions, we can build an inventory of backbone variables and the accuracy to which they must be measured. The backbone variables are those that contribute to a broad range of questions, for which one could adopt the most stringent uncertainty bounds as the measurement criterion. The network design targets should be revisited using this process as advances in scientific understanding, new technologies, and other considerations occur. This can be performed at a high level by a scientific steering group that retains oversight of the network design needs. Formal design studies (such as discussed in section 4.2) can provide useful information that, when used in conjunction with other approaches, can provide guidance on the configuration of observational assets. Given that a network of observations already exists under AON, a retrospective study on how the current observational network contributes to understanding of variability in target quantities as identified by scientific questions should be undertaken. This will inform us on how to modify the existing network to meet the defined scientific objective. Due to changing Arctic climate conditions, and the possibility that empirically

derived statistical relationships may not be stationary, network design should strive to make use of mechanistic relationships to establish the necessary density and accuracy of observations.

This six-step process outlined above does not necessarily help prioritize across diverse science questions, although it can identify observational needs that span many scientific questions of interest. How to prioritize observations within this framework remains a critical question that must be addressed by the steering group and the community at large.

For example, to address the scientific question of whether the Arctic Ocean freshwater cycle is changing requires a network that is able to detect a change in the Arctic Ocean freshwater budgets. The acceptable level of uncertainty for this change could be determined using guidance from climate model simulations that indicate an acceleration of the Arctic freshwater cycle over the twenty-first century (e.g., Holland et al. 2007). The variables of interest needed include river runoff to the Arctic Ocean, fluxes of liquid and solid (ice) freshwater through key ocean straits (e.g., Bering Strait, Fram Strait, Barents Sea opening, the Canadian Arctic Archipelago), and precipitation and evaporation over the Arctic Ocean. To determine these fluxes we require adequate information on river transports, salinity and velocity in appropriate ocean straits, sea ice thickness and velocity in those straits, and precipitation and evaporation (or perhaps the net atmospheric moisture convergence to the Arctic, which could be assumed to be the net precipitation). The spatial and temporal resolution required for these measurements would need to be determined from the dynamics of the system, using guidance from empirical and modeling studies. Additionally, for a field such as Arctic Ocean precipitation, which is difficult to constrain with an observational network, consideration should be given to what observational network is needed to adequately constrain this field in numerical weather prediction (or reanalysis) systems. Section 6 and appendix 6 go into greater detail of how the example of freshwater fluxes can also be used to illustrate other aspects of observing system design and implementation.

2.1. Status of Step 1 Within SEARCH: Preliminary Assessment of Observation Needs Driven by Science Questions

As a starting point in addressing scientific priorities, the SEARCH Understanding Change Panel made a preliminary and qualitative assessment of the present AON in terms of scientific gaps and needs (Elliott et al. 2010). In keeping with the panel's primary function in SEARCH, assessment was driven by considerations of present impediments to improved understanding of Arctic change. The panel drew upon existing documents, including the SEARCH Implementation Plan (SEARCH 2005), the 2008 Workshop Report on Arctic Observation Integration, and the draft science plan of the International Study of Arctic Change (ISAC 2010). The panel submitted its draft report in early November 2009. While the panel represented a diversity of research subfields and sought input from colleagues, the panel's report is not intended to be comprehensive; rather, it is viewed as a starting point for more rigorous and complete assessments of the AON in the context of the driving science questions. It should also be noted that the underlying science drivers of SEARCH are evolving and are presently being addressed by the SEARCH Science Steering Committee.

The panel's assessment of needs was organized into several spheres: (1) marine changes, (2) atmospheric changes, (3) terrestrial changes, (4) Arctic–global connec-

tions, and (5) integration of information and knowledge networks. The following summary is structured around this organizational framework.

Gaps in the marine sphere were highlighted through the present difficulty in answering several fundamental questions concerning Arctic change. For example, are changes in Arctic marine mammal and fish distributions outside their ranges of natural variability? The recent need to inform decisions on species status (endangered, threatened, etc.) has pointed to our incomplete information on polar bears, seals, walrus, and other marine mammals. A second example of a driving science question is: What is happening with Arctic sea ice? The answer to this question requires ocean observations that capture the subsurface drivers of sea ice changes, enabling an evaluation of the relative importance of atmospheric and oceanic forcing of sea ice. A more systematic science-driven approach to Arctic Ocean observations is needed. A third example is: Are carbon pathways in the Arctic undergoing consequential changes? Coordinated Arctic Ocean measurements, especially in the shelf seas, are needed to answer this question, which has taken on added importance in the past few years as ocean acidification has emerged as a threat to marine ecosystems and as surprisingly large methane fluxes into the atmosphere from the Russian shelf seas have been detected.

In the Arctic atmosphere, a key question that has gained prominence is: What are the roles of black carbon and other aerosols in Arctic change? It is not known whether aerosols are contributing to the larger trends observed than are simulated by models nor whether Arctic trends have been affected by “solar brightening” that may involve aerosols and/or clouds. There is a need for systematic monitoring of aerosols in the atmosphere and in snow.

In the terrestrial sphere, a key question is: What are the drivers of recent changes such as the increases of river discharge, wildfires, and vegetative “greenness” of the tundra? Potentially important roles of evapotranspiration and snow (water equivalent) are largely unknown because these variables have not been monitored adequately to enable evaluation of their changes in the context of broader Arctic changes.

With regard to Arctic–global connections, a key question is: How is the Arctic contributing to global sea level rise? The answer requires a determination of the relative roles of Greenland and smaller glaciers and ice caps in discharging fresh water. The poor sampling network for glacier mass balance is a hindrance in this regard. A second important question is: How are midlatitude climate and the global heat budget influenced by the loss of Arctic ice? The corresponding observational need is for a measurement system to quantify and track the atmosphere’s gain of heat (and moisture) from the Arctic surface.

Other gaps and observational needs highlighted in subsequent reports include the Arctic upper atmosphere (especially the ozone layer), surface albedo in the Arctic, atmospheric water vapor (in which changes can lead to high-leverage feedbacks to warming), and a high-resolution (~5 meter) pan-Arctic digital elevation map that would allow resolution of topographic slopes at scales relevant to hydrology, vegetation, and permafrost.

The observational needs summarized above represent a subjective assessment by a small (eight member) SEARCH panel. In addition to the fact that a panel constituted differently would come up with different priorities, the assessment is subjective. It lacks the quantitative rigor that is needed to substantiate prioritizations and to address observational requirements (accuracy, frequency, locations, etc.). What is also missing is a system-scale framework that would enable assessments of how particular observations would impact understanding and prediction issues that span several components of the Arctic system.

The AON design strategy recommended here represents a substantive step forward in terms of demonstrating the observational requirements for addressing particular science needs. By combining (a) driving science questions, (b) the required “accuracy” of a metric or derived variable, and (c) measurement uncertainties (related not only to instrumental measurement error but also to location and frequency of observations), the following strategy will advance AON design beyond subjective justification and into the realm of objective optimization.



Pulling water from the ground will give Paulo Olivas a look at the dissolved organic carbons in the water. At the Barrow Environmental Observatory field site near Barrow, Alaska. Photo by Elizabeth Eubanks (PolarTREC 2008), courtesy of ARCUS.

3

Survey of Environmental Observing Systems Relevant to the Arctic: Challenges, Successes, and Lessons Learned

The NSF-supported AON, guided by the broader research community and key stakeholders through the SEARCH Implementation Workshop Report (SEARCH 2005), is envisioned as a cross-disciplinary, cross-domain observing system that answers key science questions. At the same time, the core SEARCH theme of Responding to Change requires that the system also address stakeholder information needs in some form. Given these challenges and considering that key advances in observing system design and implementation have been made outside of the Arctic region, the ADI Task Force convened a community workshop in December 2009 to review and discuss lessons learned from other observing systems, with a focus on mature efforts outside of the polar regions, and to review the state of the art in observing system design approaches (see appendices 2 and 3 online for workshop agenda and participant list).

Brief summaries and key conclusions from these introductory talks at the ADI Workshop follow. Complete summaries of these presentations are compiled in appendix 4 (online).

1. **The Long Term Ecological Research (LTER) Network;** John Vande Castle

The LTER network was devised and implemented as a bottom-up research effort by the scientific community. As a highly successful, long-term project supported by NSF with twenty-six sites, including two in the (sub)Arctic, it holds important lessons for AON. While sites differ vastly in settings and aims, a consistent set of core measurements is obtained across the network. At the end of its third decade of operation, strategic planning has identified integrating social and ecological sciences and fostering cross-network integration as important priorities. Additional findings and lessons learned from LTER can be found in section 4.3.

2. **The Argo Float Program—A Case Study for an Observing System;** W. B. Owens

The Argo (Array for Real-time Geostrophic Oceanography) float program is a key component of the international ocean observing system. It was designed as an international program from the outset, with roughly half of the funding coming from the US. It was designed with close links to two major ocean-focused satellite missions (JASON and GRACE). Key to its success are clearly defined short-term goals as well as a focus on seasonal to interannual variability at 1,000 km scales. International coordination of observations is important and also helps to address questions of access to territorial waters.

3. **Transition from Research to Operations: Lessons from NOAA's TAO Array;** Michael J. McPhaden
NOAA's Tropical Atmosphere-Ocean Array (TAO) started as a research project over more than a decade in the 1980s and 1990s. Based on the success of the program, a 2001 review led to plans for a rapid transition to an operational network under oversight of the National Weather Service. While originally envisaged to be completed in three years, this transition has proven challenging and is now estimated to take until 2015, i.e., more than a decade. The lack of funding due to underestimating these challenges compounds the problem. Key lessons learned from TAO include (a) the research community should be an active participant in the management of such observing systems because new discoveries constantly shape measurement requirements, and (b) climate observations are best managed within the context of an end-to-end system from data collection, dynamic modeling, forecasting, all the way to provision of end products for society.
4. **SEACOOS Program—Lessons Learned;** Harvey Seim
The Southeastern Coastal Ocean Observing System (SEACOOS) offers a number of key lessons to AON and other observing system efforts. First, stakeholder involvement in the system should not be taken lightly and requires a set of priorities and realistic implementation timelines. The cost to sustain observations in the longer term was the single biggest expense in SEACOOS, whose assets were transferred to the Southeastern Coastal Ocean Observing Regional Association in 2008. Data management is key to success and consumed about one quarter of the total budget. Overall observing system design requires a balance between scientific understanding, model guidance, and practical constraints.
5. **Observing System Simulation Experiments and Biophysical Process Studies Related to the Predictability of Land–Ocean Interactions;** Villy Kourafalou
Coupled models can play a key role in helping design ocean observing systems through the tool of OSSEs. However, it is important to clearly distinguish between the local and the global context of a given set of observations since these constrain both the types of questions that can be answered and the specific experimental design. Based on the example of the Mississippi River plume, various advanced approaches in observing system design based on OSSEs were discussed in the presentation (with details and references provided in appendix 4).
6. **Adjoint Data Assimilation and Quantitative Network Design;** Frank Kauker
A four-dimensional variational analysis system (4D-var) for assimilation of observations was built around a coupled ice-ocean model. The potential value of such a system as a platform for OSSEs was demonstrated in two examples, one taken from the seasonal prediction of September minimum ice extent through the Arctic Sea Ice Outlook. Ensemble simulations with the system allowed for an assessment of the relative improvement in predictive skill derived from ice thickness measurements at specific locations throughout the Arctic.
7. **Arctic Ocean Reanalysis;** Andrey Proshutinsky
Integrative data assimilation for the Arctic system has been recommended by the research community in the context of SEARCH. The Arctic Ocean Reanalysis project focuses on the ocean/ice component of this effort, pursuing two different approaches; a 4D-var data assimilation system and the pan-Arctic ice-ocean modeling system (PIOMAS). Both of these approaches are suitable to guide observing system design through the completion of OSSE studies.

8. Arctic Atmosphere Reanalysis; Keith M. Hines

A core component of an integrative data assimilation system for the Arctic is the Arctic System Reanalysis (ASR) project. ASR initially aims to reconstruct observed fields for the time period 2000–2010 with assimilation of atmospheric data and a realistic representation of ice at the lower boundary. The ASR can serve as the foundation for both OSSEs and other approaches (for example, OSEs; see Table 4 for details).

9. Satellite Remote Sensing and the AON; Walt Meier

While models can provide context for and guide observations, satellite remote sensing provides a broad set of tools and data that can provide cross-scale spatial and temporal context to observations. In particular for an AON, with potentially larger regional gaps in low-priority areas and methodological challenges, remote sensing can help identify promising measurement sites. Key climate-data record time series are available starting around 1980, with particular relevance to the study of the cryosphere and land-surface processes.

10. Ecosystem Services in the Design of Observing Systems; Terry Chapin

Ecosystem services are the benefits that society derives from ecosystems. They are a potentially useful construct for observing system design because they link the biophysical environment to the needs of society. Thus, they can help in prioritizing variables to measure, provide a context for communication with stakeholders, and help integrate community-based observations. The latter in turn can inform the placement of sensors and other aspects of system design.

11. NEON Overview and Observing System Simulation Experiments; Dave Schimel

The National Ecological Observatory Network (NEON) is an observing system, but investments at this scale must be guided by quantitative analysis and careful evaluation of tradeoffs. Ecological forecasting, modeling, and analysis activities are central to the NEON process. The advent of continental-scale research will lead to changes in ecological science itself, including its related infrastructure, culture, and training. NEON provides data and infrastructure for decadal and continental-scale science and could be useful in designing an observing system that joins an emerging global network of environmental observatories.

12. Overview of Outcomes from Ocean Observing 2009 Conference and White Papers; Craig Lee and Peter Schlosser

The 2009 Arctic Observing Network meeting focused on issues surrounding network design and optimization. The broad diversity of goals makes AON optimization challenging and emphasizes the need for an agile AON design that is capable of continually evolving in response to advances in understanding, changes in the Arctic environment, and the availability of new observational technologies. Speakers provided an overview of critical lessons from other large observing networks, including the International Arctic Buoy program and the Argo float array.

13. Adaptive Observatory Network Design; Sandy Andelman

The Tropical Ecology Assessment and Monitoring (TEAM) program aims to provide real-time data to monitor tropical biodiversity and ecosystem services through a network of global field stations. These stations can act as an early warning system on the status of nature. Data collected on climate, soils, and socioeconomic settings can be used to project climate change and projected land use changes.

The Temporary Atmospheric Watch Observatory (TAWO) at Summit Station, Greenland. Photo by Kevin McMahon (PolarTREC 2011), courtesy of ARCUS.



4

Relevant Methodologies and Approaches to Rigorous Design and Optimization of Observing Systems

4.1. Statement of the Problem

Design, implementation, and optimization of a cross-disciplinary, pan-Arctic observing system such as discussed here faces a number of challenges, some of which are unique to AON. Some of these challenges could not be addressed by simple comparisons with other observing systems such as those referenced in the previous section. Such challenges need to be taken into consideration in evaluating the applicability and potential success of different approaches and methodologies used in observing system design and optimization. This circumstance is reflected in the material presented in the following sections.

In general, the overarching nature of Arctic change—the repercussions, feedbacks, and responses it engenders in different components of the Arctic system—and the timescales associated with these changes require an observing network that addresses key science questions that are much broader than that typically taken in more focused, hypothesis-driven experimental design studies. The AON is meant to address a broader suite of questions and a more comprehensive set of goals, reflected in the SEARCH science questions that drive the establishment of the AON (SEARCH 2005). Thus even the interdisciplinary set of core variables and questions that each LTER site is meant to address in the comparable LTER network is still somewhat narrower than the scope of the nascent AON.

Specific challenges associated with the establishment of the AON as envisioned in the SEARCH implementation documents include the following:

1. The Arctic research community, including researchers with federal agencies and key stakeholder groups, has been emphatic in its commitment to an incremental, bottom-up approach to implementing an observing network that responds to and is driven by key science questions and information needs. The LTER network provides a model for such an incremental approach, as opposed to the NEON model, which relies on LTER findings and infrastructure to implement a centrally driven network design.
2. Owing to the nature of Arctic environmental and socioeconomic change, the AON has always been envisioned as a network that balances fundamental science questions driving the research with stakeholder information needs. Finding such balance is challenging (as illustrated by the SEACOOS program referred to above) and introduces both additional constraints and additional

opportunities for transformative science. These issues are summarized in Table 3 with respect to the different goals of an observing system and the associated spatial and timescales.

Table 3. Observing system design parameters (AON 2010)

	Policy	Strategy	Tactics
Purpose	Science-driven network for climate research & long-term planning	Inform medium-term planning for government, industry, and science	Narrowly scoped networks defined by the needs of local stakeholders
Time Scale	Decades; value placed on long records	Seasons to decades; long records valued	Rapid spin-up, spin-down, flexible design
Spatial Scale	Distributed; far from population centers	Limited geographic scope, perhaps near population centers	Tightly focused on regions of human activity
Data	Long, consistent records; real-time data return not necessary; resource constraints govern implementation	Rapid data access (near-real time) may be required	Deliver useful products in real time; data have little shelf life; ease of access is key

3. Since the focus is on key variables, such as fluxes of heat and moisture or heat and freshwater into the Arctic through the atmosphere and ocean obtained at timescales relevant for climate change, the impacts of climate change may require an adaptive, evolutionary approach to observing system design. For example, the reductions in summer Arctic sea ice have resulted in the loss and spatial confinement of drifting ice buoys that are meant to provide key pieces of information on the changing sea ice, ocean, and atmosphere. Innovative approaches and new technologies are required to close this observation gap that has opened relative to the original implementation plan.
4. Due to the remoteness and harsh Arctic environment, external constraints such as access and siting of preexisting infrastructure or landownership and industrial activity can figure prominently into the deployment of observing system components.

The following sections of the report address in more detail how different observing system designs take such factors into consideration for a sustainable and effective network. This includes consideration of questions such as (a) What is the information content of observations from gateway arrays (budgets) vs. internal system measurements (patterns)? (b) What are the tradeoffs between flagship observatory sites and distributed networks, or should hybrid approaches be considered to achieve integration across relevant scales? and (c) What type of guidance can be given on local placement of moorings or sensor arrays? Furthermore, suitable metrics for assessing the efficacy of specific measurements will be discussed alongside potential constraints, such as cost.

4.2. Overview of Relevant Methodologies for Observing System Design and Optimization

Following presentations and discussions at the ADI Workshop in 2009, the ADI Task Force, with input from the broader research community, has developed a hierarchy of approaches for observing system design and optimization (see Table 4). The six broad methodological categories for design and optimization include:

1. integration through overarching projects, including impacts of change on human activities;
2. retrospective analysis and review of past work;
3. ecosystem services;
4. data thinning experiments;
5. model-based observing system experiments (OSEs); and
6. observing system simulation experiments (OSSEs).

In the following section we outline the various approaches, both standard and cutting-edge or exploratory, based on contributions to the ADI workshop. For each of the methodological categories we offer project descriptions to illustrate the various approaches (and subsets of types of activities within each of those approaches).

Table 4. Different approaches and specific examples for observing system design

Methodological Category	Specific Approaches and Examples of Potential Studies
Qualitative and semiquantitative evaluations	Synthesis of past reviews & disciplinary design studies; review of existing observation sites and methodologies of state of permafrost; retrospective analysis of forecasting efforts regarding management of living marine resources; statistical modeling of environmental and human dimensions variables; pattern recognition experiments using existing biogeophysical observations to understand coordinated and/or uncoordinated signatures of change in Arctic terrestrial ecosystems; thematic and physical coherence studies among all variables tested
Integration through overarching projects, including impacts of change on human activities	Synthesis of existing approaches, gap analysis; spatial scales of variability; design of repeat sections; detection of spatial-temporal patterns of change in Arctic terrestrial systems; sphere of influence of Arctic communities for snow measurements; statistical modeling of environmental and human dimensions variables
Retrospective analysis & review of past work	Identification of ecosystem services (supporting, provisioning, cultural, or regulating services); quantifying these services in biogeophysical terms, translating the service metrics to engage stakeholders in resource management
Ecosystem services	Quantitative model-based assessments
Data thinning experiments	Spatial and temporal scales for snow observation network design; optimal sampling of leading modes of variability
Model-based OSEs	Data denial experiments; sensitivity studies of key Arctic climate indices; spatial scales of variability in ocean-ice interaction
OSSEs	Assessment of hypothetical datasets collected through an observing network at specified locations on the output of predictive or diagnostic models building on the observing system

4.2.1. Integration Through Overarching Projects, Including Impacts of Change on Human Activities

Synthesis of past reviews and disciplinary design studies—developing a nearshore and coastal observing system for the North American Arctic. To date, most Arctic Ocean observing network projects have focused on basin-wide observations of the physical aspects of the ocean and sea ice using autonomous measurements. Sensors to measure ecosystem parameters remain poorly developed, and many biological parameters cannot be measured with sensors at this time. New issues are developing, such as concern about ocean acidification and the impact of intrusions of a warming Alaska coastal current on melting and formation of sea ice and consequent impacts on bowhead whale feeding areas. Development of a nearshore and coastal observing system that connects the coastal zone ecosystem to the central Arctic basin system will enable estimates of ecosystem responses to changes in the physical, chemical, and biological conditions in the ocean and their ramifications on the coast.

There are pros, cons, and challenges of using various observing platforms and technologies in the Arctic environment. In order to develop a land-shelf-slope observing network that would serve as a prototype for a nearshore and coastal observing system, it is important to synthesize what is currently known about observing the Arctic shelves; assess existing data and ice-ocean, basin-wide, coastal, and ecosystem models; and compile information regarding recent uses of observing technology in the Beaufort and Chukchi Seas (most of which is still unpublished, but which has been presented at numerous workshops in the past few years). This information can assist in the design of a robust network for a multipurpose coastal observing system. Results of the Arctic Ocean Model Inter-comparison Project (AOMIP), other NSF activities, reports from the numerous Arctic workshops held in recent years (e.g., Hopcroft et al. 2008), activities funded by the U.S. Minerals Management Service's Environmental Studies Program, and studies conducted by Conoco-Phillips, Shell, and BP as part of their offshore oil and gas exploration programs can all funnel into the design of a robust network for a multipurpose coastal observing system.

Review of existing observation sites and methodologies of state of permafrost, including assessment of observations needed to assess potential threats to infrastructure. Many potential problems related to climate change in the Arctic are associated with (1) changes in the temperature of the upper permafrost, (2) increased depth of seasonal thaw penetration, and (3) progressive thawing and disappearance of permafrost. These changes can lead to loss of soil bearing strength, increased soil permeability, and increased potential for such cryogenic processes as differential thaw settlement and heave, destructive mass movements, and thermokarst terrain. Each of these phenomena has the capacity for severe negative consequences on human infrastructure, land use, and ecosystems in the high latitudes. Ongoing permafrost monitoring activities could be assessed to develop recommendations for designing a permafrost observational component of the AON capable of detecting negative consequences of permafrost changes. These results would be delivered in an effective and useful manner to stakeholders.

A project using two representative and diverse regions—northern Alaska and northwest Siberia—could be useful for describing a permafrost observational network capable of addressing the following problems: (1) evaluation and prediction of geocryologic hazards and risk assessment associated with degradation of permafrost under changing climatic conditions, (2) evaluation of the vulnerability of Arctic communities to changes in geocryological conditions, and (3) evaluation of potential

threats to Arctic ecosystems and major habitats associated with permafrost degradation. Analysis of geocryological data can be used to assess the representativeness of current permafrost observational networks by identifying essential spatial and temporal gaps in data. This problem can be addressed by linking information about observed spatial patterns and temporal trends of permafrost parameters (e.g., active-layer thickness, permafrost temperature) with a range of surface, subsurface, and climatic characteristics. By using empirical data and modeling products, spatial regional assessments of the vulnerability of natural and anthropogenic Arctic landscapes to changes in permafrost condition can be provided at a resolution corresponding to the level of available empirical data. Results of this work can help guide development of a set of observational parameters, spatial and temporal sampling frequencies, and methodological recommendations aimed at minimizing uncertainties in spatial assessments of the vulnerability of permafrost landscapes.

Retrospective analysis of forecasting efforts from the perspective of management of living marine resources. Humans and higher trophic levels are integral to the design of an AON. They are both dependent variables and feedbacks to the Arctic system. Pinnipeds, cetaceans, and polar bears are highly dependent on the extent, thickness, topography, and phenology of sea ice for habitat quality, and these marine mammals are economically, nutritionally, and culturally important to indigenous people throughout much of the Arctic. Habitat disruption—especially for ice-associated species—is being documented. Human residents are likely to be affected by changing abundance and availability of marine mammals, but we lack formal approaches to monitor those effects.

Potential marine mammal management efforts and the needs of Arctic peoples could be enhanced by determining (1) key Arctic species by assessing their importance to indigenous people and their vulnerability to changes in the cryosphere; (2) what environmental variables, such as sea ice, most influence the availability of those species to subsistence hunters and the viability of marine mammal populations; and (3) what kind of observing system and monitoring protocols are required to develop, validate, and calibrate seasonal forecasting of ice conditions relevant to ice-dependent species and the people who depend on them.

Additional considerations such as spatial and temporal scales, lead time needed to make seasonal forecasts of ice conditions valuable to user communities, and metrics to evaluate the utility of an observing system should be included in the design to address questions relevant to the management of living marine resources.

Statistical modeling of environmental and human dimensions variables. Snowpack samples from traverse studies can be used to develop ways to observe black carbon deposition around Arctic communities. Results from such experiments will inform designs for scaling up an observing system to obtain broader spatial coverage across Alaska or other snow-covered regions.

Multilevel statistical modeling can be explored as a tool for estimating separate effects of climate, energy prices, and community population on annual community fuel use and hence estimated emissions.

Model results, together with climate projections, bear on scenarios of future resource use and would help to identify areas where mitigation steps by Arctic communities might reduce carbon emissions. Snow-sample observations can yield data on distributions of background (remote origin) vs. local origin black carbon and thereby inform design of a broader observing system.

Pattern recognition experiments using existing biogeophysical observations to understand coordinated and/or uncoordinated signatures of change in Arctic terrestrial ecosystems. Arctic terrestrial environmental monitoring systems, to date, have largely focused on individual themes and biogeophysical variables and less on integrated observations that capture the behavior of systemic change. For example, Arctic permafrost monitoring, such as Circumpolar Active Layer Monitoring (CALM), has been designed independently of hydrographic and biogeochemical flux networks. In addition, there are many observational approaches, including site-specific field measurements; instrumented ground-based networks of varying density, quality, and integrity; and airborne and satellite remote sensing. As a result, current monitoring systems remain highly fragmented and have yet to take full advantage of potential synergies inherent in conjunctive measurements. Furthermore, if Arctic terrestrial changes are indeed coordinated (as is often stated), we need monitoring systems sufficient to detect these systemic effects. Such integrated systems are not currently available, and the Terrestrial ADI Group concludes that the current AON for terrestrial/hydrological/cryospheric variables is more narrow in scope than called for in the original research plan and National Research Council report. Further, we cannot *a priori* evaluate the impact of these deficiencies and thus must conduct design experiments testing the capacity of anticipated plans to capture these dynamics.

Within this context, proof-of-concept or exploratory studies to assess different design and optimization approaches can be proposed. The challenge can be guided by a central motivating question plus several supporting questions. The overall question is:

Are there coordinated signatures of Arctic change detectable across several thematic realms and, if so, how do current observational networks capture these signals? The thematic realms refer, for example, to climate and meteorology, hydrology, permafrost dynamics, carbon balance, vegetation dynamics, human population distribution, etc. The supporting questions are:

- What is the range of spatial and temporal variation among key systems, states, and processes, and how can we use knowledge of such variability to design more effective and efficient sampling schemes?
- What types or locations of measurements are needed to identify linkages among the different components of the Arctic system and their synergies?
- Can we identify an optimal mapping system that helps us to quantify the variation in linkages in an efficient way?

While a definitive answer lies in a comprehensive analysis, these questions can be used to guide early experimentation. They will help inform a way of thinking through the design problem and identifying gaps and opportunities for improved system design concepts. Using a prototype array of existing pan-Arctic biogeophysical and social science data sets plus analysis tools, it will be possible to provide a provisional answer to this overarching question, and once this has been determined, the analysis can go on to assess current and future monitoring network designs.

The community is well-poised for such experiments. Table 5 depicts the raw material for such a study, involving seventeen pan-Arctic data sets that could be united onto standard projections, time and space domains, and resolutions. These would be united into data analysis tools (e.g., Rapid Integrated Mapping System) to enable “live” data discovery and visualization. Higher resolution studies could also be coordinated with this macro-scale assessment: for example, analysis of snow-related change across Alaska.

One important output is a mapping of areas of distinctive variability and change over space and time and to identify the chief state variables contributing to this variability. In addition, a mapping of the spatial gaps in placement of current measurement systems and analysis of their capacity to detect change will be provided. Scenarios of alternative network designs will be tested, using statistical techniques and data denial experiments. This would be done both for the pan-Arctic and Alaska domains (the latter, e.g., focusing on snow).

A set of systematic metrics will be necessary to assess the fundamental question (i.e., measures of multitheme change plus measures of observing network efficiencies). These will include both spatial and temporal covariance measures and more sophisticated indicators. Numerical experiments include modifying data quality control structures, data thinning and data denial, and refining the observation error estimates used in the data assimilation.

4.2.2. Retrospective Analysis and Review of Past Work

Synthesis of existing approaches and gap analysis. AON design for atmospheric observations and other variables must be based in reality. The Arctic has a variety of climate regimes, and this should logically be reflected in system design. New sets of observations should arguably target regimes that are presently data-sparse, such as the

Table 5. Targeted data sets that will support the Terrestrial Network Design synthesis workshop, which will focus on the pan-Arctic using a standard 25 km landmass EASE grid. Year 2000 to present will be analyzed, with longer periods as deemed necessary and when data are available. Parentheses contain current identification of source data: V = variety of sources; A = identified as available.

Targeted Datasets	Source Data
Atmospheric forcings (reanalysis, interpolated station data)	(V, A)
Fires (remote sensing)	(MODIS, A)
Permafrost (models)	(UDel, A)
Runoff amount and composition (models & interpolations)	(P-WBM, Rapid Integrated Mapping System obs., A)
Reflectance (remote sensing)	
NDVI	(MODIS, A)
Albedo	(MODIS, A)
Snow (models, remote sensing, and reanalysis)	(CSU, A)
Wildlife distributions (observation, non-AON)	(to be determined)
Vegetation (remote sensing)	(MODIS/UMd, A)
Freeze-thaw state (remote sensing and models)	(JPL/Quickscat, A)
NEE of carbon (observations and models)	(McGuire, A)
Glacier mass balance (observations and modeled)	(Fahnestock, A)
Topography (remote sensing)	(NASA, A)
Surface water map—time variation? (remote sensing)	(JPL [McDonald], to be determined)
Population distributions	(CIESIN, A)
Disappearing climates (projected future change – model)	(Conservation Int'l, A)
Current map of active observational stations/domains	(CADIS, to be determined)

central Arctic Ocean. On the other hand, AON design must recognize budget realities and logistical constraints that will force hard decisions and compromises. To provide a context for AON design from competing perspectives, it is extremely important to review the design and implementation of past observational programs with a strong atmospheric component for lessons learned. Past projects are many and include surface-based efforts like the Surface Heat Budget of the Arctic Ocean (SHEBA), aircraft missions such as the Arctic Gas and Aerosol Sampling Program (AGASP), and multi-platform efforts such as the Coordinated Eastern Arctic Experiment (CEAREX). What were the selection criteria driving past observational programs? What attempts were made to assess site importance in network design using subjective or objective methods, such as data denial experiments in a modeling framework? How were site requirements and the science questions being asked balanced against the realities of logistics and cost? With hindsight, could decision processes have been improved? Exploring these questions can provide valuable insights into AON design. Questions to be addressed by the inventory and gap analysis include: What is possible with the current set of observations? What are limitations of current observations? What is planned for the near future? Answers to these questions should be analyzed in the context of the key scientific questions that have been posed for Arctic change programs, including SEARCH (cf. draft report of SEARCH Understanding Change Panel [Elliott et al. 2010]).

Spatial scales of variability. Scaling issues and even the definitions of scale vary enormously across individual disciplines, and they hinder not only interdisciplinary research but our capacity to observe, execute process studies, and inform macroscale assessments of Arctic system change (USARC 2010). There are a great breadth of spatial and temporal scales that characterize any one Arctic science discipline and its applications, which are matched by an equally broad admixture of spatial and temporal scales across the disciplines. Such diversity arises from differences in the historical development of individual disciplines and the resulting unique nomenclatures regarding scale (e.g., microscale means something radically different to a microbial ecologist than to an Arctic Ocean sea ice modeler).

The same report (USARC 2010) also found that scale incongruities among components of the Arctic system give rise to opportunities to study intermediate scales. The existing body of research has focused traditionally on measurements made at local scales, which are important for understanding the inherent dynamics of discipline-specific processes. These same disciplines have also relied on coarse-scale models to achieve understanding over the broader domain. In contrast, intermediate spatial and temporal scales have received relatively less attention, yet it is at intermediate scales that systems are often critically defined. For example, intermediate scales could describe boundary layer fluxes that link the highly heterogeneous Arctic land surface to a well-mixed overlying atmosphere. Intermediate scales, or mesoscales, provide an important context through which coarse-scale dynamics become useful in setting the bounds of key phenomena and fine-scale dynamics can be generalized. They also are the domain of thresholds, tipping points, and system-level “surprises.” These scales have been understudied, yet provide an important opportunity for new research. Developing mesoscale observatories and harvesting information from these facilities are critical lynchpins in developing next-generation process understanding and simulation models.

Scales of human perception are much different than those associated with the study of natural systems. Arctic human systems are complex and multifaceted, encompassing both indigenous and industrial societies that vary greatly in both their domains of

perception and their human footprints. Native populations have developed strategies to effectively reduce the impact of high-frequency “noise” in the landscape by integrating their interactions over a wider domain, which tends to dampen such variations. Studying the perceptions of space-time domains and Arctic system change by traditional as well as modern Arctic communities will help to better understand our society’s readiness to adapt to Arctic environmental change. How these patterns can be inventoried and deciphered becomes an integrated environment-human observational challenge.

Finally, information has not been well structured to facilitate cross-scale studies. Given the reality of a diverse treatment of space-time issues within and across disciplines, it is not surprising that coherent information systems are not yet in place to reconcile or deal with these incongruities. Social and natural scientists organize information over very different accounting units (e.g., administrative units versus watersheds), further impeding a unified system-level picture. Jointly developing models and integrated data compendia, with a broad range of thematic data sets that are spatially and temporally harmonized, will allow cross-disciplinary research to be more easily executed.

Design of repeat sections. Understanding of the full scope and impacts of Arctic change requires temporal knowledge of the dynamic features of the Arctic Ocean; its heat, salt, and carbon budgets; and its large-scale marine ecosystems, each of which must be observed in appropriate locations and intervals. Observing systems designed to address these questions in the mid- and low-latitude oceans typically consist of three components: (1) Lagrangian drifters and floats (e.g., global Argo array), (2) Eulerian measurements at key mooring sites such as straits or well-defined boundary currents, and (3) repeat hydrographic/carbon/tracer sections. For the Arctic Ocean, the key choke points (Fram Strait, Bering Strait, and Davis Strait) are being monitored and a Lagrangian array is being implemented and optimized. Although hydrographic and tracer sections have been and are being carried out, they are typically not well coordinated, few span multiple basins or cross the entire Arctic Ocean, and very few are true repeat sections. Most of the present repeat section work with collection of water samples is focused on the upper 500 to 1,000 meters of the water column and carried out partially through aircraft surveys. The water sampling is restricted to temperature, salinity, dissolved oxygen, nutrients, and a few tracers. Biogeochemical measurements, including repeat observations of the carbon system, are absent from these shallow repeat sections.

Thus, it is not surprising that the present Arctic Ocean conductivity, temperature, depth, hydrographic, carbon, and tracer database does not permit ready study of key issues related to regional and global ocean change research. The chief problem with the present data, except in deep waters below sill depths, is significant complexity of spatial and temporal variability. A second critical problem is uneven data quality for most variables other than temperature and salinity. A third problem is lack of reliable access to Russian waters through normal diplomatic channels. For purposes of measurements unrelated to process studies, ice cover is less of a challenge today than previously, except for areas north of the Canadian Archipelago and, intermittently, in some portions of the trans-polar drift.

An important first step is to examine which set of oceanic repeat sections would be needed at a minimum to provide the critical information on shifting hydrography, heat and salt budgets, carbon system and inventories, and large-scale marine biology. The location of the sections, the variables to be measured, and the frequency at which the sections must be repeated and from which platform (icebreaker or aircraft) are all important considerations.

Detection of spatial-temporal patterns of change in Arctic terrestrial systems. To date, Arctic terrestrial environmental monitoring systems have largely focused on individual themes and biogeophysical variables and less on integrated observing systems capturing systemic change. If Arctic terrestrial changes are indeed coordinated (as is often stated), we need monitoring sufficient to detect the systemic effects. Such integrated systems are not currently available, and the Terrestrial ADI Group concludes that the current AON for terrestrial, hydrological, and cryosphere variables is much narrower in scope than the original research plan and National Research Council report on AON suggests. Furthermore, we do not know the impact of these deficiencies and therefore must conduct design experiments testing the capacity of anticipated plans to capture these dynamics.

A prototype array of pan-Arctic biogeophysical and social science data sets plus analysis tools can be used to provide a provisional answer to whether there are systemic patterns of change in the Arctic observational record.

Sphere-of-influence of Arctic communities for snow measurements. Arctic Alaska provides an opportunity to test and refine an observing and analysis system. Data on the flow of carbon-based fuels into communities can be extracted from scattered sources such as electric utility records or published reports and then organized as time series at community or regional levels. Large-scale mining and energy development are critical pieces in the assessment as well. Existing research provides rough guidance on estimating carbon emissions from fuel inputs.

4.2.3. Ecosystem Services

The AON will be particularly important for research related to ecosystem services. Ecosystem services are a potentially useful construct for AON because they provide an explicit bridge between the biophysical environment and the needs of society at local to global scales (Chapin, online appendix 4).

Ecosystem services are the benefits that society derives from ecosystems. These include (1) supporting services, which are the fundamental ecological processes that sustain ecosystem functioning; (2) provisioning services or products of ecosystems that are directly harvested by society; (3) regulating services that influence society through interactions among ecosystems in a landscape; and (4) cultural services, which are nonmaterial benefits that are important to society's well-being. Regulating services, for example, include albedo and carbon storage that determine how Arctic change influences the global climate system and therefore the well-being of society globally. Caribou or seals are provisioning services that meet important nutritional needs of Arctic indigenous people as well as providing important cultural ties to the land and sea.

Ecosystem services themselves provide several opportunities to inform and improve AON project design. First, they identify the parameters that are of particular concern to society, both globally and locally. Second, they provide a framework for dialogue with stakeholders about which changes are of particular concern and therefore to engaging stakeholders in the design and implementation of AON. Recently, progress has been made in identifying how communication with policymakers and stakeholders can be integrated in a more rigorous objective fashion into observing system design. For example, work by Chapin et al. (2006) has illustrated in the case of fire management how specific services provided by the boreal forest translate into variables or processes that need to be tracked to inform wildfire policy. Lovcraft et al. (2012) have shown how the concept of institutional density, i.e., the number

of different rule sets or regulations governing ice use and sea ice-system services in a specific area, can help inform the design of a sea-ice observing system.

Indigenous residents are keen observers of their environment because they depend on this knowledge for their survival. They have generally been the first group of observers to describe incipient changes that have widespread scientific importance, including changes in animal abundances, thickness of river ice, river discharge, wetland drying, river channel geomorphology, riparian disturbance, and effects of fire. Effects related to ecosystem services also influence human culture in important ways. For example, historically, mobile indigenous family groups allowed people to naturally adapt to fire, but modern consolidation of indigenous people into permanent settlements has made them prone to fire impacts (Chapin et al. 2006). Climate change is altering ecosystem services, particularly related to supply, access, and use. AON can help to shift the management of resources from a reactive to proactive stance. This opens the door to innovative opportunities for citizen science in which indigenous residents of the Arctic identify incipient trends that can be both an integral component of AON and affect the evolution of its design.

4.2.4. Data Thinning Experiments

Spatial and temporal scales for snow observation network design. State-of-the-art Arctic snow modeling systems and Arctic snow datasets can be used to perform a network analysis of observation spacing and distribution, observation frequency, and assimilated observation variables (e.g., snow depth vs. snow water equivalent). One objective is to perform observing network experiments using the CSU MicroMet/SnowModel/SnowTran-3D/SnowAssim snow evolution model in conjunction with University of Alaska Fairbanks and Snow-Net Arctic Alaska meteorological data and end-of-winter snow depth and density observations. The model simulation spatial and temporal domains would comprise the Arctic Alaska area most thoroughly covered by observational datasets (e.g., the Kuparuk River and adjacent watersheds during the 2009 water year).

In these OSEs, a “control” data assimilation cycle can be performed at the highest feasible model resolution while incorporating all available observations. Ensuing perturbations to that control simulation can then be tested. Experiments could include modifications to model grid resolution ranging from ≤ 100 m to those represented by regional and global climate-system models (e.g., 10 to 200 km). Additional experiments could include modifying data quality control structures, data thinning and data denial, and refining the observational error estimates. The experiments can be designed to establish cost-benefit matrices for the observing system, identify deficiencies and redundancies in the existing observing system, and ultimately optimize this Arctic observing network and the associated observational datasets from the perspective of snow-related hydrologic and atmospheric energy and moisture fluxes. These snow-related OSEs can serve as an example of similar observing system design experiments that could be focused on other Arctic climate system components.

Optimal sampling of leading modes of variability. Data thinning has been used in many other geographical regions to determine minimal observational densities for particular applications in meteorology and climatology (e.g., Ochotta et al. 2005; Cardinali et al. 2003), including soil temperature climatologies (PaiMazumder et al. 2008). This approach has been little used in the Arctic, especially in observing system design.

Existing atmospheric surface observations and satellite-derived measurements can be used to assess the impact of thinning the observational networks. One way to assess this impact is by examining the effect of the removal of subsets of observations on areal averages (regional, pan-Arctic). Variables for experimentation could include monthly temperature and precipitation (from the Climate Research Unit database) and satellite-derived winds obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multiangle Imaging Spectro-Radiometer). Particular attention should be given to the ability of spatially minimal networks (such as the International Arctic Systems for Observing the Atmosphere [IASAO], a network of intensive observatories) to capture the means and modes of variability of the Arctic atmosphere. In the case of the satellite-derived winds, some thinning will almost certainly be possible before areal means and spatial patterns are degraded, thereby guiding the strategy for data assimilation and other uses of the winds. The project could also include the computation of correlation length scales from the surface and the satellite data.

4.2.5. Model-based Observing System Experiments (OSEs)

Data denial experiments: regional and global. The SEARCH science questions deal with issues inside and beyond the Arctic region. The questions include “How are the global climate and Arctic change coupled?” and “How might Arctic change affect people outside the Arctic?” Considering Arctic observations and the AON in light of these questions, both regional and global linkages between locals and subsystems need to be considered. This likely requires both a regional and a global approach to guiding observing system design. In this context, OSEs, which are often conducted as a type of data denial experiment, can be of great value in assessing the sphere of influence of targeted existing or hypothetical observational sites. The outcomes of OSEs can thus provide guidance on the relative merit of a set of observations based on criteria derived from the relevant science questions or goals.

For studies of the Arctic atmosphere, a framework for conducting such data denial experiments is the multi-institution Arctic System Reanalysis (ASR) with comprehensive data assimilation for the Arctic. The ASR performs high-resolution data assimilation with the polar optimized version of the Weather Research and Forecasting (WRF) mesoscale atmospheric model, and includes the Noah land surface model. The high-resolution regional Arctic OSEs with Polar WRF can complement global perspective gained with OSEs on a global grid relying on the Data Assimilation Research Testbed (DART) and the Community Atmosphere Model (CAM). Such numerical experiments can evaluate the importance of observations from Arctic stations such as Barrow, Alert, and Tiksi towards the quality of reanalyses through data denial experiments for the selected months, resulting in explicit numerical results on the influence of these stations to data assimilation.

For thirty years, global climate models have projected amplified Arctic warming and Arctic sea ice loss under increasing greenhouse gas forcing. Yet, recent observed rates of Arctic climate change have exceeded most global model projections and human expectations. To understand, model, and respond to the rapidly changing Arctic conditions in this context, globally relevant Arctic observations are needed. Here, global data denial experiments can provide guidance, such as the CAM-DART tools. DART is a state-of-the-art ensemble filter data assimilation software package developed at the National Center for Atmospheric Research (NCAR) (Anderson et al. 2009). CAM is the atmospheric component of NCAR’s coupled climate model. Using DART assimilations with CAM, data denial experiments can help evaluate

the influence of pan-Arctic radio occultation observations and individual Arctic soundings (including Barrow, Alaska, and Eureka, California). Metrics that can be assessed to help prioritize the siting and types of observations as part of an observing network include root-mean-square differences attributable to point observations, and e-folding distances of the impact of a particular location on analyzed fields of atmospheric variables, such as sea level pressure, 500 mb height fields, surface flux simulations, and inversion strength, among others.

Sensitivity studies: key Arctic climate indices' dependence on atmosphere-ice-ocean state and observations. As a first step toward a comprehensive quantitative observing system design framework, two coupled ocean/sea-ice models with adjoint capabilities can be used to infer the sensitivities of key Arctic climate indices. The two models are the MITgcm (Michigan Institute of Technology General Circulation Model)/ECCO (Estimating the Climate and Circulation of the Ocean) and the NAOSIM (North Atlantic/Arctic Ocean Sea Ice Model). The coupled models can be used to:

1. improve our mechanistic understanding of relevant Arctic processes as a prerequisite for prediction on climate time scales, i.e., from seasonal to at least decadal;
2. emphasize climate indices as target functions or norms whose sensitivities can be investigated (and whose uncertainties should ultimately be reduced)—the main such quantities are changes in Arctic ocean heat and freshwater content; changes in Arctic sea-ice volume and extent, either annually averaged or at its September minimum; and heat, liquid, and solid freshwater export through key gates; and
3. recognize model imperfections that put limits on the results obtained and explore the robustness of the results through the comparison of two modeling systems. It should also be recognized that models are the only dynamical interpolators available that fulfill known physical principles (basic conservation laws) and are thus an indispensable part of the mix for design and decision.

MITgcm/ECCO model sensitivity calculations can be conducted for several of the above target norms. Sensitivities can be used in conjunction with expected or actual anomalies to infer likely perturbation responses. Dominant variables, regions, and timescales of influence can be established that will serve as guiding tools for the observing system design.

It should be noted that this is only one of several modeling tools for addressing observing system design. Both the NAOSIM and the MITgcm/ECCO infrastructures are designed to enable approaches such as observation withholding experiments, OSSEs, and sensitivity observing system experiments. In the long term, the NAOSIM team aims at building a quantitative network design structure that evaluates a given observing system in terms of its constraint on important target quantities.

Spatial scales of variability in ocean-ice interaction. A system of autonomous platforms (e.g., floats, gliders, and ice-based observatories) will be an important component of the Arctic Observing Network. In the near term, this autonomous array might consist of ice-tethered profilers, ice-detecting profiling floats, and ocean gliders operating under regional, medium-range (hundreds of kilometers) acoustic navigation. In the longer term, autonomous platforms would rely on new, low-frequency tomographic/navigation sources and receivers that would allow seamless acoustic navigation of floats, gliders, and other platforms throughout the major basins of the Arctic Ocean while also providing integral measures of heat content. Definition of the overall measurement goals, or metrics, can be used to evaluate the effectiveness of the array. Likely design goals for this array should include monitoring the heat and

freshwater (salt) content of the upper kilometer of the Arctic Ocean on seasonal to interannual time scales.

4.2.6. Observing System Simulation Experiments (OSSEs)

For parts of the Arctic observing system, including atmospheric, sea ice, and ocean measurements, there are well-established methods to evaluate the array design. In meteorology and oceanography, adjoint modeling and ensemble Kalman filter estimation can be used to investigate the sensitivity of scalar metrics to the location of observations. As an example, Köhl and Stammer (2004) presented a method to estimate the sensitivity of control metrics to observations for a North Atlantic simulation. In their study, they considered sparse data collected over the North Atlantic and showed the sensitivity of volume transport estimates across the Greenland-Scotland ridge to different measurements. In this study they showed that these estimates can depend on nonlocal measurements through the ocean dynamics; for example, measurements downstream from the ridge can place a strong constraint on transports earlier in time. In a study of mooring observations in the Bering Sea, Panteleev et al. (2008) present a similar methodology to evaluate the sensitivity to mooring measurements of the transport through Fram Straits and circulation within the Bering Sea, which also demonstrated the nonlocal sensitivity to different measurements. In this case, they found that the transport estimates were significantly constrained by upstream velocity measurements rather than solely by measurements in the strait.

Similarly, if the space and time scales of variability are known from either model simulations or observations, then optimal estimation, based on the Gauss-Markov theorem (Bretherton et al. 1976) can be used to evaluate the sensitivity of metrics to the measurement locations. Thus, there are well-established methodologies based on *a priori* statistic estimates of uncertainties either from linearized model physics or *a priori* model statistics that can be used to evaluate the sensitivities of metrics that characterize the physical state of the Arctic climate system with respect to the placement of components of the observing system.

Since these methodologies rely on either dynamic models with reasonably high fidelity or on well-determined *a priori* statistics, they are most appropriate for the more fully developed measurements of the physical environment. This evaluation process also must use well-defined metrics that characterize the problem. This means that these analyses can only be performed after the important scientific problems for the Arctic region have been formulated into actionable questions.

4.3. Lessons Learned with Respect to AON

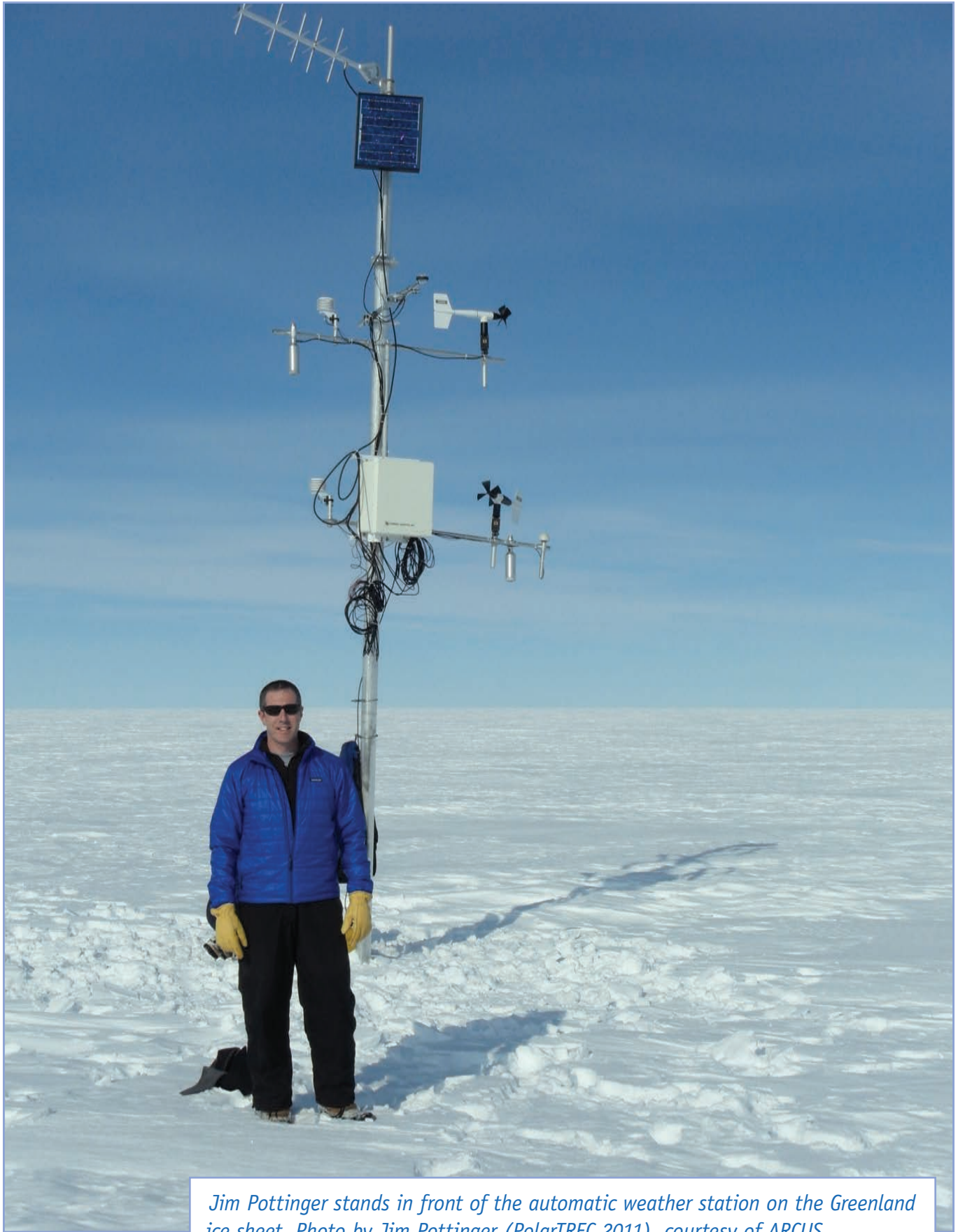
Other observing systems were examined for any lessons learned that could be applied to AON design and implementation. The findings and recommendations in the LTER thirty-year review (LTER 2011) were used to provide specific examples that are applicable to AON design and implementation:

1. An important focus is to address decadal time scales and continental spatial scales.
2. There continues to be a tension between the goal of the network-level research and the goal of the site-based research.
3. A disproportionately large percentage of scientists tend to be engaged in site-level research compared to network-level research.

4. Although most research projects at the scale of individual observation sites may provide good access to data over their individual websites, there has been slow progress in sharing and integrating data across observational sites.
5. There is a need for a greater centralized scientific leadership, empowered by the PIs and site scientists, for positioning the network to guide the broader scientific community to confront societal challenges.
6. A network with a strong central focus (e.g., an ecological focus) can make it difficult to attract scientists in other disciplines and integrate their research in a meaningful way.

A summary of lessons learned from other observing programs includes the following:

- Even networks with demonstrated success require clear articulation of the future implementation of “value-added” components for the scientific community.
- Programs with well-defined scientific problems are more successful than those with more poorly defined, broader objectives.
- Feedback from the stakeholder community, particularly the scientific community, is necessary to provide guidance on the evolution of the network.
- The network should include international and interagency contributions.
- A scientific oversight committee is crucial to the success of many programs.
- It is critical to think beyond a network of study-specific sites and towards a network of networks.
- Individual sites within a coordinated network may only be suitable for a subset of experiments, but the network as a whole would benefit immeasurably by pursuing coordinated multisite experimental studies with broader goals, such as addressing ecological science questions.
- Although data management capabilities may be adequate to support the needs of the current science questions at smaller site-specific scales, the AON as a whole needs to invest in making data comparable across sites and more readily available to those interested in network-wide analyses.
- Data management and quality control must be fully integrated into the program from the outset, but it also needs to have an oversight committee to ensure that data management effectively serves the overall purpose of the network.
- Data collected by these networks should be available as soon as possible for the broad stakeholder community, which includes the broader scientific community, resource managers, policy decision makers, and the public.
- Multiple uses of the data, including both near-real-time operational and long-term scientific analysis, increases the value of the network. The data should be preserved in its original form, but adjusted fields and quality control flags will evolve as the data is further processed.
- The products of the networks should be processed to a sufficient level so that they can be used by the stakeholders and used to inform critical societal decisions.



Jim Pottinger stands in front of the automatic weather station on the Greenland ice sheet. Photo by Jim Pottinger (PolarTREC 2011), courtesy of ARCUS.



ADI Community Survey

An online community survey was sent to a broad range of scientists and agency representatives to understand the community's view on the AON design and implementation. A total of 120 responses were received. Complete results of the community survey and the methods for analyzing survey results can be found in appendix 5. A brief summary of the key results is presented below.

The ADI survey included ten questions asking respondents to rate the importance of different challenges. Answers could range from “critical” to “not important.” The exact wording appears in appendix 5 (survey question 6).

Figure 1 graphs the mean response to each of these ten questions, on a scale from 0 (not important) to 4 (critical). Most survey respondents agreed that sustaining long-term observations is critical. Logistic constraints, regional balance, and national-level balance also had high priority. Optimizing observations across AON scientific priorities and balancing the needs and goals of all stakeholders appear less critical.

Among the 120 survey respondents, 53 were identified as being either academic (40) or agency (13) scientists. Statistically significant differences between academic and agency respondents occur on three of these questions:

- “Sustaining long-term observations” is much more often deemed critical by academic (93%) than by agency (46%) respondents.
- “Balancing observations across regions,” on the other hand, appears less critical to academic (45%) than to agency (54%) respondents.
- “Applying rigorous approaches to observing system design” is much less critical to academic (20%) than to agency (62%) respondents.

Fifty-seven respondents were identified either as present/past AON principal investigators (44), or as not AON PIs (13). On two questions, we see statistically significant differences between these groups:

- “Prioritizing the types of observations made” is seen as important, but less often critical, by AON PIs (0%) compared with other respondents (30%).
- “Applying rigorous methods to observing system design” likewise does not appear critical to AON PIs (0%), although it is critical to 39% of non-PIs.

The ADI survey also asked respondents whether they agree or disagree with a number of statements. Wording of these questions is given in appendix 5 (survey question 8).

Figure 2 charts the mean responses to these questions, scaled from 0 (strongly disagree) to 4 (strongly agree). Urgency of science questions, needs of data users, information needs of key stakeholders, and design by those carrying out the observations received the most agreement. Respondents less often agreed that observing system design is best done through modeling studies or that design and implementation should be primarily driven and supported by government agencies.

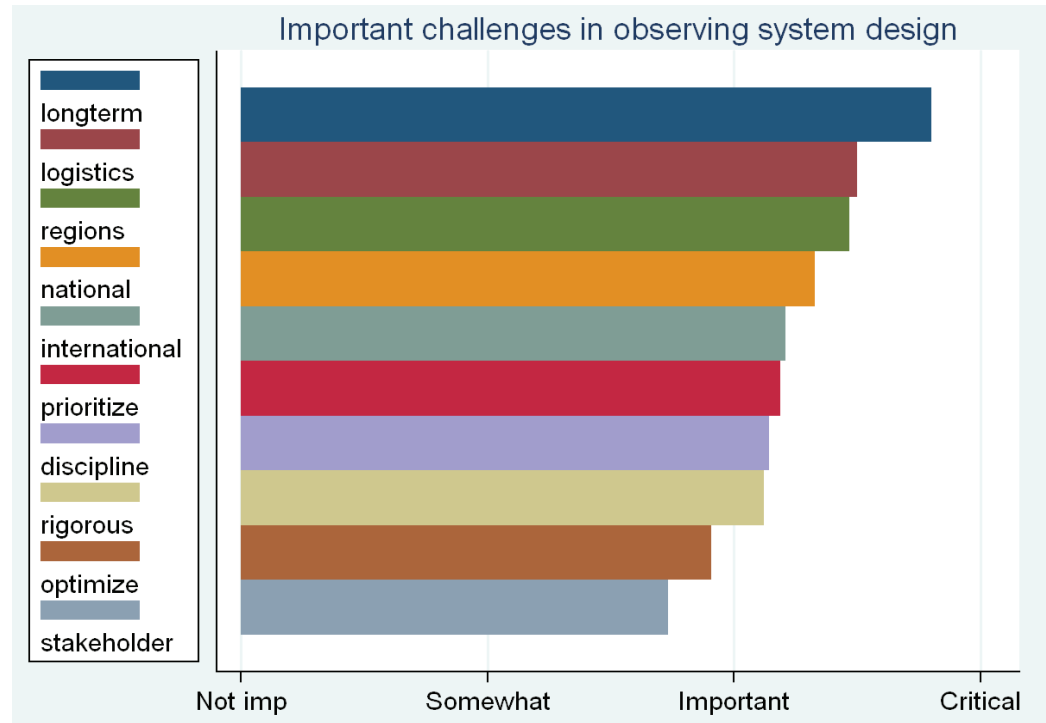


Figure 1. Summary of mean responses on the importance of ten challenges to observing system design. See text in appendix 5 (survey question 6) for the full statements of challenges that correspond to the description of each colored bar.

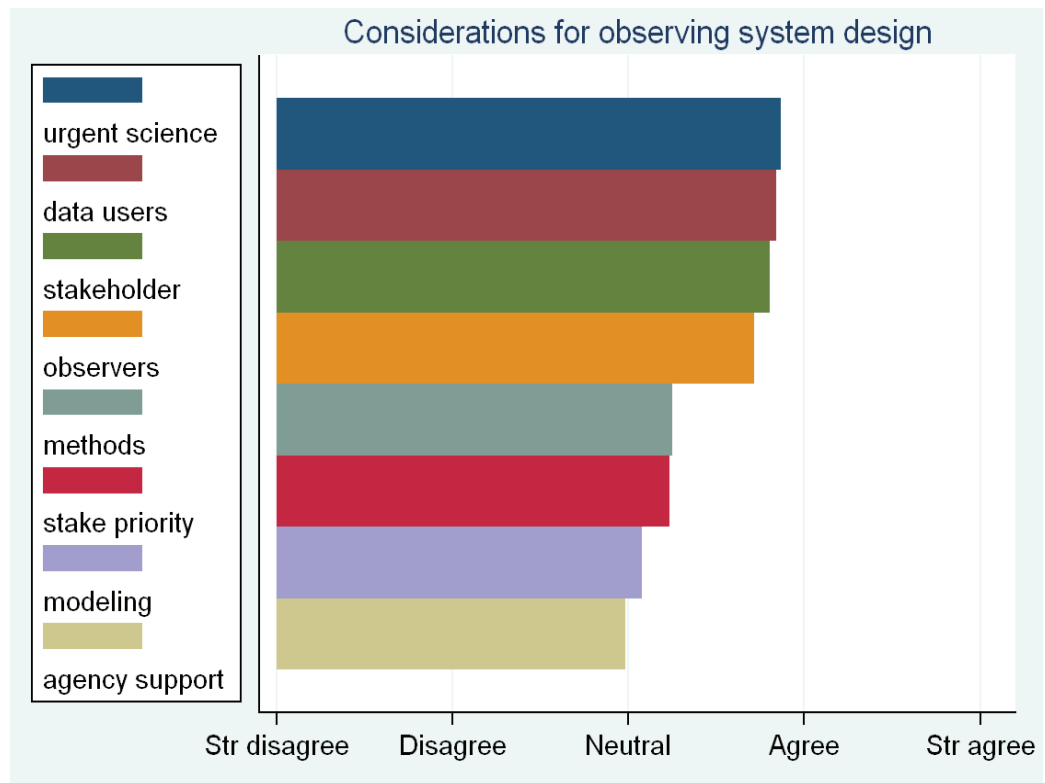


Figure 2. Summary of mean responses on agreement to statements about observing system design. See text in appendix 5 (survey question 8) for details on the full statements that correspond to the description of each colored bar.

Statistically significant differences between agency and academic scientists occur on the top three questions in Figure 2. Agency respondents tend to strongly agree (69%, compared with 23% academic) that observing system design needs input from data users and that an Arctic observing system has to meet the needs of stakeholders outside the scientific community (again, 69% agency compared with 23% of academic respondents). Academic respondents, on the other hand, are more likely to strongly agree that observing system design is best done by those carrying out the observations (25% of academics strongly agree and 50% agree, compared with 0% strongly agree and 38% agree for agency respondents).

Respondents who are not AON PIs more often strongly agree that observing system design needs input from data users (43%, compared with none of the AON PIs).

The survey also allowed open-ended responses to describe additional challenges to ADI. Respondents mentioned that making data available (including the rapid release of data), consistency in observation protocols, management, funding support, and technical limitations were additional challenges to ADI. Most respondents who provided feedback on how to overcome the challenges to ADI agreed that increased national and international coordination was required (41.5%), followed by sustained long-term funding (18%).



Above: John Sode and a research team member take measurements on a river near Thule, Greenland. Photo by John Sode (TREC 2005), courtesy of ARCUS.

Below: TREC teacher Robert Oddo and student Fran Moore take flow rate measurements. Svalbard, Norway. Photo by Robert Oddo (TREC 2005), courtesy of ARCUS.



6

ADI: Challenges and Opportunities Based on Two Brief Case Studies

6.1. Introduction

The ADI Task Force identified several challenges for the design and implementation of an AON, including different levels of maturity of understanding for different disciplines, reconciling observing needs at different scales that are important for stakeholders (seasonal and regional scales), long-term predictions (decadal and pan-Arctic scales), balancing a mix of top-down model-based studies with bottom-up adaptation of existing observing systems, and difficulty in maintaining data access and interoperability. However, opportunities also exist to improve the efficiency of the AON, such as identifying common observing measurements that would benefit various disciplines and providing opportunities to increase collaborative research to allow network scientists to get involved in cross-disciplinary, network-wide research. While section 7 addresses these aspects in more detail, two brief case studies help illustrate how some of the challenges can be addressed to foster increased networking and use of data and information products emerging from an AON.

6.2. Lessons from a Feedback Synthesis for the Arctic Hydrologic System: A Possible Framework for ADI

The priorities for an Arctic observation network differ with every group of scientists and stakeholders asked to perform this task. A clear motivating goal to focus observing activities is needed, as is an objective means to identify the obstacles standing in the way of achieving that goal. Arguably an important overarching rationale for better understanding the Arctic system is to be able to provide seasonal forecasts and decadal projections of Arctic conditions and to understand how future changes in the system will affect human society, both local populations and interests elsewhere. This goal necessarily requires a variety of modeling activities that range from single-column and high-resolution regional models forced by observations to fully coupled global models to project future evolution of the system. While progress has been made in simulating observed trends with coupled models, the spread among different models has not lessened appreciably since the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) generation. Reasons for this lack of improvement remain elusive.

Observations can be used to help identify important shortcomings in model physics in three ways: (1) providing more accurate initial conditions, (2) developing more realistic formulations or parameterizations of important processes, and (3) evaluating model performance through validation of hindcasts. One of the key obstacles in moving forward in this endeavor is identifying those important shortcomings that

are contributing to the spread among models and to unrealistic behavior within a particular model. The following discussion provides an example of a strategy for distilling a complex system into its fundamental components and the interactions among them and that allows an objective assessment of uncertainties in our understanding of those interactions. Alleviating those uncertainties can then be a focusing lens to guide an observing strategy such as AON.

A study that emerged as a part of the NSF Arctic Freshwater Integration project was a heuristic synthesis focused on how changes in the pan-Arctic hydrologic system, and the myriad of feedbacks within that system, ultimately affects life in the ocean, on land, and human society (Vörösmarty et al. 2002, 2008; Francis et al. 2009). Its objective, literature-based approach highlights uncertainties in state variables, interactions among them, and feedbacks in the system that constitute obstacles to understanding and projecting future Arctic change and thus are ripe targets for new AON resources. While this study focused on the Arctic hydrologic system, its approach may be adapted to address other specific parts of the system that may not appear explicitly in this assessment.

Summary of the Study

The main objective of this study was to distill the Arctic hydrological system into its fundamental elements and interactions. The system was divided into its main atmosphere, ocean, and land subsystems and a heuristic, graphical approach that elucidated key components and relationships in the system that directly affect life: marine primary productivity, terrestrial vegetation, and humans living in the Arctic. Because the hydrologic cycle is affected by or affects nearly all aspects of the Arctic climate system, the scope necessarily encompassed nearly all major aspects of the system and interactions, either explicitly or implicitly, that will likely emerge as high-priority targets for AON. The approach for the study consisted of four main steps:

1. Identify key components, or “hubs,” in each of three subsystems: atmosphere, ocean, and land. Three criteria guided the selection of the hubs: Each must capture essential characteristics of the system that are not captured by other hubs, have strong connections to other hubs, and be able to be described as increasing or decreasing in a pan-Arctic sense.
2. Based on observations or model results described in peer-reviewed literature, identify and characterize interactions between pairs of hubs. Interactions were defined as positive (a change in one hub leads to a change of the same sign in another), negative (opposite sign), competing effects, temporally changing effects, or uncertain. These interactions were identified with color-coded arrows in diagrams.
3. Based on the numbers of arrows directed toward or away from each hub, the hubs were characterized as either system drivers (more arrows leaving) or responders (more arrows pointed toward a hub).
4. Identify feedbacks in each subsystem by finding closed loops among arrows in the wiring diagrams, but only those that have direct linkages with one or more of the three living components of the system. This focus on living components is arguably the most compelling motivation for understanding Arctic change and provides a framework to help prioritize key variables and interactions and greatly reduce the scope of the investigation. This lens may assist in defining the ADI framework, as well.

Key findings and possible relevance for ADI (bold text):

- Some feedbacks that emerged were recognizable and their behavior understood, but many more were unfamiliar and contained uncertain interactions that result in the entire feedback loop being of unknown strength and/or sign. **The most uncertain of these feedbacks, as well as the interactions within them, may be prime targets for aiming AON. The focus should be to address not only the observation of particular variables but also the covariability that defines interactions within those feedbacks.**
- Atmospheric hubs are drivers in all three systems, and all three “life hubs” are responders in all subsystems.
- All of the physical hubs for the atmosphere are linked with the global system.
- The atmosphere subsystem contained seven feedbacks that directly affect one of the life hubs: only one is negative. Five involve direct effects of sea ice on life. Three involve direct effects of clouds on marine and terrestrial life, three have uncertain effects on life in the ocean and on land, and six participate in feedbacks of unknown sign with humans. **Precipitation emerged as a key variable responsible for uncertainty: not only the amount but also the phase, timing, and how other hubs respond to its variability. While effects of clouds on marine productivity and vegetation are negative, their strength (regionally and seasonally) is highly uncertain.**
- The ocean subsystem contained five feedbacks: all involve sea ice (area and/or volume) and four have unknown signs as they relate to marine productivity and humans. **Key uncertain interactions involve effects of varying precipitation and ice melt on mixed-layer stratification and how mixed-layer stratification and heat storage affect sea ice, factors limiting phytoplankton abundance regionally and seasonally, and competing effects of ice loss on coastal communities.**
- The terrestrial system contained four feedbacks: all involve vegetation and three have unknown signs as to their effects on vegetation and humans. The only drivers in the system are atmospheric (air temperature, snowfall, and rainfall). **Key uncertainties arise from poorly understood effects of precipitation variability (amount, type, and timing) on vegetation as well as on permafrost and the active layer depth. The relationship between active-layer depth and vegetation is also a key unknown.**
- **Some connections between hubs change with time and/or have competing effects that change sign with time, particularly in the terrestrial system. These shifts occur on different (but uncertain) time and space scales and with different intensity of impact.**

The feedbacks that emerged from this study reveal interactions among system hubs that constitute obstacles to understanding the sign and strength of those feedbacks and the impact of those feedbacks on the living parts of the system. Moreover, **a tool for prioritizing AON activities is a lens focused on just the human element and the feedbacks identified through this analysis that most directly affect human well-being.** The hubs that have strongest ties with humans are:

- **sea ice**, through its effects on shipping, resource extraction, fishing, and global circulation patterns;
- **marine productivity**, as the base of the food web for commercial and local fisheries and overall wellbeing of the ecosystem; and
- **freshwater on land**, as it relates to drinking water, infrastructure, and land travel.

Focusing on these human-critical hubs, we can then refer to the line diagrams to identify which hubs are the primary drivers and especially which interactions among the hubs are responsible for uncertainty in the feedbacks affecting human well-being. Repeating the list from above, the following assessment identifies those key drivers, but more important are the interactions that link them with sea ice, marine productivity, and freshwater:

- **Links with sea ice:** water vapor, clouds (through their effects on radiation fluxes), precipitation and evaporation (amount, timing, phase), surface air temperature and ocean mixed-layer heat storage. While not explicitly part of the diagrams, the effects of changing winds and ocean currents are also critical. These are captured implicitly in the diagrams through their effects on the state variables represented by the selected hubs.
- **Marine productivity:** sea ice area and thickness distributions, clouds (through shading of insolation), surface air temperature, mixed-layer heat storage, and freshwater content (through its effects on stratification, which influences mixing of nutrients)
- **Freshwater on land:** vegetation, permafrost, active-layer depth, surface air temperature

6.3. Observations in Support of Seasonal Ice Prediction Through the SEARCH Arctic Sea Ice Outlook

The SEARCH Arctic Sea Ice Outlook (<http://www.arcus.org/search/seaiceoutlook/>) is an international effort to provide a community-wide summary of the expected September Arctic sea ice minimum. Monthly reports released throughout the summer synthesize community estimates of the current state and expected minimum of sea ice at both pan-Arctic and regional scales. The intent of the SEARCH Arctic Sea Ice Outlook effort is to provide a forum for the review and synthesis of different seasonal sea-ice prediction approaches, foster exchange between modelers and observationalists, and summarize all available data and observations to provide the scientific community, stakeholders, and the public the best available information on the evolution of Arctic sea ice (Overland et al. 2009; Calder et al. 2010).

A survey of more than seventy users of information provided by the outlook conducted in the third year of the effort indicates that despite the informal, ad-hoc nature of the effort, it served as an information source for some stakeholder groups (in particular agencies and industry) to assess the maturity and quality of different prediction approaches as well as provide specific information on expected ice conditions. This finding has prompted an exploration of how to improve seasonal sea-ice prediction at pan-Arctic and regional levels through targeted observations that can serve as an illustration of how prediction of environmental variables (in this case sea ice extent at a given date at the regional or pan-Arctic scale) of value to scientists and stakeholders can drive observing system design and, more importantly, optimization of specific measurements.

For the Arctic sea ice outlook, several studies have indicated the importance of ice thickness information at the end of the ice growth season for initialization of coupled ice-ocean models completing ensemble simulations of ice extent with forcing for a series of different realizations of atmospheric states derived from the corresponding time period of the past one or two decades (e.g., Kauker et al. 2009; Lindsay

2010). Data-withholding experiments with respect to specific ice observations (see also section 4.2) suggest that ice observations over the Siberian Arctic shelves and the Alaska Arctic, where large variations in the distribution and thickness of multiyear ice have been observed in recent years, hold particular value in constraining predictive skill for the September sea ice minimum. This led to a series of opportunistic measurements of ice thickness in late March and early April in the U.S., Canadian, and Greenland Arctic sector to obtain dedicated ice thickness survey flights (including flights by NASA's IceBridge project, an AON project, and other collaborators) at a resolution and coverage high enough to have a measurable impact on model-based seasonal ice prediction. While the results from these experiments, completed in spring of 2012, are still under evaluation, this case study illustrates how prediction of a specific variable (and objective criteria with respect to predictive skill) can guide targeted observations in a setting that combines academic research interests (is the ice cover moving to a new state?) with operational interests (what is the expected ice severity and potential ice hazards in specific subregions of the Arctic for local communities and maritime activities?).

At the same time, such targeted observations can also markedly improve statistical and heuristic models, in particular if combined with deployment of ice mass balance buoys that allow tracking and projections of ablation rates during the course of the summer, which in combination with ice thickness surveys are critical in anticipating regional ice retreat rates.

In this context, the accuracy of the measured quantity, i.e., summer ice concentration fields derived from passive microwave satellite data, also needs to be critically examined in relation to the uncertainty in the model prediction estimates. With substantial errors due to the presence of surface meltwater in summer ice concentrations from satellite observations, surface-based observations that can help constrain, validate, and ultimately lead to improvement of the data sets are also of great value and complementary to thickness surveys. Finally, the outlook highlighted the importance of assessments of surface layer heat content for the timing and extent of the sea ice minimum but also for the subsequent fall ice advance, with specific guidance on regions in which such data could impact the quality of seasonal ice predictions at the pan-Arctic scale.



Satellite antenna installation for the NASA-U automatic weather station at the North Greenland Eemian Ice Drilling (NEEM) camp on the Greenland ice sheet. Photo by Jim Pottinger (PolarTREC 2011), courtesy of ARCUS.

7

Conclusions and Recommendations

A successful Arctic Observing Network will allow us to address interdisciplinary questions regarding environmental, ecological, and socioeconomic responses to a changing climate. The conclusions and recommendations of the ADI task force take into account the assessment of the present state and implementation plans of the AON, the synthesis of lessons learned from other observing systems, the identification and assessment of promising approaches for observing system design and optimization, and the results of the community survey.

7.1. Evaluation of the Present State of AON

It is difficult to design and optimize a multidisciplinary observation network that addresses the broad range of science questions of the AON. Any optimization effort must begin with a system specification with design targets to optimize around. Identifying the science question that the observational network will address is the first step to optimize a network (section 2), and this formed the basis for the Task Force recommendations on key science questions.

7.2. Synthesis of Lessons Learned From Other Observing Systems

The ADI Task Force convened a community workshop in December 2009 to review and discuss lessons learned from other observing systems. Brief summaries and lessons relevant to the AON were provided (section 3), with complete summaries of these presentations compiled in appendix 4. However, the design, implementation, and optimization of a cross-disciplinary, pan-Arctic observing system includes a number of challenges, some of which are unique to AON and could not be addressed by simple comparisons with other observing systems.

The Task Force used relevant lessons learned from the Long Term Ecological Research (LTER) network, other observing networks, and feedback from 120 responses to the community survey to help determine the ADI recommendations. A summary of these lessons suggests that networks with a distinct focus rather than broader, less clearly articulated objectives are more successful, in particular if coupled with feedback from stakeholders and data users on the evolution of network requirements. Data need to be comparable across individual sites, allowing for network-wide analyses and integration into an overarching network of networks. These needs are best met in a context that allows for interagency and international network contributions. Multiple uses of data and the availability of data to the broad stakeholder community, including the broader scientific community, resource managers, policy decision makers, and the public, increases the value to the network. Also, data management and quality control needs to be integrated into network design from the

outset. Moreover, a scientific oversight group is critical to successful programs. A key function of such a group is to ensure that data serve the identified (and sometimes evolving) needs and are made available as soon as possible and in a form useful and interpretable by the broader stakeholder community.

7.3. ADI Community Survey Results

The scientific community survey was launched by the ADI Task Force to obtain additional information on relevant design and optimization approaches, to get feedback on lessons learned from previous and existing efforts, and to gain insight into perspectives on priorities for AON implementation (appendix 5). Some perspectives differed between academic and agency responses, with agency responses placing greater importance on balancing observations across regions, rigorous approaches to observing system design, obtaining input from data users, and meeting the needs of stakeholders outside the scientific community compared to academic responses. Key challenges identified by a majority of the 120 respondents include the availability of data from the AON (including the rapid release of data), consistency in observation protocols, implementation of effective management models, sustained funding support, and technical limitations. Open-ended question responses provided guidance on how to overcome such challenges, with the need for national and international coordination seen as the most important priority. The Task Force recommendations on management structure address most of the critical concerns described by respondents of the community survey.

7.4. Identification and Assessment of Promising Approaches for Observing System Design and Optimization

In response to the unique challenges of AON design and implementation, the ADI Task Force, with input from the broader research community, developed a hierarchy of approaches for observing system design and optimization. The six broad methodological categories for design and optimization include (1) integration through overarching projects, including impacts of change on human activities; (2) retrospective analysis and review of past work; (3) ecosystem services; (4) data thinning experiments; (5) model-based observing system experiments; and (6) observing system simulation experiments. The first three methodological approaches are mostly qualitative in nature and would be most suitable for observing goals that are less well-defined. The last three approaches are quantitative and model-based and require a greater level of understanding of the observing system design goals and the local-scale expression of the processes that drive the observed change. Specific examples of how the different approaches could be applied to AON design were also provided in the report (section 4.2).

A complication in the methodologies for network design is that the degree to which they have been implemented to date varies widely between different disciplines. For example, OSSE and adjoint modeling analyses are well established in many fields of the physical sciences, but these approaches are not appropriate for actionable social science questions. A further complication is that there are legacy components of the AON already in place. Table 6 provides a summary of the hierarchy that is required to design and optimize elements of the AON.

The hierarchy in Table 6 also references two brief case studies that illustrate how to address several challenges identified by the ADI Task Force for the design and implementation of an AON, including different levels of maturity of understanding for different disciplines, reconciling the observing needs at different scales that are important for stakeholders (seasonal and regional scales) and long-term predictions (decadal and pan-Arctic scales), balancing a mix of top-down model-based studies with bottom-up adaptation of existing observing systems, and difficulty in maintaining data access and interoperability.

The first study considered changes relevant to the Arctic hydrological system (Francis et al. 2009). To help identify criteria and metrics useful in observing system design and optimization, a focus on the system components that directly affect life was chosen: marine primary productivity, terrestrial vegetation, and people living in the Arctic. This case study illustrated a strategy for distilling a complex system into its fundamental components and allows the objective assessment of uncertainties in our understanding of the interactions between those components.

The second case study considered by the ADI Task Force, centered on the SEARCH Arctic Sea Ice Outlook, was an effort to synthesize findings from different seasonal ice prediction approaches to improve the prediction of seasonal and interannual ice variations. The Arctic Sea Ice Outlook illustrates how a set of science questions and metrics (in this case related to pan-Arctic and regional ice extent prediction) can be arrived at jointly by different interests within the scientific community and key stakeholder groups. This greater level of specificity, compared to the example for the hydrologic cycle, allows for a discussion of different approaches that can inform the deployment of observing assets. In the case of the Arctic Sea Ice Outlook, coupled ice-ocean models provided guidance on priorities of key variables and ideal measurement locations, similar to what an OSSE would indicate.

Table 6. Elements of AON design and optimization hierarchy

AON Design Elements*	Activity	Implementation	Discussion in Report
Problem Definition	Development of science goals and definition of actionable science questions	SEARCH program, agencies, stakeholders, AON Science Steering Group	Section 2 (AON science question alignment chapter)
Strategy	Feedback and uncertainty analysis, identification of metrics, model-based assessments, process studies	Working groups, funded projects, ad-hoc meetings (researchers, agencies, stakeholders)	Section 6.2 (heuristic feedback and uncertainty analysis)
Tactics	Target quantity definition and measurement options, model-based assessments	Synthesis forums (e.g., Sea Ice Outlook, flagship site teams), funded projects, and ad-hoc meetings (researchers, agencies, stakeholders)	Section 6.3 (Sea Ice Outlook section)
Deployment Scale	Sampling array design	AON projects, OSSE/OSE teams	Section 4.2.6 (OSSE chapter/case study)

* These elements expand and refine the organization of an AON envisaged in Table 3. An example of how to apply this approach is discussed in appendix 6.

7.5. Task Force Recommendations

- 1. Key science questions:** The key science questions driving network design and optimization must be laid out in an actionable form. Actionable, in this context, indicates that questions are formulated in a way to meet at least one and ideally both of these two requirements: (a) the question translates an overarching science question or SEARCH or IARPC five-year science goal such that it links directly to specific quantities that need to be determined in the context of an observing system, and (b) data derived from addressing this actionable question allows stakeholders or governing bodies to develop policies or inform specific decisions and actions in response to Arctic change. Once such actionable questions have been formulated, one can begin to determine the quantities (e.g., fluxes, storages) that need to be measured and define metrics to inform acceptable levels of uncertainty (e.g., associated with network density). Actionable questions regarding the energy, carbon, and freshwater budgets should be a first priority since they are relevant to many disciplines. For aspects of the observing system for which understanding of design approaches is in its early stages (such as in the social sciences, as outlined by Berman 2010), network design should draw from regional pilot studies that can help determine scales of variability.
- 2. Space and time scales:** The AON should have its sights set on the pan-Arctic space scale and seasonal-to-decadal time scales, laying a foundation for and tying into complementary national and international measurement programs that delve into the regional to local scales (regional downscaling). At the same time, AON should take advantage of regional measurements that are mandated or taken by other national and international organizations. Moreover, while the overarching focus is pan-Arctic, the need to address questions of societal relevance will often require AON observing activities at the local or regional scales, which are often more relevant to stakeholders. Both in integrating different components of an observing network across a range of spatial-temporal scales and in evaluating scales of variability that can inform system design, remote-sensing approaches have an important role to play. Available remote-sensing data sets have substantial potential in addressing these tasks and can play an important role in the context of ADI.
- 3. Prioritization:** The AON should strive for a balance that addresses the physical, biological, and human components of the Arctic system. Observations should be prioritized based on the breadth of application for different actionable science questions, with higher priority assigned to approaches that can help address multiple questions. Some variables have well-established sampling methodologies and well-defined space and time scales of variability; such information will be central in network design. While the network can be designed initially based on past experience in sampling strategy, more rigorous evaluations should be carried out for comparison using OSSEs and other methodologies, such as data denial experiments. Pilot studies should be implemented to explore effective approaches for system design where the background science has not yet developed sophisticated design algorithms.
- 4. Design and optimization approaches:** Methodologies and implementation strategies for network design vary widely between disciplines, both in approach and maturity. Hence, no single blueprint or common design exists for the components of an AON. Rather, observing system design and optimization need to be considered in a hierarchy of approaches relevant for an AON (Table 6). From this

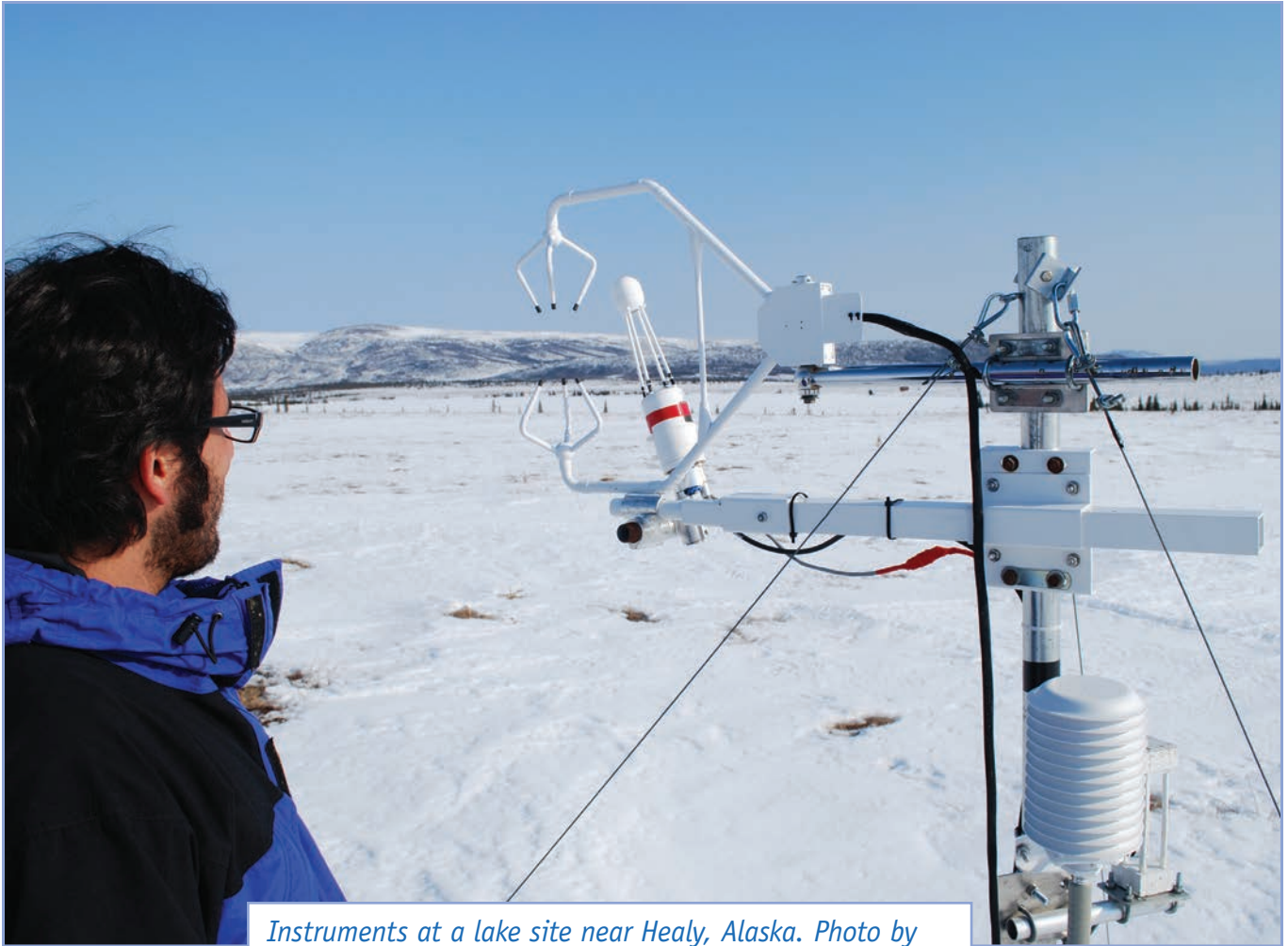
recognition, it follows that the diversity of science questions that an AON must address requires an extensive strategic analysis of their prioritization, the variety of the observational methodologies that must be implemented, and the different levels of readiness in each field. AON design and optimization should include an analysis of trade-offs between different sampling methods, particularly for a rapidly changing ice cover regime, and retrospective studies based on the existing network to evaluate the adequacy of existing components in addressing scientific questions. An important aspect of the AON design is the ability of the network to remain agile and to adapt to a rapidly changing Arctic, coupled with an evolving set of actionable scientific questions.

5. **Metrics:** Network design to address specific science questions requires quantitative metrics (targets) of allowable uncertainty in the quantities being measured. Metrics should be relevant to the present and possible future states of the Arctic as opposed to the Arctic of the past. Allowable uncertainties will depend on the science question being asked, with different science questions requiring a specific analysis of allowable uncertainties. For the latter, consensus within the scientific community is important for determining the allowable uncertainties.
6. **Management structure:** An AON Scientific Steering Group is recommended to provide a management structure that can respond to input from the SEARCH Science Steering Committee, the scientific community, AON stakeholders, representatives from international AON projects, and federal or state agencies. The Steering Group composition would reflect this diversity and be able to advise NSF and other agencies supporting the AON on network goals and provide input on how individual projects address these goals. The Steering Group would also provide guidance on how different observations may be prioritized, promote communication across AON scientists and stakeholders, and define AON data policies. This structure may require the formation of ad-hoc working groups that focus on specific issues and the establishment of a project office that provides management support to AON activities.

Some of the specific issues that the Steering Group ad-hoc working groups would address include (a) producing actionable questions from key science questions as defined in the first section of recommendations, (b) evaluating network design studies, and (c) working with agencies to develop efficient funding support mechanisms where there is overlap between agency priorities and actionable questions. The AON project office would provide day-to-day support and data services support such as (a) maintaining an inventory of AON measurements, other regional observations, and AON international partners, and (b) coordinating with AON data managers to assure optimal service to data providers, users, and stakeholders, including the dissemination of model analyses such as sensitivity studies.

7.6. Next Steps

Based on the conclusions and recommendations above, the ADI Task Force identifies a number of key next steps. These include (1) the compilation of an inventory of harmonized data from different agencies to improve data interoperability, access to data, knowledge of data holdings, and support to modeling studies; (2) planning for and implementation of an AON Steering Group; and (3) steps towards prioritizing existing and future observing activities as outlined in the hierarchical approach summarized in Table 6.



Instruments at a lake site near Healy, Alaska. Photo by John Wood (PolarTREC 2011), courtesy of ARCUS.

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Appendices 2–6

Appendices 2 through 6 are available at <http://www.arcus.org/search/aon/adi>