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

Citation

AON Design and Implementation Task Force. *Designing, Optimizing, and Implementing an Arctic Observing Network (AON): A Report by the AON Design and Implementation (ADI) Task Force* (2012). Study of Environmental Arctic Change (SEARCH), Fairbanks, AK. 64 pp.

Acknowledgements

The Arctic Observing Network (AON) Design and Implementation (ADI) Task Force consisted of Sandy Andelman, Hajo Eicken, Lawrence C. Hamilton, Marika Holland, Craig M. Lee, Breck Owens, Mohan Ramamurthy, Peter Schlosser, Harvey E. Seim, Mark C. Serreze, John R. Vande Castle, Charles Vörösmarty, and John E. Walsh. Jennifer Francis, Dmitri Nechaev, and ADI workshop participants contributed to portions of this report.

We are grateful for support and guidance from the National Science Foundation, Office of Polar Programs, in particular Erica Key, Neil Swanberg, and Buck Sanford. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the National Science Foundation.

We thank Helen Wiggins and Reija Shnoro of the Arctic Research Consortium of the United States (ARCUS) and Jill Reisdorf and Loretta Quinn of the Joint Office of Science Support of the University Corporation for Atmospheric Research (UCAR) for their assistance.

Copyediting, design, and layout by Inkworks, Russ and Sue Mitchell.

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
Qualitative and Semi-quantitative Evaluations	
Integration through overarching projects, including impacts of change on human activities	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 bio-geophysical observations to understand coordinated and/or uncoordinated signatures of change in Arctic terrestrial ecosystems; thematic and physical coherence studies among all variables tested
Retrospective analysis & review of past work	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
Ecosystem services	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
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 observing system experiments (OSEs)	Data denial experiments; sensitivity studies of key Arctic climate indices; spatial scales of variability in ocean-ice interaction
Observing system simulation experiments (OSSEs)	Assessment of hypothetical datasets collected through an observing network at specified locations, using predictive or diagnostic models to build on an observing system

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.