ARCTIC
VOL. 68, SUPPL. 1 (2015)
http://dx.doi.org/10.14430/arctic4450

A Framework for Prioritization, Design and Coordination of Arctic Long-term Observing Networks: A Perspective from the U.S. SEARCH Program

Olivia Lee,[1,2] Hajo Eicken,[1,3] George Kling[4] and Craig Lee[5]

(*Received 26 May 2014; accepted in revised form 5 November 2014*)

ABSTRACT. Arctic observing networks exist in many countries and often cross international boundaries. We review their status and the development of networked long-term observations as part of a U.S. Arctic Observing System, highlighting major challenges and opportunities for prioritizing observations, designing a network, and increasing coordination. Most Arctic observing activities focus on specific themes and ecosystem services, resulting in a relatively narrow scope of observations for each network. Across all networks there is a need to improve national and international coordination to (1) reduce potential mismatch between identified science needs and outcomes desired by society, (2) link current observing networks to emerging agency and private-sector observing programs across disciplines, and (3) present a stable set of goals and priorities to increase network utility in view of the limited funding resources. We survey the landscape of observing activities and efforts to coordinate them internationally and present a framework for prioritization and coordination based on the activities of the U.S. Study of Environmental Arctic Change (SEARCH). This framework includes a hierarchy of interconnected activities involved in the design and implementation of observing networks. Across the hierarchy, definition of "actionable" science questions helps drive network design, with priorities set by the breadth and depth of the societal applications or policy requirements that these questions can inform. We present an example of applying this design hierarchy to observations that support policy and management decisions about offshore resource development in the Chukchi Sea.

Key words: Arctic observing; stakeholders; observing network design

RÉSUMÉ. De nombreux pays sont dotés de réseaux d'observation de l'Arctique, et ces réseaux enjambent souvent des frontières internationales. Nous nous penchons sur ces réseaux de même que sur la réalisation d'observations à long terme au moyen d'un réseau américain d'observation de l'Arctique, en prenant soin d'aborder les principaux défis à relever et les possibilités à saisir pour établir les priorités en matière d'observations, pour concevoir le réseau et pour améliorer la coordination. La plupart des activités d'observation de l'Arctique portent sur des thèmes particuliers et des écoservices, ce qui produit une étendue d'observations relativement étroite pour chaque réseau. Dans le cas de tous les réseaux, il y a lieu d'améliorer la coordination nationale et internationale pour (1) réduire la possibilité d'écarts entre les besoins déterminés par la science et les résultats souhaités par la société, (2) lier les réseaux d'observation actuels aux programmes d'observation émergents du secteur public et du secteur privé dans les diverses disciplines, et (3) présenter une série d'objectifs et de priorités stables en vue de rehausser l'utilité des réseaux en fonction du financement restreint. Nous examinons les activités et les efforts d'observation afin d'en assurer la coordination à l'échelle internationale et de présenter un cadre de priorisation et de coordination fondé sur les activités de l'organisme américain Study of Environmental Arctic Change (SEARCH). Ce cadre comprend une hiérarchie d'activités interreliées se rapportant à la conception et à la mise en œuvre de réseaux d'observation. Dans cette hiérarchie, la définition des questions de science « exploitable » guide la conception de réseaux, les priorités étant fixées par la portée et l'étendue des applications sociétales ou les exigences politiques que ces questions peuvent éclairer. Nous présentons un exemple d'application de cette hiérarchie de conception aux observations sur lesquelles reposent les décisions de politique et de gestion en matière de mise en valeur des ressources au large dans la mer des Tchouktches.

Mots clés : observation de l'Arctique; parties prenantes; conception du réseau d'observation

Traduit pour la revue *Arctic* par Nicole Giguère.

[1] Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive, PO Box 757320, Fairbanks, Alaska 99775-7320, USA
[2] Corresponding author: olivia@gi.alaska.edu
[3] International Arctic Research Center, University of Alaska Fairbanks, 930 Koyukuk Drive, PO Box 757340, Fairbanks, Alaska 99775-7340, USA
[4] Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, Michigan 48109-1048, USA
[5] Ocean Physics Department, Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Box 355640, Seattle, Washington 98105-6698, USA

INTRODUCTION

Long-term observations are required for a system-level understanding of the extent, origins, and impacts of environmental and socioeconomic changes in the Arctic. This understanding in turn can help us to respond effectively to a rapidly transforming Arctic. The importance of such observations has been recognized in a range of different scientific contexts, such as global climate change (e.g., Calder et al., 2010; Serreze and Barry, 2011), ecosystem services (Chapin et al., 2005; Eicken et al., 2009), and human activities (Krupnik and Jolly, 2002; Hovelsrud et al., 2011). At the same time, the urgency of adaptation and mitigation at the local and regional levels and increasing industrial activity (Brigham, 2011; Lovecraft and Eicken, 2011) have highlighted the need for data and information products that serve different stakeholders. Such information needs are reflected in recent Arctic Council agreements on search-and-rescue operations and oil spills, both of which require a range of environmental data for emergency planning and response (EPPR Working Group, 2011).

Against this backdrop, the scientific community faces a number of challenges and opportunities. Given the rapidity of Arctic environmental change and the magnitude of the associated impacts, networks are developing along the lines of focused disciplines that can provide answers within the timeframe of individual projects. However, better coordination and prioritization of observing activities is needed to facilitate interdisciplinary research, optimize asset use, and increase data sharing to build a more complete picture of Arctic change. We present a broad view of Arctic observing needs to highlight some of the challenges and suggest a possible framework for coordinating and prioritizing observing activities. Specifically, we provide an overview of efforts to address these major challenges:

1. How can we strike a balance between scientific research needs (e.g., long-term observations to track and understand change on seasonal to multi-decadal timescales or process studies aimed at critical drivers and modulators of Arctic change) and the information needs of key stakeholders who are responding to a rapidly changing Arctic?
2. Given that most observing networks are focused on one discipline, how can we improve coordination, foster better interdisciplinary partnerships, and link to emerging agency and private-sector observing programs at local and global scales?
3. Considering the limited resources and the challenges of conducting research programs in Arctic environments, what protocols should be used to prioritize and guide investments in long-term observing?

DRIVERS OF ARCTIC OBSERVING SYSTEMS

Environmental and socioeconomic changes in the Arctic have been subjects of discussion since the 19th century (e.g., Brooks, 1938). Transformative changes have been reported by Arctic residents, indigenous experts, and the scientific community since the 1980s (see discussion in Krupnik and Jolly, 2002; Hinzman et al., 2005). However, only recently has the broader community recognized the value of synthesizing observations collected for science with information generated by Arctic residents to serve the needs of society (Carmack et al., 2012).

Most Arctic observing networks (AONs) have been designed around diverse sets of science questions. In the mid-1990s, efforts by scientists to characterize the rapidly changing Arctic led to the establishment of the U.S. Study of Environmental Arctic Change (SEARCH), which articulated goals for coordinated, multidisciplinary observing efforts (SEARCH, 2005b). Canada's ArcticNet, the European DAMOCLES (Developing Arctic Modeling and Observing Capabilities for Long-Term Environmental Studies), and the European/Scandinavian ScanNet set out on similar paths. These activities converged into the International Study of Arctic Change (ISAC) efforts to monitor and understand responses to Arctic change. The ISAC Science Plan (Murray et al., 2010) distilled overarching scientific interests and priorities into guiding questions that reflect some prioritization beyond national programs. The science plan recognized that the Arctic is in the midst of a major transition and that scientific research would play a fundamental role in informing adaptation strategies.

In contrast to science-driven observing needs, stakeholder interests in monitoring are typically based on specific concerns framed in the context of desired outcomes. However, the activities designed to advance broad understanding of the Arctic system often align poorly with efforts to achieve more targeted outcomes and address stakeholder concerns, even though the two goals are interdependent (Murray et al., 2012).

LINKING SCIENCE AND STAKEHOLDER NEEDS

Initial synthesis of individual research findings and results from programs focusing on specific aspects of change led the scientific community, through programs such as SEARCH, ScanNet, DAMOCLES and others, to articulate overarching science questions selected to improve understanding and responses to Arctic environmental change (e.g., Dickson, 1999; Overpeck et al., 2005; Callaghan et al., 2011b). However, these science questions evolved somewhat separately from the concerns raised by Arctic residents and others affected by socioeconomic change (Krupnik et al., 2011; Alessa et al., 2013; Johnson et al., 2015). Arctic system services (analogous to ecosystem services discussed in the Millennium Ecosystem Assessment, Chapin et al., 2005) provide a link between the priorities and information needs of Arctic stakeholders and those of the scientific community. Within the Arctic system, services are associated with variables that can be monitored over time. Tight links between system variables, services

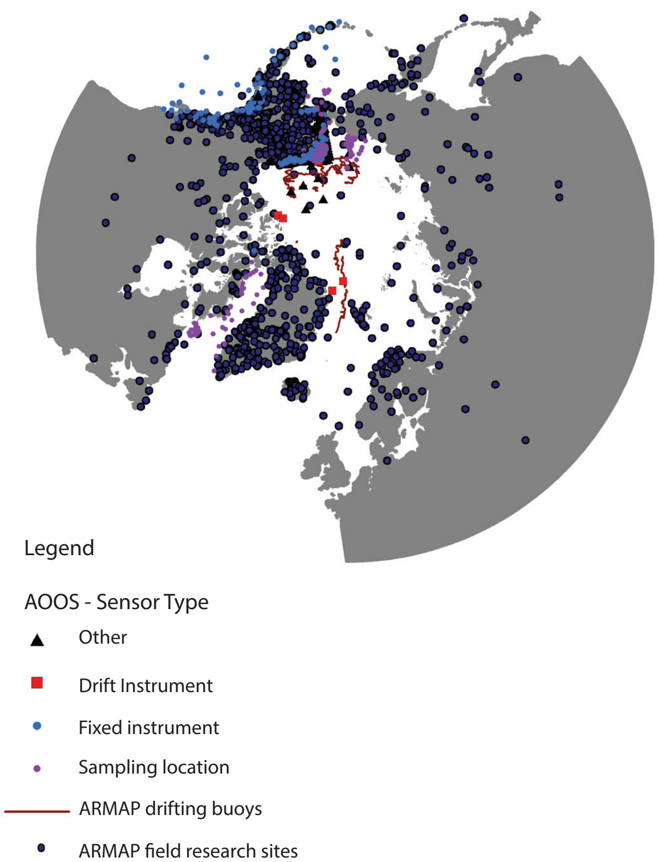

FIG. 1. Distribution of U.S. observing assets in the Arctic. AOOS sensor type shows only active marine observing assets for 2011 to 2012. Data for drifting buoys and ARMAP locations are from the Arctic Research Mapping Application and Arctic Observing Viewer (wwww.armap.org); data for sensor types are from the Alaska Ocean Observing System.

delivered to stakeholders, and their impact on desired outcomes maximize the benefits derived from long-term observations. A focus on desired outcomes also supports national and international institutional and management regimes.

Integrating stakeholder inputs and knowledge exchange into the network design is a significant challenge. These elements must be included early in the design process and ideally should build on the lessons learned from approaches that have proved successful (Weichselgartner and Marandino, 2012; Knapp and Trainor, 2013; Fazey et al., 2014). One such approach is to parse and prioritize observing activities by analyzing the spatial and temporal distribution and density of rule sets that govern resource management and human activities. An example of this policy-geographical approach focused on management of sea ice system services in the Alaskan Arctic is given by Lovecraft et al. (2013): they found that roughly two dozen institutional regimes govern sea ice use in the region, where high institutional density has produced highly contested areas characterized by substantial overlap of different rule sets.

Development of representative indicator variables can also help to synthesize and prioritize stakeholder information needs. The European Environmental Agency (EEA) has identified indicators that reflect European policy concerns and can be monitored internationally. However, only very few EEA indicators (such as sea ice and permafrost extent) target the Arctic directly. The European Arctic Climate Change, Economy and Society (ACCESS) program has now been charged with developing a new set of indicators specifically focused on sustainable development in the Arctic (J.C. Gascard and M.P. Karcher, pers. comm. 2013). Arctic Council Working Groups, working groups within the International Maritime Organization, and the Arctic Observing Assessment led by the National Science Foundation (NSF) and Sustaining Arctic Observing Networks (SAON) are also conducting assessments that may aid in identifying relevant indicators of Arctic change.

LANDSCAPE OF EXISTING OBSERVING PROGRAMS

Lack of coordination can result in suboptimal distribution of observing assets (Fig. 1). In addition to current snapshots of present-day observing activities we need information about planned observing networks; particularly amid growing interests and information needs. We synthesized information from SAON reports (SAON, 2008) and inventory of existing networks (SAON, 2010) and results from a similar effort for the U.S. Arctic sector (H. Eicken and O. Lee, unpubl. data), Arctic Observing Summit (AOS) white papers, and information from international partner programs, such as DAMOCLES, ACCESS, and ArcticNet. We focused on the observing networks in Arctic countries although we acknowledge that non-Arctic nations play an increasingly important role in Arctic observing activity. The inventory of networks was classified into the following general categories:

1. Broad networks such as the U.S. NSF AON and ArcticNet in Canada that include a broad range of interdisciplinary observations and projects;
2. Focused networks that are confined to specific themes or disciplines, such as marine ecological monitoring;
3. Commercial networks that provide observational data for profit;
4. Operations or service-oriented networks such as the Global Atmosphere Watch (GAW) feeding data to weather service and forecasting entities; and
5. Resource-extraction networks that conduct monitoring or baseline observations specifically for planned or ongoing resource extraction activities.

Table 1 shows the number of observation networks of each type reported to SAON for each country.

The majority of observation networks categorized in the SAON inventory were either thematically focused or used for specific operations and services, resulting in a relatively narrow scope of observations. Broad networks were identified only in the United States, Canada, and Norway. The lack of broad networks has important implications for the

TABLE 1. Number of observing networks by category and country as of 2010.[1]

Category	USA	Canada	Finland	Iceland	Denmark & Greenland	Russia	Norway	Sweden
Broad	1	1					1	
Commercial					1			
Focused	13	9	2	2	16	11	11	35
Operations	21	4	2	12	14	6	9	14
Resource extraction	2			2	1			
Sum	37	14	4	16	32	17	21	49

[1] Project information was obtained for each country from SAON (2010).

development of overarching observing frameworks that can overcome challenges in coordinating observations across disciplines and research groups. The United States has the highest number of networks that are related to operations, many linked to federal and state agencies. Coordination of observing activities across agencies can be a complex process that becomes more difficult when it involves sustained, long-term activities with commercial and academic partners. Efforts such as the International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT) have been exploring viable approaches to the challenges of coordinating entities with support from multiple governments.

We anticipated the greatest potential for cross-disciplinary coordination among broad networks that have components for observing the coast, ocean, cryosphere, and atmosphere and that currently place the least emphasis on humans and terrestrial systems. The majority of focused and operations networks emphasized marine ecosystem and atmosphere observations, and the networks focusing on the terrestrial, human or social, and cryosphere themes were fewest in number.

Although an understanding of the thematic focus of observing networks is useful, these network inventories do not provide sufficient information to examine the types of observations collected within each discipline. Information on specific observation data collected by each network could promote cross-disciplinary coordination focused on information needs common to multiple networks (Ellis-Evans et al., 2013; Tweedie et al., 2013).

During the 2013 AOS, data management and the lack of consistent data access policies across networks also emerged as major obstacles to supporting international coordination of observing activities (Moore et al., 2013; Pulsifer et al., 2013). Although we recognized the importance of coordinated data management for synthesis and cross-disciplinary research in International Polar Year (IPY) projects (Krupnik et al., 2011), our analysis determined that data accessibility differed by category of network and by country. Fully accessible data were most common for the atmosphere, marine, and marine ecosystem themes, but less than half of all networks offered full access to data. The U.S. NSF AON is a notable example of a broad network that provides access to downloadable data from a common database. Most focused and operations networks provided access to either full data (33% for focused and 40% for operations networks) or partial data (25% for both network categories), although some networks provided data only on request or for a fee. Resource extraction networks offered predominantly partial datasets (60%), which typically made available only metadata and published reports.

Although our overview of the landscape of observing activities focused on available information on current activities, it is also important to distinguish which projects and observing asset distributions qualify as long-term, sustained observations (i.e., extending over timescales of several decades). These monitoring observations have well-defined goals to track changes over time with an emphasis on comparable repeat observations. In the United States, one such effort is the National Park Service's Vital Signs project that identifies a list of core physical, chemical, and biological variables that are monitored over a timescale of at least 30 years (Lawler et al., 2009). An analysis of the landscape of long-term Arctic observations is needed to determine whether existing monitoring efforts provide adequate spatial and temporal coverage to measure indicators of Arctic change. Such an analysis can also help identify where future observing efforts can best be focused to build on the current landscape of long-term flagship sites. International projects such as the Back to the Future Project show that coordinated observations may allow comparisons with historical data even with gaps in the temporal coverage of observing activities (Callaghan et al., 2011a).

SEARCH ACTIVITIES IN THE UNITED STATES

SEARCH seeks to improve scientific understanding of Arctic environmental change to help society understand and respond to a rapidly changing Arctic. It plays a coordinating role between academia and U.S. agencies, emphasizing efforts to link science and stakeholder needs. Hence, lessons from SEARCH activities are particularly relevant for internationally coordinated Arctic observing efforts that aim to meet broader societal needs. The SEARCH Science Steering Committee (SSC) uses input from the broader scientific community to provide guidance to the Executive Director, SEARCH Action Teams, and the Observing

TABLE 2. Hierarchy of AON design and implementation elements.

AON design elements	General activity	Specific activity
Problem definition and prioritization	• Scenarios planning • Institutional analysis • Feedback and impact assessment	• National Arctic Strategy development by Arctic Council member states • Agency-specific assessments of research and information needs • Cross-agency assessment of Arctic information needs (e.g., IARPC, 2012; U.S. Arctic Research Commission, 2013)
Strategy	• Scenario consistency analysis • Institutional analysis • Model-based assessments • Process studies • Uncertainty analysis	• (Inter)national working group activities focused on information needs for specific themes (e.g., IASOA[1] for atmosphere, GCW for cryosphere, CBMP for biodiversity, SAON for international observing activity) • Funded projects and PI initiatives lead to bottom-up development of focused or discipline-based observing networks • Ad-hoc meetings by agencies to assess funding or institutional support needs
Tactics	• Target quantity definition and measurement options • Model-based assessments • Resource identification	• Synthesis forums (e.g., Flagship site teams, Sea Ice Outlook) • Funded programs (e.g., Landscape Conservation Cooperatives) and ad-hoc meetings
Network implementation	• Sampling array design • Site selection • Coordinated data management plan	• IARPC and SAON member agencies build funding and institutional support • Site teams at flagship sites or disciplinary networks expand the current observing capacity based on established networks • Individual AON projects (e.g. Observing System Simulation Experiments)

[1] IASOA = International Arctic Systems for Observing the Atmosphere

Change Panel. Building on a tripartite approach that integrates observing, understanding, and responding to change components, the SEARCH Action Teams have the flexibility to make significant progress in integrating stakeholder and science needs for the SEARCH five-year science goals.

SEARCH played a key role in several activities related to the building and coordination of the AON at the national level in the United States. SEARCH initially focused on the driving science questions (Morison et al., 2001; SEARCH, 2003, 2005a, b) but also aimed to improve scientific understanding of Arctic change and generate data and tools to inform effective responses to change. This led to the build-out of a core U.S. AON that drew on key pre-existing elements, such as the North Pole Environmental Observatory (NPEO; Morison et al., 2002) during the IPY. While the AON was conceptualized as an interagency effort under the auspices of the U.S. Interagency Arctic Research Policy Committee (IARPC), as detailed by Jeffries et al. (2007), to date NSF has provided the bulk of the funding support for AON. Hence, in the context of this contribution, we also refer to a U.S. Arctic observing system as an overarching effort comprising a broader range of agencies but lacking critical funding mechanisms and network infrastructure.

The SEARCH Observing Change Panel facilitated coordination among individual AON Principal Investigators (PI) through annual AON PI meetings starting in 2007. The first of these provided a means to establish communication among AON investigators. These activities were framed by the SEARCH data policy (SEARCH, 2007), which stipulates rapid, free, and open access to all AON data to maximize scientific benefits, promote collaboration, and enhance information transfer to stakeholders.

Subsequent meetings promoted international coordination, with guidance from the 2009 State of the AON report (AON, 2010) and fostered broader network integration. The AON Design and Implementation (ADI) Task Force was established by NSF in 2009. In its final report, the ADI Task Force (2012) developed recommendations on how to achieve an effective, robust, and internationally coordinated U.S. Arctic observing effort. The ADI Task Force recognized that methods and implementation strategies for network design and optimization vary widely in approach and maturity between disciplines. Hence, no single blueprint or common design exists for the components of a pan-Arctic observing network or system of systems. Rather, observing system design and optimization need to proceed through a hierarchy of relevant approaches, in which sensor placement and measurement techniques are preceded by a problem definition and strategy-development stage (Table 2). This consideration is particularly relevant for the U.S. AON because its interdisciplinary breadth requires approaches to implementation that differ from those for observing networks narrower in scope and governed by a uniform, single observing protocol, such as the GAW program. A key goal of the hierarchic process is to actually build connections between emerging, initially disparate network elements.

The top level of the hierarchy (problem definition, Table 2) was addressed through a one-year process that involved the scientific community in collaboration with the SEARCH agency partners to arrive at a set of five-year, near-term goals and corresponding focal areas. These five-year goals are not meant to detract from the importance of long-term observations for the AON, but rather provide a means to focus SEARCH activities. The SEARCH five-year science goals are:

1. Improve understanding, advance prediction, and explore consequences of changing Arctic sea ice;

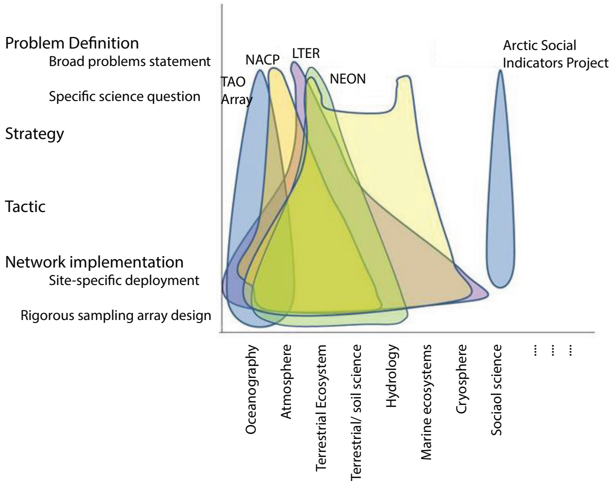

FIG. 2. Hierarchy of design and implementation elements for an international AON and the disciplinary breadth of example observation networks (TAO = Tropical Atmosphere Ocean Array, NACP = North American Carbon Program, LTER = Long Term Ecological Research Network, NEON = National Ecological Observatory Network). Networks with focused goals have narrow points at the Problem Definition level. A wide base at the Network Implementation level shows disciplinary breadth, but does not describe the extent of observing sites distributed over space.

2. Document and understand how degradation of near-surface permafrost will affect Arctic and global systems;
3. Improve predictions of future land-ice loss and impacts on sea level;
4. Analyze societal and policy implications of Arctic environmental change.

These goals, which were developed with significant input from the broader scientific community, address areas of scientific and societal urgency. The goals also complement existing agency priorities and national research plans, such as the National Ocean Policy (Executive Office of the President, 2010), the National Oceanic and Atmospheric Administration's (NOAA) Arctic Strategy (NOAA, 2011), the IARPC implementation strategy (IARPC, 2012), and the U.S. Arctic Research Commission's Goals and Objectives for Arctic Research (U.S. Arctic Research Commission, 2013). While these U.S. agencies have similar priorities, coordination is essential (1) to make efficient use of government resources and (2) to facilitate international cooperation through stable, cross-referenceable goals and priorities.

Arctic observing activities are only loosely coordinated in the United States and internationally. SEARCH involvement in planning and promoting the Arctic Observing System workshops in 2013 and 2014 is a step towards providing forums to improve national and international coordination of Arctic observations. Many observing networks develop bottom-up, from science-driven goals with similar science questions. Although focused networks may collect observations that cover multiple disciplines, most focus on very specific science questions. Mapping network disciplinary breadth to the ADI hierarchy of design and implementation (Fig. 2) illustrates this focus and shows that there is a range in network implementation strategies. Some networks use a rigorous sampling array design (e.g., the National Ecological Observatory Network [NEON] top-down, quantitative cost-benefit analysis for site selection), whereas other networks are built from existing observing sites (e.g., the Long Term Ecological Research [LTER] Network), or are not suited for a quantitative sampling design (e.g., the Arctic Social Indicators Project).

Designing an agile network is complicated by the need for consistency in the monitoring approach to identify robust patterns and trends. A coordinated multi-network framework can also help balance resources for both long-term monitoring observations and more flexible networks that can respond rapidly to new information needs for decision making. Coordination among short-term, project-specific and long-term monitoring networks may help the U.S. AON, an interagency Arctic observing system, remain agile and adapt to evolving actionable scientific questions that arise from a rapidly changing Arctic. Here, "actionable" implies (1) that an overarching science question is translated so that it links directly to specific observations and (2) that data and information derived from the observations help in the development of policies and actions in response to Arctic change.

Given the disciplinary breadth and range of science questions that the U.S. interagency AON is envisioned to include, it is unlikely that a single observing network will be capable of meeting stakeholder needs. The ADI report evaluates limitations in network design based on other observing networks and explores viable prioritization strategies (ADI Task Force, 2012). A few examples of the challenges and opportunities for AON design are also described in Table 3.

THE ADI HIERARCHY AND STAKEHOLDER INTERESTS

To achieve a streamlined network that meets goals for relevance, efficiency, persistence, and adaptability, it is crucial to set priorities and define problems at the overarching, system-wide level. The concept of "Arctic system services" can help structure and guide the top level of the implementation hierarchy. Here, Arctic system services define the benefits (ecological, economic, and cultural) and threats that emanate from the different components of the Arctic system and the system as a whole. For example, terrestrial permafrost helps retain surface freshwater that creates important habitats, transportation pathways, and hydrologic reservoirs tapped into by industry. Permafrost also locks up globally relevant amounts of greenhouse gases and helps stabilize Arctic coasts and landscapes. Arctic system services present an interface between outcomes desired by stakeholders and scientific understanding of Arctic system components and processes. Problem definition and prioritization at this interface can help drive implementation of observing network elements at the lower levels (Fig. 3).

Specific approaches in achieving the key objectives include scenario planning, analysis of institutions and

TABLE 3. Observing network strengths and challenges for AON application.

Opportunities applicable for AON development	Example networks[1]	Challenges for applying example network approach to a broad AON
Coordinating research interests and information needs among scientists, government agencies, decision makers, non-profit organizations, Arctic residents and industry stakeholders	ArcticNet, CBMP, AMAP, ALCC[2]	Broader AON will require prioritizing observations across disciplines with broad stakeholder engagement and potentially competing stakeholder interests. Changing stakeholder interests and priority science questions require a flexible, coordinated AON.
Coordinating international observation networks with cross-disciplinary research themes	CBMP, AMAP, INTERACT, ACCESS	Membership in some networks is restricted by eligibility requirements.
Building a network based on strong interagency collaboration during planning and implementation	NACP, AMAP, USCRN, ALCC	Example networks have a relatively narrow network focus and scope compared to an international AON.
Involving local stakeholders in the design and collection of observational data (e.g. community-based observations)	BSSN	Ensuring community involvement in data use and interpretation.
Using international collaborative agreements to share costs and facilitate access to sites across national boundaries	Argo Float Program, ArcticNet, INTERACT	Agreements for international funding strategies and data management plans do not cut across all observing networks. Some networks have short project timescales relative to monitoring observations needed for AON.
Providing data access (including near-real time), modeling products and/or processed information relevant for stakeholders	TAO, U.S. AON, NEON,[2] AMAP, SEARCH Sea Ice Outlook	Data may be difficult to find and access among various distributed data portals. Additional resources and collaboration will be needed to process multiple data streams to create information relevant to a broad range of stakeholders.
Identifying common measurement protocols based on best practices	LTER, ITEX, NEON, CBMP, AMAP, GCW, GAW	Implementing protocols on a voluntary participation basis across networks and countries that have already established protocols may be challenging. Balancing growing observation needs and new technology with protocols to collect data comparable to historical records.
Quantitative and cost-benefit analysis to optimize the observational network. Site selection based on available long-term data and applicability for upscaling or downscaling to meet stakeholder needs	NEON, LTER, ALCC, AMAP	Top-down design approach may not build on existing observing infrastructure. Coordinating deployments across networks is needed to conduct observations relevant for multiple disciplines and to increase utility across research questions.

[1] Acronyms not introduced in the text: ALCC = Arctic Landscape Conservation Cooperative, AMAP = Arctic Monitoring and Assessment Programme, BSSN = Bering Sea Sub Network, ITEX = International Tundra Experiment, TAO = Tropical Atmosphere Ocean Array, USCRN = United States Climate Reference Network

[2] Indicates networks that are not yet fully operational.

regulatory frameworks, or feedback and impact assessments. SEARCH, different agencies, and IARPC have already reached broad consensus on priority themes or areas of concern, as outlined in the IARPC and SEARCH five-year strategies and implementation plans. Similar priorities are related to the consequences of an ice-diminished Arctic and a warming and thawing near-surface permafrost.

At the strategy level, specific observing activities' goals, outcomes, and associated information products would be defined. This work would lead to a high-level scoping of activities and an evaluation of network data and information products, thus guiding tactics and operational network implementation (Fig. 3). In addition, funding and support strategies would be part of strategic considerations at this level in the hierarchy. IARPC, including key members of IARPC Collaboration Teams, the SEARCH SSC, and the Arctic Council's SAON initiative, would be key entities involved in advancing strategy.

At the tactics level, guidance from the upper tiers of the hierarchy is translated into specific action with respect to sensor placement, observation protocols, data management, standards, and interoperability. In addition, within this tier of the hierarchy much of the actual integration of networks across disciplines, regions, and observing projects takes place, including sharing of logistics resources. These objectives will be achieved with the help of "nodes." Nodes can

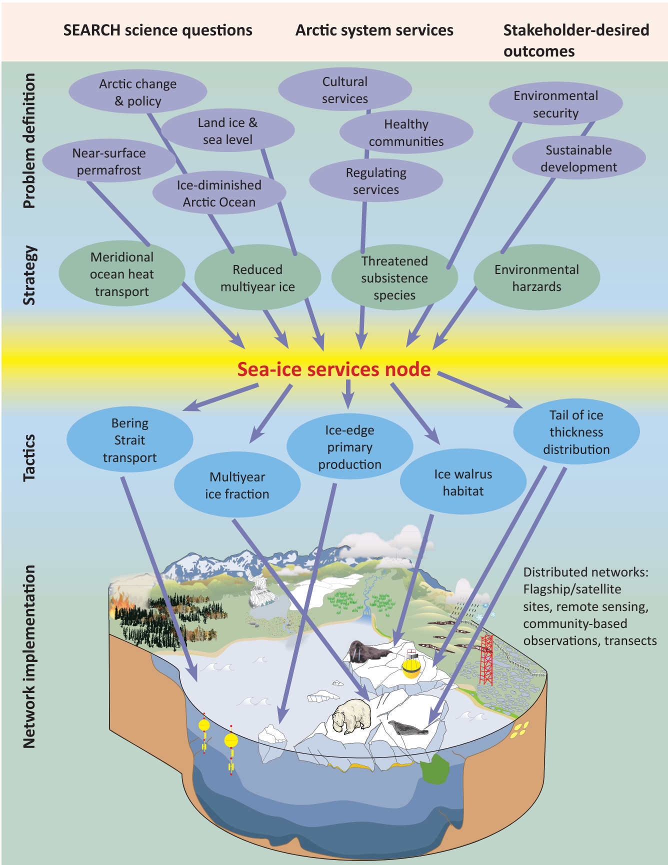

FIG. 3. Schematic of hierarchy used in design and implementation of an observing system, from problem definition to strategy, tactics, and network implementation. The coloured ovals show the topics or issues relevant at each level of the hierarchy, using the example of a sea ice services node.

be thought of as communities of practice that are emerging around key themes or interrelated sets of Arctic system services, such as those derived from permafrost or sea ice (Fig. 3). The SEARCH Action Teams, which include representatives of agencies and stakeholders, and the IARPC Collaboration Teams may lead the nodes with input from other panels and working groups as warranted. At the node level, specific input from modeling efforts such as the Next Generation Ecosystem Experiments (NGEE), and remote sensing initiatives such as the National Aeronautics and Space Administration (NASA) Arctic Boreal Vulnerability Experiment will translate into observational design or specific data and information products. Nodes will also help guide observing system simulations experiments (OSSEs) and other implementation-level studies that will provide guidance on the siting of measurement locations.

To aid in these activities, a more dedicated data node is needed, i.e., a community of practice that cuts across all themes and activities to handle data-specific implementation and management issues. Existing working and advisory groups established under IARPC, SEARCH, the Advanced Cooperative Arctic Data and Information Service (ACADIS), and data managers subsumed under the Alaska Data Integration Working Group (ADIwg) may serve as nuclei for such a cross-cutting node.

Activities at the network implementation level will be driven primarily by individual research projects, agency research, and operations-focused activities, oversight group guidance for flagship sites, and other entities conducting Arctic observations. At this level in the hierarchy, the focus is on optimizing and prioritizing specific observing activities in terms of where, when, and how to collect data. Planning at this scale is typically on a project-specific basis. However, by integrating efforts within nodes, small changes to a project's observing protocol or the inclusion of additional sensors to a planned deployment can create large benefits for the broader observing community with little incremental cost.

Ideally, coordinated observing activities within a node will also result in a unified data management plan that facilitates the development of products for multiple stakeholders. Here, the previously established link between specific observing activities and priority stakeholder and science questions will facilitate the identification of datasets and derived stakeholder-relevant products. Greater data interoperability will make it easier to ingest data from individual observing networks. Coordination of individual projects among national and international observing efforts will ensure that relevant data also contribute to international studies focused on pan-Arctic change.

Example Application in the Chukchi Sea

We present a potential application of the hierarchy for a showcase project identified at the U.S. Arctic Observing Coordination Workshop in 2012 (Perovich et al., 2012). The meeting convened scientists, data managers, stakeholders, decision makers and local, state, and federal representatives to facilitate coordination of goals and efforts in support of an interagency U.S. Arctic observing system. This showcase project on observations of changing ocean-ice-atmosphere dynamics and living resources in the Chukchi Sea would inform policy and management decisions regarding offshore oil and gas activities (Payne et al., 2013).

Problem Definition: Agencies frequently face major challenges in prioritizing and coordinating Arctic observations with limited resources and a growing number of urgent science questions. The sea ice system services "node concept" provides a mechanism for multiple agencies to support observing activities in the Chukchi Sea for a breadth of applications linked to prioritized questions. For example, sea ice concentration and thickness measurements can be used to meet forecasting and search-and-rescue goals that are of interest to the Coast Guard and industry. At the same time, such data can also help assess effects on species distributions and marine mammal behavior of interest to Native communities, co-management bodies (e.g., the Alaska Eskimo Whaling Commission), and regulatory agencies.

SEARCH can help to build relationships with agencies that have research or regulatory interests in the Chukchi Sea (e.g., the Bureau of Ocean and Energy Management (BOEM), NOAA, and the U.S. Geological Survey, USGS)

TABLE 4. Linking science questions to observing requirements, policy relevance and agency needs.

Theme	Policy focus	Research question	Observing needs	Potential agency/stakeholder interest
Development planning policy	Coastal Zone Management Act	*In what ways will increased access enable increased development?*	• Sea ice concentration • Sea ice thickness • Vessel tracking	U.S. Coast Guard, Department of Energy, Department of Interior (BOEM, U.S. Fish and Wildlife Service)
Social impacts	National Environmental Policy Act (NEPA)	*What are the measurable and perceived impacts of development on subsistence harvest of fish?*	• Subsistence hunting success	Alaska Dept. of Natural Resources, DOI (BOEM, U.S. Geological Survey, U.S. Fish and Wildlife Service), non-profit organizations, Native communities
Natural resources	Marine Mammal Protection Act, Endangered Species Act, NEPA	*What is the impact of changing ice regime on species and biological hot spots in the Chukchi Sea?*	• Sea ice concentration • Sea ice thickness • Currents • Marine mammal distributions • Primary productivity	DOI, NOAA, NASA

to include additional science perspectives during the development of agency priorities. These priority questions can then be linked with private-sector interests by leveraging partnerships between the Alaska Ocean Observing System (AOOS) and industry partners that provide data to AOOS as part of a data-sharing agreement between NOAA and oil companies.

Specific guidance can be obtained from planning and assessment efforts that are in the early stages of implementation. These include the North Slope Science Initiative's scenario planning effort, stakeholder input to the AOOS Spatial Tools for Arctic Mapping and Planning initiative, and projects supported by the NSF Arctic Science, Engineering, and Education for Sustainability program. Higher priority may be given to observing activities that meet multiple stakeholder needs or policy requirements using formal assessments or established coordination efforts (Table 4; Knapp and Trainor, 2013). Additional stakeholder input can be obtained from scoping activities or by seeking feedback from science plans.

Strategy: The SEARCH Sea Ice Action Team can help identify key variables or changing sea ice processes that need to be tracked in the Chukchi Sea. For example, agency interests may focus on identifying changes in marine mammal distributions in response to declining sea ice habitat while industry may need information to monitor potential sea ice hazards at offshore lease sites. Relevant monitoring goals can help promote synergy between stakeholder-focused interests and academic research on broader, multi-decadal scales of pan-Arctic change. Such coordination will highlight overlapping science and stakeholder information needs, foster research cutting across priority science questions, and help match agency resources and priorities with academic research efforts.

Tactics: At the tactics level, the target variables and measurement protocols are defined. The U.S. Climate Reference Network provides successful examples of how only a few types of observations (e.g., air temperature, wind speed, precipitation) can provide services to a number of federal agencies with a range of applications. Sea ice measurements in the Chukchi Sea should focus on metrics with a broad range of agency and stakeholder applications.

Identification of metrics for measurements related to ecosystem health and monitoring may require SEARCH Action Team workshops or working group activities. Where possible, efforts should build on international monitoring protocols, such as the Circumpolar Biodiversity Monitoring Program (CBMP). For target variables designed to measure social indicators (such as the impacts of offshore industry development on community health), successful implementation may require direct involvement of the Alaska Native community (Driscoll et al., 2013). Different networks can be linked by identifying similarities in observing protocols and target quantity measurements, even if the disciplinary focus differs from project to project.

Network Implementation: At this level, a quantitative analysis may be appropriate to improve discipline-specific observations and may include observing system simulation experiments and other modeling efforts (Kaminski et al., 2015). A coordinating body such as SEARCH can help identify or develop best practices for measurement protocols, and by maintaining an inventory of data needs, SEARCH could help individual projects plan sea ice observations in the Chukchi Sea. As a result, small, focused projects fit directly into broader networks and can contribute useful information for cross-disciplinary research, pan-Arctic change studies, and the development of stakeholder-relevant products.

As an example of network implementation planning for this project, we investigated observing efforts relevant to stakeholders interested in the duration of ice-free operations in the Chukchi Sea based on the variability of fall freeze-up dates. We plotted the distribution of AOOS observing assets against a trend in the offset of fall freeze-up dates from 1979 to 2012 (Fig. 4). The low density of observing assets in the southern Chukchi Sea corresponded

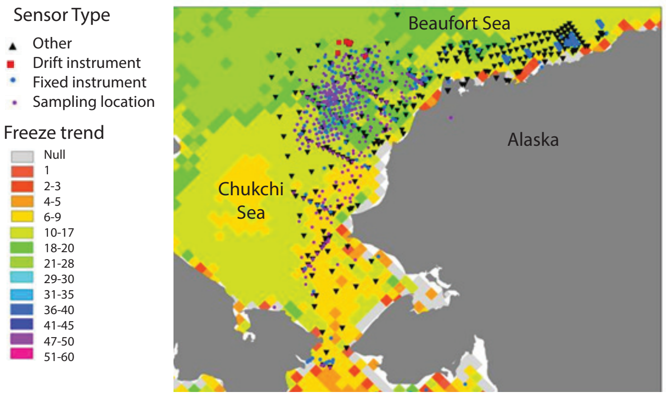

FIG. 4. Mid- to long-term observation sites in the U.S. Arctic for the years 2011–12 from information compiled by the Alaska Ocean Observing System. Also shown is the trend in the onset of fall freeze-up, in days per decade, derived from passive microwave satellite data (1979–2012, data provided by J. Stroeve, NSIDC, based on Markus et al., 2009).

to a region with large variability in fall freeze-up dates (2 to 17 days). Sophisticated modeling analyses (e.g., OSSEs) may then be used to help identify priority locations and sampling arrays for future deployments to best sample the region at the space and timescales that are also relevant to stakeholders. This example application is difficult to accomplish when detailed information on sensor locations and the types of data collected by each sensor is not readily available to most researchers. Feedback from researchers on planning and mapping tools is therefore important to enhance the utility of such tools for coordinating observing activities.

TOWARD AN INTEGRATED INTERNATIONAL OBSERVING SYSTEM

Our suggested framework discussed examples of SEARCH activities to increase coordination and prioritization at each level in the hierarchy of an Arctic observing system. Scientists and agencies can differ in their approach to design of observing systems (ADI Task Force, 2012), and there are also challenges in reconciling the different scales of interests among stakeholders. For instance, decision makers by necessity often focus on the local and regional scales from the perspective of interest in impacts on operations, environmental security, ecosystems, and people. In contrast, science interests may have a wider perspective focusing on an observing system that can help anticipate and track major changes and drivers at the pan-Arctic scale (ADI Task Force, 2012). Coordinating observing efforts internationally could introduce additional challenges, particularly as they relate to international and interagency funding strategies.

One approach to improving international coordination for existing activities and future development of an Arctic observing system is to review the existing landscape of Arctic observing programs and networks and match them with the hierarchy of design approaches outlined in Table 2. The concept of Arctic system services (Murray et al., 2012) may be used by the scientific community and stakeholders as an organizing principle. Alternatively, observing efforts may focus on common stakeholder interests based on national and international policy goals. A few sets of activities deemed of high priority and at a high level of readiness can be selected to serve as showcase projects to help advance and illustrate international coordination of observing networks. Forums such as the Arctic Observing Summit can serve an important function by bringing in operational agencies, such as those subsumed under the World Meteorological Organization (WMO), and offering them a platform to establish and share best practices.

We suggest that one important step towards future coordination of observing efforts may include drawing on the help of SAON to query Arctic Council (AC) Working Groups and other AC programs in order to facilitate better coordination and more fully engage the private sector, a point supported by the 2013 Kiruna Ministerial Declaration and outcomes. Engaging the private sector is not straightforward and may require a more concerted effort and direct collaboration with overarching industry and standards organizations. For example, efforts should be made to include any outcomes of the World Ocean Council's (WOC) Sustainable Oceans Summit that are of direct relevance to the Arctic. Future efforts to develop a partnership with WOC to address such topics jointly may also result in specific actions that can be reviewed and implemented through an AOS-associated process. Efforts to encourage sharing of industry-collected observations by establishing data-sharing agreements, or as part of future permitting requirements, can help engage private sector collaboration in the coordination of international observing activities.

Along the same lines, partnerships with international programs that are focusing on actionable science, such as some of the WMO and World Climate Research Program activities, could be of great value. This idea applies to well-established programs such as the GAW, as well as to emerging projects such as the Global Cryosphere Watch (GCW, Key et al., 2015). Using a framework such as the Global Earth Observation System of Systems to tie in existing observing activities may also be a fruitful endeavor for coordinating activities.

ACKNOWLEDGEMENTS

We thank members of the SEARCH Scientific Steering Committee, the ADI Task Force, Betsy Baker, Helen Wiggins, and Reija Shnoro for their previous work and contributions that helped to shape the content of this paper. We gratefully acknowledge support by NSF (ARC-1134951). We also thank three anonymous reviewers for their comments.

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