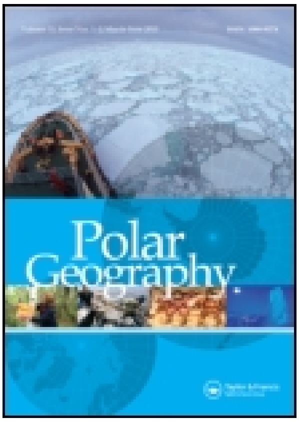

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Connecting scientific observations to stakeholder needs in sea ice social–environmental systems: the institutional geography of northern Alaska

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The institutions governing sea ice system services in the Arctic are associated with particular places, species, and environments. Yet scholars rarely consider the way these associations may present barriers to, or facilitate, effective translation of scientific data into broadly available information for stakeholders to create and debate policy. In light of rapidly changing arctic environments how can data best be collected and disseminated to affected stakeholders as usable information to facilitate effective planning? This article explores the linkages between scientific data production and policy implementation related to sea ice loss in the Arctic. The rapid decline of arctic summer sea ice is currently tracked and studied intensively but a comprehensive approach to address the changes is lacking. Our work builds upon earlier research establishing the need to approach sea ice as a complex multi-jurisdictional geophysical–social–ecological feature from a services standpoint. Our research catalogs the geography of sea ice institutions in northern Alaska to demonstrate the fragmentation in data production and distribution. We then examine two case studies. The first is a newly established cross-scale information bridge improving sea-ice and weather information relevant to walrus hunting and management. The second is the case of the emerging arctic marine traffic regime. We argue that in order to maximize data production, dissemination, and participatory capacity across stakeholders: (1) scientific observations should be tied to institutional density and sea ice services, and (2) information bridges should exist across major institutional actors.

Introduction: Systems, interests, and science

The Arctic Ocean's rapid loss of sea ice is shifting a system with a long history of indigenous subsistence use that was once closed to all but a few vessels during a short summer window to a more open system with attributes of great appeal to many interests in society. In the last half a century, the rule sets governing the Arctic that are tied to the annual cycle of sea ice (for example, institutions related to oil and gas development or protected species) have grown more dense as the range of activities in the Arctic has expanded. In parallel, Arctic Ocean regional interests have developed that represent a powerful set of actors with strong state, national, and international lobbies to promote stability or change in governing institutions. For example, the number of whales that can be harvested using the ice as a platform, how the presence of ice affects oil and gas exploration, the quality of snow and sea

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ice that can serve as a polar bear or seal habitat, or the thickness and roughness of ice to support travel, subsistence hunting, and industrial activities are all linked to sets of rules governing human activity. In each case, governmental, indigenous rights, environmental, and other interest groups pursue their goals in relation to these rules. In many cases these interests are inherently at odds, even within their own ranks, due to the trade-offs between intensive economic development and maintenance of productive ocean and coastal systems.

With the growing public attention to Arctic concerns and the need for clear regulatory frameworks under which private industry and others can function, science is looked to by decision-makers (Herrick and Sarewitz 2000), although this does not guarantee scientific evidence will be the basis of governmental decision-making. Effective long-term adaptive governance to promote system sustainability in a period of dramatic changes requires scientific understanding and inclusion of social and environmental complexity. Framed by research findings and broader interests in the North, and spurred by resources deployed during the Fourth International Polar Year 2007–2009 (IPY), a number of large-scale programs have prepared the ground for the emergence of pan-Arctic observing systems that are at least in part cognizant of information needs in the context of sustainability (for example, Arctic Observing Network [AON], ArcticNet, Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies [DAMOCLES], International Arctic Buoy Program). The AON and related research activities have also helped inform strategic action plans in the US, such as the National Oceanic and Atmospheric Administration's (NOAA) Arctic Strategy or the National Ocean Council's Strategic Action Plan.

These new multi-disciplinary large-scale investigatory endeavors are examples of initiatives encouraging scientists, limited by funding and infrastructure, to discern how to best complete policy-relevant measurements in the Arctic. Such policy- or decision-relevant research, largely funded by taxpayers, requires careful consideration of what to measure where and when in order to best benefit society as a whole. This challenge leads to a concern of balancing the information needs of different Arctic stakeholders. Given this problem context how can an arctic observing system prioritize data collection, facilitate its translation into usable information, and deliver it across diverse interests in the sea ice system to promote the opportunity for adaptive governance?

Scholarly literature indicates that scientific endeavors are more likely to respond to the needs of policy-makers and stakeholders when those affected by change have the capacity to participate in decision-making. This is the case in terms of democratic governments that function best when citizenship is inclusive and individuals have associational autonomy (i.e. can join or leave groups in society) while there is also access to alternative sources of information so that citizens can deliberate and engage in election processes (Dahl 2005). Research indicates adaptive governance functions best when diverse networks of actors are involved to bring topic area or scale-specific knowledge to bear on conservation dilemmas and set the stage for a comprehensive approach focused on learning (Brunner and Lynch 2010; Folke *et al.* 2005; Webster 2009). In short, as stakeholders pursue their interests in the institutional milieu most familiar to them they will gather information. This learning can be facilitated, and thus the policy-making environment enriched through *information bridges* that can overcome institutional fragmentation (Sarker *et al.* 2008) to better connect scientific production of data to diverse stakeholders in meaningful ways.

While our article focuses on Alaska it also addresses trans-jurisdictional and global concerns related to sea ice and its service management regimes. It addresses attributes of the problem of rapid sea-ice loss in a governance system populated by fragmented institutions in four ways. First we explain why the nature of sea ice services requires cross-scale observations and data delivery channels. Second, to determine where and what kind of observations are of greatest societal interest we explain the institutional geography tied to its services. The capacity of society to obtain and use data related to government decision-making must be considered in order to provide varied stakeholders with information usable for debate and planning of resource management. By tying observations to institutional priorities the information produced is more likely to be taken-up by interested parties across sectors. Third, in order to ensure such a use of information within the competitive arena of democratic politics, we propose information bridges across formal institutions that prevent information from being 'siloed' and potentially used in a hegemonic fashion to produce policy. And finally, we present two case studies that exemplify these three points.

The sea ice system and its services

Sea-ice retreat is one aspect of a broader suite of transformations in the North comprising climate and large-scale socio-economic change that are fundamentally altering the ecosystems upon which human livelihoods depend (Chapin *et al.* 2006). The Arctic, and in particular its sea-ice cover, is both an amplifier and driver of global climate change (Alley 1995; Serreze *et al.* 2007). In 2007, a long-term trend of thinning and shrinking arctic summer ice pack was punctuated by a record low summer sea-ice minimum extent, a 39% reduction from the long-term average – and the lowest coverage ever observed during the satellite era (Fetterer *et al.* 2011). With projections indicating a near-complete loss of Arctic summer sea ice by the late 2030s (Wang and Overland 2009), the impacts of such changes on coastal communities, ecosystems, marine shipping, and Arctic security have received increasing attention (Brigham 2010; Mueller-Stoffels and Eicken 2011). While the loss of Arctic summer sea ice has been clearly documented as a concern of many governments, comprehensive plans to address the problem are only in their early stages. There are not yet mechanisms in place to consider the diverse and interdependent changes across scales; sea ice prediction and data delivery remains a challenge at the local scales (for example, coastal villages). Additionally, while more data are required to ascertain long-term trends, the need to effectively manage new and existing data and design and optimize observing systems remains.

Drawing on interdisciplinary research related to sustainability science, Eicken *et al.* (2009) have proposed the concept of sea ice system services (SISS) to comprehensively address the hazards and opportunities presented by diminishing sea ice. By considering sea ice as a productive system, not simply a geophysical feature, one can recognize a suite of services that humans gain from the cycle and identify the information needs relevant for different sea-ice users. Major SISS identified include: the climate regulation the ice cover provides from the local to the global scale; the use of sea ice as a platform for both human (for example, travel and hunting on ice or activities part of oil and gas development) and nonhuman activities (for example, polar bear habitat); the role sea ice plays as an important feature in cultural landscapes (for example, enculturation of indigenous practices on the ice); and sea ice as a hazardous barrier to maritime traffic. Despite the range and diversity of such services each of which is affiliated with a different set of institutions, the data and information needs of ice-users are in fact quite similar. For example, seal hunters and petroleum industries are both concerned with sea ice as a platform. While their activities on the ice and views on management of an ice area may differ, they require similar data sets to ensure safety on the ice. In light of these commonalities, our article addresses where and how sea ice observations can be taken to most effectively link data and information to common priorities across the policies related to the sea ice system.

The importance of developing a more nuanced understanding of the sea-ice system is twofold. First, services flowing from the nature of the annual sea ice cycle are functionally both socially and ecologically interdependent. Second, institutions and observation systems have not yet been effectively designed to take this in to account either with rule design or data collection and dissemination. While we are mindful that the products of sea ice services are subject to becoming private or public goods based on national jurisdiction, our research argues that because the sea ice cycle creates an inherently interdependent set of common pool resources across the Arctic, system users are *socioecologically* interdependent (Sarker *et al.* 2008). Consequently, externalities, positive or negative, in one area of management (for example, ship traffic) will likely impact another (for example, marine mammal harvests). The interdependencies currently 'transcend the space and levels of management' of the resource system (Brondizio *et al.* 2009), but this does not imply that the policy goals of all interested parties are the same.

Institutions and interests

Currently, specific uses of sea ice are governed individually by a patchwork of institutions that have evolved independently over time and there is no interconnected suite of institutions or a single comprehensive institution that governs the sea-ice system as a whole. The SISS can be characterized as polycentric made up of 'multiple governing authorities at differing scales rather than a monocentric unit' (Ostrom 2010, p. 552). Without denying a broad view of institutions as 'enduring regularities of human action in situations structured by rules, norms, and shared strategies' (Crawford and Ostrom 1995) our project begins its examination on formal institutions that have been articulated in constitutive documents in order to specifically capture their role in governance of sea ice services through their associated interest groups and stakeholders, roles in management, and information requirements. In short, we view institutions as rule sets designed to govern human behavior, specifically in the context of sea ice services. Examples would be laws and policies affecting ice-dependent marine mammal hunting or the rules of ship passage in arctic waters.

Institutions matter because they create and channel power in social–ecological systems (Lovecraft 2008; Robards and Lovecraft 2010). In addition, institutional linkages between the resources and places governed and the actors subject to governance create avenues of influence for particular actors over policy implementation (Selin and vanDeveer 2003). At the same time, the implementation of policy is influenced by the design of the institutions used. For example considering fisheries in the Arctic Ocean, policy implementation may be focused on process (how can one harvest fish), property ownership (who owns the fish), or conservation (what limit is there on fishing). In modeling different institutional types Chapin *et al.* (2006) categorize institutions into four major categories of human use of or benefit from environmental resources: resource harvest, resource conservation, hazard reduction, and externality producing. Conflict arises when the objectives of one institution contradict or otherwise negatively affect another.

Institutions are attractors of competing interests related to the places, activities, and attributes of any social–environmental system. This is because actors with competing ideas and belief systems vie for public and governmental attention in order to form political coalitions to produce stability or promote change in policy (Baumgartner and Jones 1993; Cohen *et al.* 1972; Kingdon 1995; Sabatier 1999). Within any set of institutions 'advocacy coalitions' form over time. They consist of:

> actors from a variety of public and private institutions at all levels of government who share a set of basic beliefs (policy goals plus causal and other perceptions) and who seek to manipulate the rules, budgets, and personnel of governmental institutions in order to achieve these goals over time (Sabatier and Jenkins-Smith 1993, p. 5).

As regulatory activity at the federal level has expanded, there has been a corresponding rise in interest-group activity both in terms of direct lobbying and campaign contributions. This shift in the last 50 years has created 'growth, more professionalism, and the institutionalization of various advocacy functions within interest groups' (Andres 2009). Pressure groups exist to serve their members, whether industries (for example, Arctic Power) or individuals (for example, Sierra Club) and are actively engaged in searching for information to promote their causes in a competitive policy environment. Regulatory decisions are made using technical data that can be 'difficult to obtain and open to competing interpretations' but this data are also at the 'heart' of how interest groups press their claims on policy-makers (Berry and Wilcox 2009, p. 29). However, it is not just industry that seeks data and influence but any stakeholder group wanting to have an effect in an issue arena. It has been argued that industry may have an upper hand, as not all stakeholders concerned with a policy sector have the same resources to organize or effectively press claims on government (Berry and Wilcox 2009; Schattschneider 1960; Schlozman 1984). Consequently, it is probable that once institutions have a set of stakeholders established, these tend to argue for the status quo (Beier *et al.* 2009).

Science, on the other hand, is designed to test the status quo. In the Arctic these two forces are currently functioning simultaneously, for example the recent disputes over polar bear habitat demonstrate how an institutional structure for polar bear conservation that stems from the 1973 International Agreement for the Conservation of Polar Bears affects governance from local co-management up to national and international priorities. The science of sea ice loss creates data that has enabled wildlife conservation groups to push for further restrictions on the use of polar bear habitat on sea ice while industry and others seeking to explore offshore resources in the same space will evaluate that same data to support their efforts. It is in this sense that institutions are attractors and rule sets are at the heart of competition over what is regulated. We think information bridges can provide more data to more interests thus opening the regulatory process to previously marginalized interests; nevertheless, we recognize it takes more than a pressing of claims based on data alone to shift entrenched interests.

Institutional geography of the north slope of Alaska

Rules tied to the sea ice system have grown alongside social priorities (for example, conservation, harvest of subsistence foods); temporally based concerns (for example, human overharvesting of marine mammals in the nineteenth and early twentieth century, economic boom or bust); and the 'institutional thickening' of the organization and cultures of administrative bureaucracies whose design is historically neither interdependent nor collaborative (Meek 2011). Institutional thickening refers to the growth in interest group numbers, size, and influence in the regulatory policy-making in the last century (Skowronek 1998). We use the phrase 'institutional density' building on this three-fold phenomenon as a measure of the number of institutions associated with a particular location but which may focus on different attributes of the system. The Alaska coastline and nearshore waters have high institutional density because there are many sets of rules targeting different attributes of this particular social–ecological system.

Overlooking interdependencies has created silos of science, operationalized as observation sets tied to singular institutions or none at all. Frequently such observations fail to feed the data and information need of actors across sectors in any given location. This problem is exacerbated by the fact that lack of adequate information about the state and trajectory of the system can then reduce the capacity of institutions to take into account how services delivered to stakeholders are impacted by system dynamics. We do not argue that science should set social priorities. It is the members of society who must prioritize scientific efforts; however, we do argue that the best way to do this is to get relevant data and information into the hands of stakeholders, a set of actors that can include governments.

As agencies and research programs seek to create data sets of long-term sea ice observations, they can prioritize these based on institutional density and the expectation of institutional growth. Where institutions are the most dense, there will be a broader range and greater urgency of data and information needs because institutional density to some extent reflects society's response to pressing issues in a complex local context that is impacted by Arctic change. High institutional densities also imply a higher probability of conflicting uses of a particular service or resource. This concept of institutional density is illustrated in Figure 1, showing the geographic extent and applicability of different institutional regimes for the northern Arctic coast of Alaska. At this point, it is not possible to simply map the number of institutional regimes per unit area relevant for sea-ice use for a specific location to determine institutional density. Rather, a map such as shown in Figure 1 provides insight into spatial patterns, including key SISS such as the stable extent of shorefast ice important for hunting and transportation, and indicates areas with significant overlap of ice uses and associated rule sets. As to be expected, the highest institutional densities are found in the vicinity of communities such as Barrow or Nuiqsut and industrial facilities such as near Prudhoe Bay. A full-scale institutional mapping such as summarized in Table 1 (with a focus on Alaska's Arctic coast) evaluates in detail the number and scope of institutions governing ice use and their spatial extent and distribution, yielding a measure of institutional density. Figure 1 provides a more selective perspective on the primary institutions governing marine ecosystems (critical habitat for polar bears), resource extraction (oil and gas leases), maritime transport (major shipping routes with attendant regulations), and human activities (approximately 25 nautical mile radius covered by

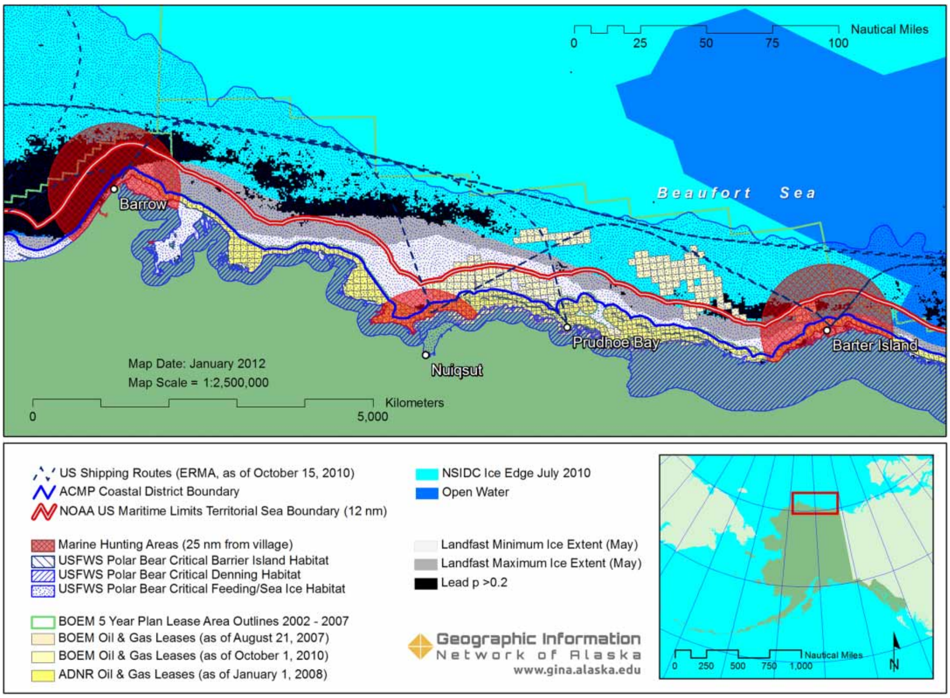

Figure 1. Map of institutional density (as represented by four key types of institutions, for discussion see text) along the North Slope of Alaska. Also shown is information about key sea ice features that are relevant from a sea ice systems services perspective. Map produced by P. Hickman, Geographic Information Network of Alaska.

hunters with boats or snowmachines on coastal sea ice). As is evident from Figure 1 as well, the sea ice cover (both shorefast stable ice and the dynamic marginal ice zone in summer) cuts across different institutional regimes and can serve or hinder different stakeholder interests. We view the institutional geography explained here and the case studies below as a key first step in moving toward integrated spatial planning of sustainable use of SISS.

Because institutions reflect and attract interests, an inventory and spatial mapping as shown in Table 1 and Figure 1 will increase the relevance of data collection and information gathering of interest to stakeholders. Nevertheless, we must still address the problem of translation from 'elites' and 'technocrats' to laypersons. Using the model of Chapin *et al.* (2006), Table 1 thus categorizes the major institutions governing use or protection of sea ice services with a focus on Arctic Alaska as a region that represents most if not all of the relevant interests and uses prevalent throughout the pan-Arctic (Eicken and Lovecraft 2011). As noted earlier, the relative needs across the institutions for data are narrow but the span of interests is broad. To avoid duplication, maximize accuracy, and minimize costs, a better method of setting data priorities and sharing results must be developed.

Translating observations into stakeholder information through information bridges

Mostly, decision-makers require information and not merely raw data sets to act on. The ability to extract information from a given data set can vary substantially

Table 1. Sea ice institutions in northern Alaska and their associated information needs and monitoring variables for sea ice system dynamics (modeled after Chapin *et al*. 2006, see text for full discussion).

Type of institution	Sea ice system service	Institution	Scale	Relevant information	Monitoring variable
Resource conservation	Shoreline protection	National Environmental Policy Act	National	Persistence of ice types, fetch	Shorefast ice extent and duration, offshore ice concentration, wind velocity
		North Slope Borough Comprehensive Plan	Regional	As above	As above
	Aesthetics of seascapes	North Slope Borough Comprehensive Plan	Regional	Density of development, ice aesthetic quality	Coastal infrastructure, presence and morphology of coastal ice
		City of Barrow Municipal Code	Local		
	Ice-dependent marine mammals	Endangered Species Act	National	Distribution and habitat qualities of pack-ice and shorefast ice	Duration and extent of shorefast and offshore sea ice, ice morphology and type, snow cover
		Marine Mammal Protection Act	National	As above	As above
		Co-management boards	Regional	As above, weather and coastal hazards	As above
	Ice-associated endangered species	Endangered Species Act	National	Distribution and habitat qualities of pack-ice and shorefast ice	Duration and extent of shorefast and offshore sea ice, ice morphology and type, snow cover
		Alaska Eskimo Whaling Commission (AEWC) Bylaws	Regional/ Tribal	As above	As above
Resource harvesting	Bowhead whales	Convention for the Regulation of Whaling	International	Habitat quality for evaluating carrying capacity	Distribution, morphology and persistence of leads and polynyas, timing of ice retreat

Table 1. (Continued).

Type of institution	Sea ice system service	Institution	Scale	Relevant information	Monitoring variable
		Endangered Species Act	National	Habitat quality and accessibility of flaw lead and offshore ice pack	As above
		Marine Mammal Protection Act	National	As above	As above
		AEWC Cooperative agreement	Cross-scale	As above	As above
		Barrow Whaling Captains Association Bylaws	Local	As above	As above; stability and morphology of shorefast ice
	Ice-associated seals	Endangered Species Act	National	Distribution and habitat qualities of pack-ice and shorefast ice	Duration and extent of shorefast and offshore sea ice, ice morphology and type, snow cover
		Marine Mammal Protection Act	National	As above	As above
		Ice Seals Committee co-management agreement	Cross-scale	As above	As above
	Walrus	Marine Mammal Protection Act	National	Distribution and habitat qualities of pack ice in relationship to accessible forage food	Ice concentration and distribution, ice thickness and morphology, rate of ice retreat
		EWC co-management agreement	Cross-scale	As above	As above
		SIWO	Local	As above, distribution and habitat qualities in relationship to communities	As above, duration and and extent of offshore sea ice
	Polar bears	Agreement on the Conservation of Polar Bears	International	Distribution and habitat qualities of pack-ice and shorefast ice	Duration and extent of shorefast and offshore sea ice, ice morphology and type
		US-Russia Bilateral Agreement	Bilateral and interlocal	As above	As above

Table 1. (Continued).

Type of institution	Sea ice system service	Institution	Scale	Relevant information	Monitoring variable
		Endangered Species Act	National	As above	As above
		Marine Mammal Protection Act	National	As above	As above
		Inuvialuit-Inupiat Polar Bear Agreement	Interlocal	As above	As above
		Nannuq Commission and North Slope Borough cooperative agreements	Cross-scale	As above	As above
	Freshwater	None	Local	Presence of piqaluyak (Iñupiaq: ice suitable for drinking water)	Distribution of multiyear floes within shorefast and coastal ice
	Arctic fish	Magnuson-Stevens Act	National	Richness of sea ice fauna and flora, ice habitat qualities	Distribution of ice biota; distribution and porosity of pressure ridges, multi-year ice concentration
		Alaska Fish and Game Code	State	As above	As above
Hazard reduction	Trajectory of oil spill, encapsulation and biodegradation of oil	Clean Water Act	National	Ice distribution and movement; presence of ice biota	Ice concentration and seasonality, ice velocity, distribution of ice biota
		Alaska Pollution Discharge Elimination System	Cross-scale	As above	As above
	Sea ice as geologic agent and coastal hazard	Coastal Zone Management Act	Cross-scale	Occurrence of ice push events, ice gouging	Onshore ice movement, ice morphology and thickness
		North Slope Borough Municipal Code Title 19	Regional	As above	As above
		City of Barrow Municipal Code	Local	As above	As above

Table 1. (Continued).

Type of institution	Sea ice system service	Institution	Scale	Relevant information	Monitoring variable
	Reflective surface for climate regulation	Kyoto Protocol	International	Radiation budget of sea ice	Ice albedo and its seasonal evolution
		Clean Air Act	National	As above	As above
Ecological externality-producing	Maritime traffic hazards	U.N. Convention on the Law of the Sea	International	Presence and persistence of hazardous ice	Timing and distribution of floating ice during navigation season, ice type distribution (multi-year ice)
		IMO Circulars	International	As above, Barnett Sea Ice Severity Index (North AK)	As above
	Platform for industrial activities	Outer Continental Shelf Lands Act	National	Trafficability, stability and bearing capacity of shorefast ice	Extent, persistence, thickness, strength and morphology of pack and shorefast ice

among stakeholders. Hence, the acquisition and dissemination of data and information related to the sea ice system plays a vital role in the adaptive capacity of people affected by existing rule sets to both enforce current standards or change management to meet stakeholder needs. We separate the concepts with data referring to raw scientific observations and information as translated findings based on data sets (Zins 2007). This issue is not merely of semantic interest since any sea-ice observing system aiming to provide information relevant to decision-makers needs to explore effective ways in achieving this goal. A major challenge is the fact that typically scientific data acquisition is driven by the need to test a set of postulates in the context of an overarching scientific problem or question. Data collected under this premise may not easily lend themselves to interpretation and evaluation in the context of applied problems. Rather, obtaining data and more importantly information derived from such data that respond to decision-maker information needs requires a substantial engagement by both academia and stakeholders and needs to be part of an interactive process (van Kerkhoff and Lebel 2006). As outlined in more detail below, Information Bridges can play important roles in this context.

As a first step, an objective survey and prioritization of information needs must occur. We argue that this goal is achieved through analysis of the institutions governing resource uses or ecosystem services. For the case of sea ice services the results of research into the applicable rules and regulations for northern Alaska listed in Table 1 provide an indication of the scope of information needs. Moreover, through the link to specific ice services, institutions typically specify the type of information that is required for the regulation or management of a given service. Such information is mostly one or several steps removed from observable data and comes with requirements for the sampling design and data processing to meet the information need. For example, resource conservation for ice-associated marine mammals is closely linked to the habitat qualities of drifting and shorefast ice. Deriving suitable indices or parameters as measures of habitat quality from raw data are not straightforward and require observation of a series of variables, such as ice thickness, morphology, and seasonality along with snow depth and the presence of sea-ice microbial communities (Table 1). While other studies have examined how such fundamental variables can be derived (Eicken *et al.* 2009, 2011b), here we are mostly concerned with the process of prioritization. In part, this has been already achieved by the institutions themselves as the rules and regulations compiled in Table 1 reflect the stakeholder concerns best represented in the governing system to date. A major challenge, nonetheless, is the compilation of an exhaustive inventory of applicable institutions. Here, the scientific community and different stakeholder groups and decision-makers are located on either side of a divide that needs to be bridged. Mostly this is due to a lack of awareness or understanding of the frameworks that govern utilization of resources or services on the one hand, and misconceptions about the way scientific research operates on the other hand.

Using institutional density as a concept to guide observational design and information dissemination can promote better cross-scale observations for most important problems including non-linear change (Peters *et al.* 2007). Put differently, our research argues that the regulatory process produces the most dense sets of institutions where there is the largest number of competing interests and the most complex problems society faces. Because stakeholders are responsive through interest group networks related to sea ice it is vital not only to provide relevant data and information in an effective manner to these institutions in order that it be used, but also for it to enter into a feedback cycle that can demand further, or different observations. But density does not imply the presence of communication channels between institutions or between scientific data collection and institutions. Because the sea ice institutional system is fragmented according to sectoral management regimes, as illustrated in Table 1, we argue that the system also requires information bridges in the form of cross-stakeholder structures to reduce duplicity and minimize costs while maximizing data and information production. We model our proposed information bridges after Sarker *et al.*'s proposed 'Information Platforms':

> An Information Platform would consist of a forum comprised of voluntary or legalized associations of the different stakeholders in each participating common pool resource, some of whom would overlap. We assume that participants in such a platform will come to recognize that the natural resources they use are interdependent, that the sets of stakeholders are therefore interdependent through their shared resource management issues, and thus that they need to take action collectively in making negotiated decisions to resolve issues (2008, p. 830).

Furthermore, such bridging organizations can better identify long-term data needs than any single agency or management network.

Cases: sea ice as a platform and as a hazard

In the case studies below we explore these aspects further in order to gauge the capacity for an emerging sea ice monitoring system to produce information relevant to short-term decisions and longer-term policy development. We describe two sea ice services and illustrate the usefulness of monitoring in informing safe maritime operations and resource management decisions. We find that monitoring is most critical to identify potential transitions or thresholds to undesirable system states. Minimizing hazards on short time scales is often de facto priority in monitoring for obvious reasons. Determining priorities for medium and long-term monitoring depends on the explicit valuation of desired system states. Such valuation is an inherent part of the institutional arrangements we propose below. However, this process of valuation is dependent on the ability of the political realm to bring conflicted stakeholders to the table, which it does through the democratic process of direct and indirect lobbying by interest groups; though as discussed earlier this process may not be easily accessible to anyone – hence the need to make data publicly and widely available. These two cases are examples of high institutional density that corresponds to high priority data and information needs, but each in a different way. The first represents an Arctic-specific suite of institutions that relate to the sea ice services of platform and habitat but which remain fragmented from one another in terms of data collection and cross-scale and long-term planning. The second represents interests that, while themselves fragmented, are not yet embedded in the Arctic. There is broad agreement that marine shipping (and tourism) will move into the Arctic as the sea ice hazard diminishes and resource extraction expands (AMSA 2009). We provide the latter case as an example of interests that could be better organized to receive and utilize data for Arctic planning and thus avoid the creation of cooperative bridges that would be more costly after new regulations and interests are entrenched.

Sea ice and weather prediction in the context of walrus harvest: Sea Ice for Walrus Outlook (SIWO)

Relevant institutions (for US Arctic waters): Convention on International Trade in Endangered Species of Wild Fauna and Flora, U.S. Marine Mammal Protection Act, Endangered Species Act, Outer Continental Shelf Lands Act, U.S. Bureau of Ocean Energy Management and Enforcement's Notice to Lessees and Operators, National Weather Service (NWS) Marine Forecasts and Advisories, Eskimo Walrus Commission (EWC) institutions, Community ordinances, and resolutions relating to walrus

Identifying information needs and relevant monitoring variables

Sea ice as a platform for subsistence hunting has ancient roots indigenous to the societies who live with ice as a major coastal substrate. The life cycle of walrus, an important subsistence resource in western and northern Alaska, is closely tied to the seasonal drift, retreat and advance of the ice pack, with mothers and calves using the ice as a means of conveyance and resting platform (Krupnik and Ray 2007). With seasonal ice retreating faster and further to the North each spring and summer, both walrus and hunters pursuing the animals are facing increasing challenges. Deterioration of the ice cover diminishes the ecological value of ice as a platform providing access to food resources, likely to impact the animals' health and overall numbers (Jay *et al*. 2011). At the same time, indigenous hunters pursuing walrus by boat and preferring to butcher animals on sea ice are incurring greater risks due to changing ice conditions and a reduced window of opportunity to access game (Kapsch *et al*. 2010). In this setting, relevant institutions (following Young 1994, meaning informal and formal rules) such as those of the EWC have identified a need for improved sea ice and weather prediction and status information to ensure a safe hunt and avoid animals or conditions not conducive to sound resource management (Metcalf and Robards 2008). Similarly, resource managers with federal agencies have investigated the information needs concerning walrus stock and behavior (Jay *et al*. 2011). One challenge is to reconcile and integrate these different types of information needs, as well as articulate the specific needs to the level of detail required for the design of an observing and prediction system.

Here, maps such as shown in Figure 1 can help identify areas of overlapping, high institutional density locations. In particular, one needs to note that the radius of marine hunting around villages is expanding as the ice cover changes. In western Alaska, hunters may now travel as much as 100 nautical miles or more in pursuit of game. Figure 1 also delineates those areas designated critical habitat, in this case for the polar bear which is listed as a threatened species under the Endangered Species Act. Equally relevant are activities such as ship traffic or resource exploration that could result in potential harassment of walrus, as defined under the Marine Mammal Protection Act. As with other species, ice features providing ecosystem services such as recurring open water in the form of coastal polynyas (shown in black in Figure 1) would also help guide the location of monitoring and prediction programs. However, a fully refined observing and prediction plan requires a more detailed analysis of institutional regimes and densities, facilitated through the establishment of an information bridge.

Information bridging for safe subsistence hunting and walrus management

We argue that a limited set of sea ice observations and derived information combined with associated ice and weather predictions can help to democratize resource governance in the Arctic, here discussed for the example of the walrus hunt, but relevant for a larger number of ice-associated protected species as well as other ice uses, for example, by industry. For the case of the walrus and the goal of reducing hazards associated with the subsistence hunt while promoting sustainable management of the resource, a forum and community of experts has been assembled over the past two years that can help illustrate the concept of information bridges and the implementation of an observing and prediction system that builds on this link. The SIWO, a partnership between the NWS, the EWC, theNOAA's Pacific Marine Environmental Lab(PMEL), the University of Alaska Fairbanks (UAF) and the Arctic Research Consortium of the United States (ARCUS) under the auspices of the Study of Environmental Arctic Change (SEARCH), was initiated in 2010. It grew from collaboration between Yupik and Iñupiaq sea-ice experts in Alaska coastal villages and UAF and the efforts of the NWS office in Anchorage to improve regional weather forecasts. Following up on broader consultation of all partners with key contributors from several Bering and Chukchi Sea villages, a weekly product comprising a high-resolution weather forecast, ice information and input from hunters and other experts through a website and other means of communication was delivered during the walrus hunting season (April through June 2010 and 2011; Eicken *et al.* 2011a).

An important aspect of this interface for knowledge exchange in relation to key institutions governing walrus and subsistence activities, is the two-way communications that include specific feedback to the NWS on model performance at the local level and to UAF and the NWS on relevant satellite remote sensing products. At the same time, SIWO also helps with the dissemination of relevant information among coastal communities in the region concerning ice, weather and walrus. While SIWO is a prototype project that is only exploring various operational approaches, it does provide specific guidance on key variables and predictors of interest to local hunters, including ice concentration at very low concentrations, ice types originating from Siberia where the tail end of the seasonal walrus migration originates, improved wind forecasts that take into account topographing steering of flow, and a number of other observables. By turning such data into actionable information relevant for travel in the marine environment and walrus hunting, such an effort may also contribute effectively to ecosystem-based management of living marine resources (see Table 1). Thus, better observations create the potential for more adaptive management, and would provide for a more appropriate scale and mode of coordination with stakeholders in villages, researchers, and industry.

Marine transport for shipping and tourism

Relevant Institutions (for US Arctic waters): United Nations Convention on the Law of the Sea, Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic, International Maritime Organization (IMO) Circulars, IMO International Convention for the Safety of Life at Sea (SOLAS), International Convention for the Prevention of Pollution from Ships, U.S. Ports and Waterways Safety Act of 1972 (potential rule for Arctic)

Identifying relevant observation variables

This case contrasts with the first in that data and observations are already informing practices of competing stakeholders but Arctic-specific institutions are only now emerging. Shipping in the Arctic seas has increased in the past few years corresponding with a reduction in summer sea ice, the exploration and development of mineral and hydrocarbon prospects, and new icebreaking technology. In 2004, over 6000 shipping vessels completed trips in the Arctic (AMSA 2009) indicating that Arctic shipping is already a significant activity. Safety of passage is a priority for both shippers and communities who bear the risk of spills of oil or other hazardous materials. The sea ice service in question here is the role of sea ice as a marine hazard, preventing or impeding a ship's progress and potentially requiring use of heavy icebreakers. Timco *et al.* (2005) interviewed 14 ship captains with experience in the Arctic in order to document information needs and data gaps for Arctic shipping. Their top variable of interest was the presence of multi-year ice, followed by ice pressure and high ice concentrations. The avoidance of multi-year ice was reported as especially important for the integrity of the ship's hull. Furthermore, entities such as the North American Ice Service (NAIS) provide a number of products based on remote sensing data in chart form to mariners. With a focus on ice hazards and the shipping industry's need for information on the evolution of ice conditions over the course of the season for a specific region, there is considerable value in parameters that combine a number of relevant factors into a single index. One such product is the Barnett Ice Severity Index (BSI). The U.S. National Ice Center calculates the BSI based on the distance from the shore to different ice concentration contours north of Alaska during the summer months, integrating furthermore the length and closing date of the navigation season. Drobot and Maslanik (2002) explored the seasonal predictability of this index based on statistical approaches. This work has been further expanded by Lindsay and Zhang who used large-scale model output to inform a statistical forecast in the context of the Arctic Sea Ice Outlook, an online forum for the synthesis of seasonal ice predictions (www.arcus.org/search/seaiceoutlook). However, while such information is helpful for broad-scale planning, it typically does not have the spatial and temporal resolution required for tactical decisions or identification of individual hazardous ice features, although progress has been made (Eicken *et al.* 2011b).

Sea ice monitoring to inform management

Within a nation's Exclusive Economic Zone (EEZ), Article 234 of the Law of the Sea Convention grants to coastal countries the right to regulate pollution prevention institutions for vessels in ice-covered areas. However, Rayfuse (2007) notes, the convention specifies that rules can be applied only:

> ...where particularly severe climatic conditions and the presence of ice covering such areas for most of the year create obstructions or exceptional hazards to navigation, and pollution of the marine environment could cause

major harm to or irreversible disturbance of the ecological balance (cited in Rayfuse 2007, pp. 204–205).

This article includes concepts that under global and Arctic environmental change, have become more ambiguous in their interpretation. Rayfuse (2007) notes that definitions of the phrases 'particularly severe,' and 'most of the year,' can now be plausibly debated among UNCLOS signatory nations (of which the USA is not).

In the USA, U.S. Coast Guard (USCG) jurisdiction over marine vessels in icy waters is complicated by a lack of codified rules coupled with the presence of internationally recognized freedom of navigation outside of territorial seas. There are established rules for icy waters with significant infrastructure such as the Port of Valdez and the Port of Anchorage. At present, the USCG issues 'Broadcast notes to mariners' describing areas of hazardous conditions to travel. The areas are described and the Captain of the Port can issue 'ice routing measures.' In the Port of Valdez, at the pipeline terminal, if floating ice reaches a certain density or percent coverage, navigation is directed through their Vessel Traffic System (Dave Seris, USCG, personal communication, July 17, 2008). Other standards and norms are described in IMO circulars, but at the present time these are non-binding and hence less likely to affect operators' activities (Jensen 2007). A precautionary approach to determining thresholds for ice severity and its consequences is reflected in the IMO's current efforts to develop a binding polar code for vessels operating in the Arctic. We assume that this document will build on existing, non-binding guidelines by the IMO for ships operating in ice-covered Arctic waters and address ship construction, safety equipment, and sea ice navigation (IMO 2010). Hence, information relevant for management of this code will likely require more detailed data on the distribution in particular of multiyear ice, which is considered a major hazard even in small concentrations. The likelihood of multiyear ice encounter enters into the definition of current polar classes (IMO 2010) and will require additional monitoring efforts to effectively track such ice types during the summer at low overall ice concentrations.

In general, it appears that sea ice observations relevant to shipping and hazard avoidance are feasible for operations along the coast and near facilities with sufficient capability to collect near real-time data on local ice conditions. However, outside of the territorial sea boundary, new institutions would have to be developed to take advantage of enhanced data gathering capabilities (see also discussion of associated remote-sensing data needs by Eicken *et al.* 2011b). It is also important to note that any requirements for ice pilots, currently a recommendation in the IMO guidelines, will tax current capacities and require additional training and education of experts.

Information bridging for Arctic shipping

At the present time, the Arctic Council and the IMO are the two policy-shaping venues in which discussions of Arctic shipping have begun to take place. However, following the SIWO information bridging model, we suggest that for effective monitoring of relevant variables and derivation of required information a forum for exchange and planning be created that involves stakeholders from the shipping industry, local communities, and the regulatory agencies with participation by researchers from academia.

Conclusions

These cases demonstrate that institutional density of regulatory regimes can help prioritize environmental observations and data production in settings where stakeholders are in need of and prepared to use such information. The social–environmental interdependence of these stakeholders and the externalities they impose upon one another through their activities further increases the relevance of such institution-guided observations. However, typically such dense policy systems lack coordination of data uptake and adaptive capacity to ingest new data to serve multiple interests over the long-term. Our proposal for information bridges among institutions and competing stakeholders – not to diminish political competition but to maximize data availability and data relevancy across scales – addresses this challenge.

What incentives are there for self-interested actors to facilitate the planning of data production and sharing of results required for an information bridge? Goldman *et al.* (2007) discuss the benefits and drawbacks of voluntary cooperation in ecosystem service conservation. In their work they seek to encourage landscape-scale coordination across local to global production of farm services and move away from farms as ‘independent units.’ In a similar fashion the sea ice system actors tend to function as independent units tied to one or more services.

Goldman *et al*. propose three major incentives; we retain their original labels but have altered their function to relate to data and information design rather than conservation: (1) *cooperation bonuses* where system users are rewarded for individual activities that facilitate broader scale data collection and dissemination, such as that implemented in the context of SIWO, (2) *competitive design incentives* tied to cooperation that would reward individual or group proposals of new ways to share data (such as through cooperative proposals for exploratory research), and (3) *ecosystem service districts* that would use legal means to create data sets to be used at the system scale, possibly mandated by stipulations that are part of resource leasing agreements or through other means such as voluntary cooperation and sharing as in the case of a recent data sharing agreement between NOAA and Shell. These three incentives move from individual activities, such as a willingness to share data sets by a single scientist or group, to collaborative or competitive efforts, such as competition for or access to funding resources, and finally to what could be a new set of regulatory institutional policy determining what data are required across many actors. It is important that information bridges policy not be a top-down directed activity but one that offers incentives to participants.

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