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Sea-Ice System Services: A Framework to Help Identify and Meet Information Needs Relevant for Arctic Observing Networks

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ABSTRACT. The need for data from an Arctic observing network to help stakeholders with planning and action is generally recognized. Two key research concerns arise: (1) potential contrasts between fundamental and applied science in the design of an observing system, and (2) development of best practices to ensure that stakeholder needs both inform and can be met from such an observing system. We propose a framework based on the concept of sea-ice system services (SISS) to meet these challenges and categorize the ways in which stakeholders perceive, measure, and use sea ice. Principal service categories are (1) climate regulator, marine hazard, and coastal buffer; (2) transportation and use as a platform; (3) cultural services obtained from the "icescape"; and (4) support of food webs and biological diversity. Our research focuses on cases of ice as platform and marine hazard in Arctic Alaska. We identify the information for each SISS category that users need to track, forecast, and adapt to changes. The resulting framework can address multiple information needs and priorities, integrate information over the relevant spatio-temporal scales, and provide an interface with local knowledge. To plan for an integrated Arctic Observing Network, we recommend a consortium-based approach with the academic community as an impartial intermediary that uses the SISS concept to identify common priorities across the range of sea-ice users.

Key words: sea ice, Arctic ecosystems, Arctic Alaska, climate change, Arctic observing system, Arctic policy, community-based observations, adaptation, Alaska Eskimo whaling communities, local knowledge

RÉSUMÉ. Il est généralement reconnu qu'il faudrait avoir accès à des données prélevées à partir d'un réseau d'observation de l'Arctique pour aider les parties prenantes à planifier et à prendre les mesures qui s'imposent. Il existe deux grandes sources de préoccupations à ce sujet : 1) les contrastes potentiels entre la science fondamentale et la science appliquée en matière de conception d'un système d'observation; et 2) la mise au point des meilleures pratiques pour s'assurer qu'un tel système d'observation informe les parties prenantes et réponde à leurs besoins. Nous proposons un cadre de référence fondé sur le concept des services d'un système de glace de mer (SISS) pour relever ces défis et catégoriser les manières dont les parties prenantes perçoivent, mesurent et utilisent la glace de mer. Les principales catégories de service sont les suivantes : 1) régulateur climatique, obstacle marin et tampon côtier; 2) moyen de transport et plateforme; (3) services culturels obtenus à partir du « paysage glaciaire »; et 4) soutien du réseau trophique et de la diversité biologique. Notre recherche porte plus précisément sur les cas où la glace sert de plateforme et présente un obstacle marin dans l'Arctique alaskien. Nous identifions l'information que les utilisateurs doivent repérer, prévoir et adapter aux changements dans le cas de chaque catégorie du SISS. Le cadre de référence qui en résulte peut répondre à de multiples besoins et priorités en matière d'information, intégrer l'information sur des échelles spatiotemporelles pertinentes et fournir une interface avec les connaissances locales. Afin de planifier en vue de l'établissement d'un réseau intégré d'observation de l'Arctique, nous recommandons la formation d'un genre de consortium composé de chercheurs, consortium servant d'intermédiaire impartial utilisant le concept SISS pour déterminer les priorités qui sont communes aux usagers de la glace de mer.

Mots clés : glace de mer, écosystèmes de l'Arctique, Arctique alaskien, changement climatique, réseau d'observation de l'Arctique, politique de l'Arctique, observations communautaires, collectivités esquimaudes de chasse à la baleine en Alaska, connaissances locales

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INTRODUCTION

Arctic Change and Arctic Observation

The Arctic sea-ice cover is both an indicator and an agent of change (Serreze et al., 2007). Model results suggest that ice-albedo feedback reinforces changes in the Arctic sea-ice cover driven by atmospheric and oceanic forcing and has major repercussions on global climate (Holland and Bitz, 2003; Hall, 2004). Observations and simulations indicate substantial reductions in Arctic sea-ice extent and thickness over the past few decades (Lindsay and Zhang, 2006; Serreze et al., 2007). In 2007, the summer sea-ice minimum extent represented a 39% reduction from the 1979–2000 average—the lowest coverage observed (Comiso et al., 2008). Sea-ice retreat is one aspect of a broader suite of transformations comprising environmental and socio-economic change in the North, fundamentally altering the ecosystems upon which human livelihoods depend (Chapin et al., 2006). Circum-Arctic nations are receiving increasing attention as projections of further sea-ice decline imply wide-ranging impacts. Such attention includes assessments of Arctic shipping and development of associated infrastructure, coastal and offshore oil and gas development, and reassessment of northern policies and territorial claims by the five littoral nations (Brigham, 2007; Cressey, 2008). Arctic coastal communities have for some time felt and responded to the impacts of a changing sea-ice cover (Huntington, 2000; Krupnik and Jolly, 2002; Gearheard et al., 2006; Laidler, 2006).

These developments have called attention to the need for an observing system that provides data needed to improve our ability to track, understand, and adapt to or mitigate change (SEARCH, 2005; Committee on Designing an Arctic Observing Network, 2006; Anisimov et al., 2007). Implementation of a comprehensive Arctic observing network, in addition to long-standing programs such as the World Meteorological Organization's network of surface weather stations or the International Arctic Buoy Program, gained momentum during the International Polar Year 2007–08 (IPY). The challenge lies in the integration of measurement programs so that they can help address pressing scientific questions. At the same time, this integration must satisfy the needs of decision makers, who require pertinent and accurate information to develop adaptation and mitigation strategies. While regional ocean observing systems (e.g., Malone and Cole, 2000), terrestrial ecological monitoring sites (e.g., Hobbie et al., 2003), and coordinated socio-economic data collection (e.g., Poppel et al., 2007) have addressed some of these aspects, comprehensive efforts at the pan-Arctic scale are only now starting to be discussed (e.g., IARPC, 2007).

Arctic Observing Networks and Stakeholder Information Needs

The emphasis placed on addressing stakeholder information needs (SEARCH, 2005; Committee on Designing an Arctic Observing Network, 2006; ArcticNet, 2007; IARPC, 2007) is driven by the requirements of adaptation to climate change at local and regional levels (Schneider et al., 2007). For the purposes of this study, we consider stakeholders as having a contractually or informally recognized interest in a region or resource (Friedman and Miles, 2002). As a focal point of a range of interests extending across all levels of government, industry, and the public (Barber et al., 2005; Kelmelis et al., 2005; Brigham, 2007), Arctic sea ice can serve as a testbed to explore different user groups' information needs and develop approaches to better serve these needs through an observing system that is integrated over a range of scales, disciplines, and knowledge systems. We focus on the overlap and differences between the requirements of scientific studies of the Arctic sea-ice mass and heat budget and the information needs of different stakeholders.

Implementation of an observing system depends strongly on how the monitored variables and the sampling locations and rates are specified. From the perspective of geophysical research, the measurement approach is dictated by the relevant spatio-temporal scales of the phenomenon under study, technical feasibility, and the types of questions asked. For example: Will Arctic summer sea ice vanish completely in coming decades, and if so, when? Answering this question requires a combination of numerical simulations and observations of the mass budget of the Arctic ice cover as a whole (Hutchings and Bitz, 2005). A study by Lindsay and Zhang (2006) suggests that for this specific purpose, measurements of ice thickness over time at only two or three strategically placed points may be sufficient. However, such ice thickness data likely would contribute little if anything to help Arctic stakeholders in planning for a future with drastically different ice conditions.

An environmental observing system that is responsive to stakeholder needs poses challenges beyond those typically encountered in science-driven observing systems designed for use by "experts" (Fischer, 2002). Such challenges may include difficulty in identifying the observable parameters that serve specific information needs and translating these into a viable measurement program, mismatches in observational scales and desired information, disagreements over prioritization, or lack of effective communication between stakeholders and the research community. In the Arctic, the IPY and a nascent dialog between different agencies and the scientific community (IARPC, 2007) provide a unique opportunity for exchange and coordination. Recent reports, such as that of Hutchings and Bitz (2005) on stakeholder requirements for sea-ice mass budget data and the U.S. National Academy of Sciences report on an integrated Arctic observing network (Committee on Designing an Arctic Observing Network, 2006), reflect the urgency of the issue. The latter study reiterates the importance of an observing network for planners, Arctic residents, and the general public but focuses almost exclusively on the "pure science" approach in laying out a design and implementation plan. Below, we outline how the approach can be broadened through guidance from the SISS framework.

Research Objectives

How can a diverse group of people and institutions plan for simultaneous use of a changing system, while reducing conflict and promoting harmonization of policies? This paper addresses the observational and policy challenges associated with rapidly changing sea ice along Alaska's northern coasts and elsewhere in the Arctic. While our focus is on sea ice and its potential harm and benefits, many of the concepts discussed have broader applicability and may contribute to the implementation of a sustained pan-Arctic observing network. Specifically, we develop the framework of sea-ice system services (SISS), which is derived from the notion of ecosystem services as defined by the United Nations' Millennium Ecosystem Assessment (MA, 2005), to aid design and implementation of an Arctic sea-ice observing network that is responsive to user and stakeholder needs. We explore two poorly understood questions of importance: (1) What are the information requirements from an Arctic (sea-ice) observing network for academia and different stakeholder groups, in particular government agencies, local residents and users of environmental services, and industry? (2) How can an effective, sustainable Arctic (sea-ice) observing network help ensure that (i) research benefits stakeholders and the public, (ii) the information users can effectively communicate their needs to the research community, and (iii) synergies between observing-system components are maximized while operational costs are minimized?

A fundamental premise of this paper is that Arctic observing networks need to address the challenges associated with the dichotomy between "pure" and "applied" or "socio-economically relevant" research. Holton and Sonnert (1999), Pielke (2007), and others argue that the classic division between pure (Newtonian) and applied (Baconian) research is ripe for a synthetic revision in the form of "Jeffersonian" research that addresses fundamental research questions in the context of pressing societal problems. We contend that tracking Arctic environmental change to understand and adapt to the entire suite of environmental, geopolitical, and socio-economic changes clearly falls into such a category.

SEA ICE AS A GEOPHYSICAL PHENOMENON WITHIN A SOCIO-ECOLOGICAL SYSTEM

Key Categories of Sea-Ice Use and Services

The Millennium Ecosystem Assessment (MA, 2005) focused on the tangible and intangible benefits that ecosystems provide in the form of services essential to human well-being. The MA considered geophysical features such as sea ice only in their role as one of a broad range of supporting functions of large ecosystems, e.g., as a habitat for key species such as walrus, polar bear, or ice-associated seals (MA, 2005; Chapin et al., 2005). Here we argue that in the Arctic, the role of sea ice for human activities and well-being reaches far beyond that function (Fig. 1). The disproportionate importance of sea ice as a geophysical feature (relative to other systems considered in the MA) derives largely from the fact that it is heavily used in the Arctic by the indigenous populations as well as by industry. Sea ice plays the role of other key infrastructure (such as roads, shoreline protection, staging areas, or thermal regulators) that is man-made in more industrially developed regions. As development has proceeded, sea ice has been integrated into planning as an infrastructural element, for example in the support of over-ice roads or artificial ice islands during oil and gas exploration (C-CORE, 2005; Instanes et al., 2005). At the same time, the increasing ship traffic to supply coastal settlements and industrial sites has to cope with sea ice as a potential hazard (Instanes et al., 2005; Brigham, 2007). In extending the MA approach, we apply the four principal classes of services (Table 1) to sea ice.

1) *Regulating services* provide benefits derived from the regulation of ecosystem functions. Examples in the MA include processes such as water purification through physical, chemical, and biological filtering or climate regulation through control of greenhouse gas concentrations. The impact of sea ice on the surface heat budget and its role as a driver and modulator of thermohaline circulation are key regulating factors in the global climate system (Serreze et al., 2007). As a geologic agent, sea ice controls a number of processes in the coastal region. Its absence at critical times of the year can enhance erosion driven thermally or by storms (Aré, 1988; Manson et al., 2005). At the same time, ice rafting of sediments by sea ice is one of the most effective sediment transport mechanisms in the Arctic (Reimnitz and Barnes, 1987; Eicken et al., 2000). As a buffer, ice can help stabilize coastal infrastructure and offer protection from storms and other environmental factors. Finally, sea ice is an important regulator of shipping because it represents a significant hazard that requires the use of ice-strengthened vessels or icebreaker support to maintain shipping routes (Brigham, 2007).
2) *Provisioning services* yield products taken from the ecosystem. For sea ice, this includes food obtained by local communities on or from the ice, such as seals and other marine mammals or fish (Nelson, 1969; Nuttall et al., 2005). In many communities, multiyear sea ice is harvested as a freshwater source (Nelson, 1969; Richard Glenn, Barrow, pers. comm. 2004). Here, we broaden the definition by including services in which sea ice is used in lieu of other products or infrastructure, for example, its important use as a platform that provides access to marine mammals or other resources.
3) *Cultural services* comprise non-material (e.g., spiritual, aesthetic, or educational) benefits. As a place that harbors many of the most important subsistence resources and as a dynamic landscape feature, sea ice often plays a central role in the daily life of coastal communities during the ice season (Nelson, 1969). Subsistence activities

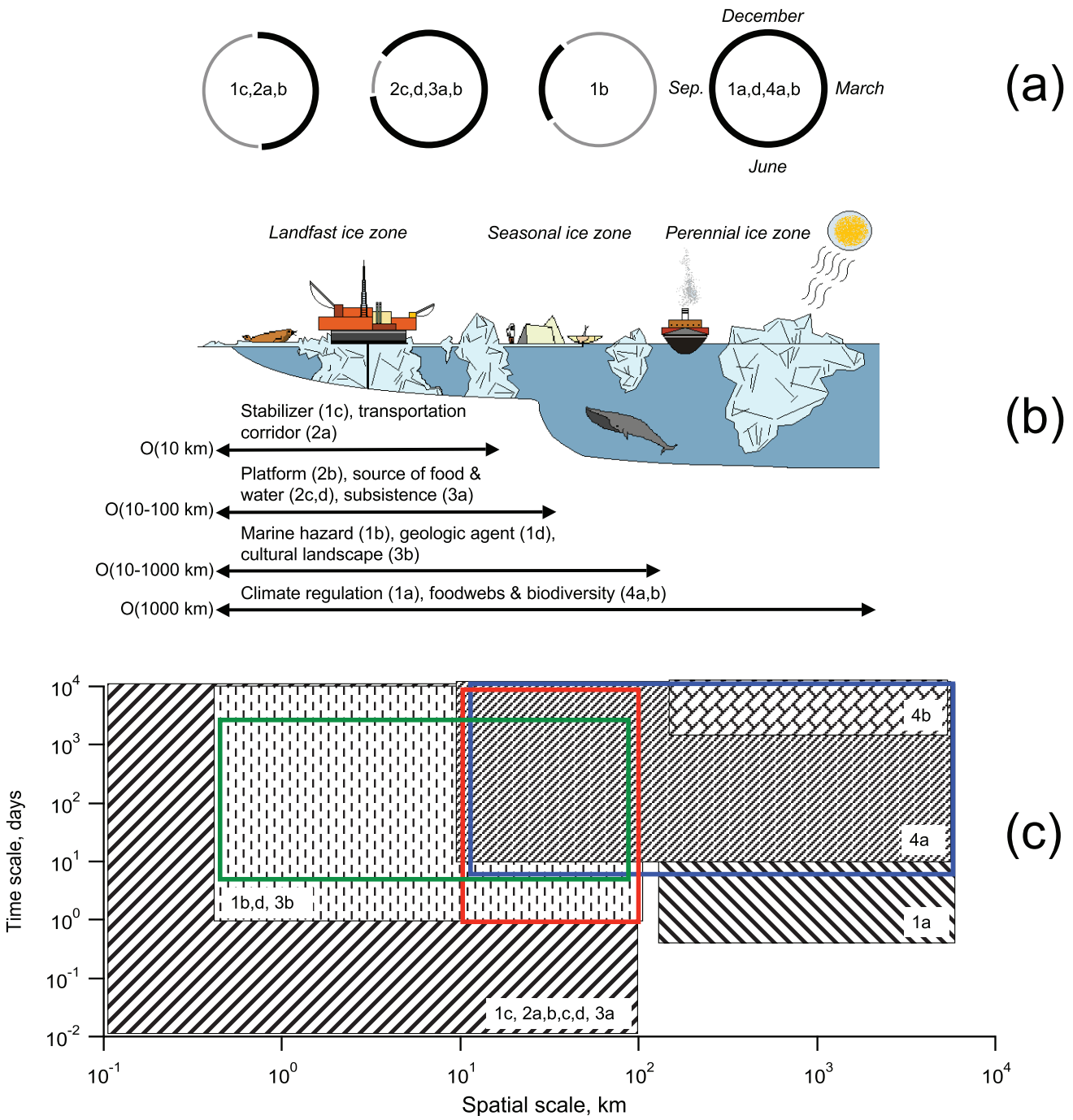

FIG. 1. Schematic depiction of the spatial and temporal scales relevant to different sea-ice system services (identified by numbers and letters used in Table 1). (a) Portion of the seasonal cycle into which the primary use falls, shown as thick circle segment. (The full circle represents the annual cycle, with 1 January at top and progressing clockwise through the seasons.) (b) Spatial extent of different sea-ice zones and associated services. The order of magnitude of the extent of these zones is indicated to the left of the arrows (e.g., 0(10 km) indicates typical width of the landfast ice zone). (c) Spatio-temporal scales relevant for different sea-ice services in the context of sampling rates, coverage, and scope of an observing system. The colored boxes represent the coverage of specific sea-ice information products, i.e., an NIC ice chart (blue), the Barnett Ice Severity Index (red, see Fig. 2 and text for details), and landfast ice stability analysis (green) by Mahoney et al. (2007a), as discussed in the text.

on the ice also fall under the category of cultural benefits; for example, sea ice provides a place for instruction and mentoring of young hunters. Tourism may benefit from sea ice in different ways and can supply substantial income to communities through the cultural services it delivers (Osanai and Sasajima, 1994).

4) *Supporting services* such as soil formation or nutrient cycling are prerequisite to the derivation of other benefits from a socio-ecological system and hence are often associated with much longer time scales (MA, 2005). The role of sea ice as a habitat falls into this category, since many of the ice-associated micro-organisms are not directly harvested, but are an important component

TABLE 1. Sea-ice system services categorization.[1]

Service Category	Type of Service	Target Variables	Measurement Approach
1. **Regulating**	a. Sea ice as regulator of Arctic and global climate	Albedo, extent, thickness, mass flux	Satellite, aerial and submarine surveys, moorings
	b. Hazard for marine shipping and coastal infrastructure	Concentration and extent, multiyear (MY) ice fraction, thickness	Satellite, aerial surveys
	c. Stabilizing element for coastal infrastructure and activities	Thickness and morphology, duration of ice season, presence of MY ice	High-resolution satellite imagery, LK[2], aerial and ground-based surveys
	d. Ice as a geologic agent: Erosion control through damping impacts of storms, buttressing permafrost coastline (bottom-fast ice), enhancing erosion through ice rafting of sediments	Duration of ice season, sediment entrainment	Satellite surveys, ground-based measurements and sampling
2. **Provisioning**	a. Transportation corridor	Stability, morphology, thickness/strength	Satellite, ground-based surveys, LK, coastal radar, in-situ instrumentation
	b. Platform for a range of activities (subsistence hunting and fishing, oil and gas development, etc.)	Stability, morphology, thickness/strength, MY ice fraction	Satellite, ground-based surveys, LK, coastal radar, in-situ instrumentation
	c. MY ice as source of freshwater	MY ice fraction and age	LK, satellite, ground-based surveys
	d. Access to food sources	Morphology, ice biota	LK, aerial, ground-based surveys, sampling
3. **Cultural**	a. Subsistence activities on and around ice	Extent, morphology, duration of ice season, ice ecosystems	LK, satellite, ground-based surveys, sampling
	b. Ice as part of cultural and spiritual landscape (including tourism, e.g., Hokkaido)	Extent, morphology, duration of ice season, ice ecosystems	LK, satellite, aerial, ground-based surveys
4. **Supporting**	a. Sea-ice based foodwebs and ice as a habitat (ice algae, under-ice fauna, seals, walrus, polar bears, etc.)	Extent, stability, morphology, duration of ice season, ice ecosystems	LK, ground-based surveys, sampling
	b. Reservoir and driver of biological diversity (e.g., extremophiles)	Extent, stability, morphology, duration of ice season, ice ecosystems	Sampling, LK

[1] Categories follow those identified by the MA (2005).

[2] LK refers to the local knowledge used to observe and understand the natural environment and may include indigenous and traditional components.

of the food web that sustains marine mammals or fish (Thomas and Dieckmann, 2003). As an extreme environment, sea ice enhances marine biodiversity; extremophiles may undergo modifications of the gene pool with a number of potential applications and uses (Rothchild and Mancinelli, 2001; Deming and Eicken, 2007). The role of sea ice in controlling coastal erosion and other processes also partly falls into the same category because of the long time scales involved.

Sustainability and Observing Systems

The services listed in Table 1 can help in organizing observable parameters to reflect distinct users' needs. An observing system responsive to such needs plays a vital role in fostering sustainability, i.e., "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987). Just as important as indicators or measures of the use itself (e.g., harvest of ringed seals on sea ice) are the measures that describe the service (e.g., sea-ice properties that promote successful reproduction and survival of ringed seals). When government decision makers implement adaptation strategies (e.g., new rules of resource use), the information made available to them shapes the parameters of their governance choices. The implications for the sea-ice system are major insofar as environmental and socio-economic or geopolitical change may substantially modify the types of services offered and their uses by competing interests. Information transmitted to decision makers must therefore stem from a comprehensive understanding of a social-ecological system (Lovecraft, 2007, 2008). To meet future requirements, an observing system must also include forecasting efforts, discussed in more depth below. The sustainability criterion can guide the identification of target variables that must be observed and predicted to ascertain sustainable use of SISS, for example, in targeting key weather and sea-ice variables for predictions of safe operational windows for offshore drilling on sea ice in winter.

To illustrate the link between SISS and key observables, we examine the climate regulation services of the ice cover, and specifically, its impact on the shortwave radiation budget of the earth, which is considered one of the most important roles of sea ice in the global climate system (Holland and Bitz, 2003; Hall, 2004; Forster et al., 2007). The amount of shortwave energy absorbed at the surface per unit area and time (Q_s) is given by the product of the incident shortwave flux (Q_{si}) and ice albedo (α) according to the formula $Q_s = (1 - \alpha)\, Q_{si}$ (e.g., Persson et al., 2002). In this context, it is helpful to consider the contribution of greenhouse gases to radiative forcing. Forster et al. (2007) found that the increase in carbon dioxide (CO_2) concentrations had contributed approximately 1.5 W m^{-2} since the beginning of the industrial age, with a doubling of CO_2 concentrations projected to increase the longwave radiative forcing by 3 to 4 W m^{-2}. These numbers can be compared to the corresponding forcing due to snow and ice albedo feedback, which has been evaluated with a climate model as between 4 and 8 W m^{-2} for the Northern Hemisphere above 30° N in spring and summer (Hall, 2004). On an annual global average, ice-albedo feedback may thus contribute to increasing the surface heat budget in the same order of magnitude as a doubling of CO_2 concentrations. Hence, measurements of α and Q_s are critical from the perspective of climate regulation services.

Unfortunately, neither of these variables is easily measured in the Arctic. While a combination of satellite remote sensing, atmospheric observations, and modeling can provide reasonable estimates of Q_{si} (Wang and Key, 2003), areally integrated measurements of surface albedo are notoriously difficult because of spatial heterogeneity and cloud cover (Walsh et al., 2001; Perovich, 2005). Consequently, albedo has to be indirectly derived from measurements of ice concentration and proxies for α, such as ice thickness (Perovich, 2005). The approach and type of measurements would then be dictated by the errors tolerable relative to the goal of estimating the radiative forcing of ice-albedo feedback. In the extreme, the observations may simply be confined to derivations of Q_{si} and measurements of ice concentration, assuming that the albedo of ice and water are constant and that solar heating of open water within and outside of the ice pack drives ice-albedo feedback (Perovich et al., 2007). For the study of sea-ice climate regulating services, this latter approach is consistent with present space-borne or ground-based sea-ice observation efforts (Hutchings and Bitz, 2005; Committee on Designing an Arctic Observing Network, 2006). Ice thickness and mass flux measurements are required to address other important roles of the ice cover in the climate system. However, such measurements may well be confined to a few, carefully selected sites and combined with simulations to arrive at estimates of, for example, total Arctic sea-ice volume (Hutchings and Bitz, 2005; Lindsay and Zhang, 2006).

For climate regulation services, the SISS framework or a standard geophysical approach are roughly equivalent in designing a measurement program. As one moves down the list in Table 1, however, this direct mapping of one approach onto the other becomes increasingly difficult. Both the ordering of different categories in Table 1 and the ranking of services within each category imply increasing difficulty in defining a set of variables that need to be tracked to improve planning and adaptation. In the case of cultural and spiritual services, for example, identification of target variables is challenging because of the subjective importance of criteria based on values or aesthetics. Hence, observatory design has to start with the identification of local uses and requires communication between stakeholders and scientists (Kofinas et al., 2002; Eamer, 2006). Such potential divergence between a fundamental-science approach and a stakeholder-oriented approach is not an indication, however, that the two are in conflict. Rather, both are required to ensure scientific-geophysical and socio-economic relevance and can serve as a starting point for broader multilateral exchange between stakeholders (Krupnik and Jolly, 2002; Eamer, 2006; Gearheard et al., 2006).

THE IMPORTANCE OF SPATIAL AND TEMPORAL SCALE: MARITIME NAVIGATION ALONG ALASKA'S NORTHERN COASTLINE

Analysis of Arctic sea-ice change is mostly based on monthly mean values of pan-Arctic ice extent, evaluated from satellite data with spatial resolutions of tens of kilometers and often analyzed many months after data acquisition. Stakeholders and users of sea-ice services commonly require data at much finer spatial scales and at higher sampling rates, made available in near-real time, to help with short-term decision making, e.g., in the context of ice hazards to shipping or response to catastrophic events such as ice override and landfast ice break-out events (George et al., 2004a). Such contrasting demands require careful analysis of information needs for the key user groups in order to arrive at an observing network that provides information and data of use to science, planning, and management. Figure 1 relates the service categories identified in Table 1 to different spatio-temporal scales, the annual ice cycle, and the typical zonation of sea ice in Arctic seas. The schematic indicates that quantification of very different types of services, such as climate regulation and biodiversity or coastal protection and ice tourism, may require information collected at comparable scales and in a comparable context. Such overlaps may lead to opportunities for synergy and cross-disciplinary exchange within integrated observing systems.

The U.S. National Ice Center (NIC) sea-ice charts can serve as an example of ice information that is delivered at the intersection of the large, climatologically relevant scale and the finer resolution demanded by stakeholders. The standard ice charts are produced weekly, with an ice analyst interpreting satellite imagery with pixel sizes ranging from tens of kilometers down to a kilometer or less (Fig. 2). Such standard products are suitable for the analysis of sea-

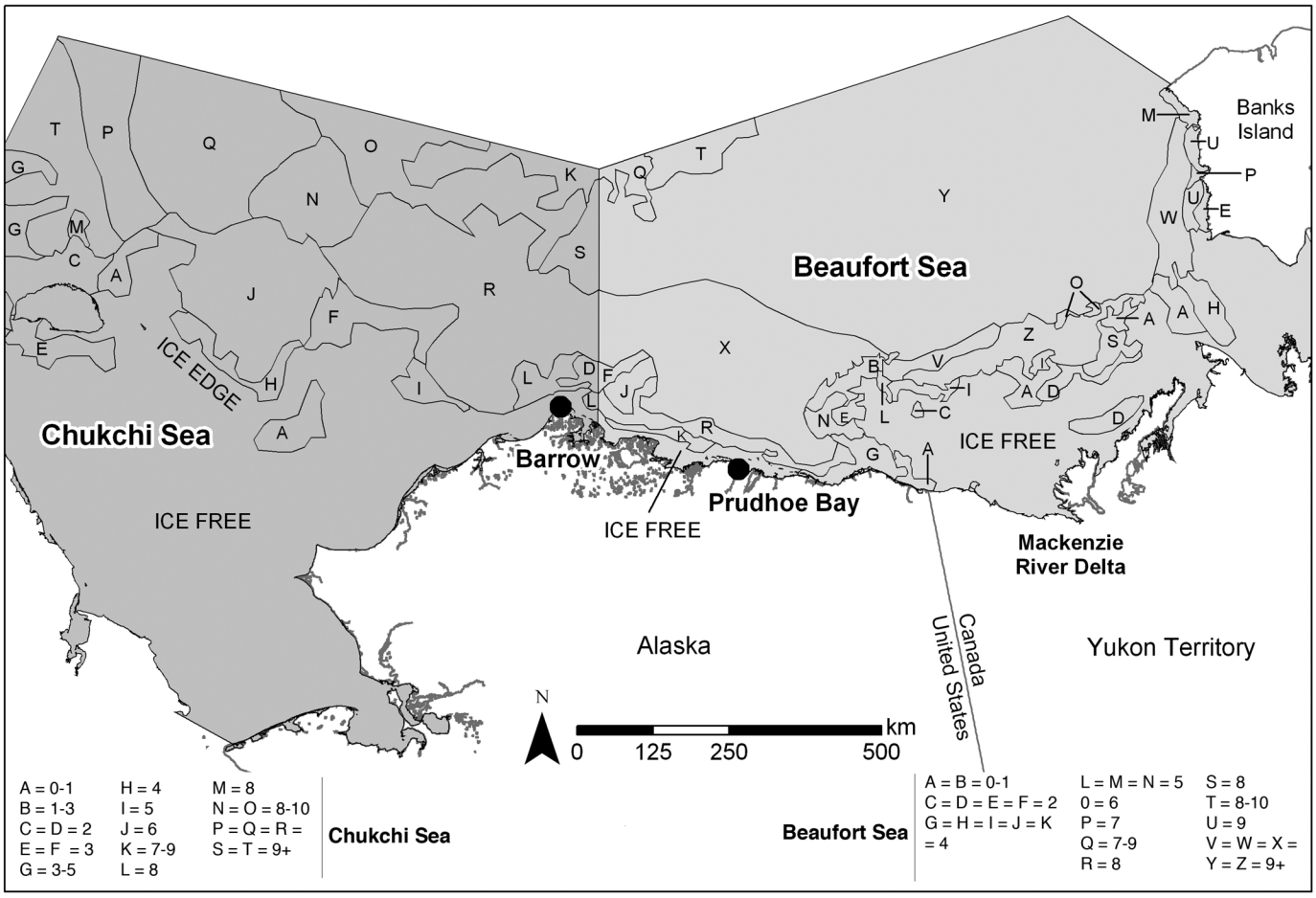

FIG. 2. Sea-ice charts for the Chukchi and Beaufort seas for 11 August 2006, adapted from ice charts produced by the U.S. National Ice Center (www.natice.noaa.gov). Satellite sources used to generate the map include passive microwave radiometer data, synthetic aperture radar (SAR) data, and visible/thermal-infrared radiometer data. WMO Egg Code letter codes, giving ice concentration in tenths, are defined below. Additional information reported in the WMO Egg Code (partial concentration, thickness, age, floe size) has been omitted.

ice variability for assessing climate regulation, seasonal ice evolution, and the probability of encountering different ice types during marine shipping (Partington et al., 2003; see mapping of data product into Fig. 1). While the charts are insufficient to provide information on, for example, land-fast ice stability at specific on-ice operation sites (Fig. 1), they can serve as a bridge between climatological and use-based information needs. Regional interpreters and forecasting offices integrate information from local sources and observing sites where available, thus validating and increasing the resolution of the product (Fig. 1). The Barnett Ice Severity Index (BSI) further illustrates integration of different information needs across relevant scales. It was developed to help track and forecast ice conditions for summer supply operations along Alaska's northern coast (Barnett, 1976). The BSI is calculated using information from barge operations and data entered into ice charts (distance to different ice-concentration isolines north of Alaska during summer months; length and closing date of the navigation season). It has some seasonal-scale predictive value and relates to key atmospheric circulation parameters (Drobot and Maslanik, 2002). Its method of computation gives the BSI a somewhat finer spatial and temporal resolution than standard ice charts (Fig. 2). Here, we ask how well large-scale, climatological sea-ice data, collected in the context of the climate-regulating functions of the ice cover, capture the variability and trends governing ice hazards and navigation that are relevant to SISS at the regional and local scale. While we discuss an example from Alaska, the underlying issues of ensuring local relevance and integrating local expertise apply throughout the Arctic. For example, the Russian Hydrometeorological Office has a long history of assessing ice conditions along the Northern Sea Route, where observations at high spatial and temporal resolution are required along straits and choke points. Such data have also been used in studies of Arctic climate variability (Polyakov et al., 2003).

With a trend towards less severe ice conditions between 1979 and 2006, the BSI exhibits substantial variation exceeding that of the pan-Arctic minimum ice extent (Fig. 3a). Arctic summer minimum ice extent explains 30% of the variance observed in the BSI for a linear model (Fig. 3b). The September (monthly mean) ice extent in the Western Beaufort Sea, which is relevant for navigation to Prudhoe Bay, explains more than 70% of the observed variance in BSI (Fig. 3c). This example illustrates how a

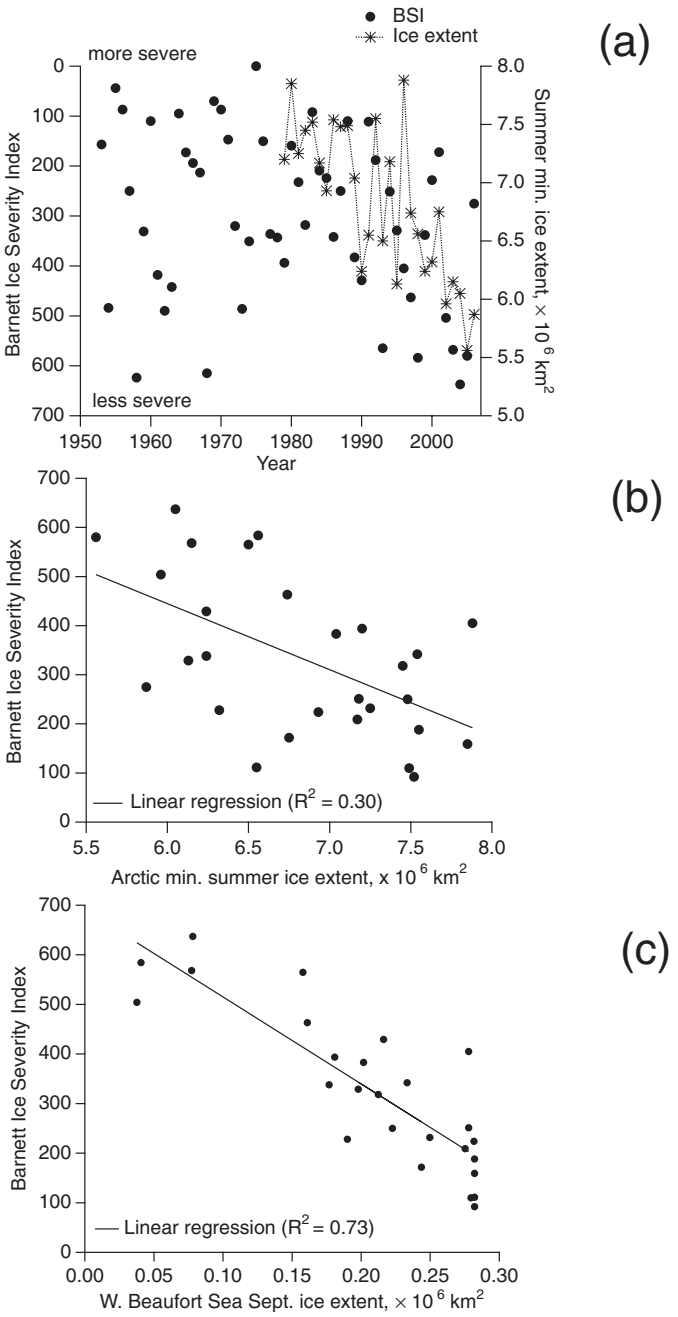

FIG. 3. (a) Time series of the Barnett Ice Severity Index (BSI), from data provided by the National Ice Center (www.natice.noaa.gov), and the Arctic summer minimum ice extent, from data provided by the National Snow and Ice Data Center (nsidc.org). (b) BSI plotted vs. Arctic minimum ice extent. The solid line indicates a linear regression fit to the data. (c) BSI plotted vs. summer minimum ice extent (September monthly mean) for the western Beaufort Sea between Barrow and Mackenzie Delta, derived from passive microwave satellite data using the same algorithm used to derive pan-Arctic ice concentrations. The solid line indicates a linear regression fit to the data.

comparison of stakeholder-defined, local parameters with large-scale, climatological variables can provide significant insight into potential challenges for planning and adaptation at the local level because the variability and spatial resolution increase as the study area size decreases. This pattern is typically referred to as "downscaling" in the context of deriving information from coarse-scale datasets at the local level (e.g., Instanes et al., 2005). In the Beaufort Sea (Fig. 3), this increase in variability and lack of predictive capacity of variables for pan-Arctic ice extent is largely a result of wind-driven changes in ice circulation; these changes have little impact on total ice extent in the semi-enclosed Arctic Basin, but strong regional effects as ice moves, for example, from the North American into the Siberian Arctic (Rigor et al., 2002). As shown by Drobot and Maslanik (2002) and Rigor et al. (2002) and implicitly in Figure 3, there is significant promise in employing statistical approaches for downscaling that are based on combinations of different measures of large-scale atmospheric and oceanic circulation.

Downscaling requires observations of stakeholder-relevant variables at the appropriate finer scale and may be limited by the spatial or temporal resolution of remote-sensing data in particular (Fig. 1). In 2006, a medium-severity ice year off Alaska (Fig. 3a), maritime activities were hampered by the presence of ice at concentrations difficult to detect in passive microwave data and moving rapidly with wind and currents on time scales not adequately captured by ice charts produced at intervals of a few days to one week (Fig. 1; Bailey, 2007). More importantly, many services derived from sea ice, such as its use as a platform for transport and hunting, require high-resolution observations within a narrow coastal zone. At this scale, coastal morphology or local wind and current patterns so strongly influence ice conditions that scaling relationships such as those expressed in Figure 3 or discussed by Drobot and Maslanik (2002) may break down altogether. To investigate this aspect further, we examine how well large-scale ice conditions track with the onset and decay of the landfast ice cover, the stability of which is crucial to many sea-ice users in Alaska.

The local-scale landfast ice data, at a few hundred meters resolution (Fig. 1) and at a temporal scale relevant for some operational purposes, are derived from a study by Mahoney et al. (2007a) of landfast ice extent off northern Alaska. The correlation matrix in Table 2 indicates how large-scale variables (e.g., Arctic minimum ice extent) and parameters (e.g., BSI) covary progressively less as one moves down in scale to the level of landfast ice stability. At the same time, differences such as the significant correlation between onset of stable landfast ice and Western Beaufort Sea September minimum ice extent for Prudhoe Bay, and the lack of such a correlation for Barrow, demonstrate the importance of local conditions. This finding, corroborated by an examination of regional variability along the coast, is due to the stabilizing effect of offshore barrier islands at Prudhoe Bay (Mahoney et al., 2007a). The lower left-hand corner in the spatio-temporal scale diagram (Fig. 1c) reflects a significant gap in current observing systems that are mostly at scales too coarse to capture such local processes. Here, local expertise holds tremendous value in the context of upscaling or downscaling. As highly relevant knowledge that has been honed by generations of Iñupiat ice experts, it can play a key role in an integrated observing system (Huntington, 2000; Gearheard et al., 2006; Druckenmiller et al., 2009).

TABLE 2. Correlation matrix for different Arctic and northern Alaska sea-ice variables.

	Arctic Annual Minimum Ice Extent	West Beaufort September Ice Extent	Barnett Ice Severity Index (BSI)
West Beaufort September Ice extent	**0.699**[1]		
BSI	**-0.55**	**-0.853**	
First landfast ice at Barrow	0.246	-0.255	0.611
First stable landfast ice at Barrow	0.075	-0.032	0.257
Landfast ice breakup at Barrow	0.362[2]	0.642[2]	*-0.769*[2]
First landfast ice at Prudhoe Bay	-0.078	-0.535	0.577
First stable landfast ice at Prudhoe Bay	-0.307	*-0.765*	**0.884**
Landfast ice breakup at Prudhoe Bay	0.221[2]	0.575[2]	-0.604[2]

[1] Bold indicates correlation coefficients (r) significant at the 99% level, and italics indicate those significant at the 95% level (two-tailed Student t test).

[2] Evaluation for minimum ice extent in the subsequent rather than the preceding season.

SEA-ICE SYSTEM SERVICES AND OBSERVING NETWORKS IN THE CONTEXT OF SEA-ICE FORECASTING

The SISS framework can help translate approaches for use-specific observations from one location to another because it frames specific measurements or types of expertise in more generally applicable categories. This is of particular interest when one considers that sea-ice users need not only observations of the state of the ice, but also predictions for likely future states. Prediction is also what policy makers use to help shape government decisions. Because of the importance of predictive time scales, we present a brief review of pertinent short-, mid- and long-term forecasts in the context of SISS.

The need for *short-term forecasts* (hours to days) is driven mostly by marine operations in ice-covered areas and the safety of hunters traveling on and around ice. Given good data on initial conditions, ice-ocean models forced by output from a weather forecast system can be quite effective in predicting ice movement and assessing associated hazards on time scales of hours to days (Preller et al., 2002). At the same time, local knowledge can also achieve significant success in forecasting, particularly in areas where wind and currents interact with the topography and bathymetry to generate complex patterns of ice movement (Nelson, 1969; Norton and Gaylord, 2004). While quantitative assessments of the benefits of sea ice in protecting shorelines from erosion are lacking, anecdotal evidence suggests that prediction of ice formation and drift during the fall storm regime could hold significant promise in planning for short-term coastal protection and mitigation efforts. A comparison between observations of coastal ice by local ice experts and satellite data indicates that during the early stages of fall freeze-up, coastal slush ice, important for the formation of protective shoreline berms during fall storms, is neither detected well from operational satellite data nor predicted well from standard freezing degree-day models (Eicken et al., in press). Here, the SISS approach can be of significant value in improving forecasts through integration of different information sources.

Mid-term predictions (several weeks to months), such as the seasonal outlooks released by national ice centers in many of the circum-Arctic countries, are key for planning of shipping and industrial operations in Arctic waters. Despite the limitations of downscaling, statistical models that integrate information about prevailing atmospheric circulation patterns and the state of the ice cover (e.g., distribution of multiyear ice) and build on past observed patterns hold significant promise for up to two months lead time (Drobot and Maslanik, 2002). As discussed for landfast ice formation and breakup, such approaches may be adapted to finer scales by integrating information and local knowledge about persistent local-scale patterns (Table 2). Lindsay et al. (2008) have shown that including fields of ice thickness and ocean temperatures can significantly improve skill in predicting the sea-ice minimum in September. At the local and regional level, with wind forcing and surface atmosphere-ice-ocean heat fluxes driving much of the observed sea-ice variability, the lack of accurate long-term weather forecasts substantially limits more sophisticated ice-ocean modeling approaches. Nevertheless, such models can yield probabilistic forecasts based on simulations for a range of past atmospheric forcing fields. Such ensemble runs can provide valuable quantitative information on the range of plausible outcomes. Thus, an ensemble prediction for the entire Arctic in spring 2008 (Zhang et al., 2008) showed the highest standard deviation in ice thickness between different simulations in the Beaufort and northern Chukchi seas, providing guidance on potential impacts and the need for observations.

Long-term predictions (years to decades) are important in the context of adaptation to environmental change. Most of the sea-ice projections are based on global circulation model output for decadal time scales (e.g., Instanes et al., 2005; Serreze et al., 2007). The challenge with these simulations is that climate models can be highly effective in describing the adjustment of the climate system to changes in forcing, but are not necessarily designed to provide detailed projections of use-specific parameters, such as ice stability or the distribution of specific ice types, at the local level. Climate models are unable to resolve the near-coastal zone, where a complex array of factors contributes

to important local variations, and climate model projections are confounded by biases in the forcing of sea ice by the atmosphere and ocean. The lack of other forecasting options often severely limits options for decision makers, as in the case of the recent listing of the polar bear as a threatened species by the U.S. Department of the Interior, which in large part had to rely on climate model projections of coarse-scale sea-ice variables (summer minimum ice extent) interpreted at the regional level where uncertainties are large (Durner et al., 2007). Diminishing polar bear habitat is an example where the SISS concept could guide development of observation and forecasting systems that explicitly target variables linked to sea ice's supporting service of providing marine mammal habitat.

A great value of forecasting efforts lies in providing a tool for synthesizing and parsing a broad range of different observations and perspectives on the ice cover. In those instances where predictions are directly linked to public and operational safety, they can serve as a means of fostering communication between different user groups and aid in developing an interface between different forms of knowledge and expertise, as in the case of predicting ice stability and impending ice-push or break-out events (Druckenmiller et al., 2009).

CASE STUDIES OF SEA ICE AS A PLATFORM

The discussion of ice-information downscaling along Alaska's northern coast focused on remote-sensing data, but revealed the importance of local-scale observations. Below, we illustrate how the SISS framework can help guide observations relevant to stakeholders at scales below those shown in Figure 1, down to the sub-meter scale. Sea-ice use is intimately tied to the knowledge, judgment, and decisions made by those living and operating in the ice environment. Given the severe consequences of poor decisions, such as loss of life or potential harm to ecosystems, sea-ice users require detailed, up-to-date information relevant to the intended use. Two case studies examine use of sea ice by Alaska Eskimo whalers and by engineers developing ice platforms for resource extraction. As we attempt to abandon the dichotomy of pure and applied science and approach use-inspired basic research, we may not fully understand the potential role of science without thoroughly examining the uses first (Stokes, 1997). Below, we discuss how the SISS framework may help organize the scope of specific measurements. At the same time, an evaluation of SISS can also help stakeholders conceptualize aspects of their lives or activities that depend on system services and are hence vulnerable to change.

The SISS framework can help identify and organize the key variables of interest to these two groups, which are concerned with ice morphology, strength, and stability, and the associated monitoring methods (Table 3). We do not consider the entire complexity of the social-ecological environment in which these people make their decisions. For example, our discussion of how Iñupiat Eskimo hunters may view and interpret sea ice overlooks the reality in which these same hunters are often dealing with local efforts to plan for oil and gas development in near and offshore Arctic waters. The policies that currently relate to governance of activities tied to sea ice are beyond the scope of this paper.

Spring Whaling by Alaska Eskimo Communities

Across much of Arctic Alaska's Bering and Chukchi Sea coasts a unique, annually recurring lead system (or flaw zone) exists in the transition region between landfast and pack ice (Norton and Gaylord, 2004). Many Alaska Eskimo communities participate in a traditional hunt from the landfast ice edge as the western Arctic stock of bowhead whales migrates through these leads toward summer feeding grounds in the Beaufort Sea (Braham et al., 1984). The absence of a similar lead pattern along Alaska's Beaufort Sea coast and the deflection of the whale migration in a north-easterly direction after it passes Point Barrow exclude coastal communities east of Barrow from hunting bowhead whales in spring. During the whaling season, hunting camps are placed along open leads in locations where the probability of a whale surfacing is high and where the ice can offer a certain level of safety and support. Whalers are concerned with a wide range of load-bearing capacities of floating sea ice as they place both moving loads (snowmobiles and sleds) and stationary loads (camps, equipment, whales for butchering) on the ice. Furthermore, they are concerned with landfast ice breaking away and detaching from the coast. In recent years and throughout history, there have been many instances of people, equipment, or whales hauled onto the ice either breaking through or floating out to sea on detached ice (George et al., 2004a). In Barrow, Alaska, where the highest concentration of Iñupiat Eskimo whalers resides, trails are constructed through the often rough landfast ice weeks before the bowhead whales arrive. The whale migration past Barrow typically spans mid-April to late May or early June (George et al., 2004b).

Throughout the fall and winter preceding the hunt, Barrow whalers observe the freeze-up and stabilization of the landfast ice, as well as how the landfast ice edge evolves as ice either attaches to the edge or breaks away (see Table 3). The year's ice events play a large role in determining not only the integrity of the landfast ice, but also the weak areas—often only a few tens or hundreds of meters across—that are susceptible to breaking off (Huntington et al., 2001; Norton, 2002; Norton and Gaylord, 2004). Although whaling crews now use satellite imagery to help estimate the width of the shorefast ice and the flaw zone (pack ice bordering the lead at the landfast ice edge), they still select routes for trails and locations for camps by scouting surface conditions from snowmobiles. Their reliance on surface transportation tends to limit whaling crews to an operational radius of 15–20 km from the community of Barrow.

After determining a safe, navigable, and time-effective route to a desirable hunting location, the whaling crews

TABLE 3. Target variables of importance to the construction of whaling trails and ice platforms, and the associated measurement approaches.

Target Variables	Measurement Approaches[1]	Primary Importance	
		Whaling Trails	Industrial Ice Platforms
Wind	Weather stations (local), satellites (regional)	Drives pack and landfast (LF) ice interaction, lead occurrence, and local sea-level changes; onshore winds concentrate ice for LF ice development	
Sea-level fluctuations	In-situ instruments (local)	Destabilize LF ice by initiating fracturing around grounded ice; may unground anchoring ice keels	
Currents	In-situ instruments (local), buoys (point-based)	Drive pack ice interaction with LF ice; ablate ice keels, potentially destabilizing LF ice	
Local water depth	Bathymetric surveys (local and regional)	Determines where ice likely to be grounded	Determines engineering requirements for ice islands
Ice thickness	In-situ gauge (local), moorings (point based)	Load-bearing capacity	Load-bearing capacity; spray ice and flooding requirements
Ice concentration	Coastal radar (local), satellites (regional)	LF ice formation in late fall; solar heating of open water in late spring leads to rapid ablation of the edges of LF ice and ice islands	
Multiyear (MY) ice concentration	Satellites (regional)	Grounding of LF ice; brittle MY ice easier to excavate, can fail catastrophically	Grounding of LF ice; MY ice is a hazard to offshore structures
Pack-ice movement	Radar (local), satellites (regional)	Can collide with and destabilize LF ice	Imparts loads against structures
Landfast (LF) ice extent	In-situ instruments (local), satellites (regional)	Trail length and travel time; water depth at ice edge	Determines proximity of ice platform to highly dynamic transition zone
Onset of freezing and thawing	Weather stations (local), satellites (regional)	First-year and LF ice formation, growth, deterioration and melt	
Air and ice temperature and ice salinity	Weather stations, in-situ probes and core samples (local)	Ice strength; growth and melt rates	Ice strength; growth and melt rates; thermal expansion; spray ice requirements (air < -20˚C)
Surface water temperature	In-situ probe (local), satellites (regional)	Onset of ice formation, bottom melt	
Ice morphology	Surface and aerial surveys (local and regional)	Trafficability; construction effort; camp location	Trafficability; protection from ice sheets impacting structures
Grounded ridges	Surface surveys (local)	Stabilization; trail and camp location	Stabilization
Snow depth	In-situ instruments (local), satellites (regional)	Inhibits ice growth in winter and early spring by insulating the growing ice; slows ice melt in late-spring and summer by reflecting solar radiation; presents hazard over thin ice	

[1] Monitoring implies observations made at a temporal and spatial resolution sufficient to observe the seasonal variability of the variable of interest to the stakeholder (see Fig. 1).

begin to excavate and level the ice, using ice picks, to produce trails wide enough to accommodate two passing snowmobiles (Fig. 4). While some hunters often select flat, interconnected pans of ice for the ease of trail construction, others cut through towering blocks of ridged ice in an effort to ensure trail stability or obtain more direct access to the landfast ice edge. Whalers are also concerned with the trafficability of trails since these serve as escape routes during emergencies. Given the dynamic nature of the environment, hunters must continually adapt when building a trail as ice ridging or break-out events can change the landscape within minutes. Once the trails reach the landfast ice edge, camps are established and on-ice butchering sites are identified in preparation for a successful hunt. Whalers typically harvest bowheads that weigh 10–50 metric tons. To establish a site that will bear such loads during the butchering process, the crews must find landfast ice that is more than a meter thick near its outer edge (Fig. 4; MacDonald, 2002). Finding suitable ice can prove difficult if stable extensions accreting at the landfast ice edge in late winter or spring do not grow sufficiently thick, or if solar heating of water and ice causes thinning and deteriorating of the ice edge late in the season. Once camped at the ice edge, whalers are concerned with a wide range of environmental variables important in defining the strength of the ice and attachment to the coast: winds and currents; fluctuations in sea level; ice thickness;

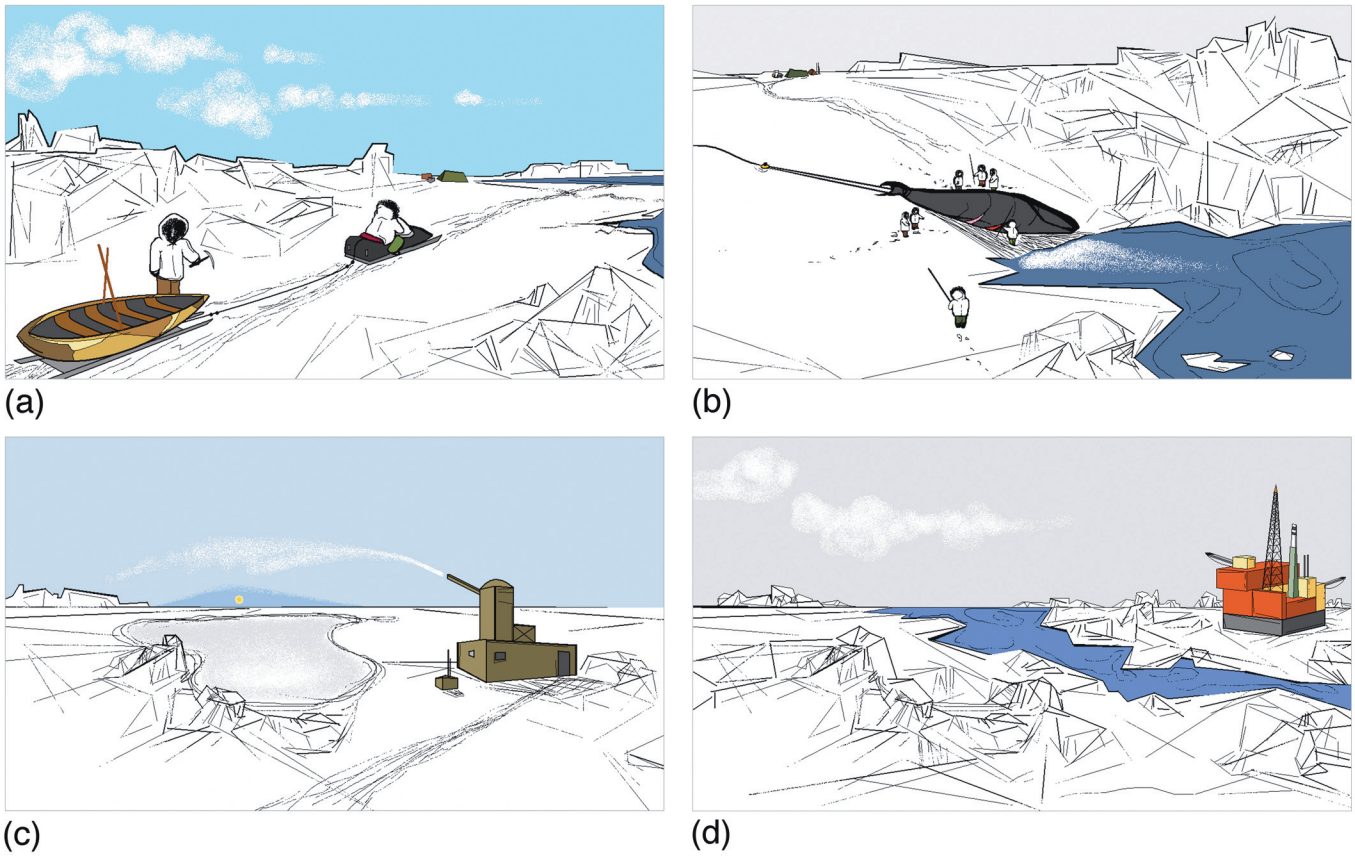

FIG. 4. Images illustrating the use of sea ice for Alaska Eskimo whaling and industrial platforms: (a) whaling trail, (b) whale being pulled onto the ice, (c) spray ice platform construction, and (d) a grounded ice island.

the concentration, proximity, and movement of pack ice and ice floes in the flaw zone; and the presence of multiyear ice and grounded ridges to stabilize the landfast ice. Table 3 expands on how these different variables are important to trail building and whale harvesting on ice.

Industrial Ice Platform Use and Construction

Starting with the Hecla exploration well in the Canadian High Arctic in 1973, oil and natural gas development in Arctic offshore waters has been supported by ice platforms, which include ice islands and over-ice roads. Ice platforms, which are constructed on both grounded and floating ice, are used for seismic surveys, drilling, airstrips, and transportation routes that connect offshore locations either to land or to other offshore locations (Ekelund and Masterson, 1980). The period allotted for ice platform construction is typically between December and early May (C-CORE, 2005, see also Fig. 1). This engineering practice is now regarded as an environmentally nondestructive means to operate in Arctic environments, where conventional practices designed for more temperate regions do not suffice (Potter and Walden, 1981).

During the construction of ice platforms, ice is viewed as a structural material. The feasibility of construction is typically assessed by drilling holes to measure ice thickness. Once level ice of an appropriate foundation thickness is found, the ice is graded and further leveled before being artificially thickened if necessary. Ice roads, which generally require thinner ice than islands, are constructed by flooding the natural ice sheet with seawater. Spray ice construction, which is the process of spraying seawater onto the surface, is usually employed when platforms of greater thickness are needed and grounding is desired (C-CORE, 2005). Since pumping water to the ice surface takes time, equipment, and energy, engineers build roads that are as thin as possible while maintaining a low probability of failure (Potter and Walden, 1981). Floating ice roads are typically constructed to support loads up to 200 metric tons, and islands to support 1300 to 1600 metric tons (Potter and Walden, 1981; C-CORE, 2005).

Ice platform engineers are generally concerned with ice strength, wave dynamic responses during the transport of heavy equipment, and loads that may be applied by the adjacent pack ice (Potter and Walden, 1981; C-CORE, 2005). The mechanical properties of ice are a function not only of thickness, but also of ice type (first-year or multiyear), temperature, salinity, porosity, the presence of cracks or heterogeneities, and the loading rate (Potter and Walden, 1981). Engineers rely on empirical relationships to determine the probability of failure as it relates to the ice's changing conditions of temperature, salinity, and stress history, which

thus become key target variables for observation (Potter and Walden, 1981). A broader review by Kerr (1996) concluded that we are lacking a dependable analytical method for determining the load-bearing capacity of floating ice sheets. Various variables are monitored to assess ice platform performance: thermistor strings measure ice temperature, survey stakes monitor ice movement, slope inclinometers measure island movement, and load panels measure load events at the perimeter. Engineers are also concerned with the sliding resistance of grounded ice islands and the physical distortion that may take place during loading events (C-CORE, 2005). Finally, trafficability of the ice surrounding man-made structures becomes important for evacuation routes (Barker et al., 2006), as it does with Eskimo whaling ice camps.

The SISS Perspective to Improve Monitoring

The decision processes that whalers and industry engineers employ when using sea ice as a platform can guide monitoring of this environment in the context of SISS. Both groups evaluate a similar set of variables before they place heavy loads on sea ice, yet they do so over different scales. For example, a whaler preparing for the hunting season in late March may be interested in how the ice thickness varies within a 15 km radius of landfast ice off Barrow, including sections of thin ice a few tens or hundreds of meters across. He ties this information to the year's preceding ice events (e.g., dynamic or thermal attachment, refreezing of cracks, etc.) to understand the spatial extent of safe and hazardous areas and to make decisions on where to place a trail. A hunter will remain concerned with the ice thickness in this area throughout the hunt until the whaling crews have withdrawn from the ice, typically in late May. Ice platform engineers, on the other hand, are charged with maximizing the amount of operational time during a given year. They are therefore interested in observing ice thickness from the onset of ice freezing throughout their entire operational season, and over a spatial extent where the floating or landfast ice is likely to impart loads on the platform (perhaps up to 100 km). These information needs may help determine the spatial and temporal resolution of satellite coverage for variables (such as those related to ice morphology) that are important to understand along with ice thickness to make informed decisions about ice integrity. The complexity and interconnectedness of the information presented in Table 3 demonstrates that an SISS perspective highlights monitoring needs to address gaps in, for example, satellite coverage. These gaps are apparent in Figure 1c (lower left hand corner in the spatio-temporal diagram), which indicates that satellite data and standard surveys mostly do not occur often enough, or at a sufficient level of detail, to be useful in assessing the evolving state of the ice from an operational and safety perspective. Here, an observing system that is located at the interface of local knowledge and geophysical research and is guided by variables relevant to sea-ice use can be of great value. An example of this approach would be the combination of coastal radar, measurements of sea level and ice/water temperature, and Iñupiaq sea-ice knowledge to assess the stability and safety of the ice cover (Mahoney et al., 2007b; Druckenmiller et al., 2009).

From the climate change perspective it is important to monitor variables that are critical to understanding trends and variability. The variables in Table 3 provide sea-ice users with relevant information during on-ice operations, but can also help establish a record of variability that identifies windows of opportunity on which future decisions can be based (Fig. 1, top). For example, long-term monitoring of landfast ice extent may help delimit the period of stable landfast ice capable of supporting an ice platform. Furthermore, such data sets reveal spatio-temporal patterns that can assist in designing a monitoring system that tracks variability and change with minimal effort.

While the focus has been on use of sea ice in Arctic Alaska, the underlying concepts discussed are broadly applicable. For example, in many Siberian locations, landfast ice is subject to less deformation and thus much smoother than off Alaska (Eicken et al., 2005), enabling the transport of goods and equipment with trucks across the untreated ice surface, or easy access for local communities to under-ice fishing locations. Such uses raise similar concerns with respect to ice stability and trafficability. Comparable issues also arise in the use of sea ice as a runway for air traffic, as often practiced in Antarctica (Barthelemy, 1996).

AN APPROACH TO ACHIEVE BETTER PARITY BETWEEN STAKEHOLDER INTERESTS AND OBSERVATIONS

We have detailed a social-ecological system created by sea ice in the North and proposed that the design of an observation system must take into account the integrated nature of the problems posed to different stakeholders by rapid change. Furthermore, we have examined how a "services"-based model can illuminate key aspects of stakeholder needs. Below we briefly discuss key policy concerns and research directions arising from this work.

Firstly, how does one identify and prioritize the varying data needs identified by stakeholders? Furthermore, these data are sure to be used for conflicting political agendas related to policy production (e.g., the need to minimize impacts of underwater noise and other industrial activities on protected species such as whales versus lease sales to encourage oil and gas development in the Alaskan Arctic seas). Because we focus in this paper on how to design and implement an observing system to provide data that is relevant for day-to-day decisions as well as scientific knowledge production, the political relevance of such a project cannot be sidestepped. Of particular concern are the conflicts and overlaps between the many national and international institutions that set rules to conserve, harvest, or mitigate services related to sea ice in the Arctic. Lack of integrated institutions can prevent effective action to mitigate user

conflict, as well as the efficient use of data for comprehensive problem solving related to sea ice (Chapin et al., 2006; C.L. Meek et al., unpubl. data).

Secondly, as one moves from global remote sensing to local, and thus personal, observation, it must be ensured that the data collected are transmitted across stakeholder interests (e.g., between oil and gas industries and whalers) and among experts and laypersons (e.g., university scientists and the indigenous peoples of Alaska's northern coast). Should such data become exclusive or narrowly targeted, it is possible that different stakeholder concerns relevant to social-ecological system sustainability would be dismissed as "uninformed and peripheral" (Irwin, 1995:62). To avoid such pitfalls, Arctic observing networks must produce contextual forms of knowledge (addressed by our proposal to relate data collection to services) and distribute them widely across scales (A.L. Lovecraft et al., unpubl. data). Success in this distribution requires management structures designed to address the problem where no institutions focused on sea ice exist.

Institutions are "sets of rules, decision-making procedures, and programs that define social practices, assign roles to the participants in these practices, and guide interactions among the occupants of these roles" (Young, 2002:5). They enable humans to interact with the natural world by providing management practices derived from rules based on information about the dynamic feedbacks between human activities and ecosystem response. The creation of suites of rules tied to specific locations or features of the environment must be regularly improved by feedback about the system, from either "Western" science or local knowledge, in order for any manager, whether a community or a state agency, to adapt. The literature on adaptive management demonstrates the complications in this process related to the time it takes for information to reach managers, the time necessary to absorb information and change rules, and the time needed for rule changes to become effective (Lee, 1993; Gunderson et al., 1995). Conflict is likely among resource users of a jointly shared system whose attributes are in flux. In most cases, there will be an older set of rules that can serve as a stopgap measure, but in the case of sea ice, there are several features that make it a particularly challenging policy problem. First, currently no comprehensive set of rules exists, regulatory or otherwise, to guide human use of sea ice. Second, the rapid retreat of sea ice and increasing use of SISS creates an urgent need for information, but without any set of organized actors ready to address the situation. Third, competing interests tied to the ice do not regularly communicate, and in most cases, the opportunities and challenges of both are tightly bound to sea ice, but in opposition (e.g., diminishing ice will increase marine transport but also threaten marine species). In fact, it may make sense for Arctic observing networks to develop parameters that can serve as quantifiable attributes of "conjoined" uses or processes within the sea-ice system. In other words, if competing interests can have variables measured that simultaneously inform both of their sets of needs, such information could lead to conflict mitigation, or at least provide scientific evidence of linkages (e.g., ice stability and its impact on subsistence whaling and industrial activities, Table 3) to better guide policy debates. In practice, this concept might be implemented through the development of a shared, integrated observing system that has broad stakeholder representation (either direct, or through suitable methods such as institutional analysis followed by stakeholder review) from the outset. Such an approach requires effective communication and the willingness to improve existing partnerships and explore new ways to partner between local communities, agencies charged with resource management, industry, and other key stakeholders. The role of academia would be to serve as program architect and coordinator, delivering data and derived information to the community of stakeholders in the role of honest broker.

These contextual facts present a situation where people are seeking an organized way to approach the retreat of sea ice. For example, oil and gas industries strive to anticipate rule changes that regulate their activities to avoid legal actions or other costly results of rule infringement. As a sector, these industries are forward-looking in terms of technology purchase and investment to follow best practices. As oil and gas development expands into previously inaccessible or economically unattractive regions, new rules and regulations, such as embodied in international norms or certifications, need to be established. Involvement of local experts and SISS users with potentially conflicting interests in the formulation and review of such norms regulating best practices can help minimize conflict and unforeseen and potentially hazardous events. Along the same lines, nations and governments are guarantors of stability for their citizens and business interests and as such need information for the government agencies that serve a variety of public and private interests. Finally, people living where the changes take place clearly need to be able to plan for their seasonal activities as well as the future. Such a context informs our proposal of a Jeffersonian approach to Arctic environmental research because it has been demonstrated that the traditional divide between "experts" and "laypersons," particularly in the arena of environmental policy, can reduce scientific accuracy, overlook key linkages between problems previously thought of as unconnected, impair sustainability at the local and regional level, and diminish the political will to address problems (Weeks, 1995; Fischer, 2002).

CONCLUSIONS AND OUTLOOK

The framework of sea-ice system services can help identify critical information needs and provide a context for adaptation and response to climate and socio-economic change. Four principal categories of services and uses of the sea-ice environment have emerged (Table 1): (1) climate regulator, marine hazard, and coastal agent or buffer, (2) provisioning for transportation and other uses as a coastal platform, (3) cultural services obtained from the "icescape"

and (4) support and structuring element for food webs and biological diversity. SISS expose different perspectives on the multiple, often competing uses of the resource:

Parallel uses of sea ice as a platform: Subsistence and industrial activities have similar information needs, although often at different scales, and reveal great potential for synergy, in particular at the interface between scientific/technical and local knowledge (explored in papers by Laidler, 2006, and Druckenmiller et al., 2009).

Competing uses of sea ice: Reductions in sea ice may result in potential conflicts between different groups, as in the case of marine mammals concentrated into small areas that are also used by industry.

Opposite uses of sea ice: While ice even at low concentrations is seen as a hazard for large-scale shipping, it serves as an important resource for indigenous hunters and boaters (e.g., as a place for butchering marine mammals or as protection from ocean waves) and acts to effectively dampen waves and reduce erosion of coastlines.

Significant benefit can be derived from mapping these different services and thus revealing the relevant scales and locales of multiple uses (windows of opportunity indicated in Fig. 1) to aid with responsible and sustainable planning. SISS can then guide the design and implementation of an observing network that extends across the relevant scales and integrates the most important information needs. To achieve these goals, further work required includes the following.

1) An institutional analysis that identifies and parses stakeholder information needs is required to help prioritize the types and locations of observations in an emerging pan-Arctic network.
2) Implementation of an integrated observing network that focuses on key services and associated information needs likely will require a combination of bottom-up and top-down approaches. The former are often driven by local and indigenous expertise and stakeholder information needs and require a structured dialogue between the scientific community and different sea-ice user groups. Lessons learned from implementing regional ocean observing systems at lower latitudes can be of some help (Weisberg et al., 2000), but ultimately a northern perspective is required (Krupnik and Jolly, 2002), which may also prove to be of value for problems outside of the Arctic. For top-down approaches towards integration, close examination of successful national and international programs, such as the International Arctic Ocean Buoy Program or the network of weather stations organized by national services and the World Meteorological Organization, may hold promise, particularly if momentum built up during the IPY can be channeled into viable legacy efforts. At the same time, technological advances in satellite remote sensing and ground-based or airborne observations will help close some of the gaps that have been identified in this study and can help strengthen connections between academia and agencies tasked with Arctic observations. However, if use of SISS continues its projected increase while ice thickness and extent maintain their decreasing trend, competing or conflicting uses likely will require a broad-based consortium approach, with academia or an appropriate agency in the role of coordinator and honest broker of data and information.
3) In order to be of value in the context of adaptation to climate and socio-economic change, the insights gained from the process outlined above will have to be anchored in policy and management frameworks that are based on sound two-way communication between experts and stakeholders. Given the substantial overlap of observing and forecasting interests between different stakeholders, and considering successful examples of partnering between different organizations and programs in the Arctic, researchers have a significant role to play in proposing approaches to cope with and successfully address such major transformations.

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