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Environmental security in Arctic ice-covered seas: From strategy to tactics of hazard identification and emergency response

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Abstract. Environmental change and increasing industrial activity in the maritime Arctic require strategies to adapt to change and ensure safe operations. This problem has been defined at the broader strategic level. We evaluate key aspects of environmental security in ice-covered waters, focusing on tactical and operational information needs, which have received less attention. Monitoring of environmental hazards and effective emergency response in sea-ice environments require high-resolution data of ice hazard distributions (e.g., multiyear ice, landfast ice break-out and ice push events), ice movement and deformation as well as ice characteristics and dynamics relevant to emergency response. We have developed a prototype coastal observing system at Barrow, Alaska that addresses such information needs. Imagery obtained from a marine X-band radar with a digital controller is combined with data from on-ice sensors (ice thickness, ice and water temperature, sea level) and assessments of potentially hazardous ice conditions by local experts. Digital imagery and data are processed and disseminated in near-real time. Using a combination of image processing approaches (optical flow, Lucas-Kanade tracker), ice velocity fields, floe trajectories and boundaries of stationary ice are derived automatically. Early onset of hazardous events is detected through Hidden Markov Modeling, providing potential decision-support in operational settings. We evaluate the utility of the system and strategies towards integration with broader emergency response efforts.

Introduction: Arctic Environmental Security

The Arctic Ocean region is in the midst of a transformation that comprises major environmental and socio-economic change. Summer minimum sea-ice extent has been subject to an average reduction of more than 10% per decade since 1979, with a record low in 2007 close to 25% below the previous record minimum (NSIDC, 2010). This reduction in ice extent is faster than projected by most climate models (Stroeve et al., 2007). Recent modeling studies suggest a near-complete loss of summer sea ice in the Arctic by the late 2030s (e.g., Wang and Overland, 2009). At the same time, offshore oil and gas development and marine traffic have grown substantially over the past decade and are projected to increase further, including in the North American Arctic (Arctic Council, 2009; Brigham, 2010). These events have triggered a broader discussion of response to, and mitigation of, environmental threats to ecosystems, coastal communities and coastal infrastructure in a rapidly changing Arctic. Here, we are concerned with

Arctic maritime environmental security. While the concept of environmental security is broadly used and often ill-defined (Belluck et al., 2007), we have refined Belluck and co-authors' definition and address two key aspects of environmental security: (1) security of the environment itself, i.e., prevention of harm as a consequence of climate change and other human activities with potential negative impacts from the geopolitical down to the community-scale, and (2) security from environmental change, such as, in this case, changes in the ice cover and weather patterns that could threaten the well-being of communities or individuals and associated infrastructure. Note that the first aspect would address the need to maintain safe operations in the Arctic that are capable of dealing with natural hazards as relevant to marine operations (e.g., shipping or resource development) thereby avoiding incidents (e.g., oil spills) that could cause long-lasting environmental harm. The second aspect would specifically address threats to infrastructure associated with such activities as a consequence of environmental change (e.g., a more dynamic ice regime or the combined action of ice and waves on structures in a seasonally ice-free Arctic).

At this point, environmental security in the Arctic Ocean region has mostly been discussed from an overarching, strategic perspective that considers the impacts of changes in the sea-ice cover over large scales in space and time, and discusses potential threats and hazards in terms of broad categories such as resource development or shipping at the pan-Arctic scale. Consequently, scientific discourse on Arctic environmental security has focused on identification of broader governance challenges rather than specific case studies at the local scale (e.g., Berkman and Young, 2009; see also the summary of a NATO Environmental Security in the Arctic Ocean Workshop, held in October 2010, available at http://www.spri.cam.ac.uk/research/aog/events/ [retrieved on 6 January 2011]). Even the Arctic Marine Shipping Assessment (AMSA), the most thorough and comprehensive examination to date of Arctic environmental security issues as related to shipping (Arctic Council, 2009), explores mostly socio-economic and geopolitical factors in constraining Arctic shipping; sea-ice conditions are mostly discussed at the pan-Arctic level as furnished by climate model simulations that were part of the 2004 Arctic Climate Impact Assessment (see also Eicken and Lovecraft, in press). To be sure, such an approach is necessary to frame the overall problem. However, with oil and gas development imminent or underway in several sectors of the Arctic and discussions within the International Maritime Organization (IMO) of a potentially mandatory polar code for maritime vessel traffic in the Arctic (Jensen, 2007), there is a clear and urgent need for an examination of environmental security at the tactical and operational level. Here, tactical refers to the shorter time and smaller spatial scales that are part of the identification and mitigation of environmental hazards such as the threat of ice to structures as well as the response to emergencies or disasters such as an oil spill (Figure 1).

The goal of this paper is to take a bottom-up, tactics-driven approach to Arctic maritime environmental security, commencing with a review of key environmental hazards and associated risks that draws on our research, recent workshops and the published literature. This effort yields insight into the relevant environmental variables that need to be tracked in an operational context. We will then assess current data and information sources that can provide this information and introduce an integrated hazard observing and tracking system. Here integration refers to the melding and synthesis of data streams from different sensor systems as well as input from local and indigenous knowledge (Druckenmiller et al., 2009). Finally, we will briefly present first data from such a system and discuss how such information can contribute to improved, robust hazard tracking and emergency response in ice-covered waters (FEMA, 2008). The study focuses on ice-related hazards, since oceanic and atmospheric hazards are typically well addressed in the context of existing frameworks and approaches developed for lower latitudes (see, e.g., Linkov et al., 2007, or Statscewich et al., this volume).

Arctic Environmental Security: Threats and Risks at the Tactical and Operational Level

Security *of* the environment (definition #1 in the section above) is mostly related to the threat sea ice poses as a navigational hazard and in its potentially destructive impact on coastal and offshore structures. Increases in vessel traffic, ranging from tourist vessels to destinational traffic associated with Arctic resource development (Arctic Council, 2009; Brigham, 2010), and expanded resource development have increased the potential for ice encounters and associated damage in recent years. At the same time, the operational ice environment has gotten milder, with thinner ice, less multiyear ice (which, due to its disproportionately greater strength, is considered a much greater hazard than first-year ice) and a longer open water season. In the U.S. and Canadian Arctic, the prevailing surface circulation transports some of the thickest and strongest sea ice anywhere in the Arctic from north of the Canadian Archipelago down into the Beaufort and Chukchi Seas (Figure 2). Even with greatly diminished summer ice in the Chukchi and western and central Beaufort Sea, this circulation pattern in combination with increased mobility of the ice pack continues to pose a significant hazard to operations throughout much of the summer and fall. A seemingly paradoxical outcome of these trends is that in 2008, three oil exploration support vessels bound for Canada were briefly trapped in ice off Barrow, Alaska, during a summer of record low ice extent in the Chukchi and Beaufort sector of the Arctic. As shown in Figure 2, this problem is exacerbated by substantial interannual variability in ice distribution over the oil and gas lease areas during the first part of the navigation season.

In assessing security *from* environmental change (definition #2 in the section above), we need to consider negative impacts of the changing Arctic sea ice cover, with pronounced thinning, reductions in summer ice extent and a prolonged ice-free season, in particular in the fall (Stroeve et al., 2007; Mahoney et al., 2007; Comiso, 2010). These changes alter and may diminish the benefits that Arctic coastal communities and other ice users derive from sea ice, e.g., through its use as a stable platform for hunting, travel and industrial operations (Eicken et al., 2009). Delayed onset of fall freeze-up increases the window for open-water operations but exposes coasts and infrastructure to the threat of major storms that were mitigated by the ice in the past. Of particular concern to coastal communities and industry is the reduced stability of sea ice, which threatens over-ice travel and on-ice operations (Eicken et al., 2009). Due to the prevalence of sea ice-associated flora and fauna in the Arctic, marine ecosystems are also affected in major ways, ranging from potential threats to ice seals and walrus to shifts in important fisheries species (Grebmeier et al., 2006).

A review of key documents and workshop recommendations provides insight into threats to environmental security in ice-covered seas, including key risks and hazards associated with the presence or absence of ice. At the strategic level, long-term environmental and sea-ice change have increased the vulnerability of coastal communities as a result of increased exposure to fall storms in open-water conditions or negative impacts of ice reduction on food security, such as availability of ice-dependent mammals (Krupnik et al., 2010). At the same time, globalization and resource exploitation trends have increased the level of maritime activities in the Arctic that carry ice-associated risks of harm to people or the environment (Arctic Council, 2009; Brigham, 2010). At the operational and tactical scale, there is consensus among a broad range of stakeholders on the environmental factors playing into hazard identification and emergency response and the associated information needs. Table 1 summarizes relevant information extracted from findings and recommendations of the Arctic Marine Shipping Assessment (Arctic Council, 2009), a workshop organized with broad stakeholder participation to address information needs for assessing and mitigating risks associated with offshore oil and gas exploration in Arctic Alaska (Eicken et al., in press), a United States Coast Guard (USCG)-sponsored workshop on developing scenarios for maritime disasters in the Arctic (CRRC, 2009), a report on oil-spill response sponsored by the U.S. Arctic Research Commission (Dickins, 2004), and other research findings.

In addition to outlining the types of ice variables that need to be monitored in given settings in the context of operational and tactical environmental security, Table 1 also provides further insight into the operationally and tactically relevant scales, which mostly extend from below the kilometer-scale to typically a few tens of kilometers. This is driven by the fact that ice velocities in the Arctic typically range on the order of 10 km day^{-1} (Rigor et al., 2002), with values in the coastal Beaufort Sea typically somewhat lower (Cornett and Kowalchuk, 1985; note however, that reduced ice concentrations in recent years may have resulted in substantial increases in ice velocity) and the highest values reported for the Alaska Arctic ranging at 3.5 km hr^{-1} observed over more than half a day in the coastal eastern Chukchi Sea (Norton and Gaylord, 2004). Considering uncertainty in the trajectory of individual ice floes, hazards typically can be recognized as such on time scales of hours to at most one day. Taking into consideration prevailing patterns in ice motion, one can identify a hazard awareness zone that needs to be monitored around a given structure or stationary vessel as indicated in Figure 2. Key ice features of relevance from an environmental hazard perspective, such as ice fields detached from the marginal ice zone or open water features in sea ice, occur on comparable scales (Eicken et al., 2009). For vessels traveling in Arctic waters, the region of potential concern becomes larger because of the distances covered over the course of a day. In the case of persistent impacts, such as an oil spill, it is the seasonal cumulative trajectory of ice that determines the radius of influence. The time and spatial scales associated with the key hazards outlined here (see also Figure 1) correspond to those identified by the North Slope coastal oil spill tactics manual and the contingency plans it relates to (Alaska Clean Seas, 2007).

Tracking Ice Parameters Relevant to Environmental Security

Identification and monitoring of ice-associated hazards for tactical purposes requires an observing system that is capable of tracking the key sea-ice variables identified in Table 1 at the spatial and temporal scales relevant in an operational setting (Figure 1), and disseminating this information in a timely fashion. Such data can be obtained through satellite remote sensing, airborne, underwater or ground-based remote sensing and observation systems, drifting sensors, direct measurements or local knowledge from expert observers.

Satellite remote sensing provides the most comprehensive spatial coverage. Ice concentration fields and information about ice type (young ice, first-year and multiyear ice) are derived routinely at 25 km grid cell size for the entire Alaska Arctic coastline shown in Figure 2. Such data can be downlinked several times per day from the passive microwave radiometers in polar orbit as part of the Defense Meteorological Satellite Program (DMSP) (Massom, 2009; Comiso, 2010). The Advanced Microwave Scanning Radiometer (AMSR-E) can provide similar data (though at lower acquisition rates) at 12.5 km grid cell size. Processing at ground stations in the U.S. can yield such data within minutes to tens of minutes after acquisition, and information from these satellites is integrated into weekly or higher-frequency ice charts produced by the North American Ice Service (NAIS). NAIS also relies on radar and visible-range satellite data to produce charts during the navigation season. However, for rapid-response applications daily availability and delays associated with delivering ice-chart information limit the tactical use of such charts. Passive-microwave data is widely used in a strategic context, e.g., to analyze the probability of encountering ice at a given location based on data obtained over the past three decades. However, the spatial resolution of the data is generally too coarse to be of use in operational settings and may indicate a complete absence of ice in sparse conditions when isolated floes can still present a hazard. Moreover, after the onset of surface melt, altered microwave signatures greatly increase the error in ice concentration estimates, in particular in settings of relevance to shipping or offshore operations (Massom, 2009). Additionally, identification of hazardous multiyear ice types is challenging and often unreliable during the summer season and data quality of cells along the coastline can be degraded (Massom, 2009). Finally, daily or twice daily repeat rates of standard products are only marginally effective in operational settings where ice, in particular in open water conditions, can cover several kilometers to tens of kilometers of distances during this time frame.

Visible and infra-red range satellite imagery such as the Advanced Very High Resolution Radiometer (AVHRR) or the Moderate Resolution Imaging Spectrometer (MODIS) have much higher resolution (typical grid cell sizes of ca. 1 and 0.25 km, respectively) and generally higher repeat coverage. For example, at a location near the center of a larger tract of active offshore oil and gas leases in the Chukchi Sea (71˚N 164˚W, Figure 2) which is the target of substantial exploration with associated vessel and drill-ship activities, on the order of 25 AVHRR and 15 MODIS scenes are available every day from a receiving station such as that of the Geographic Information Network of Alaska (GINA, www.gina.alaska.edu). However, such imagery does not allow identification of hazardous ice types such as multiyear or heavily ridged ice. Moreover, and more problematically, mean cloudiness in Arctic regions ranges around 80% from May through October, typically in the form of continuous stratus cloud cover (Beesley and Moritz, 1999), limiting the reliance on such imagery for operational purposes.

Synthetic aperture radar (SAR) satellite data provide substantial advantages in this context because of the ability of SAR to operate independent of weather and light conditions. Also, SAR sensors can provide high-resolution images, typically with a 100 m grid cell size and an effective resolution somewhat lower due to SAR speckle (Massom, 2009). SAR is also of great use in distinguishing between different ice types and identifying potentially hazardous ice, making it the sensor of choice for many studies concerned with ensuring safety of operations in Arctic regions (Massom, 2009; Ochilov and Clausi, 2010). However, depending on the sensor's wavelength, ice type discrimination during summer can be severely curtailed due to masking of signatures by surface melt. Also, in sparse ice conditions, radar scatter from surface waves can mask the presence of isolated ice floes. Nevertheless, the ability to identify individual floes in moderate concentrations makes SAR imagery suitable not just for ice detection but also the tracking of floes (Table 1). Outside of the melt season, the dependence of the radar backscatter signal on surface roughness also provides valuable information on ice morphology that is key for many operational applications (Table 1). Hence, it is of value to consider the repeat rate of SAR imagery in locations such as the center of the Chukchi lease area in Figure 2. A detailed analysis of available SAR data from the four operational instruments (the Canadian Radarsat-1, the European Remote Sensing Satellite 2 [ERS-2] and Envisat Advanced SAR [ASAR] and the Japanese Phased Array type L-band SAR [PALSAR]) that account for the vast bulk of current data acquisitions, conducted through an exhaustive search of all available imagery between February 1 and April 30, 2008 is summarized in Figure 3. Thus, separation of SAR scenes in time averages at 0.9 ± 0.7 days for all considered data. With two exceptions, values range between 0.1 and 3 days separation on any given day. Thus, sampling rates – assuming that all data are available within a few hours after acquisition at most, which may be unrealistic for some of the systems – are such that they cover the upper range of operationally relevant time scales. However, if only data from the main commercial provider for the North American Arctic, Radarsat-1 and 2, are considered then repeat rates shift to about 1 to 3 per day. Note that, for all the calculations above and Figure 3, only satellites that implement a global acquisition strategy and whose data are generally available were considered. Other satellite systems such as TerraSAR-X, TanDEM-X (both Germany), and Cosmo-SkyMed (Italy) were not included because they either focus on on-demand data acquisition, or their data is not easily accessible in near-time.

Airborne systems, including unmanned aerial vehicles (UAVs), are highly capable, in particular with respect to ice and ice type detection. UAVs hold significant promise for future developments that may allow better ice type discrimination and ice tracking. At the present time, airborne systems provide the method of choice to scale down satellite observations to the operational level (Figure 2). However, they are limited in their ability to provide near-continuous coverage at high sampling rates and can be severely constrained by visibility and weather conditions. Compared to satellite observations, they also represent a comparably high-cost solution.

Autonomous underwater vehicles, while of great value in obtaining relevant information about the state and dynamics of the upper ocean and ice thickness distributions, are currently mostly of interest as a way to complement other information sources, but are not (yet) capable of delivering the coverage in space and time required for operational tracking of currents and ice movement.

The same can be said of drifting sensors, which are routinely used to track individual floes in operational settings and can provide information on the trajectory of potentially contaminated ice away from a spill site (Tiffin et al., 2010). However, unless deployed in great numbers, including upstream of the site of interest, drifters are mostly of value in complementing other types of data acquired over a broader local or regional swath. If combined with larger scale sensors, modern drifting sensors have significant potential, as they include sophisticated sensor systems that can provide critical ancillary information on the state of the sea ice and the upper ocean (Proshutinsky et al., 2005).

Surface-based radar systems, both ocean radar (see Statscewich et al., this volume) and ice radar, can provide information on a number of variables relevant in an environmental security context at the spatial and temporal resolution necessary for tactics and operations (Table 1, Figure 1). While the utility and application of radar in maritime settings for ice detection has long been established (e.g., Lewis et al., 1987), recent progress in digital processing of radar imagery (Higgins, 2010; Rohith et al., submitted) now also allows for derivation of ice velocity and other crucial information. High-performance radar can cover an area of hundreds of square kilometers or more at hundreds of meters resolution and sampling rates well below one per minute. Moreover, the compactness of marine radar systems renders them easily deployable in emergency situations, including as part of ocean radar systems such as that described by Statscewich et al. (this volume). The ubiquity of standard marine radars on vessels also opens up the possibility of networked radar systems (Kotovirta et al., 2010). Below, we introduce an ice radar system consisting of commercial-of-the-shelf (COTS) components and software developed specifically to provide ice information of tactical and operational relevance.

Finally, local and indigenous knowledge can be of great value in providing critical information and guidance in the context of hazard assessment and emergency response. The significant contribution by local knowledge-holders has been established in a variety of settings, although formal integration into the response process in Arctic settings is still in its infancy (see more detailed evaluation by Eicken et al., in press). However, as discussed by Druckenmiller et al. (2009), in settings where there is significant use of the environment by local hunters or other knowledge-holders, local knowledge can be more effective in anticipating or predicting hazardous events than geophysical models if the latter lack necessary detail in representing the local environment and key processes. We will further discuss effective integration of local expertise into hazard assessments and emergency response below.

A Tactics-Oriented Radar-Based Observatory to Track Ice-Associated Hazards and Guide Emergency Response

We have developed a coastal ice observatory centered on a weather-independent ice imaging and tracking system built out of COTS components that acquires imagery at spatial resolutions and sampling frequencies sufficient to close the gap discussed above (see also Figure 1) and satisfy the data and information needs in a tactical or operational setting. The coastal observatory also includes ice-based sensors to further identify and discriminate between environmental hazards. Through community partnerships and outreach efforts we are working to create a two-way exchange with local environmental knowledge (Druckenmiller et al., 2009). In general, local and time-specific "on the ground" assessments of ice conditions and the resulting implications to specific activities (e.g., snowmobile trafficability, route-finding, load hauling, etc.) provide valuable information on both the meaning and usefulness of more remotely acquired data streams. While the overall system is designed to be deployable from a wide variety of platforms, with eventual integration into mobile units independent of shore power described by Statscewich et al. (this volume), a prototype has been established in the community of Barrow in northern Alaska (Figure 4). The goal of the Barrow-based system is to address information needs of the community as well as those typical of other settings, in particular in the vicinity of critical infrastructure or commercial operations. As outlined above and detailed in CRRC (2009), Arctic Council (2009) and Eicken et al. (2009, in press), key ice-associated risks or hazards that need to be identified and tracked in this context include: (1) Stability, extent and morphology of landfast ice in the context of across-ice transportation and placement of temporary infrastructure; (2) dangerous ice events, in particular landfast ice break-outs, ice push and beach ride-up events, ice gouging and high-velocity impacts of ice on structures; (3) tracking of hazardous ice (multiyear ice floes, massive ridges etc.) and vessels; (4) ice deformation; and (5) ice floe or ice feature tracking (dispersal of oil or other contaminants, tracking of personnel in search-and-rescue situations).

As outlined in Figure 4, identification, mapping and tracking of these key hazards relies primarily on a marine radar, with imagery processed to obtain quantitative information on ice properties and movement as well as derived information products that are of potential use in decision support. Criteria employed in selection of the marine radar unit include range, resolution and target detection, as well as atmospheric attenuation and the size of the array (Table 2). Moreover, in order to deploy the system effectively in the context of emergency response, size and interoperability with USCG assets are key considerations. Based on these constraints, we have opted for an X-band (3 cm) system, currently a Furuno FR7112, to be replaced by a more powerful FAR2127 based on a system design study (Table 2). Mounted 22.5 m above sea-level, the radar routinely detects ice within a radius of 10 to 15 km. Large ice features or vessels are detectable at significantly longer ranges. Control of the radar and acquisition of digital imagery are achieved through a Xenex XN2000S radar controller/digitizer, providing 1024x1024 images at nominally 6-bit dynamic range. This set-up allows programming of the radar and data transfer through the local internet service provider. Bandwidth constraints at Barrow limit routine image acquisition and for operational purposes one scene is digitized, compressed and transferred to the processing site at the University of Alaska Fairbanks (UAF) every 4 minutes. Images are range-corrected, rectified and combined with a landmask and time stamp and posted online typically within less than an hour after acquisition. Acquisition and processing rates as high as 1 scene per minute are sustainable if bandwidth for data transfer were not a limitation. For the upgraded new system (Table 2), a Russell Technologies RTI XIR3000C Radar Processor will be purchased jointly with the FAR2127.

A key factor in operating radars in seasonally ice-covered waters is to minimize icing of the open array. We have found that coating the array with car wax and using battery pad heaters can reduce but not eliminate icing problems. During fall freeze-up in particular, icing can be a severe problem. Depending on the site (we also operate a similar radar system in Wales, Alaska at the western-most tip of the Seward Peninsula in Bering Strait), we have found that increased drag on iced arrays increases wear on the gears and results in damaged gearboxes typically within 2 to 3 years of continuous operation. A potential remedy to these problems is to work with a radar system that includes a factory-installed high-performance de-icing kit. Such kits are available for some commercial radar systems and are part of the upgrade to a FAR2127 for our Barrow site.

Radar imagery and animations of ice movement generated for the past 72 hours disseminated through the observatory website are of interest to the community of Barrow to assess ice development over the course of the winter, identify potential hazards and use as an additional tool in planning activities on the ice. Ideally, decision support in the context of the hazards identified above requires automated extraction of quantitative measures of ice movement and morphology as well as derived parameters indicative of hazardous conditions. To achieve this goal, our team has developed a series of algorithms to identify movement of individual ice features, derive tracks of such features, calculate velocity fields and identify conditions that may be possibly hazardous. The details of these approaches are described elsewhere (Rohith et al., submitted); here we briefly review the overall approach and show examples of key products.

The challenge in extracting information about ice motion from marine radar imagery is that ice features are rarely persistent in the imagery over the time scales associated with drift through the radar footprint, because the orientation and signature of ice reflectors (typically associated with rough or deformed ice) relative to the radar changes as a result of lateral and vertical displacement of ice. Moreover, sea ice consists of a mixture of smooth and rough ice such that large areas of the image may contain very few or no reflectors or trackable features. To address this challenge, we have combined an approach capable of tracking individual features (Lucas-Kanade tracker, Lucas and Kanade, 1981; see Figure 4 for an example showing the number of tracked points in the radar image analysis panel) with an analysis of dense optical flow (employing normalized cross-correlation approaches) to arrive at an interpolated optical flow field. An example of tracked features is shown in Figure 5, with the blue lines illustrating trajectories of typical shore-parallel ice motion.

The red tracks in Figure 5 are an example of an operational sea ice-related hazard that can only be detected by a continuously operating system such as the coastal radar. These represent the trajectories of targets that exhibited non-linear (e.g., start-stop) motion in time that contrast with the trajectories of surrounding targets. In this case, the red tracks are those of ice floes that abruptly came to rest, most likely as a result of interaction with the seafloor (i.e., seafloor gouging). Such events represent a significant hazard to buried cables or pipelines. While gouge distributions and densities can be obtained from submarine sonar data, analysis of radar imagery provides insights into the types of gouging events and driving processes. Although we have not yet processed enough data for validation, we hypothesize that the same approach can also identify potentially hazardous multiyear ice floes or deep-draft ridges that exhibit differential motion and different acceleration/deceleration relative to the thinner first-year ice pack.

As outlined in detail by Rohith et al. (submitted), velocity fields obtained from optical flow analysis can then be combined with deformable shape approaches to identify contours that delineate the boundaries of stationary, stable and moving ice. In the setting at Barrow, these contours have been shown to coincide, to within tens to a few hundreds of meters, with the landfast ice edge based on manual delineation and analysis of satellite data (Rohith et al., submitted). Since coastal villages typically have tens to hundreds of people out on the ice, mostly along the landfast ice edge where the hunt concentrates in spring, such automated mapping and tracking of the landfast ice edge boundary is of great value from a marine safety perspective (Druckenmiller et al., 2009). Even more useful than the delineation of stable ice is the identification of potential precursor events prior to a landfast ice break-out or ice push event. Past research (e.g., Mahoney et al., 2007) suggests that radar backscatter signals exhibit anomalous variations in time ("flickering") due to ungrounding of ice prior to a break-out. Here, we implemented a Hidden Markov Model approach (Rohith et al., submitted) to automatically identify and tag such potential precursor events (Figure 6). The stochastic model describes ice velocity and backscatter variations in a multi-dimensional phase space which includes measures of local velocity field and divergence. The predictive model is built on the statistics of past observations and outcomes. Using the information from training data of observed hazardous ice events, the system is then capable of identifying anomalous events as they unfold. Success of the algorithm in identifying hazardous events depends on the length of the existing data record. Though we trained the system on a limited data set available to date, it was nevertheless able to identify 5 out of 7 positive test cases correctly (see example in Figure 6) and did not identify any false positives.

As outlined in Figure 4, the information obtained from the coastal radar is central to the ice hazards monitoring system. However, the observatory taps into an important stream of ancillary data, provided by an automated on-ice sensor system. Similar to other drifting sensor packages (e.g., as described by Proshutinsky et al., 2005), this site is installed in the early winter in landfast ice in the Barrow region and tracks the evolution of ice thickness and snow depth, ice and under-ice water temperature and sea-level variations (Druckenmiller et al., 2009). The site is powered by a combination of wind turbine and gel-pack batteries with near real-time data transmission to the processing site via wireless data transfer. Data are typically posted online within 1 hr of acquisition. Local knowledge from indigenous, Iñupiat ice experts and analysis of data available to date (Mahoney et al., 2007; Druckenmiller et al., 2009) indicates hazardous ice events such as break-outs or ice push events are typically associated with a sequence of increases/drops in sea level that unground stabilizing ice ridges and then flush ice out from shore. Hence, detection of such variations in sea-level (or warm water pulses capable of melting back ridge keels) can further qualify or augment information on imminent break-out events from the radar. Local ice experts take such information into account as they assess ice-related hazards and risks. However, at this time we do not have sufficient data to integrate these two data streams into fully automated decision-support system, which is the goal of planned further work.

Finally, recognizing the substantial breadth and depth of local and indigenous knowledge, such as by hunters in coastal Alaska communities (Druckenmiller et al., 2009; Krupnik et al., 2010), that can provide important framing information as well as expertise in assessing and predicting ice hazards, we have worked towards building a two-way exchange between geophysical and Iñupiaq ice knowledge. Local ice experts possess an understanding of environmental patterns and variability such that they are often able to readily discuss the likelihood, duration, and representativeness of specific observations of ice conditions or features from remotely sensed products. The challenge, and one area where our two-way exchange is arguably making progress, is in finding ways to communicate across barriers of technological understanding and scale such that we are confident that collectively we are discussing the same thing (e.g., ensuring that potential ice hazards identified in satellite imagery are the same as those identified by individuals on or near the ice). As illustrated in Figure 4, local ice experts have guided the design of key components of the observing system (placement of sensors, types of measurements made, effective dissemination of information) and are using data from the system to augment their own, comprehensive understanding of environmental conditions. At the same time, recognized success in identifying and predicting ice hazards by local/indigenous experts can significantly enhance the value of an ice hazards tracking system to a broader range of users. In many cases, the technological familiarity of the Barrow hunting community may be representative of those that may be recruited to assist with large-scale emergency response efforts in remote Arctic environments. An as-of-yet unresolved challenge lies in creating a framework for reliable and sustainable interfacing of geophysical and local knowledge—one that provides mutual benefit and allows us to work toward locally valued and understood solutions and tools for promoting environmental security. At Barrow, Druckenmiller et al. (2010) have had some success in collecting data directly relevant to ice use by the local community and generating updated maps of ice conditions and ice use (in this case mostly ice trails for transportation) that can be widely shared and act as nucleus of exchange.

Conclusions and Outlook

An analysis of key aspects of environmental security in ice-covered marine environments indicates a wealth of resources ranging from satellite reconnaissance to ground-based observations that can inform strategy, tactics and operations. At the same time, a number of challenges emerge. First, there is a clear need for further work on sensing systems at high spatial and temporal resolution required for effective operations in ice-covered waters. The integrated radar system presented here can help address this need but is not yet mature enough to provide information and decision support that can be integrated into operational drift forecasts, such as is currently the case with ocean radars that are part of U.S. coastal ocean observing systems (see Statscewich et al., this volume). The data processing and system integration approaches outlined in our work may help with progress along that path.

Second, as illustrated in Figures 1 and 2, there is great potential for seamless coverage of a given region with different sensor systems; however, more thought has to be given to integration of such systems. Considering the broad range of ice characteristics and associated challenges for different ice detection and tracking methods, it is less likely that a single sensor or platform type (such as the ocean radar systems for tracking of surface currents) will satisfy the tactical and operational information needs in ice-covered waters.

Third, even the most advanced observing sensor or system requires integration into a hazard assessment and emergency response tactics and operations structure in order to be effective. While key ice-associated hazards and risks have been discussed above, translating such risks into operational procedures and response frameworks may require further work, in particular in applying approaches developed for low latitudes or onshore Arctic environments (e.g., FEMA, 2008; Alaska Clean Seas, 2007). While the prototype radar system described here has a very limited range and footprint, COTS system upgrades can expand this to a range of a few tens of kilometers or more. Ultimately, the goal is to provide an observing system that is compact and robust enough to be deployed in a range of Arctic settings, can be integrated with an autonomous power ocean radar described by Statscewich et al. (this volume), and has system and software specifications that allow operation by USCG and other field personnel in the framework of an incident response structure. In particular in coastal locations, integration with local and indigenous expertise and ancillary on-ice sensor systems is likely to increase system efficacy substantially.

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Table 1: Ice-associated threats to Arctic maritime activities

Activity or asset	Hazard or threat	Relevant variable	Setting/scale
Shipping	Ice contact & damage	Ice concentration, ice type	Marginal ice zone, 10s-100s km
Use of ice as platform	Ice break-out or breaking through of personnel & equipment	Landfast ice stability/anchoring strength, thickness, morphology	Landfast ice, <1-10s km
Coastal & offshore infrastructure	Loading, impact & damage by drifting ice, ice push & gouging	Ice velocity, floe size, thickness, ice type/strength	Coastal & offshore drift ice, <1-10s km
Emergency/spill response	Oil spill or vessel sinking in ice, dispersal of contaminants by ice	Ice velocity, trajectory of contaminated ice, morphology	Landfast & drift ice, <1-100s km

Table 2: Key characteristics of COTS marine radar systems

Variable	X-band A[1]	X-band B[2]	S-band[3]
Power	25 kW	10 kW	30 kW
Array size	2.4 m	1.7 m	3.7 m
Atmospheric attenuation	Medium	Medium	Low
*Azimuthal resolution**	166 m	209 m	314 m
Range resolution	75 m	105 m	105 m
*Min. detected height**	0.4 m	0.3	0.6 m

* At 10 km range; 1: Furuno FR7112; 2: Furuno FAR2127; 3: Furuno FAR2137S

Figures:

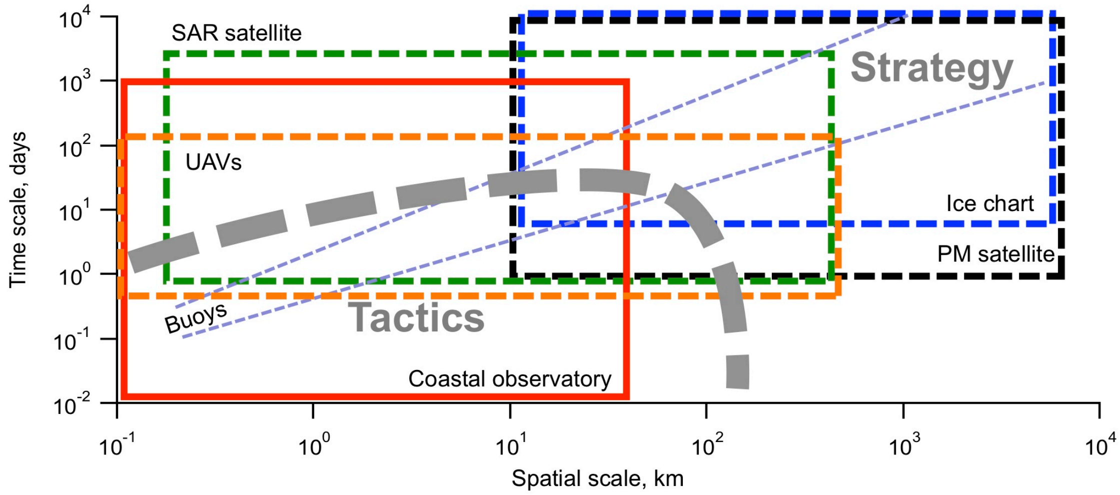

Figure 1: Schematic of spatial and temporal resolution and coverage of sensor systems that provide relevant information in the context of Arctic environmental security in ice-covered waters; the thick grey dashed line delineates the fields of tactical and strategic information providing decision support. The colored boxes represent the coverage and resolution provided by key sea-ice information products, including passive microwave satellite ice concentration data (black), North American Ice Service ice charts (blue), SAR satellite imagery (green), unmanned aerial vehicles (orange), drifting sensors (purple) and the coastal radar and ice observatory introduced in the text (red).

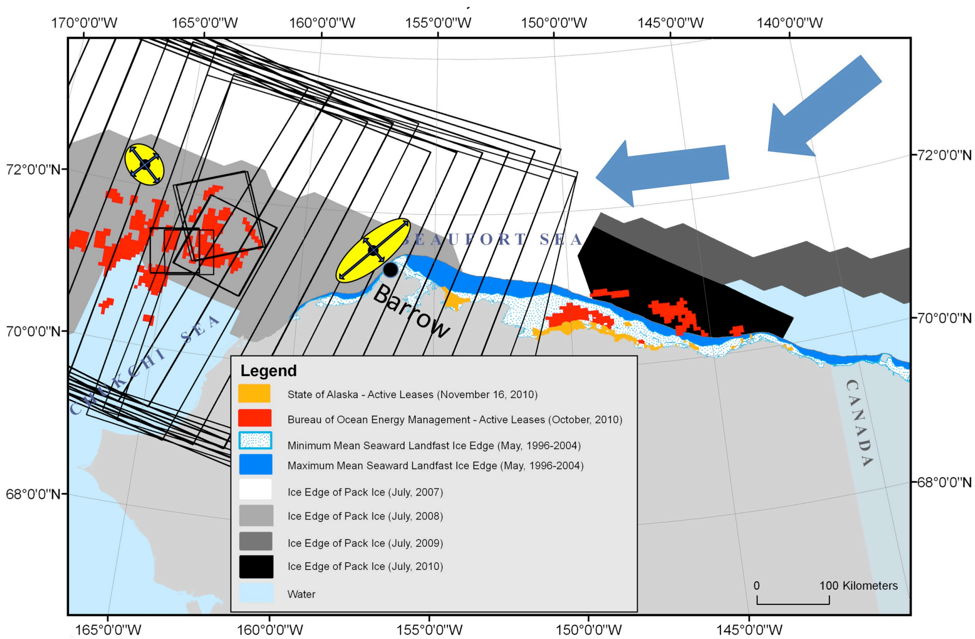

Fig. 2: Map showing active offshore oil and gas lease areas (see legend), location of the ice edge (defined by 15% ice concentration contour) during recent years in early summer, direction of prevailing ice movement (blue arrows) and ellipses indicating maximum ice displacement from a center point at two locations. The distribution of sea ice in July shown on the map is meant to illustrate the interannual variability in ice concentration (or presence and absence) in the Chukchi and Beaufort lease areas during the first part of the navigation season. Coverage of SAR satellite data at a single point (71˚N 164˚W) for the time period summarized in Figure 3 is also shown (black outlines).

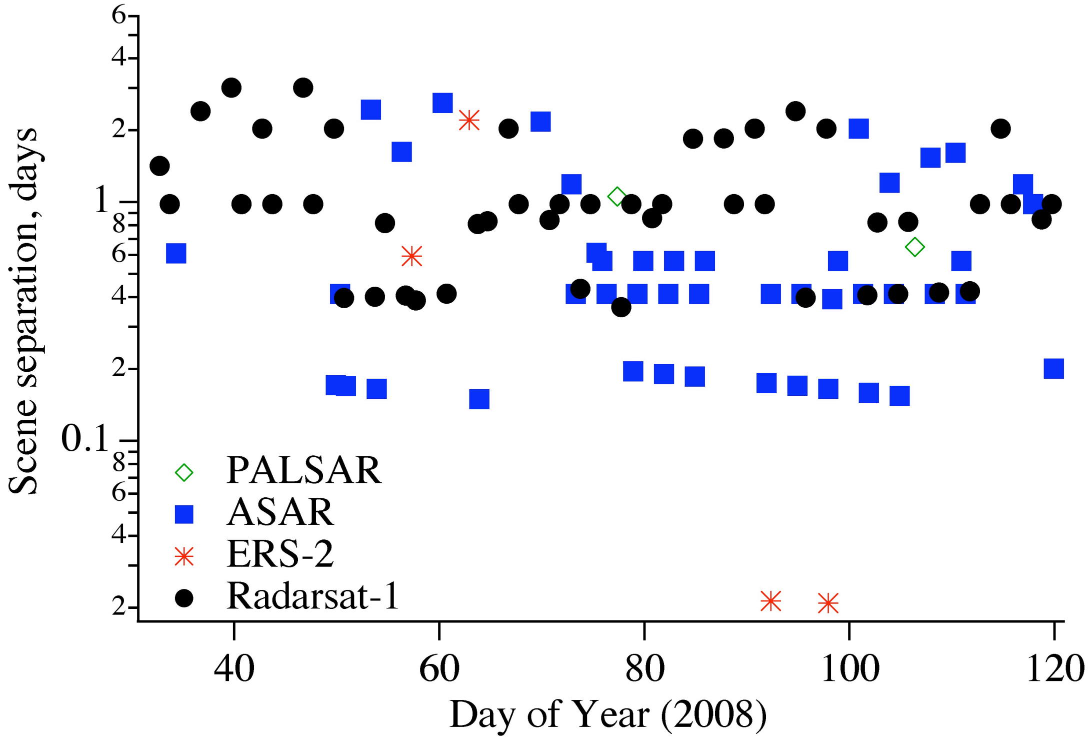

Figure 3: Temporal coverage of SAR satellite data at a point at the center of the Chukchi Sea oil and gas lease area (71˚N 164˚W) for the time period February 1 through April 30, 2008.

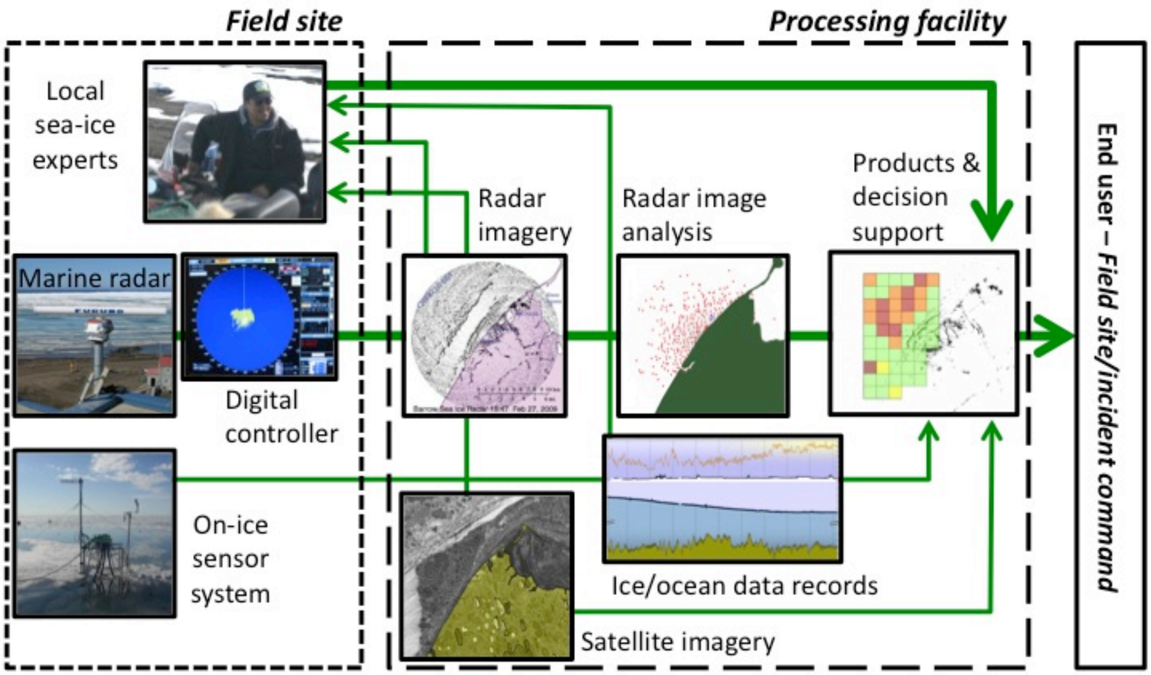

Figure 4: Schematic diagram of the ice observatory, indicating system components and data and information flow. Assessment of hazards and potential response primarily involve products derived from radar processing stream and local expert knowledge, with ancillary information provided by satellite imagery and on-ice sensor systems. Note that while information flow is towards the end user and local ice experts, observing system design was very much driven by the user community.

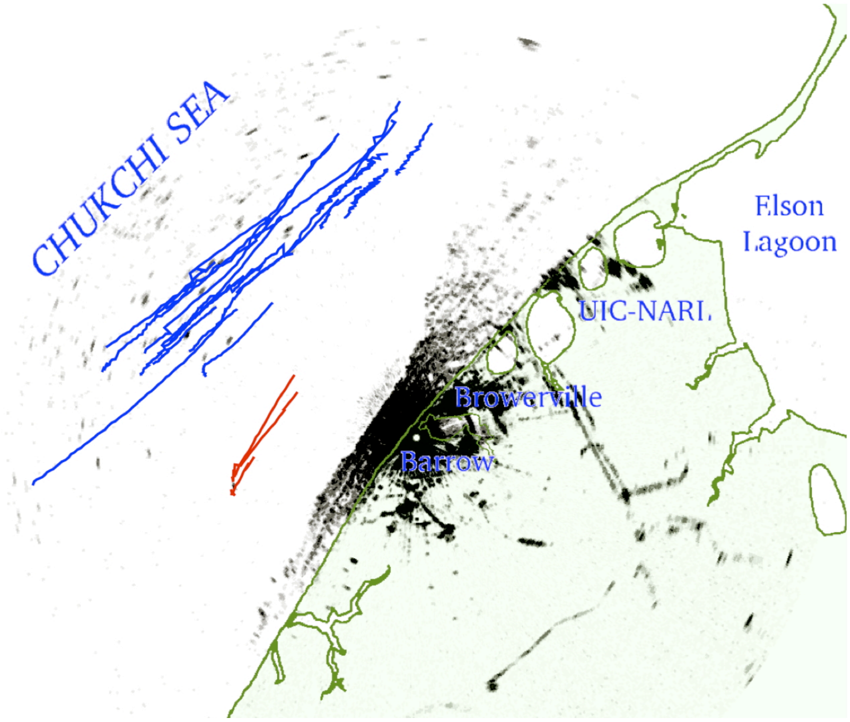

Figure 5: Trajectories of ice features obtained from automated analysis of the interpolated optical flow field on 24 March 2010. Ice movement is from the Northeast to the Southwest (North is up). Red trajectories highlight anomalous ice motion associated with deep-draft floes gouging the seafloor, as detected by automated ice trajectory analysis.

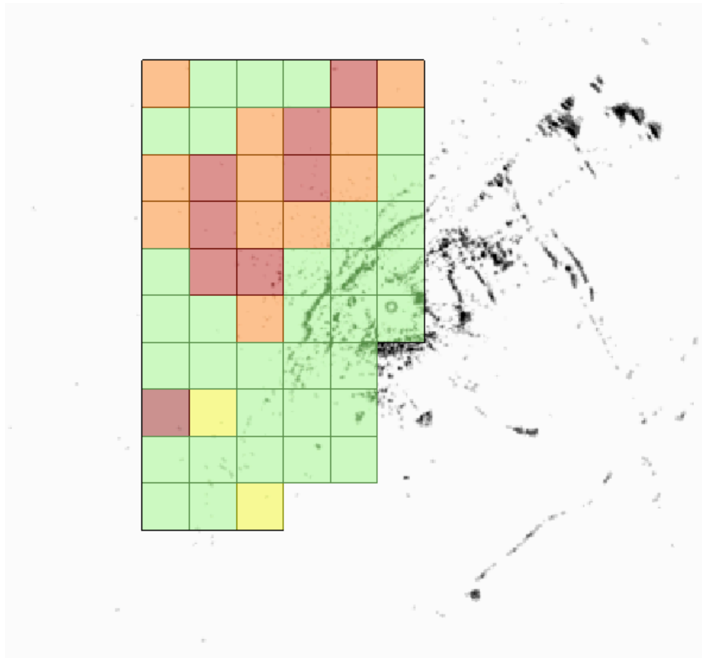

Figure 6: Example of an automated landfast ice break-out event detection using a Hidden Markov Model approach to analysis of ice trajectory data, on 31 January 2007, 15:50h local time. Orange and red squares indicate potentially unstable or failing landfast ice and green indicates stationary regions or freely flowing ice (scene has the same coverage as radar image shown in Figure 5).