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Sustained Observations of Changing Arctic Coastal and Marine Environments and Their Potential Contribution to Arctic Maritime Domain Awareness: A Case Study in Northern Alaska

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ABSTRACT. Increased maritime activities and rapid environmental change pose significant hazards, both natural and technological, to Arctic maritime operators and coastal communities. Currently, U.S. and foreign research activities account for more than half of the sustained hazard-relevant observations in the U.S. maritime Arctic, but hazard assessment and emergency response are hampered by a lack of dedicated hazard monitoring installations in the Arctic. In the present study, we consider a number of different sustained environmental observations associated with research into atmosphere-ice-ocean processes, and discuss how they can help support the toolkit of emergency responders. Building on a case study at Utqiaġvik (Barrow), Alaska, we investigate potential hazards in the seasonally ice-covered coastal zone. Guided by recent incidents requiring emergency response, we analyze data from coastal radar and other observing assets, such as an ice mass balance site and oceanographic moorings, in order to outline a framework for coastal maritime hazard assessments that builds on diverse observing systems infrastructure. This approach links Arctic system science research to operational information needs in the context of the development of a Common Operational Picture (COP) for Maritime Domain Awareness (MDA) relevant for Arctic coastal and offshore regions. A COP in these regions needs to consider threats not typically part of the classic MDA framework, including sea ice or slow-onset hazards. An environmental security and MDA testbed is proposed for northern Alaska, building on research and community assets to help guide a hybrid research-operational framework that supports effective emergency response in Arctic regions.

Key words: observing systems; coastal hazards; Arctic shipping; sea ice; radar; ice drift; currents; decision support; risk

RÉSUMÉ. L’augmentation des activités maritimes et l’évolution rapide de l’environnement présentent des risques naturels et technologiques importants pour les opérateurs maritimes et les collectivités côtières de l’Arctique. Actuellement, les travaux de recherche, tant américains qu’étrangers, représentent plus de la moitié des observations prolongées liées aux dangers dans l’Arctique maritime américain, mais l’évaluation des risques et les interventions d’urgence sont entravées par le manque d’installations consacrées à la surveillance des dangers dans l’Arctique. Dans la présente étude, nous nous penchons sur diverses observations environnementales prolongées en matière de recherche sur les processus atmosphère-glace-océan et nous discutons de la façon dont elles peuvent contribuer aux interventions d’urgence. En nous appuyant sur une étude de cas faite à Utqiaġvik (Barrow), en Alaska, nous étudions les risques potentiels inhérents à la zone côtière couverte de glace saisonnière. Motivés par des incidents récents qui ont nécessité des interventions d’urgence, nous analysons les données provenant des radars côtiers et d’autres ressources d’observation, comme un site de bilan de masse des glaciers et des amarrages océanographiques, afin d’établir un cadre pour évaluer les risques maritimes côtiers, cadre qui s’appuie sur diverses infrastructures de systèmes d’observation. Cette approche relie la recherche scientifique sur le système arctique aux besoins d’information opérationnelle dans le contexte du développement d’une image commune de la situation opérationnelle (ICSO) pour la connaissance du domaine maritime (CDM) pertinente des zones côtières et extracôtières de l’Arctique. Une ICSO dans

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ces zones doit prendre en compte les menaces ne faisant généralement pas partie du cadre classique de la CDM, y compris la glace de mer ou les dangers à évolution lente. En s'appuyant sur des travaux de recherche et l'apport des collectivités, un banc d'essai en matière de sécurité environnementale et de CDM est proposé pour le nord de l'Alaska afin de guider un cadre hybride de recherche et d'opération qui favoriserait une intervention d'urgence efficace dans les régions arctiques.

Mots clés : systèmes d'observation; risques côtiers; transport maritime dans l'Arctique; glace de mer; radar; dérive de la glace; courants; aide à la prise de décision; risque

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BACKGROUND

A rise in Arctic maritime activities in conjunction with rapid climate change has increased the exposure of coastal communities and infrastructure to environmental and technological hazards (Brigham, 2014; Pizzolato et al., 2014; Eicken and Mahoney, 2015; Eguiluz et al., 2016). Mitigating associated risks and fostering safe maritime operations requires environmental observations, data, and information products that can help operators assess risks and inform responses in the case of an emergency or disaster. The urgency of these issues has been recognized at the national and international level. The binding Arctic Council agreements on search and rescue and oil spill response highlight the need for an effective, cooperative emergency response framework (Arctic Council, 2011, 2013). The Arctic Council's Emergency Prevention, Preparedness and Response Working Group (EPPR WG) and the Arctic Coast Guard Forum are key entities to enhance emergency response capacity by scaling up or coordinating national efforts at the pan-Arctic level.

Efforts to date have focused on emergency preparedness and response in terms of trained personnel, assets, protocols, and frameworks (EPPR, 1998, 2014; Arctic Council, 2013). For the time period between 2015–17, key goals or themes addressed by the EPPR WG include (1) an International Exercise under the auspices of the Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic; (2) a project on Prevention, Preparedness and Response for Small Communities; and (3) development of a Database of Arctic Response Assets. EPPR WG is also beginning to address activities focused on the theme of search and rescue, which has come under the EPPR purview. Other relevant activities for the Arctic Observing Summit (AOS) 2016 are EPPR's examination of the use of unmanned aerial systems in Arctic response activities, as well as its designation of the National Oceanic and Atmospheric Administration's (NOAA) Arctic Environmental Response Management Application (Arctic ERMA) as an EPPR pilot project (Arctic Council, 2015).

Many parts of the Arctic that could be impacted by a maritime disaster are remote and lack local response assets and infrastructure. At the same time, the increase in maritime activities may outpace the deployment of assets dedicated to enhancing Arctic or Maritime Domain Awareness (MDA). This includes instrumentation and hardware to monitor the physical and ecological environment, as well as the type and extent of human activities related to hazards and vulnerabilities in the region. In light of such shortfalls, environmental data collected in the context of sustained observations of Arctic change play an important role in providing environmental intelligence that contributes to MDA (Sullivan, 2015). Recent studies in the U.S. Arctic showed that such sustained observations in the marine environment are conducted by an array of different entities. U.S. academic research institutions account for over a third of such observations, federal agencies and research institutions from foreign nations for about one quarter each, with local and state government and industry making up the remainder (Lee et al., 2015; Eicken et al., 2016). In sum, U.S. and foreign research activities by research institutions account for more than half of the sustained observations potentially relevant for hazard assessment and emergency response in the U.S. maritime Arctic.

The impacts of rapid climate change have resulted in an array of major natural hazards, many of them associated with slow-onset, that threaten coastal communities and infrastructure with coastal erosion and subsidence, such as coastal permafrost thaw (Ravens et al., 2012; Barnhart et al., 2014). Rapid-onset hazards are typically better tracked and prepared for than slow-onset hazards, leaving a gap in the response and adaptation capacity while challenging the classic picture of MDA in the Arctic.

This raises an important question that guides our work: in the event of a maritime emergency or disaster, how can response efforts best draw on such research resources, specifically to observe assets and data streams that contribute to sustained observations of Arctic environmental change? Here, we direct our attention to the coastal Arctic Ocean and marginal seas, where the presence of ice represents a major hazard and where human activities and risk exposure are at a maximum (e.g., Laidler et al., 2009; Eicken and Mahoney, 2015; Clark et al., 2016). Operations relevant in this context include shipping, subsistence activities by local communities, resource development, and tourism. Drawing on a case study in the North American Arctic we identify promising approaches and next steps in bridging gaps between the research and EPPR communities, in particular in providing a Common Operational Picture (COP) that informs MDA in the context of emergency response.

Specifically, we recommend several measures to mitigate risks and to exercise these in a testbed system. These measures include rapidly delivered in situ and remotely sensed sensor data that are distributed on a common grid using open standards, "on-demand" high-resolution coastal forecasting, active engagement with end users to determine needs and preferred methods of operation, and the use of existing tools to provide situational awareness, such as desktop Graphical Information System (GIS) and web mapping systems like Arctic ERMA (Merten, 2013; Merten et al., 2014).

MARITIME DOMAIN AWARENESS IN ARCTIC ICE-COVERED SEAS

Traditional definitions of MDA are couched in terms of understanding and tracking any aspect of the maritime domain that could impact the security, safety, economy, or the environment of a particular region or nation (Department of Homeland Security, 2005). In this context, the maritime domain encompasses the seas, coasts, and associated waterways and the activities therein. In most applications, the focus of MDA is on vessels or anthropogenic threats or, to a lesser extent, ocean state and weather conditions (Department of Homeland Security, 2005; Bruno et al., 2010). At high latitudes, several major environmental hazards and threats are associated with the presence of ice in the ocean, often in combination with hazardous weather or strong ocean currents (Eicken and Mahoney, 2015).

These environmental hazards have a disproportionate importance in the Arctic. First, they may amplify the risks associated with technological failure or human error in a remote environment, and therefore require advances in MDA research and technology specific to the Arctic maritime domain. Second, changes in sea ice extent and seasonality are major drivers in enhancing coastal erosion, flooding, and threatening the livelihood of Arctic coastal communities (Ravens et al., 2012; Barnhart et al., 2014). Third, such changes are also driving other slow-onset hazards such as permafrost thaw. While changes in sea ice, seasonality, and permafrost are not part of the classic definition of MDA (Department of Homeland Security, 2005), we regard them of comparable importance to rapid-onset maritime hazards because of their disproportionate importance in the Arctic. At the same time, emergency response frameworks may not be effective in addressing such slow-onset hazards in the Arctic (see discussion by Eicken and Mahoney, 2015; Huggel et al., 2015), which can further increase exposure and vulnerability of communities over time.

Relevant and necessary advances in Arctic MDA include the development of robust approaches to vessel detection using standard remote sensing or acoustic techniques (Bruno et al., 2010), tracking systems such as the Automated Identification System (AIS; Eguiluz et al., 2016), or inversion of high-frequency ocean radar data (Statscewich et al., 2014). At the same time, information about the state of the environment is needed to inform the development of a COP, identify hazards (including slow-onset hazards) threatening coastal communities and industry infrastructure, and support vessel detection and tracking. Here, we focus on development of interoperable data sources for use in COPs and briefly explore how to foster integration of relevant data obtained in the context of sustained Arctic observations. As a case study, we consider a subregion of the North Slope of Alaska, centered roughly on Point Barrow, the northernmost point on the North American landmass near the town of Utqiaġvik (formerly Barrow), defining the boundary between the Chukchi and Beaufort Seas (Fig. 1).

For the framework and case study discussed below, we recognize the following types of hazards (Fig. 2): (1) technological hazards, such as equipment failure or an oil spill caused by human error in operation of equipment; (2) natural hazards that present a direct threat to maritime activities, such as presence of sea ice, icing conditions, extreme weather, and ocean state; (3) natural hazards that present a direct threat to coastal communities, infrastructure, and human activities, including coastal storms, hazardous shorefast and drift ice conditions, coastal flooding, and extreme weather events; and (4) slow-onset hazards that threaten coastal communities and infrastructure, such as through sustained reductions in summer ice extent, decreased stability, and presence of shorefast ice or permafrost thaw. The first three types of hazards will be addressed here. Detailed consideration of hazards of the fourth type is outside of the scope of this study, but we recognize that they may greatly amplify the impact of other hazards and can drive short-timescale catastrophic events (Cutter et al., 2008).

A CASE STUDY AT UTQIAĠVIK, ALASKA

The Point Barrow region and North Slope of Alaska are the setting for a range of activities relevant in the context of this study. Oil and gas exploration, such as of the Liberty deposit, as well as ongoing hydrocarbon production, such as at the Northstar site, are extant to the east in the coastal Beaufort Sea. Maritime traffic typically hugs the coast on either side of Point Barrow to minimize distance and to avoid ice that often lingers well into summer towards the north. Small-craft adventure tourism and cruise ship traffic has increased in recent years (Eguiluz et al., 2016). The greatest proportion of small craft and vessel traffic is associated with subsistence hunters from Utqiaġvik and neighboring communities who harvest marine mammals and fish in the region. Also, Utqiaġvik and surrounding regions have experienced increasing threats to community infrastructure and well-being from coastal erosion, flooding, and extreme weather events (Gearheard et al., 2006; Brunner and Lynch, 2010).

The combination of marine activity and environmental hazards near Point Barrow have the effect of creating

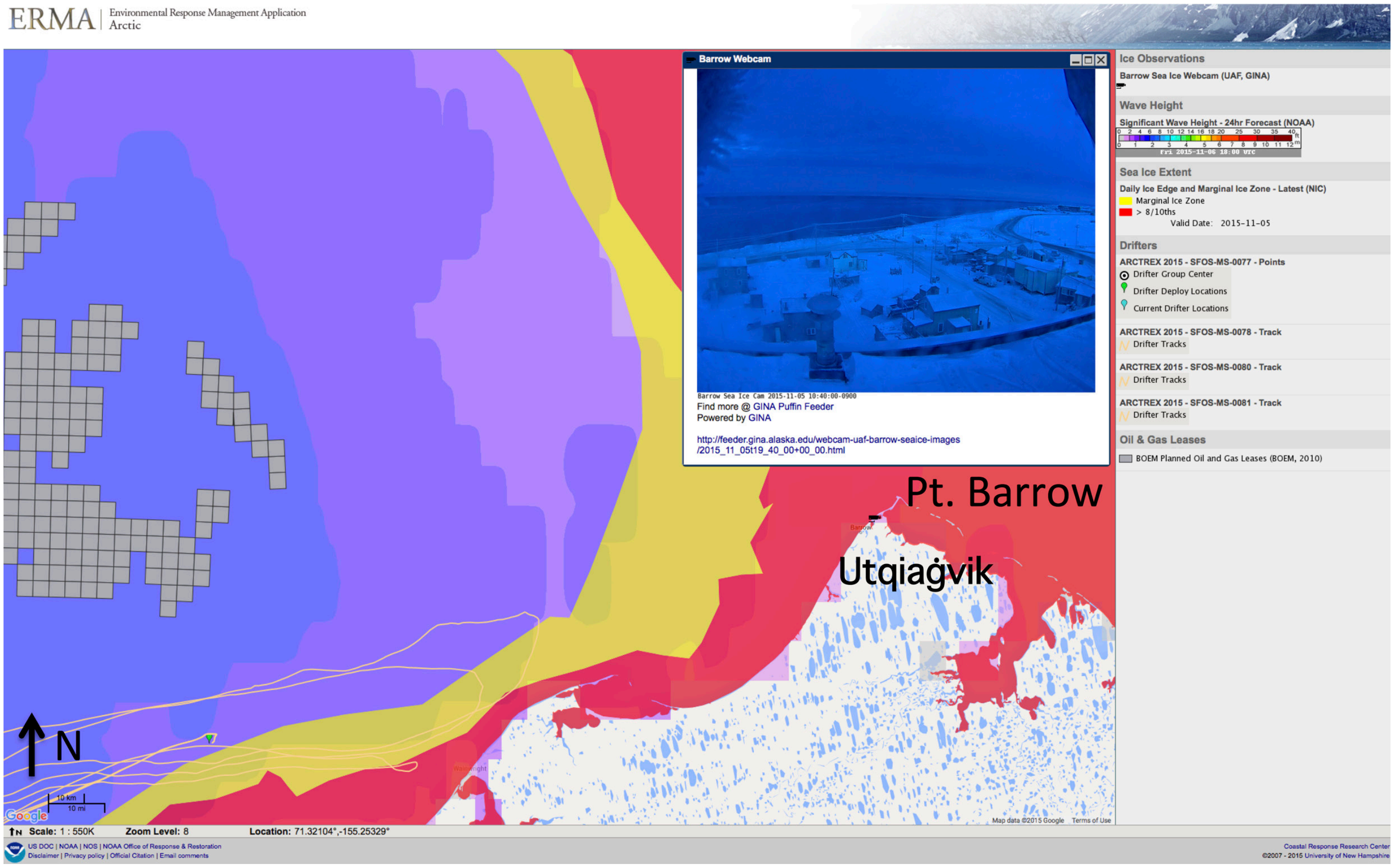

FIG. 1. Map of the Utqiaġvik and Pt. Barrow region and part of the North Slope of Alaska, as seen in NOAA's Arctic ERMA interface. Out of a larger number of variables, key locations, such as oil and gas lease areas, ice conditions on 5 November 2015 based on NOAA National Ice Center ice charts, sea state (24-hour forecast of wave height), trajectories of surface drifters released in September 2015 and an image of the Barrow Sea Ice Webcam showing new ice forming nearshore with some open water and thicker young ice further offshore are overlaid. The camera also captures atmospheric riming conditions.

a natural 'choke point,' increasing the likelihood of an incident and requiring improved tools for identifying and forecasting hazards. Such activity and relevant hazards are illustrated by three local incidents, plus a fourth that took place in Nome but involved similar hazards that are found near Utqiaġvik (Table 1). These incidents motivate and inform our work, and make the marine environment near Utqiaġvik and along Alaska's Arctic coastline an ideal location to explore various aspects of MDA and COP development in a hybrid research-operational setting.

Utqiaġvik is also home to a large number of long-term terrestrial and marine research projects (Norton, 2001). This includes a strong presence by federal, state, and local agencies, as well as a broad range of U.S. and international universities and research institutions. There is a significant increase in non-Arctic nations conducting research in the region (Eicken et al., 2016). The Iñupiat population at Utqiaġvik has a long, well-established history of sharing insights from Indigenous knowledge of the environment, providing essential support and collaboration on research projects. Indeed, this history includes a number of major research efforts that would not have succeeded without the involvement and assistance of local experts. The remoteness of the location—the nearest U.S. Coast Guard (USCG) base in Kodiak is some 1500 km distant—and the challenging environmental conditions put significant emphasis on expertise and assets within the local community. Such assets could include sensor systems currently deployed in collaboration with the local community for long-term studies of environmental change and related research, which are also potentially relevant in the case of emergency response.

Standard COPs typically draw on a variety of data sets to determine whether the potential for an *engagement*, *rendezvous*, or *anomaly* exists (Shahir et al., 2014). An *engagement* is the first stage of the evaluation process and occurs when a vessel is brought within a specified distance of a hazard, which may be another vessel. If a potential engagement is identified, then a second stage of evaluation assesses the potential for an actual *rendezvous,* which conforms with a specific pre-identified scenario. If such a scenario is deemed a risk to people, a vessel, or infrastructure, then it is classed as an *anomaly* and a third stage is initiated in which a decision-maker needs to be involved to take action. The problem in Arctic regions is that a lack of environmental intelligence can compromise MDA and foil the establishment of an accurate COP at the critical first stage of identifying potential engagement, curbing the effectiveness of prevention or response efforts. In the winter of 2014–15, the ice entrainment and drift of

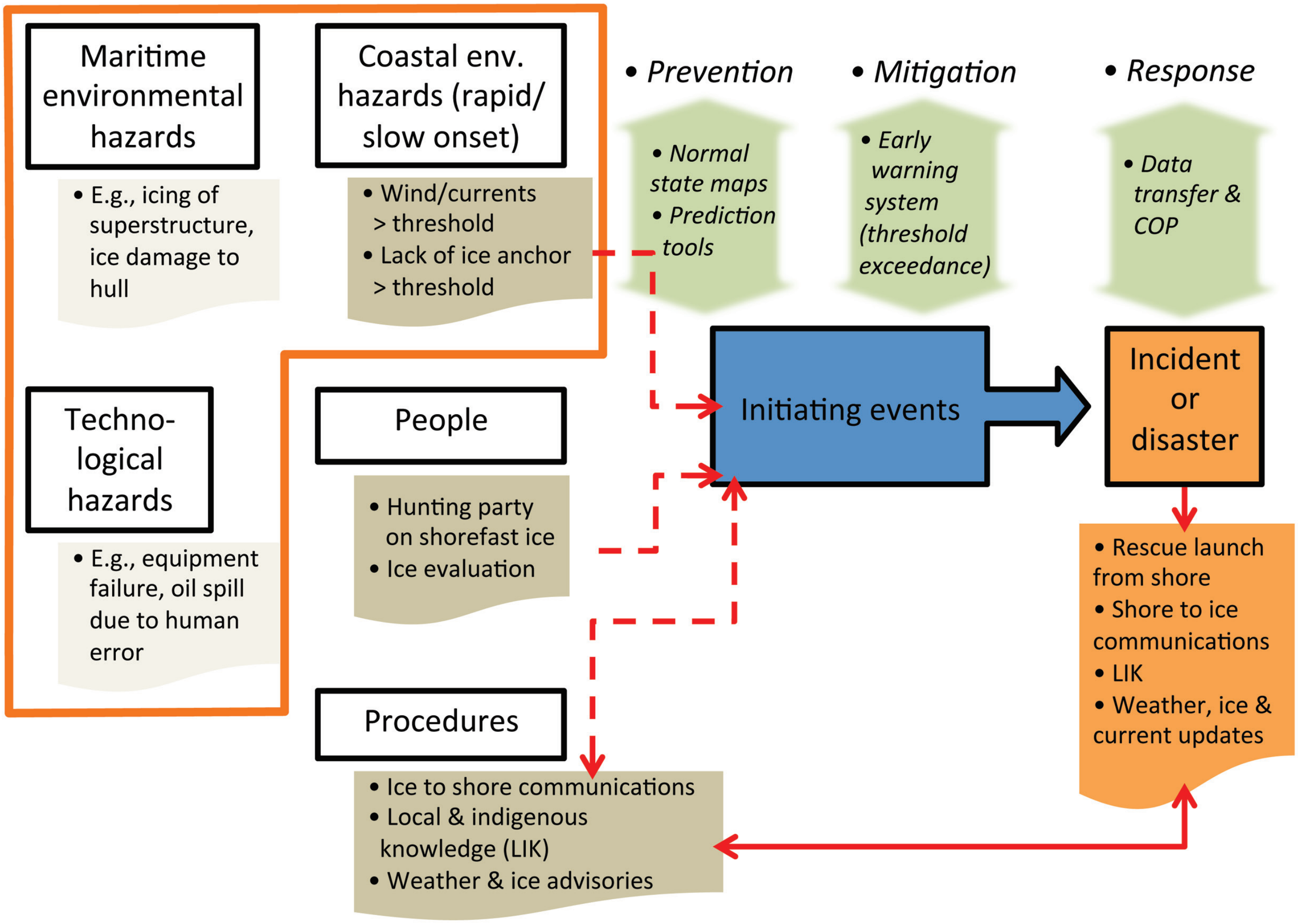

FIG. 2. Schematic outline of different types of hazards relevant in the context of this study (orange frame at left), and an overarching total hazards framework for the landfast ice breakout incident at Barrow in April 2014. Shown are factors leading into events that may initiate an incident or disaster (red dashed arrows). Input from sustained observations and associated modeling/forecasting and their relevance for hazard mitigation and incident prevention and response are shown in italics. Shaded beige and orange flags indicate specific aspects of incident C (Table 1, Landfast ice breakout and rescue) discussed in more detail in the text. Approach is based on a marine risk assessment framework described by Vinnem (2007) and adapted by Eicken and Mahoney (2015).

a fuel barge in the eastern Beaufort Sea past Point Barrow and into Russian waters serves as an example of this problem (CBC News, 2015). Moreover, the short-term, sequence-of-events based approach to COP establishment does not necessarily apply to slow-onset hazards, which will require further research into whether and how the classic COP framework can be applied to these hazards.

In the context of this study, developing data sources and operator knowledge to inform a COP includes the following steps and prerequisites: (1) identification of available sensor system capabilities, including satellite remote sensing products, and relevance to response scenarios; (2) identification of available environmental data (e.g., wave height, water level, and ice concentration) from operational models including “on-demand” high-resolution models initiated in response to a particular event; (3) assessment and integration of these data streams into a common reference framework; and (4) automated or supervised evaluation of the potential for engagement, rendezvous, or anomaly with potentially hazardous outcomes.

To illustrate the scope of step (1), Table 2 shows key capabilities and constraints of selected research sensor networks for the Point Barrow region. These include: remote sensing data downlinked and processed by the Geographic Information Network of Alaska (GINA; gina.alaska.edu) at the University of Alaska Fairbanks (UAF), serving both researchers and the National Weather Service; synthetic aperture radar data obtained through the Alaska Satellite Facility; an HF ocean radar (Statscewich et al., 2014); an ice radar (Eicken et al., 2011; Jones et al., 2016); unmanned aerial systems deployed by the Alaska Center for Unmanned Aerial Systems Integration (ACUASI); and Iñupiaq ice experts contributing to a seasonal ice zone observing network (Eicken et al., 2014). A capabilities assessment such as this can help identify potential gaps as well as guide the integration of different data streams. Note also that several of the variables relevant in an MDA and COP context shown here are tracked as part of long-term environmental observations with a focus on Arctic system science and climate change research.

TABLE 1. Four recent maritime incidents involving ice hazards near Barrow and Nome.

Incident	Response	Hazards involved	Relevant long-term observation data
A. Beaching of sailing vessel *Altan Girl* by coastal ice push, Barrow, July 2014[1]	Local assistance required to unground vessel	Ice pressure; vessel beset and grounded	Mean and synoptic ice velocity fields from coastal radar (also captured incident itself)
B. Fuel barge *National-II* broke loose from tug and entrapped in drifting ice pack, Beaufort/Chukchi Seas, Oct 2014 – May 2015	Deployment of tracking device and monitoring of drift	Ice pressure; threat of fuel spill	Projected barge drift from retrospective analysis of buoy drift and remote sensing data
C. Breakout of landfast ice with hunting crews, Barrow, AK, April 2014	Recovery of people and equipment via small boats launched from shore	Landfast ice; detachment; floe fragmentation; threats to life, health and property	Mean and synoptic ice velocity fields from coastal radar (also captured incident itself)
D. Winter energy supply mission, Nome, AK, December 2011 – January 2012	USCGC *Healy* escort of tanker *Renda* and over-ice fuel transfer	Ice pressure; landfast ice detachment; threat of fuel spill	Long-term ice data lacking at Nome; same data as under A are relevant here

[1] Incident occurred shortly after the sailing vessel was rescued by the USCGC *Healy* after becoming entrapped in the pack several tens of kilometres north of Barrow (J.C. George and R. Suydam, pers. comm. 2016).

ICE HAZARDS AND SUSTAINED OBSERVATIONS AT POINT BARROW

For the purposes of this case study and the incidents outlined in Table 1, we focus on the specific example of how MDA and potential emergency response can be served by sustained sea ice observations based on a coastal radar system, an ice mass balance site, and community-based observations by Iñupiaq ice experts. Technical details for the ice radar system and algorithms developed for automated tracking of ice motion and identification of ice hazards are provided by Eicken et al. (2011), MV et al. (2013), and Jones et al. (2016). In brief, a marine Furuno FR7112 10kW X-band marine radar has been operating since 2007 at Utqiaġvik, being mounted 22.5 m above sea level. For tracking of ice motion and shorefast processes, the radar has been operating at an effective range of 11 km. A Xenex XC2000 digital controller generates digital images every 4 min that are then transferred to UAF every 10 min for processing. A georeferenced, orthorectified data product with an effective pixel size of 21.5 m is archived, with derived products such as ice velocity fields (MV et al., 2013), and distributed to different stakeholders as kmz files. To generate monthly mean ice velocity fields, all data points for each grid point for a specific month and year are averaged; a monthly mean climatology is then derived by averaging over a specific month for all years for which data are available. For this study, we have considered data from January 2007 through September 2016.

The ice mass balance site records a time series of ice thickness and snow depth, as well as relative sea level and ice temperature (Druckenmiller et al., 2009). Community-based observations are carried out as described by Eicken et al. (2014) and comprise a range of mostly qualitative observations relevant from an ice use and ice safety perspective.

These sustained observations are complemented by long-term monitoring sites maintained by NOAA in the form of the Earth System Research Laboratory's Barrow Observatory (Stone et al., 2002) and the National Weather Service Office at Utqiaġvik. The U.S. Department of Energy maintains two Atmospheric Radiation Measurement Program (ARM) sites in the region, one at Utqiaġvik and one at Oliktok Point, 250 km to the east, comprising a range of radiation measurements as well as operation of an X-band radar to track atmospheric moisture and precipitation (Verlinde et al., 2016).

ICE HAZARD TRACKING AND INCIDENT RESPONSE AT UTQIAĠVIK, ALASKA

To illustrate the potential utility and specific role of data and derived information products obtained from sustained observations of Arctic environmental change in the context of hazard assessment and incident response, we consider a case study at Utqiaġvik, Alaska. The relevance of ice/ocean hazards in the context of four recent incidents in the region and links to long-term observation data are summarized in Table 1. The type of environmental hazard data central to these four incidents will be reviewed below and comprises information on (1) anomalous ice motion events (high speeds, rapid reversals, etc.); (2) convergence (in particular shoreward) of ice with potential for vessel trapping; and (3) landfast ice breakouts and detachments. In addition, identifying the position of vessels, snowmobiles, or people on the ice or water during these incidents is of potential importance.

Anomalous Ice Motion Events

Detection of anomalous ice motion events requires an ice drift climatology or "normal" ice drift pattern against which

TABLE 2. Capabilities of the University of Alaska Fairbanks research program components for the Barrow/North Slope of Alaska region relevant for Common Operational Picture (COP) applications. S-OBS indicates variables tracked as part of a long-term environmental observing program. C = capable, V = varying capacity, N = no capacity, n/a = not applicable, and ? = further information needed.

		Satellite				Radar		UAS
		Optical				HF	Ice radar	ACUASI[1]
Category	Factor	High res	Med res	Low res	SAR	5 MHz	10 GHz	Med weight
Environmental:								
	Day	C	C	C	C	C	C	C
	Night	N	N	V	C	V	C	C
	Clouds	N	N	V	C	C	C	V
	Water vapor	C	C	C	V	C	C	C
	Precipitation	C	C	C	C	C	V	C
	Winds	C	C	C	C	C	C	C
	Configurable sensor	C	C	C	C	N	N	V
	Operating temperatures	all year	all year	all year	all year	Jul–Nov	all year	all year
	Ice/snow/water differentiation	C	C	C	C	N	V	C
Range:								
	Current range from coast	n/a	n/a	n/a	n/a	50–200 km	10 km	100 miles
	Maximum range from coast	n/a	n/a	n/a	n/a	200 km	50–70 km	?
Electromagnetic interference:								
	Proximity	C	C	C	V	V	N	V
	Radiation/induction	?	?	?	?	V	C	V
Communications link:								
	Minimum bandwidth	?	?	?	?	Iridium	wifi	900 MHz
	Optimal bandwidth	?	?	?	?	Fiber optic	Fiber optic	Iridium
Processing times:								
	Quick look available	< 20 min	< 20 min	< 20 min	< 20 min	C	5–30 min	C
	Full product in < 12 h	C	C	C	N	C	C	C
	Full product in > 12 h	C	C	C	C	C	C	C
Infrastructure:								
	Electric power source	Onboard	Onboard	Onboard	Onboard	RPM	power grid	Onboard
	Duration of power	Years	Years	Years	Years	all season	constant	20+ h
	Maintenance free	C	C	C	C	N	n/a	N
Data costs:								
	Acquisition costs	High	High	High	High	Low	Low	Low
	Distribution/Licensing	?	?	?	?	?	?	n/a
	No cost	?	?	?	?	public domain	public domain	?
Detection:								
	Vessel	C	C	C	C	C	C	C
	Landfast ice edge	C	C	C	C (S-OBS)	N	C (S-OBS)	?
	Surface current–water	N	N	N	N	C (S-OBS)	N	N
	Surface current–drift ice	N	N	N	V	N	V (S-OBS)	N
	Ice breakout event	N	N	N	N	N	C (S-OBS)	N
	Ice cover					N	C	C
	Ice surface topography					N	C	V
	Ice thickness					N	N	N
	Water pooling on ice					N	N	C
Ice coverage:								
	100% coverage	C	C	C	C	N	C	C
	50% mixed	C	C	C	C	N	C	C
	0% coverage (open water)	C	C	C	C	C	C	C

[1] UAS ACUASI = Unmanned aerial system, Alaska Center for Unmanned Aerial Systems Integration.

specific velocity vectors can be compared, both in terms of magnitude and direction. Mean ice velocity fields for the months of July and November (Figs. 3 and 4) illustrate the breakup/freeze-up transition seasons, when both local boats and commercial or government vessels may be in the region. The mean velocity fields provide information about the normal or expected extent of stagnant or landfast ice, as well as the mean speed and direction of ice movement. Based on an evaluation of the entire data set, thresholds for high or anomalously high speeds can be defined (illustrated here by red vectors denoting high velocities > 0.2 m s^{-1}). The magnitude of the ice velocity in such derived fields depends on spatial and temporal sampling or averaging intervals, with peak magnitudes tending to be lower for greater intervals (Hutchings et al., 2011). Hence, detection thresholds for anomalous ice velocity events need to be defined in terms of an operational sampling interval. A daily velocity field for 14 July 2014 (Fig. 5) exhibits ice speeds of up to 1 m s^{-1} or more, which is in part explained by the shorter averaging interval.

Determination of ice speed thresholds that define hazardous operating conditions needs to take into account both the frequency distribution of ice drift, as well as operational constraints and relevant response time scales.

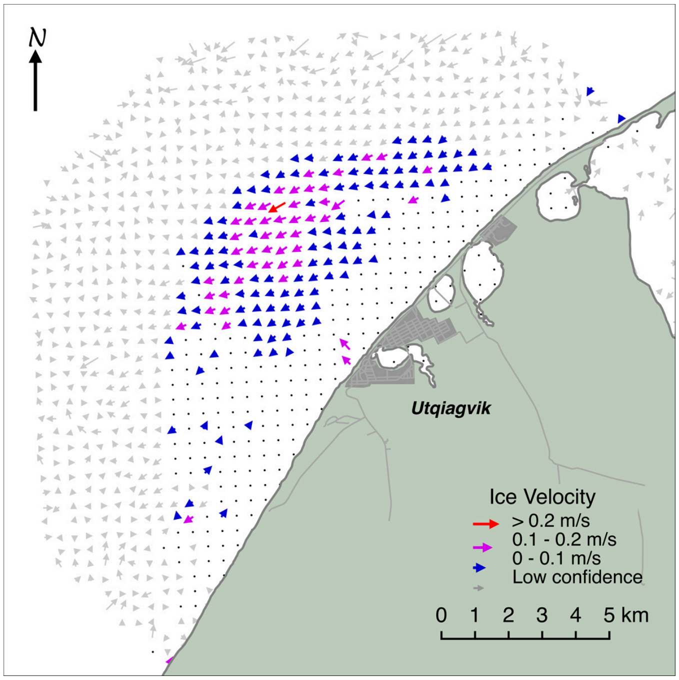

FIG. 3. Mean monthly ice velocity map for November, based on radar data from 2007 through 2015. Low confidence velocities correspond to grid points that generated less than 5% of the number of tracked ice velocity data points as that of the grid cell with the maximum number of data points.

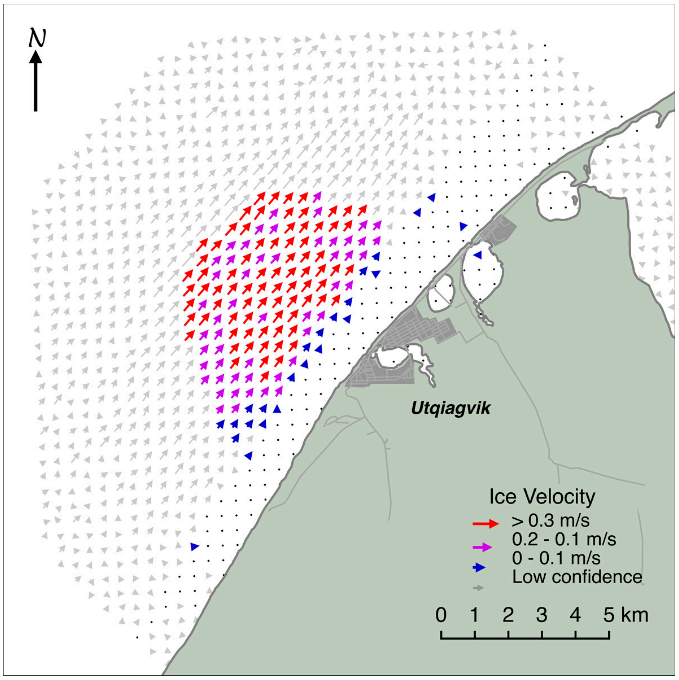

FIG. 4. Mean monthly ice velocity map for July, based on radar data from 2007 through 2016. Details as in Figure 3.

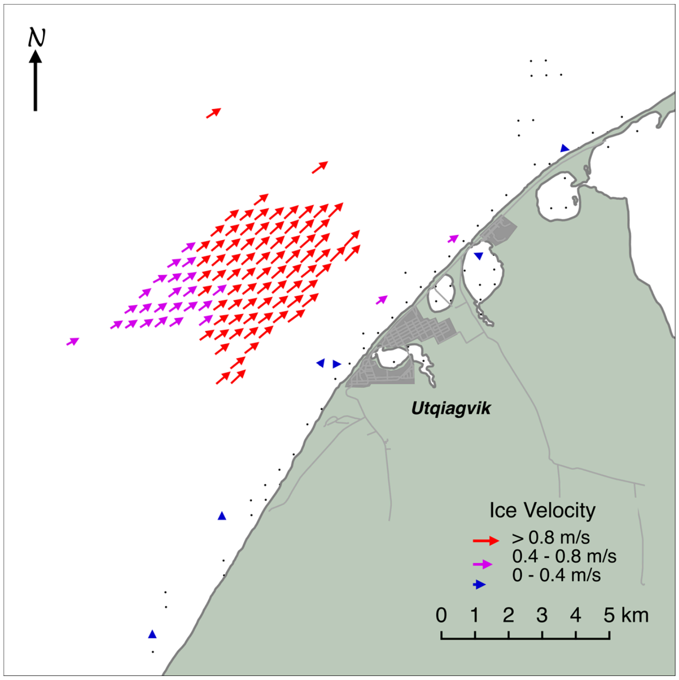

FIG. 5. Mean daily ice velocity map for 14 July 2014. On this day, the sailing vessel *Altan Girl* was beset by ice, pushed onshore and grounded in shallow water (Table 1).

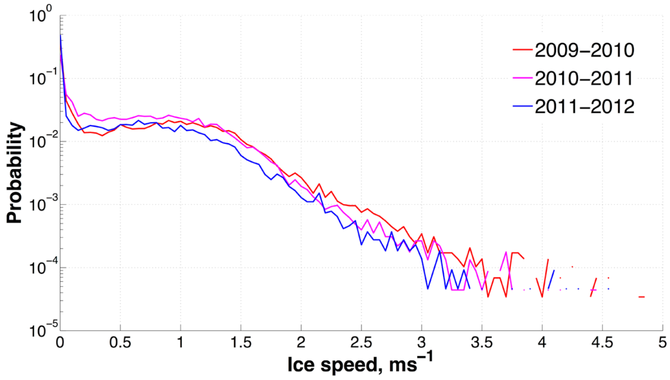

FIG. 6. Frequency distribution of ice drift speeds obtained from moored ice profiling sonar deployed within the footprint of the ice radar (details in Mahoney et al., 2015).

Here, we focus on the former, as shown in Figure 6, which represents an analysis of ice velocities obtained from ice profiling sonar in the footprint of the ice radar between 2009 and 2012 at sampling intervals of 15 min (Mahoney et al., 2015). The plot indicates that ice speeds at or above 1 m $\mathrm{s^{-1}}$ are part of an exponential tail of the distribution, accounting for roughly one quarter of all data points. In a decision-support context, such as for Arctic ERMA, automatically identifying and highlighting the occurrence of anomalous ice velocities is critical in hazard assessment and response.

The November and July mean ice velocity fields (Figs. 3 and 4) illustrate the value of such visual guidance, for example, by highlighting spatial patterns of extreme ice drift. For this particular location in the Chukchi and Beaufort Seas, they also show the value of ice drift climatology data in providing a clear picture of contrasting mean states of ice movement. During fall freeze-up, drift is predominantly towards the western sector, whereas during spring breakup it is towards the eastern sector. This drift pattern is relevant for the types of hazards or incidents that

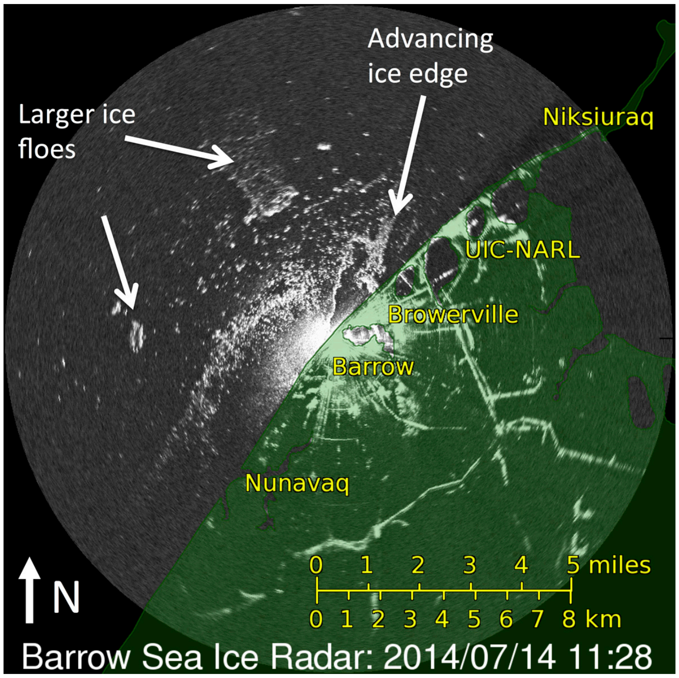

FIG. 7. Sea ice radar image for 14 July 2014 showing the front of the advancing ice edge and larger ice floes associated with besetting and grounding of sailing vessel *Altan Girl* (Table 1).

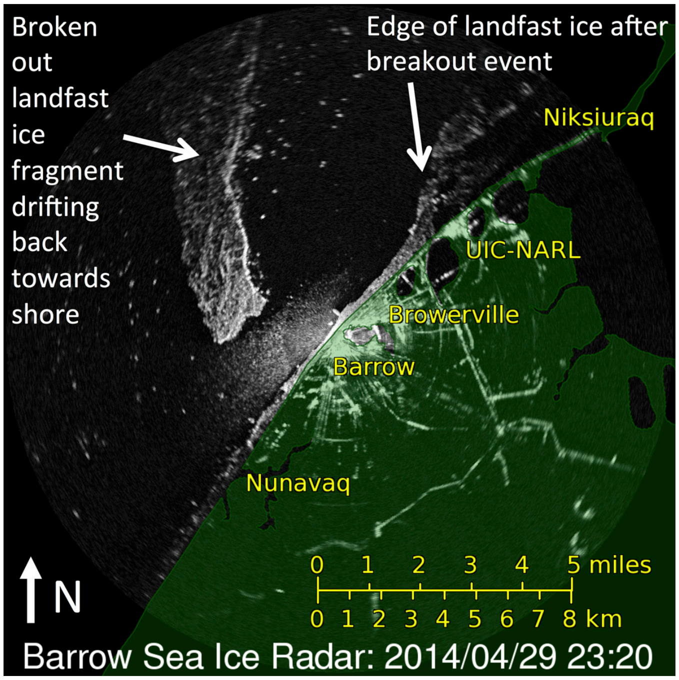

FIG. 8. Sea ice radar image for 29 April 2014, 2320 h Alaska Standard Time, showing a fragment of landfast ice near the center of the image that had been created during the course of a landfast ice breakout event earlier in the day. The freely drifting ice floe is moving towards the shorefast ice and about to collide with remnants of the landfast ice in the right part of the image. The corresponding velocity vectors of different pieces of ice visible in this scene are shown in Figure 9, with the incident itself and the rescue effort of stranded hunters summarized in Table 1.

would be expected, such that the entrapment and shoreward motion toward the east of the vessel *Altan Girl* on 14 July 2014 (Fig. 5, Table 1) did in fact occur in line with prevailing ice drift direction, but higher than average daily mean speeds. Similarly, the westward trajectory of the ice-entrapped fuel barge *National-II* past Point Barrow in mid-November 2014 also followed climatological drift direction, but with abnormally high speed.

Shoreward Convergence of Sea Ice

The risk of entrapment, shoreward push, and grounding of the sailing vessel *Altan* Girl in July 2014 was foreseeable based on the mean July ice drift velocity field (Fig. 4). There is a small, but non-negligible shoreward component of the mean field that may result in grounding towards the spit at Point Barrow, as well as towards the outward bulge in the coastline near the town of Utqiaġvik. The daily mean field for 14 July 2014 (Fig. 5) shows this even more clearly. For this particular incident, although analysis of the ice velocity fields can also provide insights into patterns of ice deformation and convergence, as detailed by Jones et al. (2016), evaluation of the original radar imagery might have provided additional guidance on specific hazards. Thus, the ice radar captured the advancing front of loose drift ice converging towards the spit off Point Barrow (Fig. 7). It also detected and tracked ice floes of 1 km or more in size, which helped compact and confine the loose aggregations of small floes and brash ice.

Landfast Ice Breakout and Detachment

Breakout and detachment of landfast ice is a major hazard throughout the Arctic and sub-Arctic, where individual people, communities, or industry use the ice as a platform for a range of activities (Eicken et al., 2009). On the North Slope, over the past few decades, hundreds of people have been involved in such breakouts, requiring self-rescue or air or surface-based evacuation (George et al., 2004; Druckenmiller et al., 2009). On 29 April 2014, a large swath of shorefast ice broke out in front of the town, with members of two hunting parties stranded on the ice. Weather conditions did not allow for search and rescue flights to launch, but a shore-based small craft was able to launch from the newly opened ice edge and retrieve the crew and equipment. The radar imagery and derived velocity fields (Figs. 8 and 9) reveal that, during this time period, sea ice exhibited complex drift patterns with a reversal in drift direction and drift speeds at times reaching 1 m s^{-1}.

It is unclear to what extent the search and rescue crew at Barrow Rescue Base relied on printouts of the radar maps provided to them as the incident evolved. However, the radar maps themselves demonstrated their potential utility in local response efforts and resulted in improvements to the way information is displayed in the maps, based on input received from local responders and others tracking the rescue effort. Moreover, the automated ice velocity tracking clearly resolved finer details of complicated ice movement patterns, such as different drift directions of floes in the scene shown

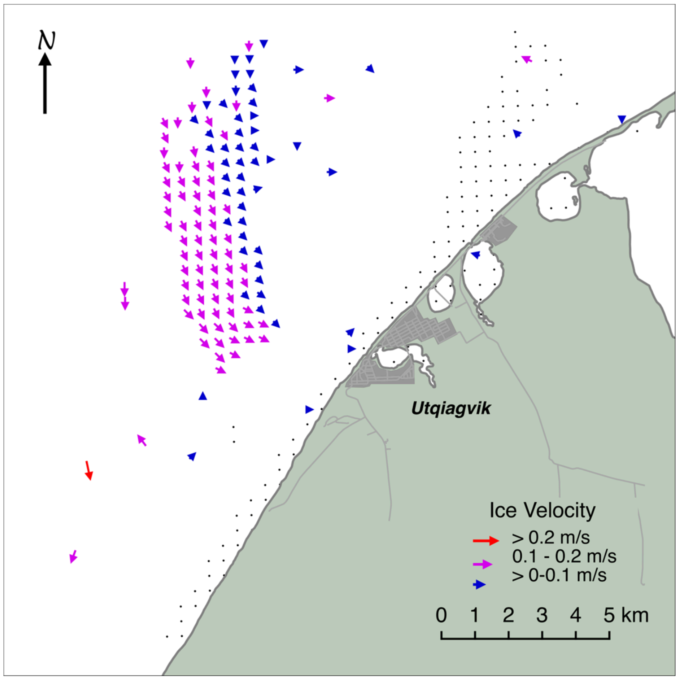

FIG. 9. Ice velocity field for former landfast ice fragments during the course of a breakout event on 29 April 2014 at 2320 h Alaska Standard Time (corresponding to scene shown in Fig. 8). The velocity vectors derived from a triplet of radar scenes centered on 2320 h. Different vector colors conform to the legend in Figure 3. Note that the different drift direction is a result of differential motion of ice floes and fragments as a function of ice roughness, draft, and mass, and local wind and current forcing.

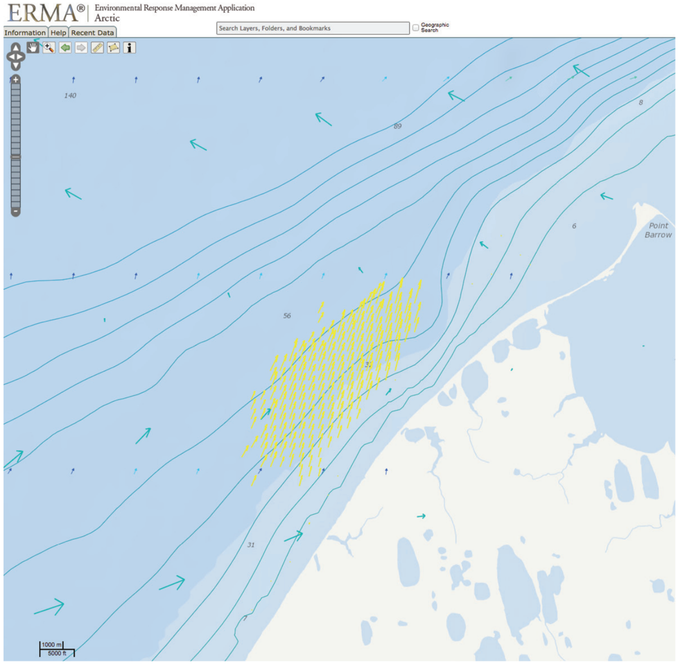

FIG. 10. Screenshot of the Arctic ERMA decision support interface showing a comparison between the daily mean ice velocity field for 12 May 2016 based on ice radar observations (yellow) and output from the HIOMAS model (larger arrows in green; note that HIOMAS vectors are magnified by a factor of 2 compared to ice radar vectors). Shown in blue are mean surface current velocities for May 2016 as derived from the Navy's operational Hybrid Coordinate Ocean Model (HYCOM).

in Figures 8 and 9. These contrasting patterns of movement are due to different wind and current action on pieces of ice as a function of ice roughness, draft, and floe mass.

Surface craft assumed to have been part of the rescue effort are also discernible in the radar imagery, based on manual tracking of their trajectory. It remains to be determined whether a radar-sampling rate higher than once every 4 min (currently limited mostly by data transfer rates) may allow for automated tracking of small surface vessels. A detailed study was conducted in summer 2013 to compare the relative performance of the ice radar and a high-frequency (HF) ocean radar system (Statscewich et al., 2014) in comparison with Automatic Identification System (AIS) data (J. Jones et al., unpubl. data). Both ice radar and HF radar detected at least one quarter of all AIS-equipped vessels in the area, and typically detected over half of them. However, the ice radar picked up numerous small craft (< 10 m in length) that were neither registered by HF radar nor AIS. In search and rescue operations such as this landfast ice breakout and other emergency situations, detection of such small craft may be highly relevant in the context of emergency response.

TOWARDS AN ENVIRONMENTAL SECURITY AND MDA TESTBED

In the discussions above of MDA and common operational pictures in Arctic ice-covered seas and of the Utqiaġvik case study, we provided a brief assessment of available observing system assets (Tables 1 and 2) and their potential contribution to MDA, hazard assessment, and emergency response. However, as illustrated in Figure 2, collection of such data is not sufficient in and of itself. Rather, in order to inform or support decisions made in the context of hazard assessment and emergency response, various data streams from sustained observations and other types of observing efforts have to be integrated and transformed into information that can be communicated and acted upon in a specific operational setting. Data from sustained observations plays a key role in helping to define the mean or normal state, such that anomalies and potential hazards can be detected in the prevention and mitigation phase (Fig. 2). If available in near-real time, such data may be assimilated into model simulations, such as for output from the High-Resolution Arctic Ice-Ocean Modeling and Assimilation System (HIOMAS; see also Zhang et al., 2012) that can provide large-scale ice velocity fields at resolutions of a few kilometres (Fig. 10). In the case of an incident or imminent disaster, such as the landfast ice breakout event requiring rescue of personnel (Table 1, Figs. 2 and 8), data streams from observing system assets can contribute to the development of a COP that informs the rescue and response efforts.

Integration and automated evaluation of a range of data streams require that the COP builds on rapid data processing, appropriate distribution methods, and flexibility to accommodate a variety of data streams and use cases.

Data processing should focus on transferring the raw data quickly from the acquisition point, transforming it into an information product on a common grid. Distribution channels must make use of appropriate networks and transfer protocols while allowing data to be either pushed or pulled as necessary during routine operations or an incident response (Fig. 2). At the same time, the underlying framework needs the flexibility to allow integration into a variety of systems, as well as for use cases requiring limited bandwidth, alternative projections, scalability, symbol styling, and attribute querying. Stakeholder engagement confirmed that USCG District 17 (Alaska) gravitated towards two major categories of COP interfaces: Desktop GIS systems and Web Map systems. Building on GINA's resources, a demonstration system was developed to provide data sets and data feeds via open standards such as Open Geospatial Consortium (OGC) Web Mapping Services (WMS), Keyhole Markup Language (KML), Geographic JavaScript Object Notation (GeoJSON), and standardized map tile interfaces as endpoints for distribution. Such interoperable feeds would be at the core of an operational system that could provide a relevant COP.

A range of system integration approaches have been identified or scoped out. These include the Alaska Ocean Observing System's (AOOS) Arctic Data Integration Portal (portal.aoos.org/arctic), and work conducted by the Department of Homeland Security (DHS) Arctic Domain Awareness Center (ADAC). However, a fundamental challenge remains in bridging the research-to-operations gap. This problem is amplified if research infrastructure is to be relied upon for operations and emergency response. To circumvent this challenge, it will be critical to form partnerships between the research community and key entities charged with providing information for emergency response. Additionally, any approach must draw on technology and infrastructure that is well integrated into local, national, or international response networks. Here, the State of Alaska Division of Homeland Security and Emergency Management (AKDHSEM) is of particular relevance, especially in terms of its emergency response guide for small communities (AKDHSEM, 2014), which would need to integrate information about MDA and COP relevant to community-level first responders. For the maritime domain, the Marine Exchange of Alaska (MXAK) is an important potential partner; in the context of the shore-based AIS infrastructure the MXAK has built up in recent years and with respect to the information provided to mariners at the local level.

For the present case study in the North Slope region, but also Arctic-wide, NOAA's Arctic ERMA (Merten et al., 2014) is of particular relevance. Arctic ERMA is already capable of integrating many types of relevant baseline data sets as well as operationally relevant environmental information such as ice charts or radar data, and has hence emerged as a centerpiece of information integration efforts. It is also capable of interfacing with local and traditional knowledge (Merten et al., 2014). At the same time, it is the tool of record to be used by USCG and other responders in the management of oil spill response and restoration. The application resides on federally accredited, secure infrastructure but is also able to use cloud-based computing services to address higher demands and portability during major response efforts. The next steps in advancing the utility of Arctic ERMA as an integrative framework would include interaction with the research community (Lovecraft et al., 2016) to help define priorities of variables to be observed and more effective integration of dynamic, near-real time information relevant for MDA and decision support into the ERMA framework. The interface between Arctic ERMA and community-level response may also require further consideration, for example, in the context of community response guides (AKDHSEM, 2014).

The availability of a common reference framework, computational infrastructure, and a core set of data streams could open the door for a broader evaluation of other resources and data sets that would enter into and substantially enhance development of a COP. The North Slope of Alaska (in particular, the Point Barrow region) is an ideal location to further explore and test such approaches, given both the level of maritime activity and the wide array of data collected in the region for environmental change research. Indeed, this process was started following the landfast ice breakout event summarized above and in Table 1, with the UAF ice radar system generating near-real time information on ice velocity at Utqiaġvik, shared with USCG District 17 and others through a web interface and data feed maintained by GINA. There is also potential to expand this capability using data from an atmospheric radar system operated in Utqiaġvik by the U.S. Department of Energy's Atmospheric Radiation Measurement North Slope Site (DOE-ARM; www.arm.gov/sites/nsa/C1).

While the DOE-ARM radar has been installed to obtain data on atmospheric precipitation and other climate variables, a first assessment indicates that the system may also be of potential value in providing information on ice movement and hazards (Fig. 11). The low-elevation, horizon-scan mode of the radar captures a range of sea-ice features and processes relevant in the context of hazard assessment and response, such as landfast ice breakout events (illustrated in the example shown in Fig. 11). Moreover, processing temporal sequences of radar data (currently only available at lower sampling rates than the coastal marine radar) indicates that data quality, at least during parts of the year, is sufficient to allow for derivation of ice velocity fields equivalent to those obtained from the dedicated ice radar (Fig. 12). With more than twice the range, the atmospheric radar covers much of the area of concern from a local community and vessel traffic perspective. The ARM program collects long-term, essential climate variable data at two locations in coastal Arctic Alaska. As such, it illustrates the potential value to be derived if relevant ARM data were disseminated to the operational hazards assessment community in a dual-use approach.

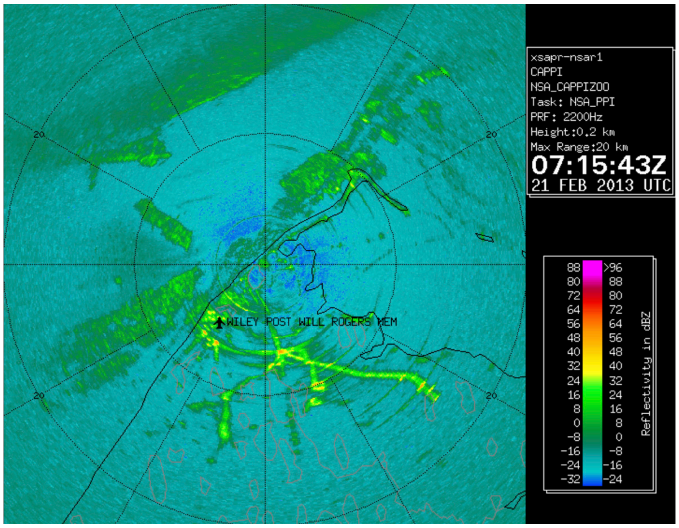

FIG. 11. Radar backscatter image from low-elevation horizon scan by DOE-ARM X-band precipitation radar system. The scene shows ice conditions comparable to those in Figure 8, with a fragment derived from the breakout event visible between the shorefast ice in the south and the offshore pack ice in the north. Range of image is twice that of scene shown in Figure 8, such that inner circle (radius c. 10 km) corresponds to the area covered by ice radar in that figure.

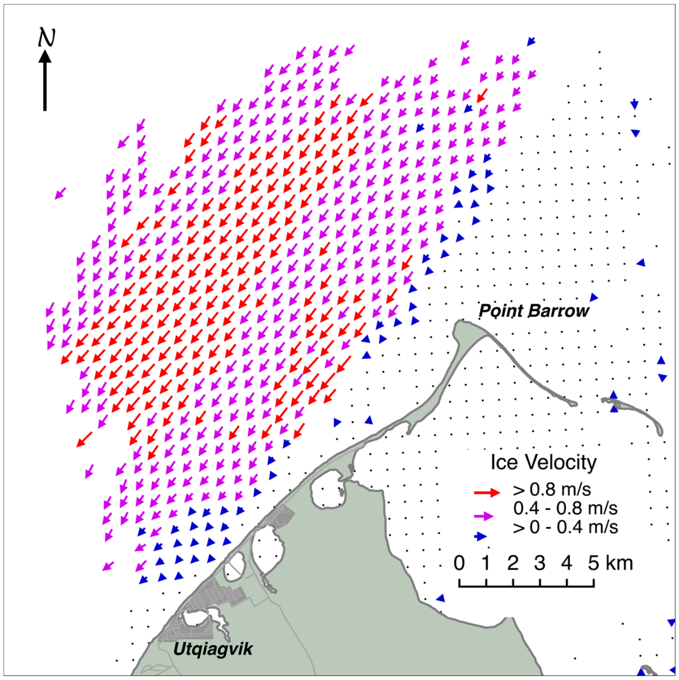

FIG. 12. Mean ice velocity field for 9 January 2014 derived from radar backscatter data obtained through low-elevation horizon scans by DOE-ARM X-band precipitation radar system. Note greater coverage of radar system extending well beyond Pt. Barrow as compared to coastal ice radar (e.g., Fig. 3).

Effective integration of different sensor systems and translation of research activities and findings into improved operations will also have to draw on numerical models. For the scenarios considered in this study, this will most likely be some type of coupled ice-ocean model (Zhang et al., 2012) with atmospheric forcing derived from reanalysis for hindcasts, or weather prediction systems for forecasts. Such work would be conducted in partnership with NOAA's Arctic Testbed. The NOAA Arctic Testbed goals are to improve marine, weather, climate, and sea ice forecasting decision support capability to meet expanding needs in the Arctic, in particular through evaluation and improvement of new modeling and data acquisition approaches, drawing on agency partners and the broader research community (Petrescu, 2015). We propose that significant advances in Arctic MDA could be achieved through the expansion of the testbed approach and implementation of a comparable effort. A North Slope Arctic MDA Testbed could serve as a proving ground to test and compare new sensor technology, automated observation systems, new modeling and process parameterization approaches, as well as different data fusion and integration methods. The Point Barrow region is ideal for such a testbed because of the multitude of sustained observing activities and associated data sets, relative ease of access, variety of environmental and operational hazards encountered in the region, and the support and interest of the local community.

A further potential benefit of such a testbed would be the availability of data sets, infrastructure, data product reference frameworks, and on-site support that would greatly increase the efficiency and potential impact of any individual sensor deployment, data acquisition, or field experiment. Some of the work under ADAC and other efforts, such as validation of coupled ice-ocean models for tracking of oil spills or improvement of coastal erosion and flooding models (Ravens et al., 2012; Ravens and Allen, 2012), would help provide a framework to evaluate the impact of specific types of measurements or observations on the accuracy and utility of predictions feeding into a COP and MDA system. Hence, such a testbed would also play an important role in helping identify, calibrate, and refine guidance from stakeholders and decision makers on the types of observation and modeling efforts needed to meet their most pressing demands. A challenge in this context is to ensure that available information and data sets are shared in near-real time with all relevant agencies and entities from the local to the (inter)national level, in formats and products that potential users are familiar with and can easily access. Such output would also have to be archived to be available for retrospective analysis, which is an important part of the testbed approach.

CONCLUSIONS AND NEXT STEPS

We conclude that sustained observations and data sets obtained as part of research efforts tracking Arctic environmental change can play an important role in informing, planning, and bolstering capacity for emergency response in maritime settings. A major challenge in achieving positive outcomes is the lack of communication and exchange between the emergency response sector and the marine and coastal climate research community.

The conclusions from this study may help in identifying promising steps forward in closing that gap, in particular through the Arctic Observing Summit and Arctic Council Working Group process.

There is significant value to be derived from the implementation of a framework for an MDA testbed on the North Slope of Alaska that serves (1) federal and state agencies, (2) the national and international academic research community, (3) local stakeholders, including partners in Community-Based Observing Networks (CBONS, Alessa et al., 2016), and (4) others interested in building capacity and increasing effectiveness of emergency response. Such a framework would include concepts and designs to bound the effort, a web-based portal and data and information service, and formal and informal agreements on contributions and collaboration between testbed partners and outside participants.

The example of the ARM atmospheric radar system serves to illustrate both the promise and challenge associated with such dual-use data and information partnerships, which have significant potential in meeting information needs at the community and emergency response level. Thus, as a climate research program, ARM is not in a position to provide data with the frequency and in the format needed by the response community. The response community is challenged to find ways to identify the potential value of such data and to provide support for dual-use data processing and dissemination. Data availability and integration contribute but do not guarantee operator knowledge relevant to MDA and response situations. Hence, relevant instruction, development of training modules, and mentorship should be part of any MDA testbed and COP development from the outset.

At the same time, long time-series observations of climate data variables play an important role in identifying anomalous and potentially hazardous conditions, as illustrated in the case study shown in Figures 4, 5 and 7. Probabilistic approaches to hazard assessments (e.g., in the design of offshore and coastal structures; ISO, 2010), are increasingly in need of such data including for an assessment of the statistics of extreme values (Fig. 6). Both a testbed in the Point Barrow region and broader efforts at data integration from sustained observations, as well as forecasts into operations, hazard assessment, and emergency response, require clear understanding of the requirements and preferences of operational users of such data. Surveys, interviews, and examples of specific data use-cases are needed to achieve this goal and help set priorities for data feed development and decision support tools.

In parallel with the establishment of a testbed, the analysis of available assets presented here suggests that a field exercise that builds on table-top exercises would be timely and could draw on and evaluate key aspects of a nascent environmental security and MDA testbed on the North Slope of Alaska. A prime goal for such an exercise would be to improve data and information product availability for key partners from the local to the national level, including but not limited to North Slope Borough Search and Rescue and Barrow Rescue Base, AKDHSEM, MXAK, USCG, NOAA Office of Response and Restoration, Alaska Clean Seas, and others tasked with emergency management and response.

In the Arctic, oil spill response efforts and search and rescue missions are typically planned based on low (> 6 km) resolution forecasts of environmental parameters such as ocean currents and sea ice concentration. However, coastal environmental parameters are subject to significant spatial variation, so our ability to respond to oil spills or to mount search and rescue missions in coastal settings is limited. Fortunately, preliminary investigations under ADAC have shown that high (100 m) resolution modeling and forecasting driven by existing low-resolution models and forecasts can be a low-cost and simple way to improve MDA. Further, such capabilities can be employed "on-demand" so that computer resources need only be used at specific locations when needed.

The focus of this study was on rapid-onset hazards. However, the study region is strongly impacted by slow-onset hazards such as coastal erosion or sea ice change. The potential threat from such hazards highlights the need for a research plan that identifies effective ways of expanding classic MDA and COP concepts to address challenges posed by slow-onset hazards that are typically not well addressed in a rapid-onset hazard response framework.

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REFERENCES

AKDHSEM (Alaska Division of Homeland Security and Emergency Management). 2014. Alaska emergency response guide for small communities. 49 p.
https://climatechange.alaska.gov/docs/AK-Emergency-Response-Guide-Small-Communities-2014-Final.pdf

Alessa, L., Williams, P., Kliskey, A., Beaujean, G., Ward, H., Ingott, J., and Ingott, E. 2016. Incorporating community-based observing networks for enhanced preparedness and responses to marine Arctic critical events. Arctic Observing Summit, 15–18 March 2016, Fairbanks, Alaska. 16 p.

Arctic Council. 2011. Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic. 18 p.
http://library.arcticportal.org/1474/

———. 2013. Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic. 230 p. https://oaarchive.arctic-council.org/bitstream/handle/11374/529/EDOCS-2068-v1-ACMMSE08_KIRUNA_2013_agreement_on_oil_pollution_preparedness_and_response_signedAppendices_Original_130510.PDF?sequence=6&isAllowed=y

———. 2015. Arctic environmental response management application. Report to the 09. Ministerial Meeting in Iqaluit, Canada, 24–25 April 2015. Arctic Council Secretariat. http://hdl.handle.net/11374/400

Barnhart, K.R., Overeem, I., and Anderson, R.S. 2014. The effect of changing sea ice on the physical vulnerability of Arctic coasts. Cryosphere 8(5):1777–1799. https://doi.org/10.5194/tc-8-1777-2014

Brigham, L.W. 2014. Environmental and economic security challenges in a changing U.S. maritime Arctic. Stanford, California: Hoover Institution, Stanford University.

Brunner, R.D., and Lynch, A.H. 2010. Adaptive governance and climate change. Chicago: University of Chicago Press. 404 p. https://doi.org/10.1007/978-1-935704-01-0

Bruno, M., Chung, K.W., Salloum, H., Sedunov, A., Sedunov, N., Sutin, A., Graber, H., and Mallas, P. 2010. Concurrent use of satellite imaging and passive acoustics for maritime domain awareness. 2010 International Waterside Security Conference, 35 November 2010, Carrara, Italy. 8 p. http://ieeexplore.ieee.org/document/5730229/authors?part=1

CBC News. 2015. NTCL barge that drifted to Russia is on its way home. July 28. http://www.cbc.ca/news/canada/north/ntcl-barge-that-drifted-to-russia-is-on-its-way-home-1.3170595

Clark, D.G., Ford, J.D., Berrang-Ford, L., Pearce, T., Kowal, S., and Gough, W.A. 2016. The role of environmental factors in search and rescue incidents in Nunavut, Canada. Public Health 137:44–49. https://doi.org/10.1016/j.puhe.2016.06.003

Cutter, S.L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., and Webb, J. 2008. A place-based model for understanding community resilience to natural disasters. Global Environmental Change 18(4):598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

Department of Homeland Security. 2005. National strategy for maritime security: National plan to achieve maritime domain awareness. Washington, D.C.: Department of Homeland Security. 33 p. https://www.dhs.gov/national-plan-achieve-maritime-domain-awareness

Druckenmiller, M.L., Eicken, H., Johnson, M.A., Pringle, D.J., and Williams, C.C. 2009. Toward an integrated coastal sea-ice observatory: System components and a case study at Barrow, Alaska. Cold Regions Science and Technology 56(2-3):61–72. https://doi.org/10.1016/j.coldregions.2008.12.003

Eguiluz, V.M., Fernández-Gracia, J., Irigoien, X., and Duarte, C.M. 2016. A quantitative assessment of Arctic shipping in 2010–2014. Scientific Reports 6: 30682. https://doi.org/10.1038/srep30682

Eicken, H., and Mahoney, A.R. 2015. Sea ice: Hazards, risks and implications for disasters. In: Ellis, J.T., Sherman, D.J., and Shroder, J.F., Jr., eds. Coastal and marine hazards, risks and disasters. Oxford: Elsevier. 381–401. https://doi.org/10.1016/B978-0-12-396483-0.00013-3

Eicken, H., Lovecraft, A.L., and Druckenmiller, M.L. 2009. Sea-ice system services: A framework to help identify and meet information needs relevant for Arctic observing networks. Arctic 62(2):119–136. https://doi.org/10.14430/arctic126

Eicken, H., Jones, J., Meyer, F., Mahoney, A., Druckenmiller, M.L., MV, R., and Kambhamettu, C. 2011. Environmental security in Arctic ice-covered seas: From strategy to tactics of hazard identification and emergency response. Marine Technology Society Journal 45(3):37–48. https://doi.org/10.4031/MTSJ.45.3.1

Eicken, H., Kaufman, M., Krupnik, I., Pulsifer, P., Apangalook, L., Apangalook, P., Weyapuk, W., Jr., and Leavitt, J. 2014. A framework and database for community sea ice observations in a changing Arctic: An Alaskan prototype for multiple users. Polar Geography 37(1):5–27. https://doi.org/10.1080/1088937X.2013.873090

Eicken, H., Lee, O.A., and Lovecraft, A.L. 2016. Evolving roles of observing systems and data co-management in Arctic Ocean governance. OCEANS 2016 MTS/IEEE Monterey, California. 8 p. https://doi.org/10.1109/OCEANS.2016.7761298

EPPR (Emergency Prevention, Preparedness and Response). 1998. Field guide for oil spill response in Arctic waters. Yellowknife: Environment Canada. 348 p.

———. 2014. EPPR Working Group Meeting: Final Report. Seattle, Washington: EPPR. 32 p. http://arctic-council.org/eppr/wp-content/uploads/2010/04/December_4_2014_Seattle_USA.pdf

Gearheard, S., Matumeak, W., Angutikjuaq, I., Maslanik, J., Huntington, H.P., Leavitt, J., Matumeak Kagak, D., Tigullaraq, G., and Barry, R.G. 2006. "It's not that simple": A collaborative comparison of sea ice environments, their uses, observed changes, and adaptations in Barrow, Alaska, USA, and Clyde River, Nunavut, Canada. Ambio 35(4):203–211. https://doi.org/10.1579/0044-7447(2006)35[203:INTSAC]2.0.CO;2

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton D.W., and Glenn, R. 2004. Observations on shorefast ice dynamics in Arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4):363–374. https://doi.org/10.14430/arctic514

Huggel, C., Stone, D., Eicken, H., and Hansen, G. 2015. Potential and limitations of the attribution of climate change impacts for informing loss and damage discussions and policies. Climatic Change 133(3):453–467. https://doi.org/10.1007/s10584-015-1441-z

Huntington, H.P., Raychelle, D., Hartsig, A., Harun, K., Heiman, M., Meehan, R., Noongwook, G., et al. 2015. Vessels, risks, and rules: Planning for safe shipping in Bering Strait. Marine Policy 51:119–127. https://doi.org/10.1016/j.marpol.2014.07.027

Hutchings, J.K., Roberts, A., Geiger, C.A., and Richter-Menge, J. 2011. Spatial and temporal characterization of sea-ice deformation. Annals of Glaciology 52(57):360–368. https://doi.org/10.3189/172756411795931769

ISO (International Organization for Standardization). 2010. ISO 19906:2010: Petroleum and natural gas industries – Arctic offshore structures. Geneva: ISO.

Jones, J., Eicken, H., Mahoney, A., MV, R., Kambhamettu, C., Yasushi, F., Ohshima, K.I., and George, J.C. 2016. Landfast sea ice breakouts: Stabilizing ice features, oceanic and atmospheric forcing at Barrow, Alaska. Continental Shelf Research 126:50–63. https://doi.org/10.1016/j.csr.2016.07.015

Laidler, G.J., Ford, J.D., Gough, W.A., Ikummaq, T., Gagnon, A.S., Kowal, S., Qrunnut, K., and Irngaut, C. 2009. Travelling and hunting in a changing Arctic: Assessing Inuit vulnerability to sea ice change in Igloolik, Nunavut. Climatic Change 94 (3-4):363–397. https://doi.org/10.1007/s10584-008-9512-z

Lee, O., Eicken, H., Kling, G., and Lee, C. 2015. A framework for prioritization, design and coordination of Arctic long-term observing networks: A perspective from the U.S. SEARCH Program. Arctic 68(Suppl. 1):76–88. https://doi.org/10.14430/arctic4450

Lovecraft, A.L., Meek, C., and Eicken, H. 2016. Data portals as institutional bridges: Connecting scientific observations to stakeholder needs in sea ice social-environmental systems. Arctic Observing Summit, 15–18 March 2016, Fairbanks, Alaska. 12 p.

Mahoney, A.R., Eicken, H., Fukamachi, Y., Ohshima, K.I., Simizu, D., Kambhamettu, C., MV, R., Hendricks, S., and Jones, J. 2015. Taking a look at both sides of the ice: Comparison of ice thickness and drift speed as observed from moored, airborne, and shore-based instruments near Barrow, Alaska. Annals of Glaciology 56(69):363–372. https://doi.org/10.3189/2015AoG69A565

Merten, A. 2013. New tool for first responders in the Arctic: Arctic ERMA. Witness the Arctic, Spring 2013(2). https://www.arcus.org/witness-the-arctic/2013/2/article/19951

Merten, A.A., Winters-Staszak, Z., and Kinner, N.E. 2014. Incorporating traditional knowledge and subsistence mapping into the Arctic Environmental Response Management Application. International Oil Spill Conference Proceedings 2014(1):1512–1523. https://doi.org/10.7901/2169-3358-2014.1.1512

MV, R., Jones, J., Eicken, H., and Kambhamettu, C. 2013. Extracting quantitative information on coastal ice dynamics and ice hazard events from marine radar digital imagery. IEEE Transactions on Geoscience and Remote Sensing 51(5):2556–2570. https://doi.org/10.1109/TGRS.2012.2217972

Norton, D.W., ed. 2001. Fifty more years below zero: Tributes and meditations for the Naval Arctic Research Laboratory's first half century at Barrow, Alaska. Fairbanks and Calgary: The Arctic Institute of North America.

Petrescu, E. 2015. An update on the Arctic test bed. Fairbanks: NOAA/NWS Alaska Region Headquarters, Environmental and Scientific Services Division. http://www.testbeds.noaa.gov/events/2015/workshop/presentations/tue-petrescu-atb.pdf

Pizzolato, L., Howell, S.E.L., Derksen, C., Dawson, J., and Copland, L. 2014. Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Climatic Change 123(2):161–173. https://doi.org/10.1007/s10584-013-1038-3

Ravens, T.M., and Allen, J. 2012. Inundation on the Yukon Kuskokwim Delta for present and future climates. Paper presented at the American Geophysical Union Fall Meeting, 3–7 December 2012, San Francisco, California.

Ravens, T.M., Jones, B.M., Zhang, J., Arp, C.D., and Schmutz, J.A. 2012. Process-based coastal erosion modeling for Drew Point, North Slope, Alaska. Journal of Waterway, Port, Coastal, and Ocean Engineering 138(2):122–130. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000106

Shahir, H.Y., Glasser, U., Nalbandyan, N., and Wehn, H. 2014. Maritime situation analysis: A multi-vessel interaction and anomaly detection framework. 2014 IEEE Joint Intelligence and Security Informatics Conference, 24–26 September 2014. 192–199. http://ieeexplore.ieee.org/document/6975572/

Statscewich, H., Roarty, H., Smith, M., Page, E., Glenn, S., and Weingartner, T. 2014. Enhancing Arctic Maritime Domain Awareness through an off-grid multi-sensor instrument platform. Marine Technology Society Journal 48(5):97–109. https://doi.org/10.4031/MTSJ.48.5.1

Stone, R.S., Dutton, E.G., Harris, J.M., and Longenecker, D. 2002. Earlier spring snowmelt in northern Alaska as an indicator of climate change. Journal of Geophysical Research 107(D10). https://doi.org/10.1029/2000JD000286

Sullivan, K. 2015. Statement from Dr. Kathryn Sullivan on NOAA's Fiscal Year 2016 Budget Request. Washington, D.C.: NOAA. 2 p. http://www.noaanews.noaa.gov/stories2015/20150203_statement-sullivan-noaa-fiscal-year-2016-budget-request.html

Verlinde, J., Zak, B.D., Shupe, M.D., Ivey, M.D., and Stamnes, K. 2016. Chapter 8 - The ARM North Slope of Alaska (NSA) sites. AMS Meteorological Monographs 57:8.1–8.13.

Vinnem, J.-E. 2007. Offshore risk assessment: Principles, modelling and applications of QRA studies, 2nd ed. London: Springer-Verlag. 578 p.

Zhang, J., Lindsay, R., Schweiger, A., and Rigor, I. 2012. Recent changes in the dynamic properties of declining Arctic sea ice: A model study. Geophysical Research Letters 39(20), L20503. https://doi.org/10.1029/2012GL053545