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ARTICLE

Broadening the sea-ice forecaster toolbox with community observations: a case study from the northern Bering Sea

Gregory J. Deemer, Uma S. Bhatt, Hajo Eicken, Pamela G. Posey, Jennifer K. Hutchings, James Nelson, Rebecca Heim, Richard A. Allard, Helen Wiggins, and Kristina Creek

Abstract: Impacts of a warming climate are amplified in the Arctic. One notorious impact is recent and record-breaking summertime sea-ice loss. Expanding areas of open water and a prolonged ice-free season create opportunity for some industries but challenge indigenous peoples relying on sea ice for transportation and access to food. The observed and projected increase of Arctic maritime activity requires accurate sea-ice forecasts to protect life, environment, and property. Motivated by emerging prediction needs on the operational timescale (≤10 days), this study explores where local indigenous knowledge (LIK) fits into the forecaster toolbox and how it can be woven into useful sea-ice information products. The 2011 spring ice retreat season in the Bering Sea is presented as a forecasting case study. LIK, housed in a database of community-based ice and weather logs, and an ice-ocean forecast model developed by the US Navy are analyzed for their ability to provide information relevant to stakeholder needs. Additionally, metrics for verifying numerical sea-ice forecasts on multiple scales are derived. The model exhibits skill relative to persistence and climatology on the regional scale. At the community scale, we discuss how LIK and new model guidance can enhance public sea-ice information resources.

Key words: sea ice, forecasting, Bering Sea, indigenous knowledge, community observations, operations.

Résumé : Les impacts du réchauffement climatique sont amplifiés en Arctique. Un impact certain est la récente perte record de glace de mer en été. L’expansion des zones d’eau libre et une saison sans glace prolongée créent des occasions pour quelques industries, mais constituent un défi pour les peuples autochtones qui comptent sur la glace de mer pour le transport et l’accès à la nourriture. L’augmentation observée et projetée de l’activité maritime arctique nécessite des prévisions de glace de mer précises afin de protéger la vie, l’environnement et la propriété. Cette étude, motivée par de nouveaux besoins de prédiction sur une échelle de temps opérationnelle (≤10 jours), explore à savoir à quel niveau la connaissance indigène locale (CIL) peut s’insérer dans la boîte à outils des prévisionnistes et comment cette connaissance peut être intégrée dans des produits servant d’information sur la glace de mer. La saison de recul des glaces au printemps

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G.J. Deemer* and U.S. Bhatt. Department of Atmospheric Sciences, University of Alaska Fairbanks, Fairbanks, AK 99775, USA.
H. Eicken. International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK 99775, USA.
P.G. Posey and R.A. Allard. Naval Research Laboratory, Stennis Space Center, Mississippi, MS 39529, USA.
J.K. Hutchings. Oregon State University, Corvalis, OR 97331, USA.
J. Nelson and R. Heim. Alaska Region, NOAA/National Weather Service, Anchorage, AK 99502, USA.
H. Wiggins and K. Creek. Arctic Research Consortium of the United States, Fairbanks, AK 99709, USA.
Corresponding author: Greg Deemer (e-mail: gregory.j.deemer@gmail.com).
*Current address: National Snow and Ice Data Center, CIRES/University of Colorado Boulder, 449 UCB, Boulder, CO 80309, USA.

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2011 en mer de Béring est présentée comme une étude de cas de prédiction. La CIL, sauvegardée dans une base de données de registres des glaces et de météorologie provenant de la communauté, ainsi qu'un modèle de prévision des glaces et océans développé par la marine américaine sont analysés afin d'évaluer leur capacité à fournir des informations pertinentes pour les besoins des parties prenantes. De plus, des mesures numériques pour vérifier les prévisions de glace de mer sur plusieurs échelles sont dérivées. Le modèle a démontré sa capacité quant à la persistance et à la climatologie à l'échelle régionale. Nous discutons comment, à l'échelle communautaire, la CIL et une nouvelle orientation du modèle peuvent améliorer les ressources d'information publique sur la glace de mer. [Traduit par la Rédaction]

Mots-clés : glace de mer, prévision, mer de Béring, connaissance indigène, observations communautaires, opérations.

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Introduction and background

The need for improved sea-ice forecasts and contributions by local and indigenous knowledge holders

Continued summertime retreat of Arctic sea ice alters the timing and duration of the open water season (Walsh 2008). Consequently, changes in the seasonal cycle constrain subsistence hunting for coastal communities (Gearheard et al. 2006; Kapsch et al. 2010) while at the same time providing a lengthened window-of-operation for industry and other commerce (e.g., Crandall and Thurston 2010; Dennis and Mooney 2016). To address growing societal information needs, forecasts of sea ice need to be improved on multiple scales (Eicken 2013). Seasonal to decadal prediction is required to understand impacts of retreating summer sea ice on the planetary heat budget and oceanic and atmospheric circulation systems as well as the terrestrial environment (Committee on the Future of Arctic Sea Ice Research in Support of Seasonal to Decadal Prediction (National Research Council) 2012). Regional projections are needed to help Arctic nations plan for the increase of sea-ice users and their conflicting interests (Lovecraft et al. 2013) with appropriate governance, regulation, and strategies for sustainability (Brigham 2007; Rayfuse 2007; Baker and Mooney 2013). The weather timescale, generally recognized as being ≤10 days and most commonly associated with the term "forecasting", needs immediate attention to aid decision making for all stakeholders operating on, or in the presence of, sea ice.

A major step forward was made in 2011, when the National Oceanographic and Atmospheric Administration (NOAA) put forth their Arctic Vision and Strategy (NOAA 2011*a*) listing sea-ice forecasting as the first of six core goals. More recently, the NOAA Arctic Action Plan (NOAA 2014*a*) reiterated the call for forecast improvements needed to support the advancement of US security interests, a line of effort in the US National Arctic Strategy (White House 2013). Additional departmental workshops (NOAA 2011*b*, 2014*b*) support intensive efforts to improve sea-ice prediction with local and indigenous observations listed as a desirable information source. However, the familiar pathways (e.g., model development, data assimilation schemes, and satellite observation programs) are given the most attention therein, leaving a gap in the pathway forward for incorporating local and indigenous knowledge (LIK) into the operational toolbox.

The need for LIK in the realm of operational sea-ice forecasting derives from its distinct advantages in providing context as well as insights into linkages between physical processes and their impacts at the forecast-relevant scale. Holders of LIK have an understanding of the coastal environment that operational ice centers serve, set in a long-term historical context (Eicken 2010) that pre-dates modern observing systems as well-respected senior observers pass information to apprentices within the community. This context then aids in detection of rare and (or) hazardous events that might otherwise

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seem inconspicuous to persons unfamiliar with the local environment. Additionally, LIK of sea ice seldom stands alone, without connection to broader environmental and biological processes. Rather than focusing on an isolated, singular sea-ice variable, LIK may also include one or more connections between sea ice, currents, tides, winds, important events in the lifecycle of biota (e.g., migration patterns), and perspective on long-term changes (Huntington et al. 2009; Eicken 2010). Forecasters or public agency partners have much to gain from these observations, as their mission to inform nontraditional operators of risk and regulation can be enhanced directly through the narrative that LIK provides.

Lastly, even with advances in observational instrumentation and numerical modeling techniques that increase the spatiotemporal resolution of the forecaster toolbox, LIK retains an advantage in being able to deliver information at the community scale, where small but significant hazards and their precursor processes can threaten marine navigation and subsistence activities. In a reflection on new weather and ice forecast resources that serve his community of Gambell, Alaska, George Noongwook, an experienced hunter within the village states (in Oozeva et al. 2004): "Despite the information obtained, visual or otherwise, there is no replacement to traditional knowledge". In further description of how LIK is considered alongside modern forecasts to make the decision to risk a hunt or take no action, Noongwook says: "you have made good judgment in the end because of this alternative tool that you can use for your benefit". (Oozeva et al. 2004). In this paper, we argue that the alternative tool of LIK, when considered by the forecast provider, can also be useful in guiding other forecast consumers to good judgment and responsible actions.

Distinguishing indigenous knowledge from other human observations

Human observations of the environment are often made through established monitoring system frameworks. A monitoring system might be composed of citizen scientists or individuals instructed to make targeted observations of specific events and occurrences. More importantly, the targeted observations are often performed for a singular project. Observations collected by a citizen scientist can be achieved with basic training. In the case of sea-ice research, a relevant example is recording defined sea-ice variables while aboard a polar cruise (Farmer et al. 2016). A cooperative observer program (e.g., NOAA 2010) takes the role of a citizen scientist one step further by providing installation, training, and maintenance for standardized instrumentation. Participants in the cooperative observer program form part of a wide network that is both long term and self-sustaining.

Local and indigenous knowledge (LIK), the latter also referred to as "traditional" or "traditional environmental knowledge", is distinct in comparison to standardized observations completed through citizen science and cooperative frameworks. Indigenous persons born into a community where the understanding of physical, environmental, and ecological processes is essential to survival, and are part of a broader holistic worldview, hold a knowledge of sea ice that is learned and refined over a lifetime and not confined to any particular interval of time. Academic knowledge of the sea-ice environment is acquired in a setting that differs greatly in comparison to local communities. More specifically, LIK is gathered to understand environmental hazards that affect the livelihood of community members.

Anthropologist Jean-Michael Huctin summarized the knowledge of indigenous environmental experts succinctly as: "the Inuit hunters have Ph.D.'s in living in nature" (Folger and Jazbec 2015). The analogy to an advanced degree is appropriate, as indigenous knowledge is subject to continuous peer review from fellow observers before being passed down through generations (Oozeva et al. 2004). Careful fact-checking establishes

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disciplinary expertise held by key informants (i.e., elders) who are trusted by the community to consult those seeking local perspectives and guidance (Huntington et al. 2009; Eicken 2010). Nonindigenous residents of the Arctic can also hold valuable local knowledge, as their experiences hunting, fishing, and traveling in the region lead to observations of, and insights into, environmental processes.

Established coastal community observation networks

The emergence of community observation databases for the Arctic is relatively new. For the villages of northern and western Alaska, the roots of systematic LIK observations can be traced back to a letter of concern written by the former head of the Eskimo Walrus Commission, Caleb Pungowiyi, in Nome, Alaska, to the Marine Mammal Conservation in Washington, DC, in late 1998. This letter raised the concern that despite an increasing volume of literature being published on environmental changes occurring in the western Arctic, voices of community members were not being considered seriously in the process (Krupnik 2002). The response from the Marine Mammal Commission, borne out of the Marine Mammal Protection Act of 1972 and the agency involved in developing policy and tracking issues impacting marine mammals, was to organize a workshop bringing together both indigenous Alaskans and academic scientists in the fall of 2000. Workshop participants, seeing that additional efforts of aligning the language used between scientists and holders of LIK were needed after the initial meeting, decided to launch a pilot observation project. Indigenous experts Conrad Oozeva and George Noongwook from the villages of Gambell and Savoonga, Alaska, respectively, offered to keep sea-ice and weather records the following winter of 2000–2001. The observations serve both as a cultural preservation resource for youth and as a guide for practitioners of western science to understand the connection of ice and weather to subsistence resources valued by indigenous communities.

The successes of the pilot observing project during the winter of 2000–2001 on St. Lawrence Island, along with the increased recognition of important contributions by indigenous experts in the environmental sciences, fueled the creation of a seminal, pan-Arctic project as part of the International Polar Year (IPY) 2007–2008, known as Sea Ice Knowledge and Use (SIKU) (Krupnik et al. 2010*a*). Intersecting with the SIKU organizational structure is the Seasonal Ice Zone Observing Network (SIZONet) that supports an Alaska project to record, archive, and share indigenous sea-ice knowledge and expertise. The SIZONet database, developed in collaboration with the Exchange for Local Observations and Knowledge of the Arctic (ELOKA), includes systematic (i.e., near-daily) text observations and photographs of weather, sea ice, hunting practices, environmental indicators, and their historical context (https://eloka-arctic.org/sizonet). Observations from community members are either hand written or typed digitally, accrued over the course of a month, and sent to data curators at the University of Alaska Fairbanks to ingest and tag with key topics (e.g., sea ice, weather, and hunting) for discoverability by database users. The project is one of the first with a focus on sea ice in the Arctic, but just one example of broader efforts focusing on LIK not limited to the high latitudes (Eicken et al. 2014).

Investigators in SIKU and SIZONet recognized the need and opportunity to make local and traditional knowledge available beyond the research context. One connection to the project is a sea-ice user-focused program aimed at providing more useful information on sea-ice cover on weekly to seasonal timescales to address practical needs of indigenous communities, marine-living resource managers, and marine biologists (Eicken et al. 2011). The primary need for coastal villages is a channel of communication and forum in which conditions relevant to marine safety can be shared. In 2010, the Sea Ice for Walrus Outlook (SIWO) (www.arcus.org/search-program/siwo) was launched under the Study of

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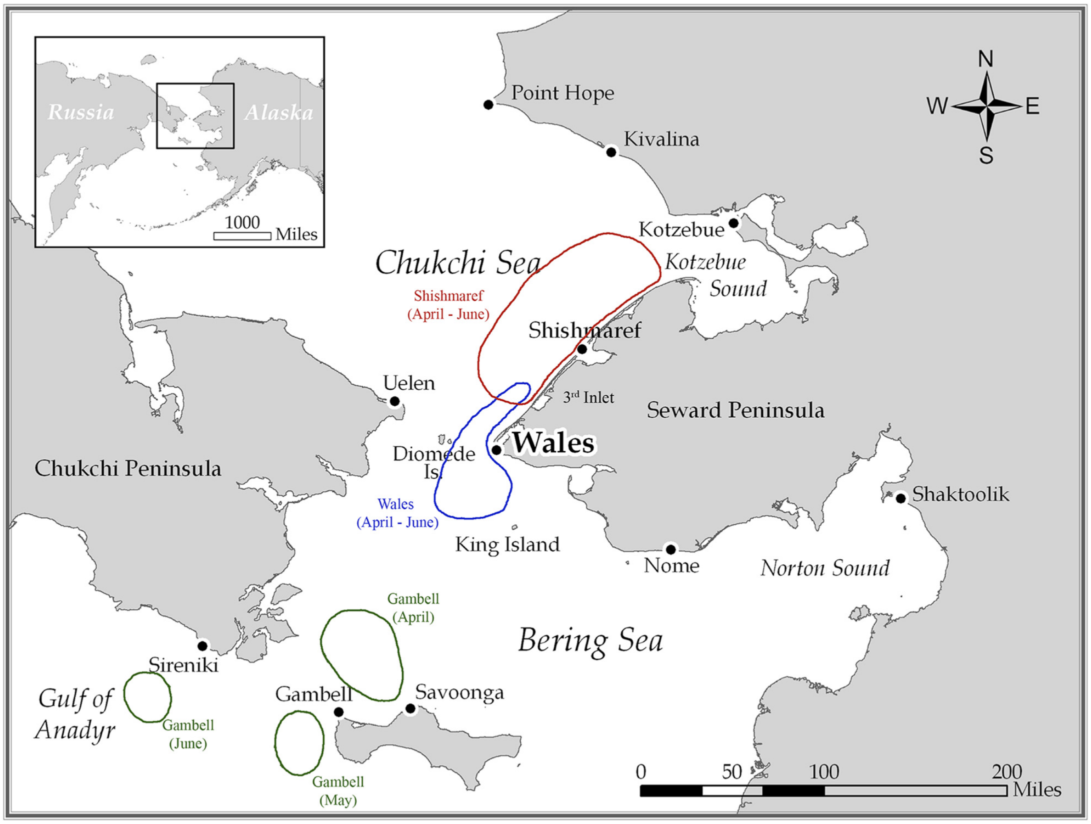
Fig. 1. Sea Ice for Walrus Outlook (SIWO) communities of Gambell, Wales, and Shishmaref, Alaska. Annotations show the regions of interest for each community over the course of a typical hunting season.



Environmental Arctic Change (SEARCH) and in conjunction with the SIZONet observation program to fill this need. Alaska indigenous communities, the Eskimo Walrus Commission, the National Weather Service (NWS) Alaska region, the University of Alaska Fairbanks, and the NOAA Pacific Marine Environmental Laboratory (PMEL) are all production partners of the outlook.

SIWO functions seasonally from April through June during the sea-ice retreat season in the northern Bering and southern Chukchi seas (Fig. 1). The outlook is updated once per week with weather and sea-ice outlooks. Observations from communities are submitted when possible and are then manually uploaded to the web portal. Observation and knowledge sharing is not limited to Alaska indigenous communities. Researchers and members of the public alike contribute relevant information for building current and historical perspectives on ice conditions, ice use by communities, marine mammals, and subsistence activities. Fit-for-purpose satellite imagery and references to operational sea-ice products are also provided, producing a full suite of information for outlook users. After the SIWO season concludes, a retrospective analysis of the outlook with respect to improved Arctic environmental observations in the context of prediction capabilities is also published.

Sea-ice processes in the Bering Sea

Sea ice in the Bering Sea normally reaches its maximum extent in March (Niebauer 1980) and is absent during the summer months. Ice formation leading up to the maximum can be

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described as a conveyor belt, where ice grows in situ along the eastern and southern land–sea boundaries and is advected by northeasterly winds towards the shelf break (Pease 1980). Most sea ice within the Bering Sea is formed in situ with minimal southward transport through the Bering Strait. Episodes of southward transport do occur when strong northerly winds correlate with current reversals (Roach et al. 1995), but such episodes are typically short-lived and contribute little to the total Bering ice mass, as discussed by Kozo et al. (1987). Unrafted ice thickness at the end of the growth season is usually around 0.5 m, but ice deformation can create ice features up to 10 times the thickness of contributing floes (Pease 1980). The Bering shelf break defines the southern limit of the sea-ice cover, where ice originating in the north melts over the deeper warm water column of the Aleutian Basin (Hendricks et al. 1985). Since the beginning of the satellite record, the extent of the wintertime ice pack in the Bering Sea has moved southward, in contrast with diminishing winter extent across the Arctic. Upper atmospheric circulation patterns and climate oscillations in the North Pacific have been found to correlate with the positive trend in Bering Sea winter maximum ice extent (Matthewman and Magnusdottir 2011; Wendler et al. 2013), but a leading mechanism has yet to be determined. Ice retreat in the Bering Sea is coincident with a northward shift in the trajectory of the North Pacific storm track (Overland 1981; Overland and Pease 1982; Schumacher and Kinder 1983). Given sufficient time in spring, the radiation balance would melt the ice pack altogether (Curry et al. 1995), but storms will play a key role in advancing sea-ice decay (Pease 1980). Sea-ice breakup in the Bering Sea represents a time when many sea-ice forecast stakeholders are active.

National Weather Service operational sea-ice products and product consumers

The NWS Alaska Sea Ice Program (ASIP) produces sea-ice analyses for the Bering, Chukchi, and Beaufort seas extending to 80°N as well as Cook Inlet. The primary data source for the creation of analyses originates from satellite remote sensing resources. Conventional aircraft, coastal radar, visual and infrared airborne and satellite imagery, passive microwave sensors, laser airborne profilers, scatterometers, and variations of synthetic aperture radar, when available, are brought together into geospatial software to render a final product (WMO 2010). The ASIP analysis is produced daily and consists of a pair of marine charts and a detailed text description (Heim and Schreck 2017). One chart is dedicated to sea-ice concentration (Fig. 2*a*) and the other displays the stage of ice development and ice type. A key feature that analysts meticulously depict is the ice edge. In many regional- to climate-scale studies, the ice edge is defined as the 15% sea-ice concentration contour, as it provides the most consistent agreement between legacy passive microwave remote sensing products and observations (Cavalieri et al. 1991). However, in the context of operational sea-ice centers, the ice edge defines ice-free ocean from neighboring areas with concentrations greater than zero. More specifically, ASIP adopts the WMO ice edge definition of: demarcation at any given time between the open sea and sea ice of any kind, whether fast or drifting. It may be termed "compacted" or "diffuse" (WMO 1970). The ice–no-ice boundary is produced as a conservative measure to serve as a navigational aid.

ASIP issues a 5 day sea-ice forecast every Monday, Wednesday, and Friday. The forecast consists of a spatial marine chart (Fig. 2*b*) and a supporting text discussion. The forecast chart is composed of four key elements: pack ice (>80% concentration), the marginal ice zone (≤80% concentration), shorefast ice, and sea-ice-free waters. Each prediction focuses on the net drift near the ice edge, where the largest changes are expected over a 5 day forecast period.

The stakeholder group for the NWS Ice Desk is diverse and closely connected to the agency's products. Commercial fishing in the Bering Sea accounts for nearly half of

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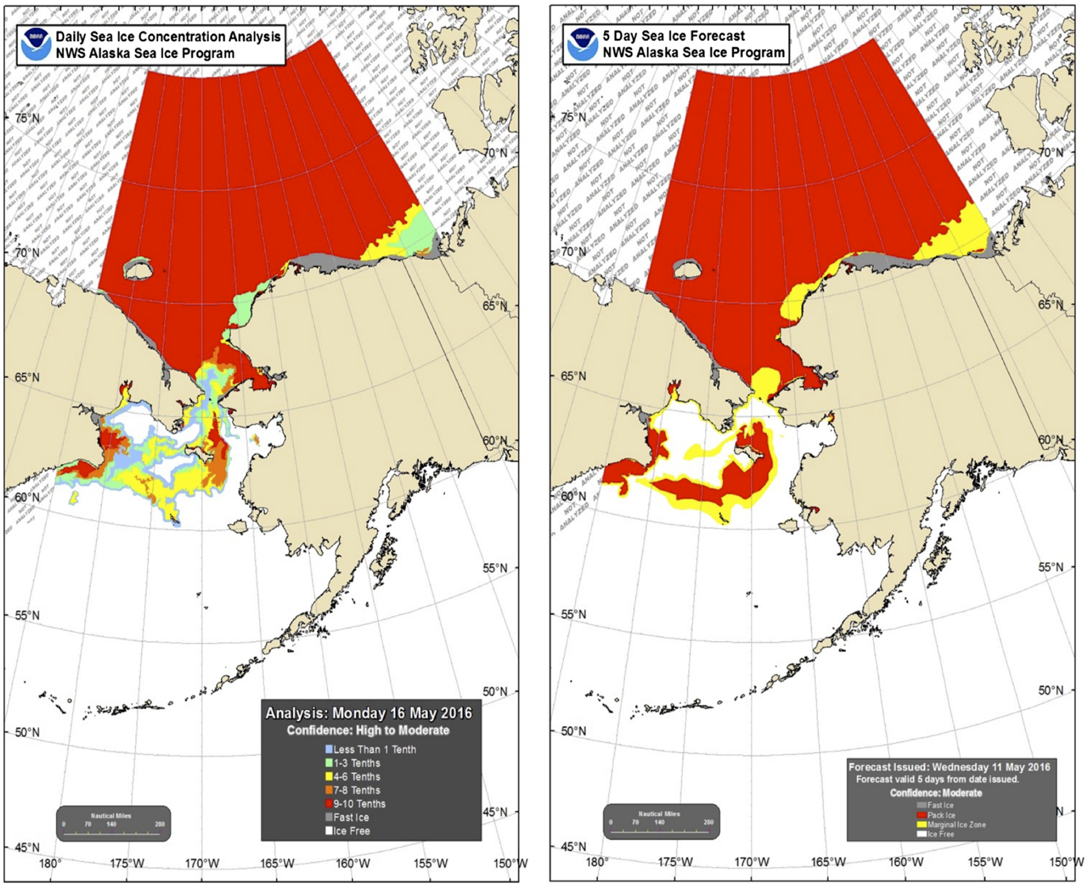
Fig. 2. (*a*) Present-day National Weather Service (NWS) sea-ice analysis for 16 May 2016 using Sea Ice GeoReferenced Information and Data (SIGRID)-3 standards (WMO 2014). The sea-ice stage of development chart (not shown here) accompanies the concentration analysis (http://www.weather.gov/afc/ice). (*b*) Sea-ice forecast chart created 11 May 2016, valid 16 May 2016, showing the expected extent for the marginal ice zone (<80%), the ice pack (≥80%), and shorefast ice.



(a) (b)

the US annual catch and can be heavily impacted by sea ice, threatening vessels and crew or access to processing facilities. Coastal population centers and industrial installations rely on heavy cargo and commodity deliveries via barge in the absence of ice. Other stakeholders are interested in rivers that terminate along ice-impacted coasts, which remain off limits to travel until offshore ice clears. Emergency and hazard managers such as the US Coast Guard and NOAA's Office of Restoration and Response as well as commercial fishing fleets are major users of ASIP products. The connection between ASIP sea-ice forecasts and users is already strong but could be further enhanced through the narrative and knowledge that exists in LIK, if made available.

The operational sea-ice forecaster toolbox

Operational sea-ice forecasters utilize a diverse set of tools when generating sea-ice forecast products. Knowledge-based experience of local currents, bathymetry, and nuances in localized regions, which all act dynamically upon sea ice throughout changing seasons, is utilized in generating forecasts. In addition, buoy data, ship and aviation reports, and local

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shore-based observations (not limited to LIK) are common sources of ground truth information used for the verification of satellite imagery depicting sea-ice conditions and are also used in the prognosis of operational-scale sea-ice changes. Additional forecast guidance is provided by a suite of weather and sea-ice model solutions. Numerical weather prediction models common to all NWS offices, simple sea-ice drift models (Grumbine 1998, 2013), and the newer Arctic Cap Nowcast Forecast System are referenced in the production of the 5 day forecast charts and text discussion.

The setting of Gambell, Alaska, as a local-scale case study

The village of Gambell (Fig. 1) is a key community for the SIKU and SIZONet projects. Experts from Gambell were among the first to collaborate with project organizers in 2006. Within the indigenous Yupik community, there are hundreds of sea-ice forecast stakeholders (Krupnik et al. 2010*b*) who primarily use sea ice for both a cultural (e.g., spiritual or educational) and provisioning (e.g., taking subsistence resources) purpose, following Eicken et al. (2009).

The icescape around Gambell is characterized by deformed ice, held in place by grounded floes and ridges along the northern coastline, with drifting sea ice offshore. A typical maximum distance traveled from the village in pursuit of marine mammals is 75 km, but changing ice seasonality in a warming climate results in lengthier boating time and distance traveled (Kapsch et al. 2010; Eicken et al. 2014). A present-day hunt typically consists of three to five male family members or relatives in a 16 ft. long aluminum-hulled skiff or more traditional walrus skin boat with sail and oar. Hunters often use drifting sea ice directly as a platform for butchering their catch or as a method of transportation by piloting the boat on top of a sea-ice floe and drifting with the current. They also make use of drifting sea ice as a tactical method to avoid rougher seas in the open ocean. In the event of a successful hunt, added weight of the catch destabilizes a crew's boat, presenting another hazard in challenging marine conditions. A subtler hazard includes the background change in climate, which diverges from long-held local knowledge. George Noongwook elaborates on these issues, saying: "there is indeed a change coming into your environment because of Arctic warming [. . .] and it puts at risk peoples lives because of the changing weather conditions and the new ice regime" (Oozeva et al. 2004). Improved forecasts would help captains and their crews minimize uncertainty and reduce the risk in making decisions to leave shore in search of game.

Research objectives

Advances in sea-ice modeling are underway (Reynolds et al. 2016) and will progress to become an integrated part of the sea-ice forecaster's toolbox, just as numerical models were welcomed for weather prediction. However, will deterministic models identify ice features or other related physical–environmental processes of importance to users? Our key objective is to lead a discussion on how LIK can be useful in operational prediction and as a resource for validating the efforts of the modeling community while at the same time providing information useful to multiple consumers.

The first component of our objective is to establish a baseline skill assessment of the US Navy operational sea-ice model. The baseline will be a measure of the model's performance on the regional scale and over the course of a spring melt season. To date, only pan-Arctic validation and ice edge forecasts of the Arctic Cap Nowcast Forecast System (ACNFS) have been performed (Posey et al. 2010; 2015). Our effort focuses on sea-ice prediction within the ice extent defined as ≥15% concentration and is targeted at the Bering Sea.

The second component of our objective is to determine what information or value can LIK add to operational sea-ice products. We narrow the forecast scope to a community-scale case

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study in the northern Bering Sea and present sea-ice forecast information relative to stakeholder needs. LIK is discussed in parallel with both operational products and model solutions to uncover areas of need. While this research is focused on one particular season in the Bering Sea, it serves as a representative example of how LIK can be used in an operational setting.

Data and forecast tool evaluation methods

Local indigenous knowledge

Contributions to SIZONet and SIWO during the spring 2011 retreat season are considered in this study. LIK holders who participated were encouraged to include standard meteorological data on winds and temperatures, but observations were not carried out according to a standard protocol. Rather, any guidance to observers was to capture and log information and LIK relevant to ice use and services provided by the sea ice for the specific community (Eicken et al. 2009, 2014). The contributing observers were identified as experts within each community through a broader, consensus-based process detailed in Eicken et al. (2014). The observations are in text format and sometimes contain photographs to support a narrative. Observations were gathered while on the shore, in personal transportation vehicles (e.g., watercraft, snow mobile, and ATV), or collected from various other experts in the communities and processed for consensus before being used to generate a summary.

Indigenous participants focused on information relevant to local community needs. Experts in the communities of Gambell, Shishmaref, Toksook Bay, and Wales, representing the northern Bering Sea region in the SIZONet database, submitted 139 observations between 1 April and 30 June 2011. Gambell and Wales observers provided 137 observations, 81 of which were taken in Wales. At the same time, SIWO functioned on a once per week basis for 14 weeks during the April through June retreat season, showcasing 28 contributions, 18 of which were LIK. University researchers offered their discussion on nine occasions, and a federal agency employee provided aerial photography of coastal sea ice.

The Arctic Cap Nowcast Forecast System

The ACNFS is a 1/12° resolution sea-ice forecast modeling system based on the HYbrid Coordinate Ocean Model (HYCOM) coupled via the Earth System Modeling Framework (ESMF) to the Los Alamos National Laboratory Community Ice CodE (CICE) and uses the Navy Coupled Ocean Data Assimilation (NCODA) system (Posey et al. 2010). The nominal, horizontal resolution within the Bering Sea is on the order of 4.5–5.5 km^2.

Oceanic data assimilated into the system include satellite observations of sea surface height and temperature as well as in situ ocean observations from Argos floats. The spatial extent of the Argos floats is limited to the deep basins and observations in the Bering Sea are sparse. Advanced Very High Resolution Radiometer (AVHRR), MeteoSat Second Generation (MSG), Geostationary Operational Environmental Satellites (GOES), and the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) provide observations for sea surface temperature and height during the 2011 case study. Real-time data gathered from Special Sensor Microwave Imager/Sounder (SSMIS) radiometers aboard Defense Military Satellite Program (DMSP) platforms are used to initialize sea-ice concentration. Three-hourly atmospheric forcing is supplied to the ACNFS from the 0.5° Navy Operational Global Atmospheric Prediction System (Hogan and Rosmond 1991), which assimilates observations using a 4-D variational assimilation system (Rosmond and Xu 2006).

The ACNFS runs in real time at the Naval Oceanographic Office located at the Stennis Space Center in Stennis, Mississippi. The model system runs once per day in three different stages. First, a 72 h hindcast is performed to assimilate late-arriving altimeter observations. The second stage of the model run creates a nowcast that captures and assimilates data in

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the most recent 12 h. The model nowcast is also known as the analysis and is the best representation of real-time conditions with the assimilated data. In the final stage of each run, the model system produces five forecasts in a 24 h time step extending out to 120 h.

The ACNFS has been validated in the context of addressing improvements from its predecessor on the pan-Arctic scale (Posey et al. 2010) and at the time of this study was still undergoing forecast verification and skill testing (Hebert et al. 2015; Posey et al. 2015). Targeted verification studies for the Bering Sea have not yet been presented and are explored further in this paper. During the 90 day evaluation period, the modeling system had 8 days of down time, halting production of new analyses and forecast products. These days were removed from the evaluation. Data removal leads to small difference in the number of forecasts throughout the season, but utilizing all available forecast lead times results in 71–76 samples available for this study.

The Global Ocean Forecast System (GOFS) 3.1 is slated to take the place of the ACNFS in 2017. GOFS 3.1 is an incremental change to the ACNFS and uses the same horizontal model resolution. Once declared operational, GOFS 3.1 will provide the Navy with a global sea-ice–ocean prediction capability that includes both the Arctic and Antarctic.

Regional-scale forecast verification of the ACNFS

Persistence and climatology are low-skill reference forecasts in this study. All climatologies are gridded products constructed from a 1979–2000 period of record, which was the accepted definition used by the National Snow and Ice Data Center at the time of analysis. All climate data were regridded from their native resolution using bilinear interpolation to match the 1°–12° grid of the ACNFS. The temporal resolution of the climatologies is daily.

Sea-ice climatology data: concentration, thickness, and drift speed

The 25 km × 25 km passive microwave sea-ice concentration climatology (Peng et al. 2013) uses a blend of the NASA Team-I and Bootstrap algorithms. This climatology differs from SSMIS data assimilated by the ACNFS, which uses the Navy AES-York algorithm (Hollinger et al. 1991). At the time of this study, archived SSMIS data processed by the AES-York algorithm were unavailable. A thorough evaluation and intercomparison of the sea-ice detection algorithms can be found in Steffen et al. (1992). The verification study presented in this paper does not account for the differences in concentration provided by the two algorithms. However, over the course of a season and across the regional scale, these differences should be negligible.

The Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) provides the best spatial representation of ice thickness in the Bering Sea. PIOMAS is a reanalysis of Arctic sea ice (Zhang and Rothrock 2001) through time and provides a popular index for the pan-Arctic value and trend in sea-ice volume. PIOMAS has been validated using in situ data (Lindsay 2013) and shows strong correlations with in situ observations. The modeled ice cover in PIOMAS slightly underestimates thick ice and overestimates thin ice (Schweiger et al. 2011). A local-scale validation study (Zhang et al. 2010) using upward looking sonar records in the St. Lawrence Island polynya of the northern Bering Sea shows that observed dynamic ice thickening is captured by the model, but with a small departure in the timing of ridging and rafting events.

A multisensor data set (Fowler et al. 2013) is used to produce the sea-ice drift climatology. The data include ice drift from in situ buoys, derived ice displacement from passive microwave radiometers, and inferred sea-ice motion using NCEP/NCAR reanalysis forcing. Because in situ sea-ice drift observations in the Bering Sea are absent, climatological sea-ice drift in the region depends entirely on reanalyzed forcing and motion derived from passive microwave sources. A 7 day moving average is applied to reduce weather and tidal noise.

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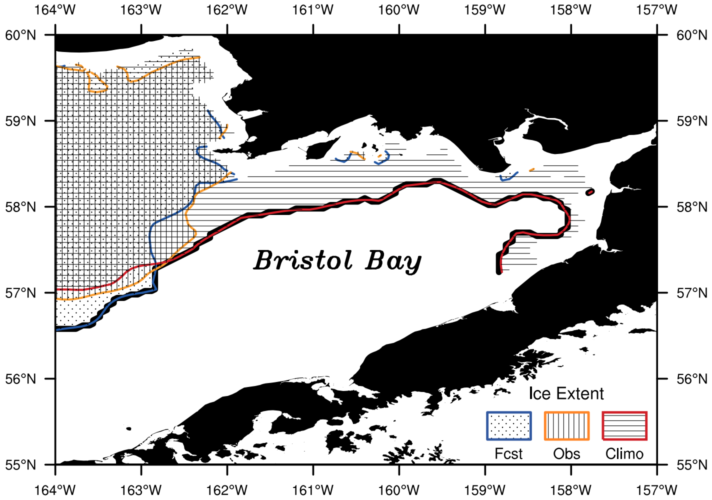
Fig. 3. Defining a daily dynamic analysis domain for regional verification. Blue, 120 h Arctic Cap Nowcast Forecast System (ACNFS) forecast extent created on 00z 2 April 2011; orange, ACNFS analysis (orange line) on 00z 7 April 2011; red, climatological ice extent from SSMI on 7 April. A bold black line capturing maximum extent illustrates the dynamic domain in the skill score calculation.



The skill score method

Forecast skill refers to the relative accuracy of a set of forecasts, with respect to a set of standard control, or reference, forecasts (Wilks 2011). This study adopts a skill score based on the ratio of mean squared error (MSE) of the predictand to the MSE of the reference and is used to evaluate the scalar variables of sea-ice concentration, thickness, and drift speed. Generally, the expression takes the following form (Jolliffe and Stephenson 2003):

$$(1)\quad \mathrm{MSESS} = 1 - \frac{\mathrm{MSE}_P}{\mathrm{MSE}_R} \Rightarrow \frac{\Sigma(P-O)^2}{\Sigma(R-O)^2}$$

MSESS translates to MSE skill score, hereafter shortened to skill score (SS). O denotes an observed value, synonymous with the model analysis field in this study. P and R represent the predictand and reference, respectively. Perfect forecasts receive a score of unity. Positive scores are assigned to forecasts that outperform the reference, and negative scores indicate no skill relative to the reference. We take the SS one step further in regional analysis and normalize forecast performance over the course of the 2011 spring retreat season through a summation of skillful forecasts ($\mathrm{SS} > 0$) relative to number of days with sea ice present, captured by a dynamic domain that follows the changing daily ice extent (Fig. 3). The resulting metric used in this study is named the skillful forecast fraction (SFF). Where SFF is equal to unity, all forecasts produced over the duration of the season were skillful. Forecasts are evaluated using both climatology and persistence as reference forecasts, and SFF is reported with a subscript c, t, and d for ice concentration, thickness, and drift, respectively.

Community-scale forecast verification

The core goal of this study is to consider LIK alongside known forecaster tools. For the first time to our knowledge, the contents of LIK observations are discussed in the context of local-scale ice analysis and forecasting. In the case of ASIP, we bring together operational products, the ACNFS, and LIK from one northern Bering Sea community and view all tools through the eyes of a forecaster.

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Local indigenous knowledge contributions from the community of Gambell, Alaska

The SIKU/SIZONet project, following the successful pilot project of documenting how ice and weather observations are made by indigenous environmental experts in Gambell (Oozeva et al. 2004), commenced in early 2006 to begin collaboration on a more widespread effort to ensure that local knowledge is available to the broader scientific community. The first expert member of the communities included within SIKU/SIZONet to begin taking dedicated observations was Leonard Apangalook, a local whaling captain, in spring 2006. His son Paul Apangalook later took over the effort in late 2008 and was in his third year of observing during the time of our case study. Paul Apangalook is the key community expert whose thoughtful observations are featured within this local case study. Paul Apangalook contributed near-daily observations over the course of the 2011 ice retreat season, with observations ending shortly after he reports that ice was gone for the season on 22 May. Observations were typically reported in the morning, with a brief statement about the weather, augmented with data gathered from dialing the Automatic Weather Observation Station (AWOS) located at the village airstrip.

Operational ASIP products in spring 2011

ASIP forecasts and analyses presented in this section differ from those produced after October 2015 (cf. National Weather Service operational sea-ice products and product consumers section). The daily analysis product had evolved over time from a focus on mariner needs during the early evolution of the NWS sea-ice program. In the spring of 2011, sea-ice analyses from the ASIP were comprised of broad-scale polygons, drawn to encapsulate areas of similar sea ice concentration and stage of development (Fig. 4*a*). The ice description within each spatial region was described in a plain language format. From the latest analysis, the 5 day forecast chart (produced only on Mondays, Wednesdays, and Fridays) was first copied and then edited with emphasis placed on the position of the ice edge or any special requests from other operators within the broader ice pack. The forecast product at that time was also accompanied by a text advisory describing the ice edge location, with coordinates of the inflection points, and expected movement during the forecast period (Fig. 4*b*).

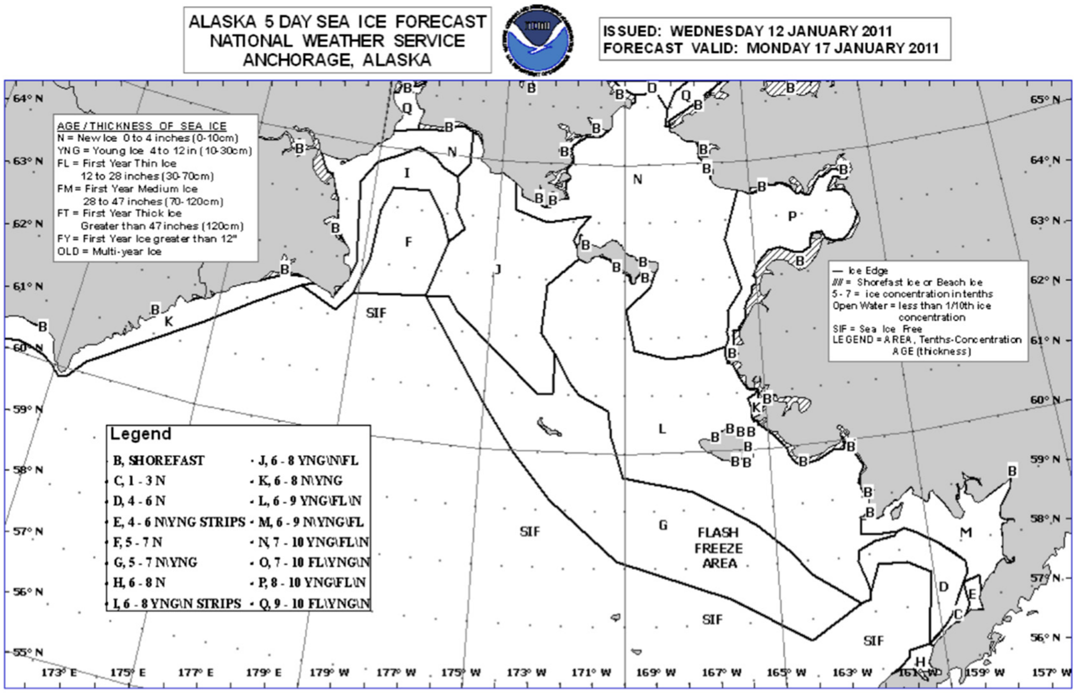
Verification of the ACNFS at the community scale

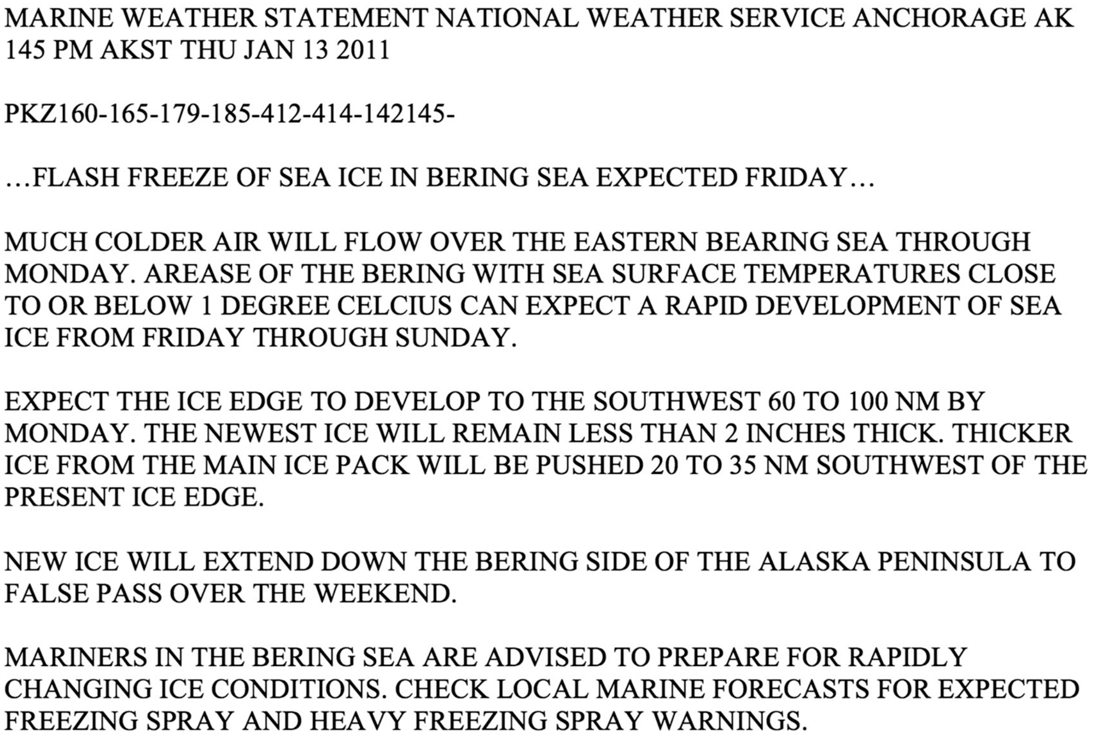
We explore the opportunity to address indigenous sea-ice stakeholder needs through user-inspired definitions of key sea-ice variables. Thresholds in sea-ice concentration relevant to the local scale are defined in this study by the work of Kapsch et al. (2010) who summarized that successful — and hence preferred — hunts are likely associated with sea-ice concentrations ≤30%, wind speeds 5–9 m s^{-1}, ambient temperatures between −5 and +5 °C, and visibility >6 km. Additionally, sea-ice area or the physical-inferred floe surface area is introduced for insights into how the concentration within the extent changes over changing forecast lead times. The sea-ice extent and sea-ice area forecasts are evaluated using absolute error and percent change relative to persistence forecasts, in bulk, over a 75 km radial area defined by Kapsch et al. (2010) as a maximum hunting distance. The final variable to be evaluated is the drift of sea ice in the nearshore region by qualitative methods alone, through comparison of local observations of ice movement contained within Paul Apangalook's records pulled from the SIZONet database.

Results

This study focuses on the springtime sea-ice retreat season in the Bering Sea (Fig. 5) as defined by the 90 day period from 1 April through 30 June. The breakup season represents

Fig. 4. Sea-ice forecast products available in 2011. Maritime charts with polygons bound sea ice with similar characteristics (top) and a marine advisory statement (bottom) issued to discuss critical events and movement of the ice edge.





MARINE WEATHER STATEMENT NATIONAL WEATHER SERVICE ANCHORAGE AK
145 PM AKST THU JAN 13 2011

PKZ160-165-179-185-412-414-142145-

…FLASH FREEZE OF SEA ICE IN BERING SEA EXPECTED FRIDAY…

MUCH COLDER AIR WILL FLOW OVER THE EASTERN BEARING SEA THROUGH MONDAY. AREASE OF THE BERING WITH SEA SURFACE TEMPERATURES CLOSE TO OR BELOW 1 DEGREE CELCIUS CAN EXPECT A RAPID DEVELOPMENT OF SEA ICE FROM FRIDAY THROUGH SUNDAY.

EXPECT THE ICE EDGE TO DEVELOP TO THE SOUTHWEST 60 TO 100 NM BY MONDAY. THE NEWEST ICE WILL REMAIN LESS THAN 2 INCHES THICK. THICKER ICE FROM THE MAIN ICE PACK WILL BE PUSHED 20 TO 35 NM SOUTHWEST OF THE PRESENT ICE EDGE.

NEW ICE WILL EXTEND DOWN THE BERING SIDE OF THE ALASKA PENINSULA TO FALSE PASS OVER THE WEEKEND.

MARINERS IN THE BERING SEA ARE ADVISED TO PREPARE FOR RAPIDLY CHANGING ICE CONDITIONS. CHECK LOCAL MARINE FORECASTS FOR EXPECTED FREEZING SPRAY AND HEAVY FREEZING SPRAY WARNINGS.

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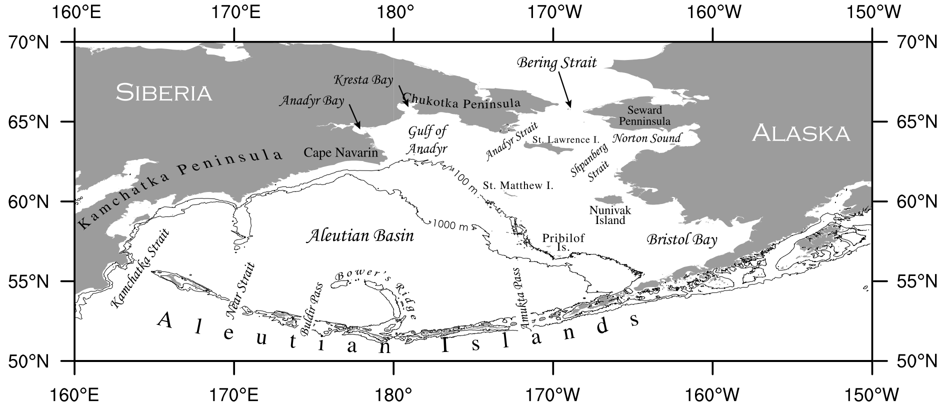
Fig. 5. Geographical places and names in Beringia. The 100 and 1000 m bathymetric contours are plotted (https://www.uaf.edu/sfos/research/projects/alaska-region-digital-ele/).



a time when many sea-ice forecast stakeholders are active and looking for guidance from operational centers to support decision making.

Progression of the 2011 sea-ice retreat season

The number of days with ice present during the study period varies spatially (Fig. 6*a*). At the beginning of the 2011 ice retreat season, 1.15×10^6 km^2 of the Bering Sea was ice covered. As the first week of April drew to a close, a strong storm approached from the North Pacific. Over the days of 6–7 April, the storm deepened and slid atop the central Bering Sea. On 7 April, the NWS ASIP issued a sea-ice advisory text product for the Bering Sea detailing the expected impacts of the approaching storm (NWS 2011). The marine advisory warned of localized beach erosion and the fracture and onshore movement of landfast ice cover.

Communities have the best opportunity to verify sea-ice advisories such as the 6 April prediction. For example, Paul Apangalook reports that: “The NWS issued an ice advisory for the area of ice being pushed onshore by surging seas. It did not occur as forecasted” (Apangalook et al. 2013). This example of a false positive represents only one location in the ASIP forecast region, which contains thousands of miles of coastline. Onshore ice movement along other stretches of coastline may have agreed with the forecast, but impacts of the storm in other localities are undocumented.

Unsettled weather continued in the wake of the storm system in early April. Persistent northerly winds pushed the ice southward to the maximum seasonal extent on 15 April, but a highly broken and fractured icescape reflected the effects of the large storm (SIWO 2011*a*). Northerly winds in late April pushed ice southward out of Bristol Bay where it soon melted. At the same time, thinner ice in the sea-ice production zones of both the Siberian and St. Lawrence Island polynyas melted and exposed open water. Unsettled weather was common in May and ice retreated at a near-normal rate of ~25 000 km^2 day^{-1}. In the first week of May, open water emerged from Cape Navarin to Anadyr Strait ahead of the climatological normal (Fig. 6*b*) and divided the ice pack in the Gulf of Anadyr from the pack in the north-central Bering. In late May, ice retreat north of St. Lawrence Island appeared to be dominated by export through the Bering Strait, a typical pattern of ice retreat described by Travers (2012). Ice in Kresta Bay cleared out weeks ahead of the average breakup date, impacting the timing of the Pacific walrus migration and local hunting communities dependent upon the last wave of large game to drift through the region atop the ice

Fig. 6. (*a*) Ice days during the 2011 spring retreat season from April through June and (*b*) ice day anomaly during the 2011 spring retreat season. “Ice days” refers to the number of days where sea ice was present in concentrations ≥15%.

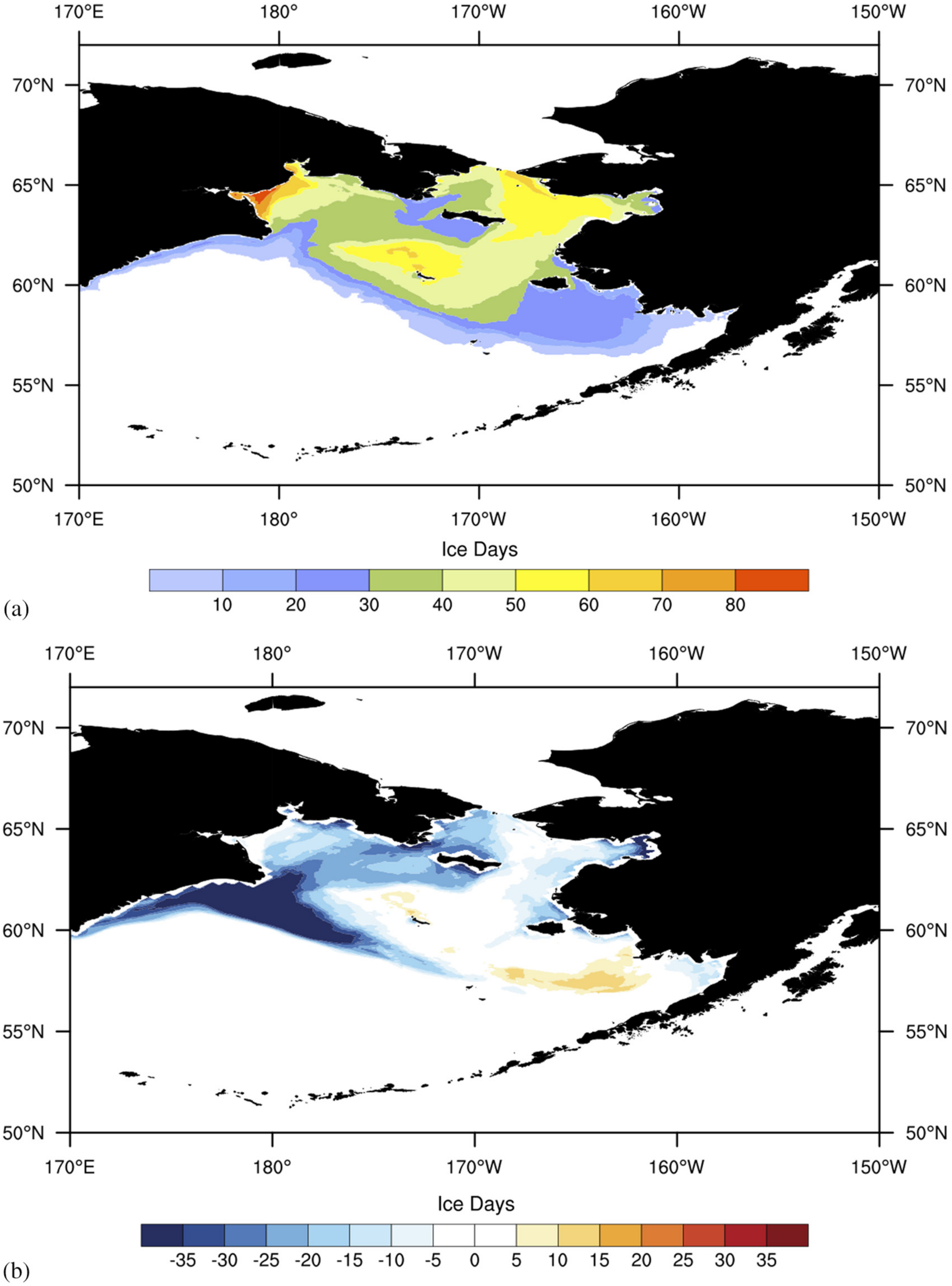


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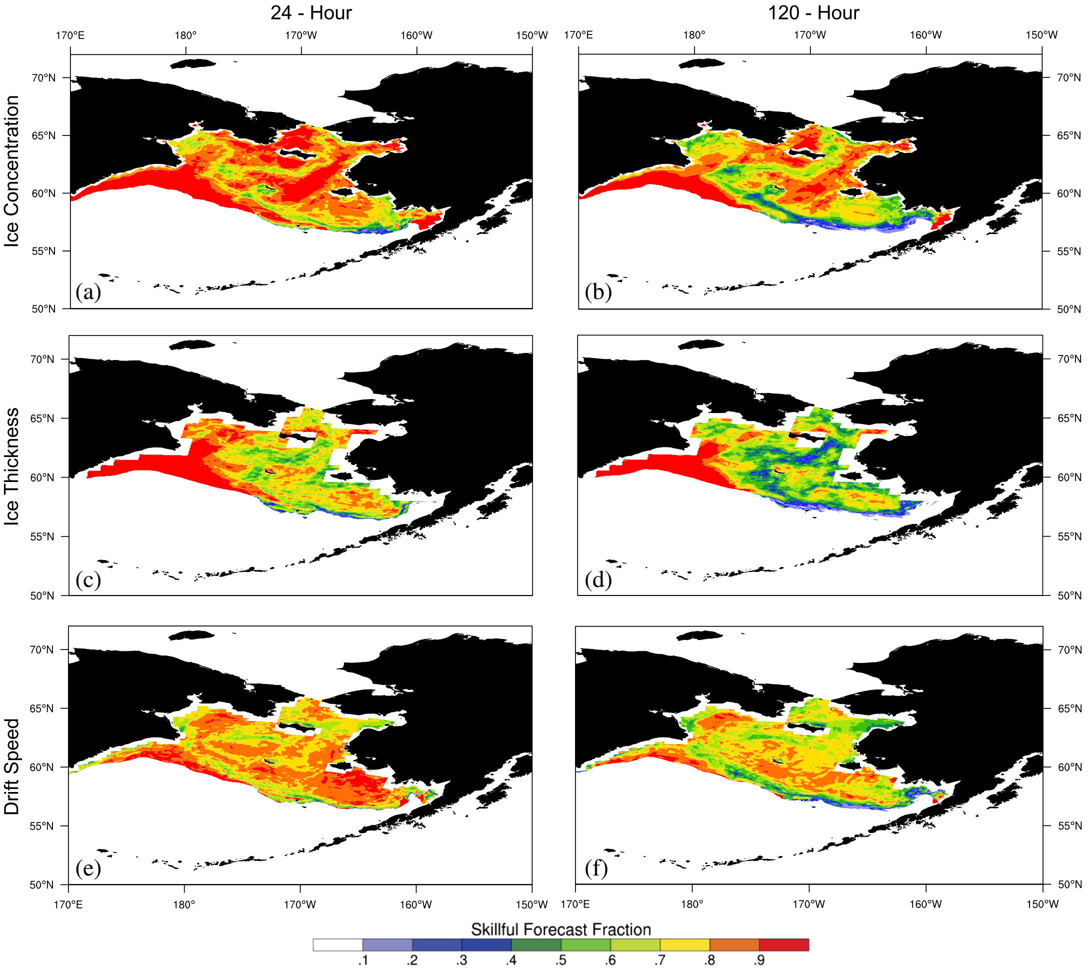
Fig. 7. Skillful forecast fraction (SFF) with climatology as the reference forecast. The left panels show the seasonal summary of 24 h forecasts. The right panels show the summary of 120 h forecasts. Ice concentration, ice thickness, and ice drift are in row-order top to bottom, respectively.



(SIWO 2011*b*). The last ice in the Bering Sea, along the coast of Anadyr Bay, melted in late June following the climatological normal melt out period.

Regional baseline skill assessment of the ACNFS

Regional sea-ice forecasts were evaluated against climatology (Fig. 7). Common to all six panels is an area with SFF with perfect skill south of Cape Navarin and at the climatological maximum extent during the melt season defined in this paper. In the perfect-score region, the model system correctly predicts the absence of ice when climatology suggests a more southern ice edge (Fig. 6*b*). As expected, results also indicate a decline in the number of skilled forecasts produced between the 1 and 5 day prediction, as seen by a shift from higher to lower SFF in each variable.

In the ice concentration panels (Figs. 7*a* and 7*b*), a belt of low SFF_c (<0.5) aligns with the Bering shelf break, coinciding with the seasonal maximum in 2011. The ice edge remained near stationary near the shelf break for multiple weeks during the retreat season,

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challenging the model to forecast the impact of warm waters (Hendricks et al. 1985), along-isobath currents (Kinder et al. 1975), and wind stress on the overlying ice cover. Also present is a narrow swath of low SFF_c originating in the eastern Bering Strait and extending to the eastern shore of St. Lawrence Island. This ribbon-like feature aligns closely with a known horizontal density gradient in the underlying ocean (Schumacher et al. 1983; Clement et al. 2005; Danielson et al. 2006; Danielson et al. 2011), where a baroclinic jet can influence ice edge location. However, a more focused study of model dynamics over multiple melt seasons is recommended for confirmation.

Figures 7c and 7d show SFF_t. An appreciable loss of information exists along the coast due to the coarse grid of our PIOMAS climatology. High SFF_t (>0.8) in Bristol Bay suggests that the ACNFS captured thermodynamic growth in the 2011 season with greater accuracy than climatology. Ice thickness in the Bristol Bay offshore region is typically driven by thermodynamics, but tidal forces acting nearshore can lead to significant rafting and rubble. SFF_t is also high in major deformation zones of windward shorelines that block southward drifting ice, but our simple SFF algorithm cannot determine if accurate forecasts are the result of dynamic or thermodynamic influences on ice thickness.

Skillful prediction of sea-ice drift speed relative to climatology (Figs. 7*e* and 7*f*) occurs less often near shorelines, in particular the coastlines of Cape Navarin, St. Matthews, and St. Lawrence islands and Norton Sound. Alternatively, sea-ice drift forecasts over the central Bering shelf show higher SFF_d, suggesting that ice drift speed is predicted with greater accuracy in the free drift mode.

Regional forecast skill relative to persistence

With persistence set as the reference forecast, spatial SFF patterns are muted (Fig. 8). The key difference in predictive skill with both concentration and thickness is an increase in $SFF_{c,t}$ for longer forecast lead times. SFF_c with a 120 h lead is quite low near the seasonal maximum extent for 2011 (Fig. 8*b*) and is consistent with a study by Dammann et al. (2013) that shows that current sea-ice models underestimate sea-ice variability near the ice edge. Conversely, basin-average SFF_d decreases with increasing forecast lead time. Shifts in SFF from 1 to 5 day forecasts reflect the relative rates of change for each variable. For example, on a basin average, sea-ice concentration and thickness changes are expected to be small during the operational timescale. Therefore, persistence is a reasonably good predictor. Only predictions of drift speed resulted in a gross decrease with increasing lead time, a reflection of higher variability imparted by the atmospheric model.

A forecasting case study at the local scale: Gambell, Alaska, 7 May 2011

This case study primarily focuses on the forecast of the local ice edge towards the town of Gambell over a 5 day period leading up to 7 May. Operational sea-ice products, LIK, and model forecasts describing the icescape are presented. Local observations by Paul Apangalook, an environmental expert in Gambell, provide ground truth and local context to the forecasting case study. Products issued by ASIP and numerical model output from the ACNFS are assessed for their ability to describe and predict the local ice environment.

Local indigenous knowledge from Gambell, Alaska

Observations presented within this section describe both the history of sea ice in April 2011 leading up to the 5 day case study and observations during the case study period. A monthly summary piece composed by Paul Apangalook provides information about the preconditioning of sea ice at the local scale through a narrative summary for April (SIWO 2011*b*). In Paul Apangalook's summary, the ice is described as remaining thin and sparse with some thicker floes interleaved in the pack. Open water became more common as the month progressed and multiple sea-ice-free days were observed beginning 21 April.

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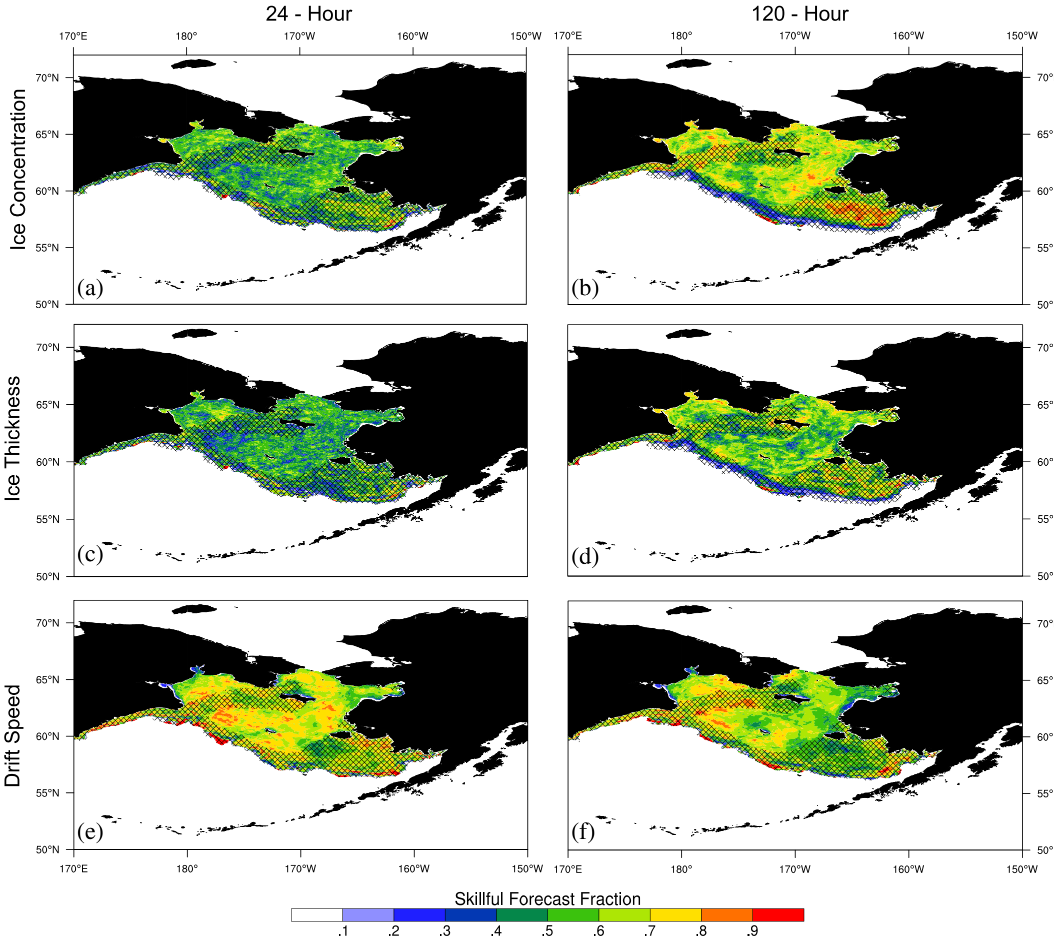
Fig. 8. Same as Fig. 7, except with persistence as the reference forecast. The hatched area shows ice days ≤30.



The ice that reemerged in Paul Apangalook's field of view originated from the south and west and was thicker and transported by a current, increasing in strength over time, and drifting to the north. Ice remained compact and visible to the northwest and numerous game animals were spotted daily.

In the first week of May, local surface high pressure developed and persisted over the Chukotka Peninsula. Favorable weather thresholds for subsistence stakeholders, nearshore leads, and offshore pack ice in low concentration led captains to take to the water. Ground-based observations from Paul Apangalook provide context for atmospheric conditions and the local ice pack throughout the operational-scale verification study:

> Light winds from the North, 30 F [–1 °C], overcast. There is ice to the northwest at the closest point at about 13 miles [21 km]. It is oriented southwest to northeast, concentrating further north. It is thicker floes and scattered, with about a mile wide open lead separating another pack that is several miles wide to the northwest and stretches for miles in either direction. There are a lot of maklaks [Bearded Seals] hauled out and walrus in the water. Many boats went out getting walrus and maklaks. A concentration of many large bowheads were spotted out west [. . .]. Paul Apangalook, Gambell, Alaska, 3 May 2011.

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Additional information on the abundance, type of game, and hunting success in the area reflects the tight links between ice and the use of the ice by game or hunters. For instance, the observation from 4 May 2011 that includes information about ice thickness is likely relative to whether or not ice can support adult walrus or boating teams:

> Light winds, 32 F [0 °C], overcast. Scattered ice to the west about 12 miles [19 km] out. The ice consists of broken up floes, both large and small mixed with melting ice and broken ice. It is mostly thick and stable. Plenty of game [...]. Paul Apangalook, Gambell, Alaska, 4 May 2011.

The observation also mentions the brokenness of floes, reflecting stormy weather conditions during the preceding weeks. From the vantage point of Paul Apangalook on 4 May, the ice edge of the local pack also approached a mile closer to the observer, with no comment on changes to the orientation. The following day, the edge of the local ice pack approached much closer to the village:

> The ice pack remains the same. The edge is about seven miles [11 km]. It is packed in places and considerably scattered as well. It is the same as described on the 4th. Several boats went out, some to the northwest, others to the west. There were a concentration of walrus hauled out about fifteen miles to the northwest, all females. Some had been calving. Several boats went out and were able to bring home a load. Paul Apangalook, Gambell, Alaska, 5 May 2011.

As the ice pack drifted closer to the shore at Gambell, the concentration seemed to change as well, banding together in some areas within the pack while being more dispersed in others. A key statement repeated in this observation is that the *ice remains the same as the day before*. Since there was a 5 mile (9 km) change in the location of the ice edge, the mention of "no change" may be related to the type of ice present in the pack, the relative concentration, and the stability of that ice to support game and crew. A brief statement of the ice pack remaining the same is also made on 6 May, with no indication of the ice edge movement towards or away from the village. The final observation on 7 May again mentions no change in the ice pack but confirms that over the previous 5 days, with quiescent weather prevailing, the edge of the local ice pack has moved 9 miles (14 km) closer to the village:

> Calm, 34 °F [1 °C], clear. The ice pack remains the same [from yesterday]; four miles at the closest point west. It goes north beyond the horizon and oriented southwest. Many boats were able to get walrus about 11 to 14 miles [18–23 km] west southwest and at least one boat 30 miles [48 km] southwest of the village. Paul Apangalook, Gambell, Alaska, 7 May 2011.

National Weather Service sea-ice products available to the Gambell community

The NWS sea-ice forecast for 7 May 2011 became available on 2 May 2011 (Fig. 9). The operational ice edge on 2 May was located hundreds of kilometres to the south. The analysis and accompanying sea-ice advisory called for the ice edge to retreat 20–30 nautical miles to the north over the next 5 days. However, seeing that the ice edge lay far to the south, sea-ice changes in the northern Bering Sea near Gambell were not addressed in the text valid on 7 May. The 2 May NWS sea-ice analysis and thus the spatial forecast for 7 May at Gambell prescribe an average sea-ice concentration of 50%–70% across the strait. The ice types

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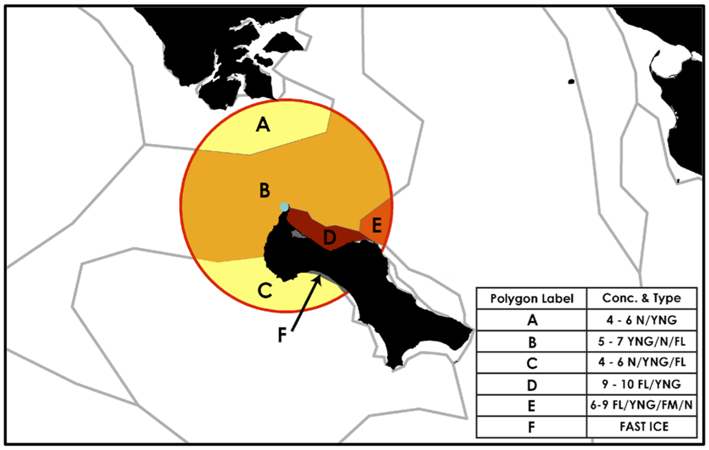
Fig. 9. Subset of NWS Alaska Sea Ice Program 5 day forecast created 2 May 2011, valid 07 May 2011, at 1600 AKDT. Grey lines are polygon boundaries that fall outside the 75 km radial area defining the hunting region. Plot legend gives concentration in tenths. Dominant ice type within each polygon reads left to right. N, new; YNG, young; FL, first year thin; FM, first year medium sea ice following World Meteorological Organization (WMO) definitions. Supporting text pulled from sea-ice advisory 1600 AKDT, 2 May 2011.



Polygon Label	Conc. & Type
A	4 - 6 N/YNG
B	5 - 7 YNG/N/FL
C	4 - 6 N/YNG/FL
D	9 - 10 FL/YNG
E	6-9 FL/YNG/FM/N
F	FAST ICE

-BERING SEA-

PKZ185-ST MATTHEW ISLAND WATERS-
PKZ180-SOUTHWEST ALASKA WATERS CAPE NEWENHAM TO DALL POINT-

THE ICE EDGE LIES FROM CAPE NEWENHAM TO 58.8N 163.7W TO 57.6N 163.9W TO 57.1N 166.5W TO 58N 168.6W TO 57.9N 173.2W TO 60N 177.4W TO 57.8N 177.7E AND CONTINUES ALONG THE RUSSIAN COAST. THE ICE EDGE WEST OF 168W IS 6 TO 9 TENTHS YOUNG…NEW AND FIRST YEAR THIN ICE IN STRIPS. THE ICE EDGE EAST OF 168W IS 1 TO 4 TENTHS NEW…YOUNG AND FIRST YEAR THIN ICE IN STRIPS.

FORECAST THROUGH SATURDAY…WARMING TEMPERATURES AND THE TIDES WILL RETREAT THE ICE EDGE TO THE NORTH 20 TO 30 NM THROUGH SATURDAY.

composing the pack consisted of new, young, and first-year thin as the three most dominant ice types (WMO 1970).

In 2011, the production of ice analyses was limited to Mondays, Wednesdays, and Fridays, making verification of the forecast valid Saturday 7 May unattainable. However, the 6 May analysis (not shown) indicates some large-scale ice movement in the Anadyr Strait through a shift in polygon boundaries, but ice concentrations remain near 50%–70% across the area of interest.

Verification of the ACNFS near Gambell

The 2 May ACNFS analysis indicates sea ice present near Gambell (Fig. 10). Two key features in the analysis agree with the observation made by Paul Apangalook on 3 May. One band of ice is nestled against the northern and eastern coast of the village and a second is offshore, separated by sea-ice-free ocean. The ACFNS surface currents were unavailable in this evaluation. However, a conceptual understanding of the Anadyr current is known for calm weather similar to this case study. In the absence of strong wind forcing, the Anadyr current tends to bifurcate around St. Lawrence Island with one branch flowing north towards Bering Strait and the southern branch flowing to the east, around the south side of the island. The resulting net ice drift prevailing through this case study should be expected to be toward the western and northern shores of Gambell.

Five ACNFS forecasts, valid at 1600 AKDT 7 May (8 May 0000z) are evaluated (Fig. 11). For each of the five lead times, a derived ice extent and area are compared to the 7 May

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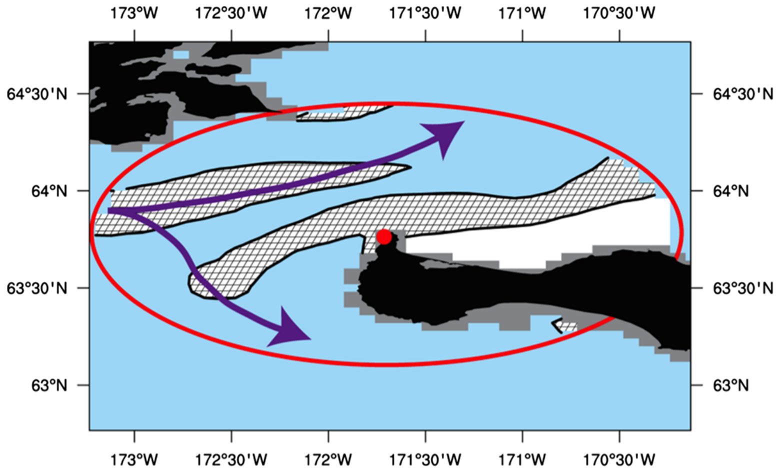
Fig. 10. ACNFS sea-ice concentration analysis for 3 May 2011 00z (2 May 2011 1600 AKDT) binned by hatched area ≤30% and white area ≥30%. The red ring and dot represent a 75 km hunting buffer and village of Gambell, respectively. Purple streamlines are a conceptual surface current model for the Anadyr Strait under calm atmospheric conditions.



ACNFS analysis. Ice extent in the context of what is useful for hunters is defined here in the 0%–30% concentration threshold. Sea-ice area refers to the empirical ice floe surface area useable by local stakeholders as a platform.

In Fig. 11, the model solution of ice extent in the Anadyr Strait appears consistently too close to the village of Gambell, with the long axis of the ice pack predicted in a more zonal orientation than the 7 May analysis. Nearshore ice, defined only in the same 0%–30% concentration threshold, appears well represented in the predictions, remaining packed against the coast. The presence of a small patch of ice near the southern extent of the analysis region is also predicted accurately from 96 h out, with the best agreement in extent in the 24 h prediction.

Overall, prediction of ice extent in the analysis region was slightly more expansive than the 7 May analysis. This is further quantified by absolute error of the hits and misses in the extent prediction (Fig. 11, bottom). Positive errors, where the model predicted a more expansive ice extent, are larger than negative errors in all but the 24 h prediction, although the total magnitude of error is smallest 24 h out. A percent change comparison to a persistence forecast is presented in Fig. 11 (center). Positive percent change indicates the ACNFS consistently had smaller errors than a persistence forecast. Percent changes from persistence in ice area and ice extent show a similar shape. Ice area is strongly dependent on the extent, but the percent change results show that the concentration forecasts are reasonable, and there are no erratic changes in concentration from spurious ice being added or removed by the model forecasts.

Discussion and conclusions

Changes in Arctic summertime sea-ice loss (Stroeve et al. 2007) place more demand on the forecaster, who will need numerous tools for the job. LIK has gained substantial visibility in the field of sea-ice research, but there is opportunity yet for this information source to be used in an operational setting. The natural narrative of LIK and the detailed information on local ice features and linked processes should be used to serve in the validation efforts of new technologies for monitoring and prediction.

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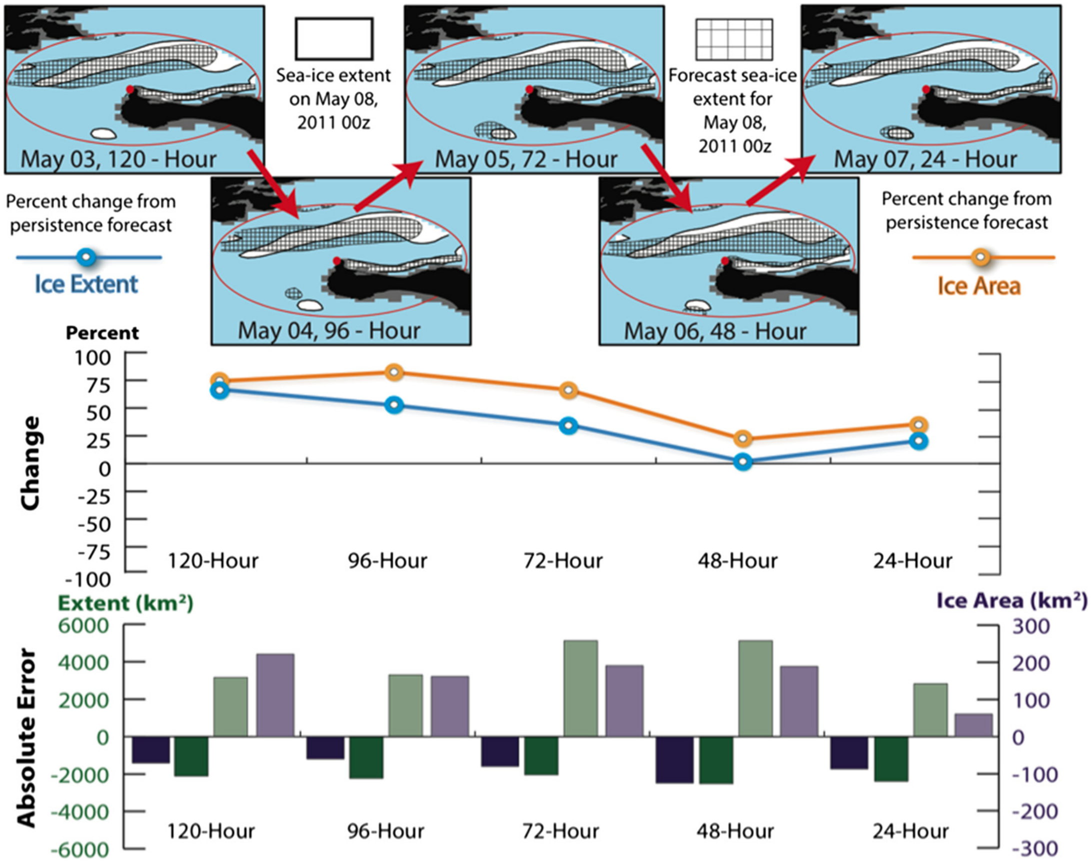
Fig. 11. ACNFS sea-ice forecast guidance for 8 May 2011 00z (7 May 2011 1600 AKDT) near western St. Lawrence Island. The five upper panels show the forecast ice extent for 8 May 00z at different lead times. Red arrows guide the progression of the case study. The red dot and ring in forecast panels are the same as in Fig. 10. Ice information outside the ring is masked. Grey grid cells near coastlines represent the ACNFS land mask. The line graph shows the percent difference from a persistence forecast of both ice extent and ice area. Ice area is the product of extent and concentration and represents the physical surface area of sea ice within the 75 km hunting buffer. Negative differences indicate that persistence is a better forecast. Positive percent differences show that the model forecast had less error than persistence. The bar chart at the bottom of the figure shows the absolute error in the forecasts for both ice extent and ice area.



Discussion of ACNFS skill

The ACNFS is in line to be upgraded to GOFS 3.1 and become a vetted guidance model for operational forecasting at the NWS. To date, the Bering Sea has not been the focus of a forecast verification study for the ACNFS. We present a simple metric for aggregating spatial forecast skill through time on a dynamic domain that follows changes in the ice cover. During the 2011 retreat season, ACNFS forecasts were skilled relative to climatology. Forecast skill relative to persistence increased with lead time for the variables that have a small rate of change on the operational timescale. The verification domain in this evaluation included ice in concentrations >15%. Selecting only the marginal ice zone (<80%), following Posey et al. (2015), would offer more fitting metrics in line with the new NWS forecast product that focuses on changes in the marginal ice zone.

Challenges will remain for gridded sea-ice forecast verification. Limited observational data constrain climatological evaluations, and climatologies derived from coarse data sets

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may not offer the best representation of spatial variability in the Bering Sea. Also, in this study, daily extent derived from the 1979 to 2000 climatology will differ from the current 1981–2010 reference in the Bering Sea, as winter- and springtime extent has increased in recent years (Matthewman and Magnusdottir 2011). The difference in extent will result in a change in the magnitude of SFF, but the trend in SFF values across lead times should not be impacted.

Persistence verification against the model itself introduces the potential risk for cyclical logic. Additionally, in situ validation of the ACNFS within the Bering Sea has yet to be performed, leaving the magnitude of the model bias and error unknown. Uncertainties aside, we can conclude that on the regional scale, SFF for all variables changed as expected from 24 to 120 h forecasts, indicating that the model performed well systematically and is useful as a forecast guidance product during the spring in the Bering Sea.

Community-scale guidance through the eyes of a forecaster

It is clear that access to local observations and model guidance allows the analyst to place more detail in the 2011 Gambell forecast than that provided by using persistence of sea ice within broad polygons. Even with international ice chart standards adopted in late 2015 that allow analysts to show considerably more detail in the forecast of the marginal ice zone, further enhancements are still possible by including LIK observations and high-resolution model guidance in the text narrative delivered alongside marine charts. In the case of 7 May 2011, information relative to stakeholder interests was supplied by both local observations and model predictions. At the same time, local observations act to ground truth the model and verify forecasts. This discussion outlines three conceptual forecast use cases for information contained within the local observations presented from Gambell: (1) sea-ice extent and ice edge location, (2) sea-ice type, and (3) marine mammal sightings.

As the case study began on 2 May, the ACNFS produced two linear bands of ice in low concentration. Currently, analysts rely almost entirely on satellite remote sensing to cross-validate models. Passive microwave data are readily available, but in an effort to use data both independent of the model and with finer spatial resolution, the analyst may reach for visible imagery (Fig. 12). Even with high natural contrast between ice and surrounding water, thin clouds obscure ice in low concentration, making ice extent boundaries difficult to extract. However, the local observer clearly states that an area of open water exists between two features within Anadyr Strait, validating the nowcast. Accurate ice extent information would serve not only coastal communities using ice as a platform but also commercial stakeholders interested in ice avoidance. In fact, the study area is of key concern in the context of increased Arctic shipping activities (Huntington et al. 2015) and we view input from local and indigenous observers as critical in maximizing hazard detection to support increased vessel traffic through the Bering Strait region.

Throughout the Gambell case study, local observations confirm the approaching edge of the local ice pack, but nominal distances supplied by the observations can help in determining that advection of ice is too fast, a known bias in the high Arctic (Posey et al. 2010). Any additional comments on the unchanging ice, which is interpreted here as being in reference to the type of sea ice present within the ice pack, can be used to validate sea-ice stage of development products. A complete understanding of ice thickness in the context of the local observations could then lead to proper classification within WMO nomenclature (i.e., WMO 1970). Ice type and references to stability (e.g., ice thickness linked to the use of ice as a safe platform) can be discussed to support ice-class vessels permitted to operate in low ice concentration but must still avoid thicker ice, which presents a hazard and (or) initiates ice management procedures.

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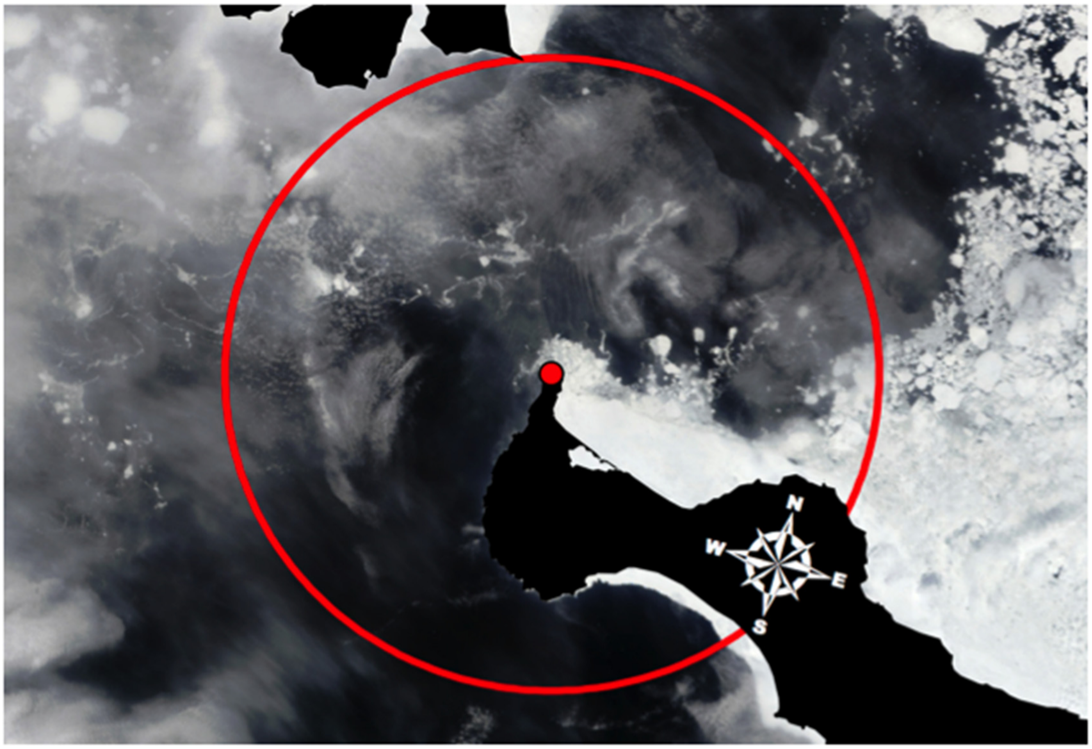
Fig. 12. 2 May 2318z true-color MODIS granule acquired by Terra at 250 m. The red circle and dot are the same as in Fig. 11. To the west and south of Gambell, in the upper left quadrant of the tile, sea ice in low concentration obscured by thin low-level stratoform clouds is visible in brighter white, geometric shapes. Landfast ice can be seen along the coastline to the east of the village and the south side of the island. To the north and east, ice in higher concentration is being compacted by westerly winds and south to north currents.



The relationship between sea-ice concentration/thickness and marine mammals is not currently included in sea-ice information products. Availability, abundance, and behavior of marine mammals (i.e., hauling out, calving, etc.) are associated with ice type and distribution (Ray et al. 2010; Sacco 2015) and are thus a key component of LIK sea-ice observations. Regulatory requirements might dictate that commercial operators must not only avoid ice (e.g., Shell 2011) but also avoid ice-associated mammals (e.g., Shell 2015). The connection of biological processes to ice retreat is therefore a key advantage of local observations to aid in conflict avoidance and compliance with federal regulations amongst a diverse number of sea-ice users and forecast consumers.

Challenges facing local indigenous knowledge in operations

The need to include local knowledge in Arctic research initiatives is well established (Huntington et al. 2005; Committee on Designing an Arctic Observing Network (National Research Council) 2006; Couzin 2007; Jeffries et al. 2007; Eicken 2010). The *research* context, however, relates to the timeframe in which the observations are taken, transmitted to database administrators, uploaded, analyzed, discussed, and approved through peer review. The operational window for generating forecasts is small. Analysts constrained for time to meet rapid and recurring deadlines may not be able to fully decipher the context surrounding the observation, which is a critical component when working with traditional sea-ice knowledge (Druckenmiller et al. 2009; Huntington et al. 2009). In many conditions, the

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rates of change in macroscopic and floe-scale sea-ice properties are slower than those of weather processes, leading to slower depreciation in operational value. This is particularly the case for sea-ice hazards that are robust enough to survive well into the operational season for industry. In fact, the operational timescale may need to be redefined for sea ice, as many industrial stakeholders must make decisions weeks to months ahead of taking action.

An additional challenge relating to the understanding and appropriate use of observations in context is forecast liability. In the event of loss due to a missed prediction, which may have derived information from or directly featured LIK, the forecast service provider assumes responsibility. Unlike the ASIP, which has a long-running partnership with local communities in their forecast jurisdiction, and operational programs in place like SIWO that aid in broadening the observation network, liability risk may dissuade private sector firms from incorporating and referring to local indigenous observations (Klein and Pielke 2002). Industry operating within the Arctic has forecast needs beyond those currently served by large-scale products (e.g., Raye 2015). However, we argue that industry operating in the Arctic has much to gain from the inclusion of LIK in forecasting, both in their daily operational activity and in the unlikely need for emergency response. Furthermore, advocacy for the credibility of LIK in the operational context will be needed for many forecast consumers who lack exposure to the type of information provided by local expertise. Even if implementation of LIK in sea-ice products occurred the day this paper is published, the end user may still exercise the option to dismiss an unfamiliar information source.

Gaining and maintaining dialogue in a broad network of experts bordering the Arctic and its marginal seas is not trivial. Pioneering programs like SIWO have developed pathways to get observations to the forecaster more quickly, but observations enter the data stream manually and often have a latency of a few days. Communication infrastructure does lag in rural communities, but connectivity is constantly improving. Social media outlets (Facebook and Twitter in the case of SIWO) offer a way for observations to be shared more freely but only reach a limited audience and are unscreened. Underlying the productivity of the observation program is the availability of local experts. After all, key informants in any observation program do have lives to attend to that take priority over any observation and these lapses in observation due to competing interests must be respected (Huntington et al. 2009).

Closing remarks

The Bering Sea served as a multiscale case study to demonstrate two forecasting tools, a pan-Arctic forecast model and observations containing LIK in coastal communities, which are accessible to operational forecasters at the ASIP. On the regional scale, the ACNFS shows skill during the course of the spring retreat season, when stakeholder activity increases sharply. The modeling tool also shows skill at the local scale, but under specific atmospheric conditions, where a small positive bias in drift speed was apparent. It is in these local, nearshore dynamic areas (e.g., Bering Strait) where LIK offers added detail relevant to both the observers themselves and other stakeholders with different interests. While the context of the observations must be considered to preserve the meaning and relevance to sea-ice users, information on local sea-ice conditions and their relations to other environmental variables can augment parameterized model solutions. We see LIK as a viable tool for addressing a variety of sea-ice information needs in a time of rapid change not only in the Bering Straits region but also in other coastal regions of the Arctic.

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