ON USING NUMERICAL SEA-ICE PREDICTION AND INDIGENOUS OBSERVATIONS TO IMPROVE OPERATIONAL SEA-ICE FORECASTS DURING SPRING IN THE BERING SEA

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Abstract

Impacts of a rapidly changing climate are amplified in the Arctic. The most notorious change has come in the form of record-breaking summertime sea-ice retreat. Larger areas of open water and a prolonged ice-free season create opportunity for some industries, but bring new challenges to indigenous populations that rely on sea-ice cover for subsistence. Observed and projected increases in Arctic maritime activities require accurate sea-ice forecasts on the weather timescale, which are currently lacking. Motivated by emerging needs, this study explores how new modeling developments and local-scale observations can contribute to improving sea-ice forecasts.

The Arctic Cap Nowcast/Forecast System, a research sea-ice forecast model developed by the U.S. Navy, is evaluated for forecast skill. Forecasts of ice concentration, thickness, and drift speed produced by the model from April through June 2011 in the Bering Sea have been investigated to determine how the model performs relative to persistence and climatology. Results show that model forecasts can outperform forecasts based on climatology or persistence. However, predictive skill is less consistent during powerful, synoptic-scale events and near the Bering Slope.

Forecast case studies in Western Alaska are presented. Community-based observations from recognized indigenous sea-ice experts have been analyzed to gauge the prospect of using local observations in the operational sea-ice monitoring and prediction process. Local observations are discussed in the context of cross-validating model guidance, data sources used in operational ice monitoring, and public sea-ice information products issued by the U.S. National Weather Service. Instrumentation for observing sea-ice and weather at the local scale was supplied to key observers. The instrumentation shows utility in the field and may help translate the context of indigenous observations and provide ground-truth data for use by forecasters.

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Chapter 1

Introduction and Background

1.1 The Need for Sea-Ice Forecasts

Record summertime retreat of Arctic sea ice over the past decade has altered the timing and duration of the open water season (Walsh 2008). Consequently, changes in the seasonal cycle constrain subsistence hunting activities for coastal communities (Gearheard et al. 2006; Kapsch et al. 2010) while at the same time offering a lengthened window-of-operation for industry and other commerce. Increasing marine traffic in an ice-diminished Arctic requires improvements in sea-ice forecasting for environmental stewardship, human safety, and adaptation by local residents.

It is recognized that forecasting improvements need to be addressed for multiple scales (Eicken 2013). Seasonal to decadal prediction is required to understand impacts of retreating summer sea ice on the planetary heat budget, 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 2012). Regional projections are needed to help Arctic nations plan for the imminent diversification of sea-ice users with appropriate governance, regulation, and strategies for sustainability (Baker and Mooney 2013; Rayfuse 2007; Brigham 2007). The weather timescale, generally recognized as being ≤ 10 days and most commonly associated with the term 'forecasting', needs immediate attention to respond to quickly changing conditions that challenge all users operating on, or in the presence of sea ice.

Data scarcity in the Arctic is problematic for forecast verification and hinders proper assessment of advances in Arctic prediction. Extreme logistical difficulties and the enormous expense of establishing and maintaining station networks (Comiso 2006), along with a general lack of demand until recent decades are the driving forces behind a shortage of long-term, standardized observations. In-situ measurements of pertinent sea-ice variables (i.e. thickness, drift speed, ice age, and others) present even greater technical, geophysical, and logistical challenges. Remote sensing methods for sea-ice monitoring have many benefits (e.g. Sandven and Johannessen 2006; Dierking 2013), but sometimes have considerable monetary costs or insufficient resolution. Local observers make observations of sea-ice, weather, and other environmental variables and emphasize the way in which the parameters are interrelated. This information offers insights into local-scale processes that might not be known to a forecasting office that focuses on a much larger scale.

The need to respond to and predict changing conditions in the Arctic has led to increasing collaboration between researchers and Arctic indigenous peoples (Couzin 2007). Scientific goals identified in the Arctic Climate Impact Assessment placed indigenous perspectives near the top of the list of science initiatives (ACIA 2005). Eicken (2010), explains that "those willing to engage with local, indigenous ice experts from the very outset of a scientific study can gain much from having these experts and the knowledge shared by them and their community define or inform the development of research questions and hypotheses". This statement, as well as many other similar studies, reflects our understanding of how local and traditional knowledge can be woven into research-related science, but none have explicitly addressed the opportunity for local observations to advance the discipline of operational forecasting. To build on the Eicken (2010) statement here, those employed in commercial operations that are willing to engage local communities also have much to gain in both situational awareness of sea-ice conditions but also short-term prediction and decision-making for human safety and environmental security.

If common needs are going to be met by sea-ice users and operational forecast stakeholders, a collaborative effort will be needed for observation and information sharing to bridge the limitations of existing monitoring networks (Committee on Designing an Arctic Observing Network

2006). This research aims to connect existing sea-ice forecast products, new modeling systems under development, and community-scale observations in order to improve operational sea-ice forecasts. More specifically, this thesis outlines how forecasts and ice information services produced by the U.S. National Weather Service can be combined with a forecast modeling system in development at the U.S. Naval Research Lab as well as community observations from the Bering Straits region to add valuable detail to forecasts which serve multiple stakeholder groups.

1.2 Operational Sea – Ice Forecasting: A United States Perspective

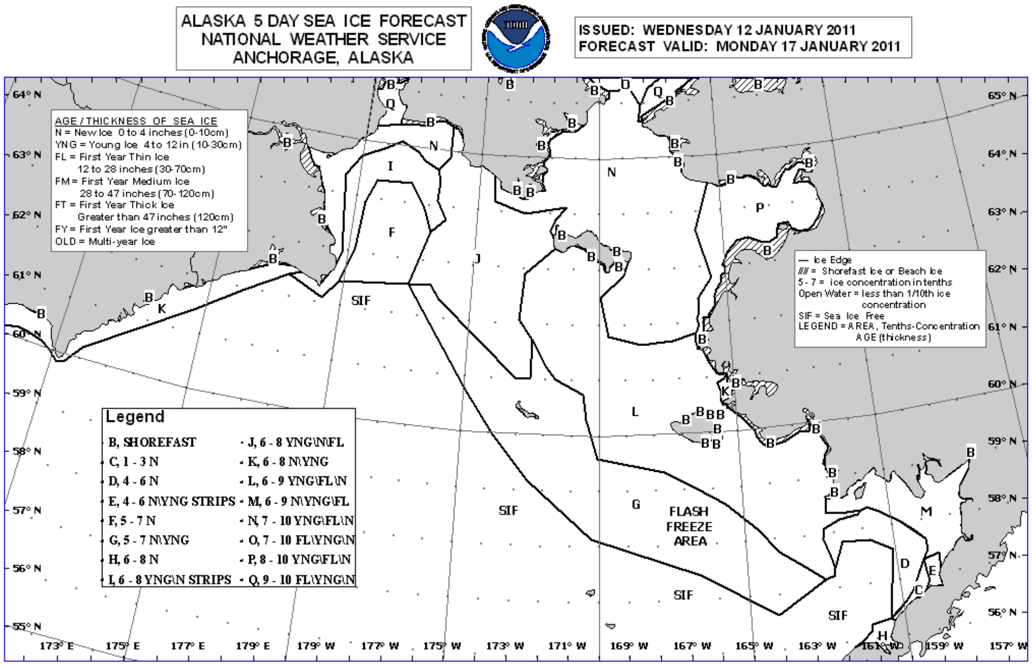
The United States government has been monitoring sea ice since the late 1960's, when the National Weather Service began describing sea-ice conditions in Alaska's ice-covered seas. The year-round operations consisted of text forecasts and reports from aerial reconnaissance. The forecasts included plain language ice descriptions and a 48-hour prediction of ice edge movement. Attention to the program grew as Arctic activities expanded on Alaska's northern coastline in the 1970s:

> "The Sea Ice Program was a relatively low profile program until the summer of 1975. This was the summer when a billion dollars worth of material was due to be delivered to Prudhoe Bay via tug and barge. The ice didn't withdraw as it normally does. Millions of dollars were wasted "waiting out" or fighting the ice, and, all of a sudden, everyone became interested in the ice service." (NWS Alaskan Borealis Briefs 1978)

The Navy/NOAA Joint Ice Center, now known as the National Ice Center (NIC), was established in 1976 to offer navigational ice analyses in support of the US armed forces. The NIC has a global responsibility that includes sea-ice monitoring in the Arctic and Antarctic as well as monitoring ice on freshwater bodies that are of interest for both military and civilian operations. While an overlap in sea-ice information products generated for the western Arctic by both the NIC and NWS provides continuity, the NWS program is able to deliver impact-based decision support services for stakeholders off the Alaskan coast at a higher spatiotemporal resolution.

The main product created by a sea-ice monitoring and prediction center is a sea-ice analysis. An analysis is created with the aid of public and commercial satellite products. The role of the ice analyst is to transform satellite retrievals of sea ice into a spatial chart, using their skilled interpretation to group regions of similar ice characteristics. The process is guided by a standardized sea-ice nomenclature and sea-ice observation format defined by the World Meteorological Organization (WMO 1970; WMO 2010). Sea-ice areas with similar concentration, thickness, age, and stage of development are captured in spatial polygons that are used for marine navigation. An ice analyst will also note the location of the sea-ice edge, which is defined by a line that separates a sea-ice free area from a bordering region with an ice concentration greater than zero. The ice edge in an operational ice chart can also be described as the ice / no-ice boundary. The number of customers needing navigational support and the location of the customer influences the amount and placement of detail given in each ice analysis. Sea-ice analysts at the NIC and NWS also produce sea-ice forecast products, but only forecasts created at the NWS will be discussed in the context of this thesis.

The NWS Sea Ice Program issues 5-day sea-ice forecasts. The forecast consists of a spatial marine chart and a supporting text product. An example of these products can be seen in Figure 1.1. The prediction focuses on the speed and direction of ice drift near the analyzed ice edge, where the ice pack is anticipated to undergo the largest change over five days. The ice edge is not analyzed as an independent variable. Instead, the interconnection of polygon edges that border a sea-ice free region defines the ice edge. A forecast for a specific location within the ice pack will only be created if a customer submits a request. If no order is placed, then polygons created in the most recent ice analysis will be held constant over the five-day period (Rebecca Heim, personal communication 2013). This forecasting method is known as persistence.



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

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

MUCH COLDER AIR WILL FLOW OVER THE EASTERN BERING SEA THROUGH MONDAY. AREAS OF THE BERING WITH SEA SURFACE TEMPERATURES CLOSE TO OR BELOW 1 DEGREE CELSIUS CAN EXPECT 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.

Figure 1.1. A forecast produced by the NWS Sea Ice Program in Anchorage, AK. Graphical maritime chart with polygons indicating the expected location of sea ice with similar characteristics after 5 days (top) and a special marine weather statement issued supporting the forecast map (bottom).

The prediction of sea-ice drift is based on forecaster intuition and guided by a suite of atmospheric models common to all NWS offices. Ice drift inferred from surface wind forecasts are compared to the Marine Modeling and Analysis Branch (MMAB) sea-ice drift model to create a forecast of ice displacement over some time. The model applies a conventional rule-of-thumb that ice travels 45 degrees to the right of the wind vector in the northern hemisphere and at roughly 2% of the wind speed. The physics governing the MMAB drift model were originally outlined by Skiles (1968) and later modified by Thorndike and Colony (1982) to represent ice drift in the Arctic Ocean. There are two major weaknesses with this model: 1) the horizontal resolution is on the order of 100 km and, 2) when a forecast point lies within 400km of the coast, the model loses accuracy (Thorndike and Colony 1982). The majority of the analysis region lies within 400km of the nearest coastline, which is problematic for the NWS Sea-Ice Program. The MMAB drift model was implemented in 1997 and has been a consistent and skillful guidance product for operations (Grumbine 1998). A guidance product refers to computer-generated solutions that are used in the preparation of published forecasts. However, the call for more detailed and user-specific sea-ice information products, accompanied by the recent surge in commercial activity in the maritime Arctic (Corbett et al. 2010) must be met with additional sea-ice observations and prediction tools.

Sea-ice analysis and forecasting that supports industry activities in the Arctic must focus on the finer scale in order to identify and monitor potential sea-ice hazards (Eicken et al. 2011). Just as the NWS provides a higher-resolution product nested within the NIC region of responsibility, some industry vanguards have developed proprietary forecasting units to support offshore projects within a small operational theater. The use of trained personnel to analyze high-resolution satellite imagery over a smaller region results in sea-ice charts that provide considerably more detail than those available from federal programs (Shell 2011). Sea-ice products from industry are also supported by commercial weather service companies, which provide meteorological information in critical areas and over short periods of time that would otherwise go unresolved in a broad-area public forecast. The specialized forecasting and analysis units developed by industry for industry are necessary for safe and efficient marine operations and vessel transit. Without exclusive industry programs, the demand for forecasts would quickly overwhelm public offices that have a broader region of responsibility and stakeholder interest (Shell 2011).

The coming of the satellite era was the first step in efficient operational sea-ice monitoring. Subsequent advances in remote sensing and computer science set the pace for improving confidence in sea-ice products and ease of dissemination over recent decades. However, the prediction of sea-ice over short timescales remains overwhelmingly dependent on a heuristic methodology unique to the individual forecaster. Experience of the forecaster is undoubtedly important and the human element is likely to remain an integral part of the forecasting process to avoid atrophy in skill (Bosart 2003). But, with added demand and detail required by an increasing number of sea-ice forecast stakeholders, a skillful next-generation guidance product can alleviate strain on the forecaster who is already subject to the arduous process of ice analysis. Numerical sea-ice drift guidance (Grumbine 1998) has proven useful for predicting the *net* drift of ice over some lead-time, but offers little more predictive detail about the path that individual ice features take over the rule-of-thumb ice drift first documented by polar pioneers (Nansen 1902).

To date, efforts at meeting ice information needs of the stakeholder have been met with increases in spatial resolution of similar products (e.g. industry analyses have a higher resolution than the National Weather Service, which is nested with the National Ice Center area of responsibility). However, if these different forecasting entities are going to meet the demand for improved quality in sea-ice prediction to ensure a safe Arctic offshore environment, then access to new tools is needed.

A forecasting tool may be in the form of an earth-system or coupled ice-ocean model or in the form of collaboration with long-time residents of the Arctic coast who can supply ground-based observations and expertise of the ice.

1.3 The Bering Sea as an Operational Forecasting Springboard

The Bering Sea is resource rich. The region is a proven oil- and gas-bearing province, a hugely productive marine environment, contains a wealth of local knowledge held by indigenous peoples, and stands as a threshold to the western Arctic Ocean. Geographic location and resource diversity attracts a broad array of stakeholders. Sea-ice, which is present in the waters of the Bering Sea for roughly half the year, is viewed differently by stakeholders (Eicken et al. 2009) and must be predicted with the needs of the customers in mind. Thus, the interrelated sea-ice forecasting needs in Bering Sea will function as a proxy for other regions in the Arctic where there is no tradition of multiple sea-ice user groups coexisting (Haley et al. 2011). Here, the seasonal ice zone of the Bering Sea (Figure 1.2) serves as an arena for evaluating operational forecasts, a state of the art sea-ice prediction model, and discussing the role that local communities play in a more integrated sea-ice forecasting system.

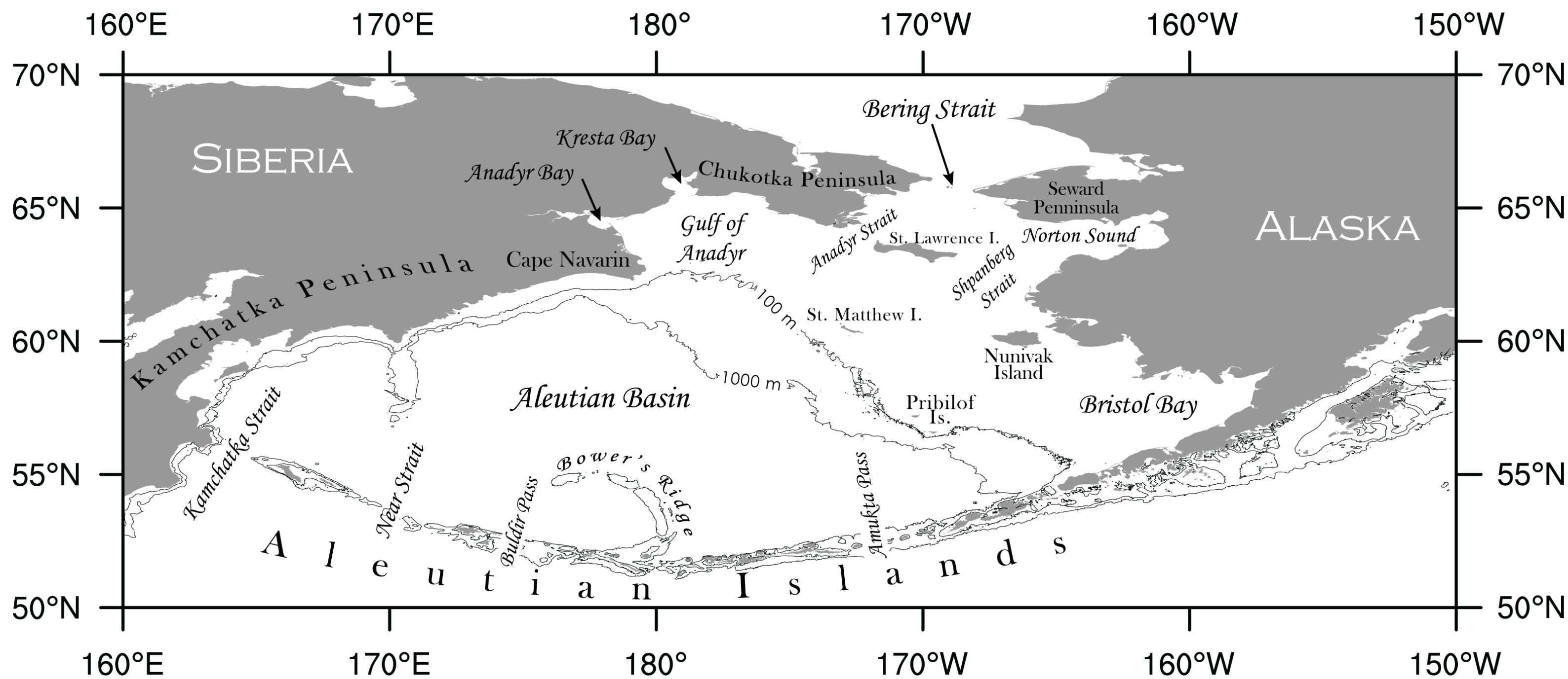


Figure 1.2. Geographical place names of the Bering Sea. 100m and 1000m bathymetric contours plotted.

A schematic representation of products, needs, and information exchanged in a more integrated sea-ice forecasting system proposed in this thesis are presented in Figure 1.3 and itemized in Table 1.1. The discussion to follow is a walk through Figure 1.3. Within the system, stakeholders are the contributors to a local-scale monitoring network and relay intelligence on sea-ice conditions, weather conditions, and hazards to forecast service providers. Community-based observations can serve as a principal hazard detection program at the local scale. Local detection is advantageous since dangerous ice may often be unresolved at the resolution of publically available satellite products (tens of kilometers to <1 km), hidden during cloud-covered days, or may become disguised through reintegration into a consolidated ice pack. Identification of hazards within shipping lanes can then be distributed as an ice information product relevant for marine transit. Another component of the Arctic ice cover which can present a hazard for commercial stakeholders are landfast ice ridges. The landfast ice ridges may not always be a threat to marine safety, but can be hazardous if they become adrift in offshore shipping lanes. The largest landfast sea-ice ridges are often grounded and therefore remain stationary into the summer season. The fate of some grounded ridges is in-situ decay during the summer. However, other ridges may become detached unexpectedly along with the landfast ice extent through a combination of complex processes during the winter months (Jones 2013; Mahoney et al. 2007). Observations of complete or partial breakout or removal of deformed ice features comprising shorefast ice are therefore useful for forecast offices. Current practice within the operational forecast community is to analyze the seaward landfast ice edge (Mahoney et al. 2005), but forecast offices do not disseminate the severity of ridging near the ice edge. Observations and descriptions of intraseasonal changes in landfast ice morphology are not readily available to operational forecasters.

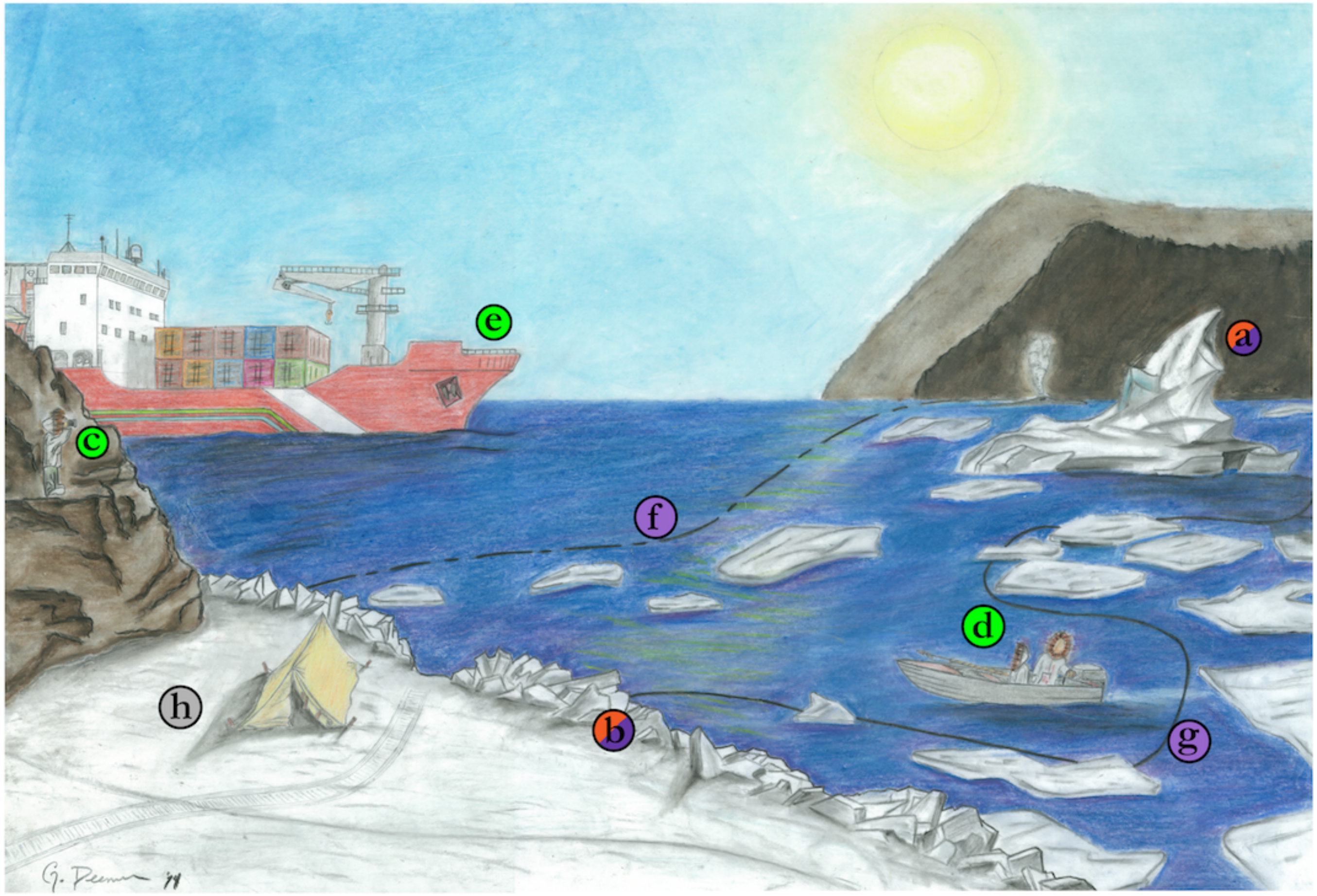


Figure 1.3. Schematic of a proposed, integrated sea-ice forecasting system utilizing local-scale surface observations (annotations are categorized in Table 1.1). Observations relevant to personal needs or other stakeholders (c, d, e) can be exchanged with forecasting agencies and disseminated appropriately as ice information products or incorporated in the discussion of sea-ice forecasts. Observations may include ice hazards for commercial vessels (a, b) or reports of low-concentration sea-ice (g) that will promote safe hunting and boating for local communities. Forecast products from public agencies are focused on the offshore pack ice and may integrate both hand-analyzed products (f) of the ice pack and model-derived products (g). Landfast (h) ice, which is of interest for many stakeholders, may contain hazardous sea ice (a, b), but is not treated explicitly in operational sea-ice forecast services.

Table 1.1. Itemized Components of a community-integrated operational sea-ice forecasting system proposed in this thesis. Letters correspond to annotations in Figure 1.3.

Category	Description
Hazards	a. Multiyear ice / glacial ice / highly deformed first-year ice b. Sea-ice ridges at the landfast ice edge
Observers / Stakeholders	c., d. Community members / local environmental experts / hunters and indigenous sea-ice users e. Industry, commercial, or tourism with ice sensitive vessels
Forecast Products	a., b. Sea ice hazard monitoring f. Sea-ice edge as analyzed by a human forecaster ____ _ _____ _ _____ g. Intermediate sea-ice concentration contour produced by a modeling system___________________
Other Interests	h. Shorefast ice stability / lifecycle / breakouts

Observations taken aboard vessels may also be incorporated into the sea-ice information workflow. A more rigorous and standardized reporting system is already in place for ship-based observations of sea ice (e.g., Joint Technical Commission for Oceanography and Marine Meteorology in-situ Observations Platform Support (JCOMMOPS), Ship-of-Opportunity Program (SOOP), Volunteer Ship Observing Scheme (VOS)), but non-government vessels are not currently required to submit regular sea-ice reports. Observations of preferred and safe hunting conditions, related to access to low ice concentrations (Kapsch et al. 2010), can be provided by vessels.

The current methodology that local residents use to predict the movement of sea-ice drift is based on line of sight of the ice cover in the upstream direction. Surfaced-based observations are then compared to satellite imagery to estimate the ice drift speed and the timing in which the ice will pass by the village (Winton Weyapuk Jr., personal communication 2014). For example, tall features such as local terrain or the sail of landfast ice ridges supply a perch for viewing offshore pack ice. Therefore, offshore observations of sea ice that can be utilized by locals or hunters traveling in personal watercraft or trying to use drifting ice as a platform would be of value for coastal communities to ensure safe transit.

Additionally, a push towards a unified polar code that regulates ship construction, equipping and operations in the Arctic has been initiated by the International Maritime Organization (Jensen 2007). Observation and validation of spatial marine charts provided by ice analysts will become increasingly important for enforcing new standards. Interpretation of local sea ice edge location, movement, and constituent ice type by coastal villages can provide information necessary for the most ice-sensitive vessels entering regulated waters.

Lastly, landfast sea ice, which is of disproportionate importance relative to its contribution to the total sea-ice area in the Arctic, is utilized not only by indigenous peoples but also by industry (Eicken et al. 2009). The timing of events in the landfast ice cycle, such as when the surface is stable enough for transportation or if breakouts will occur are of vital importance for those who depend on landfast ice services. Progress has been made in monitoring (Druckenmiller et al. 2009) and predicting (Petrich et al. 2012; Mahoney et al. 2007; Jones 2013) events in the landfast ice cycle on the Alaska coastline. However, the dynamics of events relative to the landfast ice cycle differ substantially with geographic location and present a significant challenge to operational prediction. Currently, the explicit prediction of events in the landfast ice cycle at the local level falls outside the responsibility of forecast offices. To clarify ambiguity relating to forecasts of important landfast ice events, the research community, along with the users of landfast ice, must work together and communicate with forecasting agencies to define product needs and limits of predictability.

1.4 Sea Ice Characteristics in the Bering Sea

Sea ice in the Bering Sea normally reaches its maximum extent in March (Niebauer 1980). Ice formation leading up to the maximum can be described as a conveyor belt, with ice growing in situ on the southern land-sea boundaries and being advected by northeasterly winds towards the shelf break (Pease 1980). According to Leonov (1960), approximately 97% of 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 0.5m, 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 to diminishing winter extent across the Arctic (Wendler et al. 2013; Perovich et al. 2013). 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 (Wendler et al. 2013; Matthewman and Magnusdottir 2011), but a leading mechanism has yet to be determined. Ice retreat in the Bering Sea is signaled with a northward shift in the trajectory of the north Pacific storm track (Overland 1981; Schumacher and Kinder 1983; Overland and Pease 1982). 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).

1.5 Thesis Overview and Goals

This thesis combines operational sea-ice information products and forecasts in the United States, observations made by Alaskans in the Bering Straits region, and a new forecast guidance model from the U.S. Naval Research Lab to propose a more integrated sea-ice forecasting system. The sea-ice retreat season in the Bering Sea, defined as 01 April through 30 June, is used as a test bed for the proposed system. Local observations, public operational sea-ice information products, and model output from 2011 and 2013 are analyzed in the context of improving operational forecast and providing for sea-ice information need from multiple stakeholder groups.

In Chapter 2, forecast verification techniques that have long been used in the discipline of numerical weather prediction have been modified to function with sea-ice forecast models. The concept of forecast skill, and deterministic methods for quantifying skill, are introduced. Climatological sea-ice datasets are also outlined. Chapter 3 presents the results of the forecast verification study for the spring retreat season in 2011. The key goal in this chapter is to see if any detectable patterns emerge on a regional scale. Results in both time and space are discussed in the context of using the model as a guidance product.

The fourth chapter presents two cases studies that bring operational products, model guidance, and community-scale observations closer together. The first case study, focusing on prediction leading up to 07 May 2011, explores how model forecasts and local observations that are part of a longer-term program (Eicken et al. 2014) can be used to improve sea-ice forecast products near the village of Gambell, AK. The second case study, on 17 June 2013, shows how local knowledge can be supplemented by more standardized observations to avoid miscommunication of sea-ice information. Observations collected following fieldwork to the communities of Wales, AK is also discussed in the context of model forecast validation. General conclusions to the thesis are contained within Chapter 5.

Chapter 2

Sea-Ice Forecast Model and Analysis Methods

2.1 The Arctic Cap Nowcast Forecast System

2.1.1 Background Leading to Forecast Model Selection

Forecasting sea ice is the number one goal of the National Oceanic and Atmospheric Administration listed in the 2011 Arctic Vision and Strategy (NOAA 2011a). In response to the NOAA Arctic Vision and Strategy, the NWS-Alaska Region held a sea-ice forecasting workshop, inviting members of the operational, research, and industry communities to collaborate and identify pressing needs (NOAA 2011b). One outcome of the workshop was a memorandum of agreement (MOA) between the National Weather Service and the Naval Research Laboratory Gary Hufford, personal communication 2011) to share output from the Arctic Cap Nowcast/Forecast System (ACNFS), a prognostic ice-ocean model. The MOA addresses the need expressed by the NWS for model guidance products to aid sea-ice forecasters at the Anchorage "Ice Desk". Before the model could be used in operations, key variables need to be analyzed. This study evaluates forecasts from the ACNFS in the Bering Sea for the spring retreat season. While the ACNFS has been validated in the context of addressing improvements from its predecessor on the pan-Arctic scale (Posey et al. 2010) there is no published effort specifically addressing forecast performance in the Bering Sea.

2.1.2 Model Configuration

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 ranges from about 4.5km^2 to 5.5km^2. The ACNFS is the interim sea-ice forecast system spanning the operational transition period between the Polar Ice Prediction System (PIPS) version 2.0 (Posey and Preller 1997) and the Global Ocean Forecast System (GOFS) version 3.0. The U.S. National Ice Center is the main customer of ACNFS products. The NIC receives 26 ACNFS products and derives others to aid in the creation of pan Arctic sea-ice analyses. The description of the modeling system as it is written here is relevant only to the model version which created the forecasts evaluated in this study and may not reflect the most recent update.

2.1.3 Data Assimilated in Near Real-Time

Oceanic data assimilated into the system include satellite observations of sea surface height and temperature as well as in-situ ocean observations that supply vertical profiles of temperature, salinity, and velocity. The 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. Oceanic profiles are gathered from conductivity temperature and depth (CTD) sensors aboard the Argos buoy network. The spatial extent of the Argos buoys is limited to the deep basins and observations in the Bering Sea are sparse during the period of interest in this study. Real-time data gathered from Special Sensor Microwave Imaging (SSMI) 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 observational data common to operational weather forecast models using a 4-dimensional variational assimilation system (Rosmond and Xu 2006).

2.1.4 Computational Process of the ACNFS

The ACNFS is run in real time at the Naval Oceanographic Office located at the Stennis Space Center in Stennis, MS. The model system is run once per day in three different stages. First, a 72-hour hindcast is performed. The second stage of the model run creates a nowcast that captures and assimilates data in the most recent 12 hours. 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 24-hour intervals reaching out 120 hours.

2.2 ACNFS Forecast Evaluation with a Skill Score Metric

In this study, the prediction of sea-ice concentration, thickness, and drift speed are analyzed for the spring retreat season in the Bering Sea. The sea-ice retreat season is defined here as the 90-day period beginning 01 April and concluding 30 June. Availability of archived forecasts limited the study to 2011. During the 90-day evaluation period, the modeling system had eight days of down time, when the production of new analyses and forecast products were not created. These eight days were removed from the evaluation. Additionally, forecasts produced before 31 March 2011 or forecasts that verified after 30 June 2011 were omitted. Data removal leads to small difference in the number of forecasts in the seasonal calculations depending on the length of prediction (Table 2.1).

Table 2.1. Number of forecasts included in the skill score calculation per lead-time.

Forecast Hour	Verification Days
24	76
48	75
72	76
96	73
120	71

Forecast skill refers to the relative accuracy of a set of forecasts, with respect to some set of standard control, or reference, forecasts (Wilks 2011). Here, a fundamental metric of forecast skill, used extensively in the discipline of numerical weather prediction, is applied to ACNFS forecasts during the 2011 sea-ice retreat season in the Bering Sea. A skill score founded on the ratio of mean squared error (MSE) of the predictand to the MSE of the reference is appropriate for the continuous scalar variables of ice concentration, ice thickness, and ice velocity magnitude being analyzed. Generally, the expression takes the form found in Jolliffe and Stephenson (2003).

$$MSESS = 1 - \frac{MSE_P}{MSE_R} \Rightarrow 1 - \frac{\sum(P - O)^2}{\sum(R - O)^2} \quad (1)$$

MSESS translates to MSE skill score, O denotes an observed value and subscripts P and R represent the predictand and reference, respectively. Here, the observed value is the analysis product generated by the modeling system. 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. Forecasts are evaluated using both climatology and persistence as reference forecasts. MSESS, hereafter shortened to skill score (SS), is used in both spatial and time series analysis on a regional scale.

2.3 Regional Forecast Verification of Sea-Ice Variables

The regional evaluation of predictive skill for ACNFS products is performed on a dynamic domain within the Bering Sea. The dynamic domain is defined by the daily sea-ice extent within the basin is used to evaluate forecast skill of sea-ice variables. Figure 2.1 presents an example of how the dynamic domain is determined if ice is found in either the model forecast, observation, or reference forecast. Sea-ice extent is commonly expressed using a threshold method, or sea-ice cover per unit ocean area when using satellite-derived ice concentration. This analysis adopts the fifteen percent concentration threshold where the ocean is considered ice-covered if the concentration is greater than or equal to the threshold value. The fifteen percent cutoff is most frequently used because it provides the most consistent agreement between satellite and ground observations (NSIDC 2014). If the concentration falls below the prescribed threshold, then the ocean surface is considered sea-ice free.

The Bering Sea is part of the seasonal ice zone, where all sea ice will either melt or be advected out of the region over the course of the retreat season. Nearly 1.2 million km^2 of ocean was ice-covered at the beginning of April in 2011 and entirely open water by late June, resulting in a spatially varying number of days with ice present. Figure 2.2 displays the number of days in which sea ice was present in the Bering Sea in the 2011 case study. The number of ice days at any location in the Bering Sea will dictate the sample size in the spatial SS calculation at the grid cell level, and the area-averaged SS in time series.

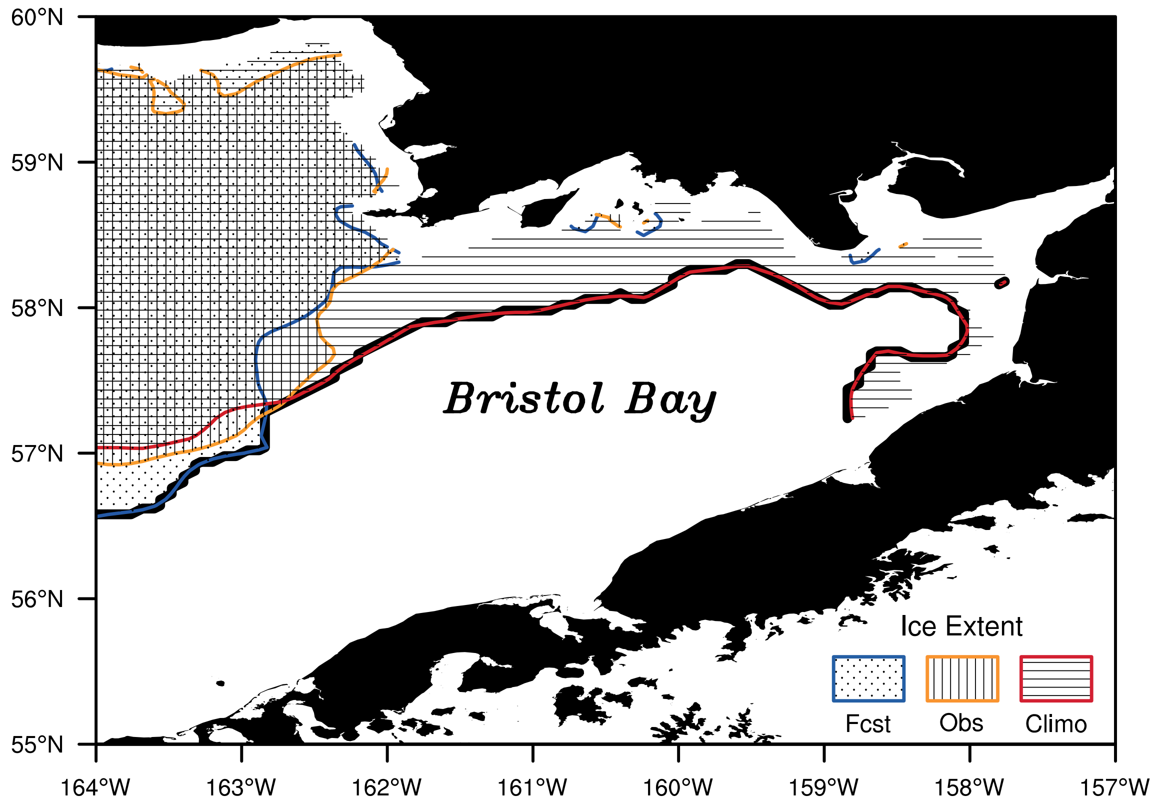


Figure 2.1. Defining the daily ice extent domain. The blue line represents the ACNFS 120 – hour forecast sea-ice extent created 00z Apr. 02, 2011, the ACNFS analyzed (observed) sea-ice extent when the forecast verified (orange line) on 00z Apr. 07, 2011, and the climatological ice extent from SSMI on April, 07 (red line). The thick black line is an example of capturing the maximum possible extent for each day to use as dynamic domain in the skill score calculation.

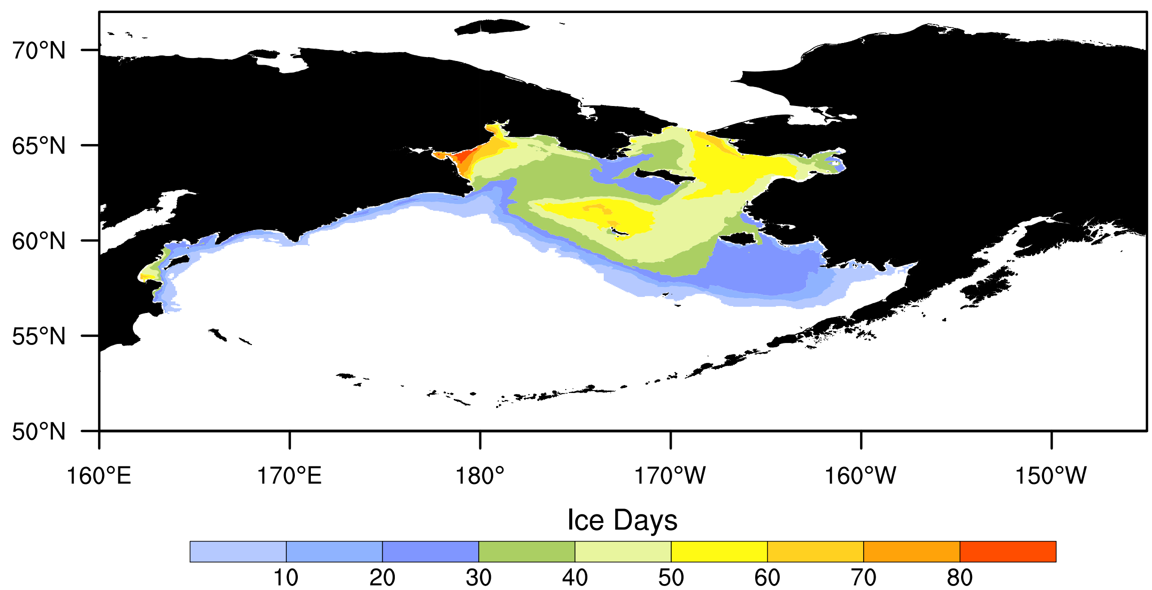


Figure 2.2. Number of ice days in the Bering Sea during the 2011 spring retreat season from April through June. Ice days refers to the number of days where sea ice was present in concentrations greater than or equal to 15%.

2.3.1 Regional Forecast Skill in the Spatial Domain

From Equation 1, it can be shown that the limits of the SS expression are $[1, -\infty)$. As the MSE of the reference forecast becomes << 1, the SS grows towards negative infinity. If one or more days exist where the reference forecast performs exceedingly well with respect to the model-generated forecast at any grid cell, then a seasonal average SS will be strongly influenced by extreme negative values. Since the question asked is whether or not the model system can outperform the reference forecast, each day is treated independently in the spatial SS analysis. This creates a binary condition described by Equation 2.

$$Skillful = \begin{cases} 1, & SS > 0 \\ 0, & SS \leq 0 \end{cases} \tag{2}$$

If the daily forecast SS is greater than zero, then it is flagged as being skillful with respect to the reference forecast. The daily binary maps are then accumulated over the season and normalized by the ice days (Figure 2.2) to yield the skillful forecast fraction (SFF). The SFF is a diagnostic metric of model prediction over time, indicating the fraction of skillful forecasts relative to the total number of forecasts produced.

2.3.2 Regional Forecast Skill in the Time Domain

Forecast verification in the time domain is based on the same skill score methodology used in spatial verification (Equation 1). However, when using MSE Skill Score in time series, an asymptotic error arises as the MSE of the reference forecast approaches zero. Since the skill score is calculated for every grid cell contained within the ice extent domain, a cell with MSE_R equaling exactly zero when MSE_P is non-zero, was removed. For any given day within the 2011 retreat season, the number of data points removed during the calculation was orders of magnitude smaller than the total sample size and the impact is considered negligible. Each daily calculation for a given extent (Figure 2.1) is spatially averaged to give the mean SS. The result is a bulk SS value, which gives insight into model performance during different synoptic-scale conditions and changing ice extent. The mean value is then normalized by the sea-ice extent area as shown in Equation 3, where m is an individual grid cell and M is the sum of all m, defining the ice extent. The solution to Equation 3 represents the average skill score across the ice extent for a single day. An advantage of the daily mean SS is that it provides the ability to evaluate the magnitude of forecast skill that could not be addressed with the binary condition in the spatial verification.

$$\overline{SS} = \frac{1}{A_M} \sum_{m=1}^{M} \left(1 - \frac{MSE_P}{MSE_R}\right) A_m \tag{3}$$

2.4 Climatological Reference Datasets

The climatologies used in this study span a 22-year period from 1979-2000, to be consistent with the climatological sea-ice data record in use by the National Snow and Ice Data Center (NSIDC) when the analysis was performed. Temporal resolution of the climatologies is once daily, and the spatial resolution varies. All climatologies have been regridded to the 1/12° resolution of the ACNFS using a bilinear interpolation while their land masks were preserved at their original resolution.

2.4.1 Sea-Ice Concentration Climatology

The 25x25km climatology of sea-ice concentration is derived from passive microwave data (Peng et al. 2013) using a blend of the NASA Team-I and Bootstrap algorithms. This climatology differs from SSMI data ingested into the ACNFS, which employs the AES-York algorithm (Hollinger et al. 1991). At this time, a climatological archive of sea-ice concentration data retrieved using the AES-York algorithm is unavailable. A thorough evaluation and intercomparison of the sea-ice detection algorithms can be found in Steffen et al. (1992).

2.4.2 Sea-Ice Thickness Climatology

Measurements of ice thickness in the Bering Sea are sparse. New efforts are being made to synthesize modern and historical thickness data (e.g. Lindsay 2013) and mounting interest in Arctic sea ice has contributed to recent growth in sea-ice thickness data resources. However, a significant void of in-situ ice thickness measurements in the marginal ice zone persists. For this reason, the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) is selected as the best spatial, long-term representation of ice thickness in the Bering Sea (Zhang and Rothrock 2003). PIOMAS is a reanalysis of Arctic sea ice. The model is most commonly referenced as an index for the pan-Arctic trend in sea-ice volume. PIOMAS has been validated using the Lindsay (2013) database and shows strong correlation with the observations. The modeled ice cover in PIOMAS demonstrates a slight underestimation of the thickest ice and overestimation of thin ice (Schweiger et al. 2011). Validation of PIOMAS has only been performed over the Arctic and its marginal seas, leaving ice thickness uncertainty in the seasonal ice zone of the Bering Sea unknown. Zhang et al. (2010) compared upward looking sonar records with simulations from a sea-ice model identical to that used in PIOMAS (Zhang and Rothrock 2001) in the St. Lawrence Island polynya region and found that observed ice thickness increases are captured in the model, but with a small departure in the timing of ridging and rafting events.

2.4.3 Sea-Ice Drift Speed Climatology

A sea-ice drift product for the Arctic has recently become available (Fowler et al. 2013). This multi-sensor dataset includes ice drift from in-situ buoys, derived ice displacement from passive microwave radiometers, and inferred sea ice motion using NCEP/NCAR reanalysis forcing. Because of the absence of in situ sea-ice drift observations in the Bering Sea, climatological sea-ice drift in the region will be dependent on passive microwave sources and atmospheric reanalysis forcing. The temporal resolution of the climatology is once per day. Interannual variability from storm systems during the 22-year base period and potential tidal influences on sea-ice motion were smoothed using a seven-day moving average.

Chapter 3

Results of ACNFS Forecast Verification in the Bering Sea

In this chapter of the thesis, results from ACNFS forecast evaluation using the mean squared error skill score metric (see Chapter 2 for method details) are presented and discussed. A spatial and temporal view of skill is presented for the 2011 spring sea-ice retreat season in the Bering Sea.

3.1 The 2011 Sea-Ice Retreat Season

The springtime sea-ice retreat season in the Bering Sea will be defined in this study as the 90-day period from 01 April through 30 June. The breakup season represents a time when many sea-ice forecast stakeholders are active. Model analysis from the ACNFS will be used to describe the retreat pattern for the 2011 retreat season, which is treated as a case study for model evaluation. Passive microwave climatology of sea ice in the Bering Sea is used to put the 2011 season in the context of long-term conditions.

Sea-ice extent in the Bering Sea, as seen from passive microwave radiometers, is unremarkable in 2011 and is not categorized as either a heavy or light ice year (Wendler et al. 2013). However, to a local community member in a remote coastal village in the northern Bering, the development of the 2011 sea-ice season was in contrast with historical norms:

> "The ice pack [at Gambell] is different thus far compared to that of the past. It is generally agreed that it has a poorer quality, probably from mostly fluctuating temperatures; storms; and not fully developing, as it had before, into thicker ice. It is in all probability prone to rapid melting with the coming of warmer spring climates. Paul Apangalook Gambell, AK, 08 April 2011." (Apangalook et al. 2013)

The ice extent in the first week of the 2011 retreat season was on the order of 1.15×10^6 km^2 and covered much of the Bering Shelf. As the first week of April 2011 drew to a close, a strong low-pressure system churned in the western North Pacific. Over the days of April 6th and 7th, the storm would deepen to a minimum central pressure below 940 hPa and slide over the Bering Sea ice pack (Figure 3.1). Leading up to the April storm, the NWS Sea Ice Program issued a sea-ice advisory text product for Bering Sea. The special statement warned of "dangerous ice conditions" (NWS 2011) in addition to predicting the fracture, breakup, and onshore ice movement of shorefast sea ice at many coastal locations in western Alaska. Verification of such forecasts can only be attained onshore by community-based observations. For example, an observer on St. Lawrence Island reports "The NWS issued an ice advisory for the area of ice being pushed onshore by surging seas. It did not occur as forecasted. Paul Apangalook Gambell, AK 07 April 2011." (Apangalook et al. 2013). This example of a false positive represents only one location on the Bering Sea coastline where the forecast may have in fact verified, but impacts of the storm in other communities are undocumented.

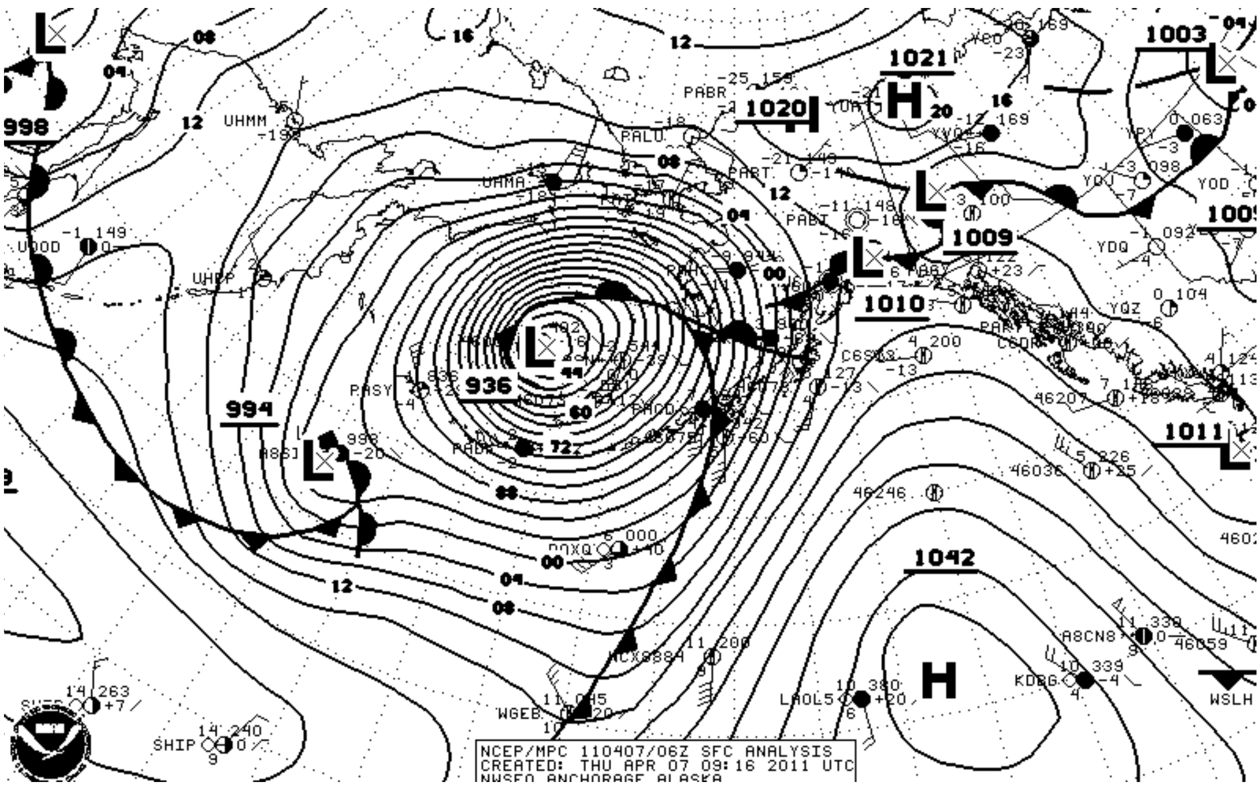


Figure 3.1. Synoptic weather map of the north Pacific. April 07, 2011 0600z. The graphic depicts a powerful mid-latitude cyclone over the Bering Sea that influenced the 2011 sea-ice retreat season.

Unsettled weather with windy conditions prevailed in the wake of the storm system. Strong northerly winds drew out the ice edge to the seasonal maximum on April 15. The Bering Sea icescape continued to reflect the effects of the large storm into late April, as many small broken-up floes comprised the ice cover (SIWO 2011a). Following a period of tumultuous weather at the start of the season, ice extent followed a climatological breakup pattern in the Bering Sea through the end of April. The first signs of retreat occurred in Bristol Bay, where the thin ice was drawn out to the south under northerly winds, resulting in a northwestward retreat of the local ice edge. At the same time, thinner sea ice in the production zones of the Siberian polynya, located in the Gulf of Anadyr and the St. Lawrence Island polynya melted, exposing open water.

Quiescent weather dominated in May, when the decline in ice extent progressed at an average rate of 25,000km^2 per day. A large area of open water expanded from Cape Navarin to Anadyr Strait in the first week of May, which was earlier than the climatological normal (Figure 3.2). This feature separated the ice mass in the central Bering Sea from the sea ice remaining in the Gulf of Anadyr. Ice retreat north of St. Lawrence Island in late May was likely dominated by export through Bering Strait (Travers 2012). Sea ice in Kresta Bay cleared out in late May, weeks before the climatological average breakup date (SIWO 2011b). The last pieces of ice in the Bering Sea agree well with climatology and remained along the near-shore region of Anadyr Bay through late June.

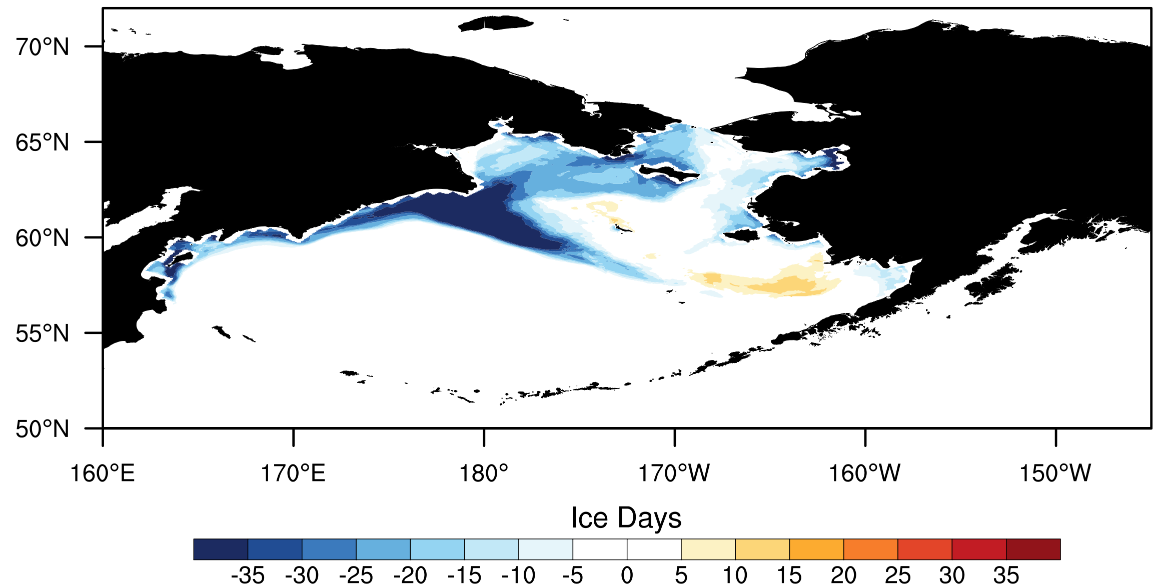


Figure 3.2. Ice day anomaly during the 2011 sea-ice retreat season in the Bering Sea. Ice days refers to the number of days when sea ice was present in concentrations greater than or equal to 15%. Negative anomalies are in blue and positive anomalies are red during the 90-day retreat season from April – June.

3.2 Spatial Verification Results Using Climatology as a Reference Forecast

Figure 3.3 shows SFF for 1-day and 5-day forecasts of the three sea-ice variables in the Bering Sea with climatology as a low-skill reference value. A feature common to all six panels is a hot spot (SFF > 0.9) in a region southeast of Cape Navarin, in the northern Aleutian Basin. The presence of this high-skill feature is attributed to the ocean surface remaining nearly ice free during the 2011 retreat season when climatology indicates the ice extent existing further south (Figure 3.2). Thus, the forecasts provide useful information in this region by accurately predicting sea-ice free conditions over an area that is ice covered at this time based on climatology. A common decrease in the number of skillful forecasts produced between the 1-day and 5-day prediction occurs for all variables.

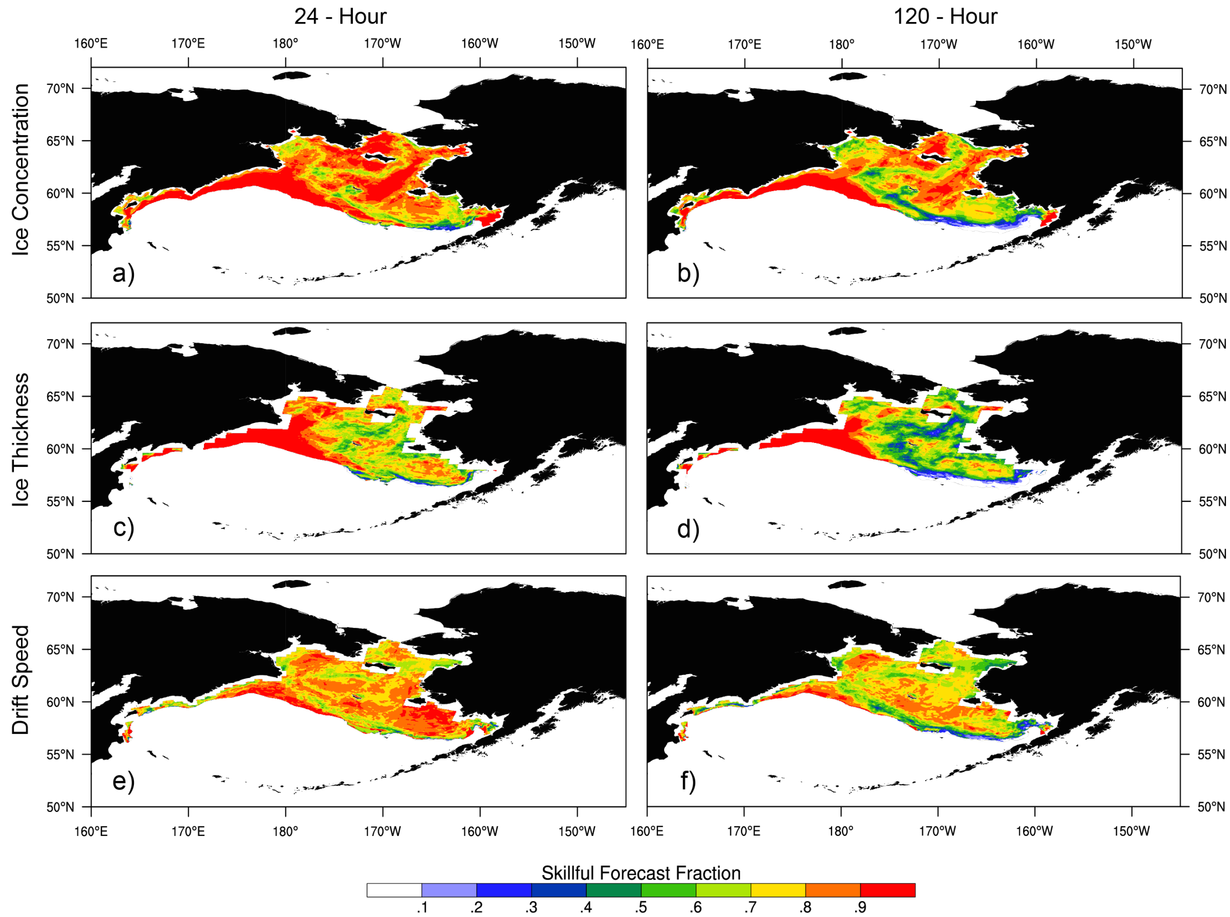


Figure 3.3. Skillful forecast fraction (SFF) with climatology as the reference forecast. Panels on the left show the seasonal summary of 1-day forecasts and the panels on the right show the summary of 5-day forecasts. Ice concentration (a, b), ice thickness (c, d), and ice drift speed (e, f) are ordered in rows from top to bottom, respectively.

3.2.1 Sea-Ice Concentration Forecasts Relative to Climatology

The top two panels of Figure 3.3 display SFF for area ice concentration. Both panels show a ribbon of decreased forecast skill originating in the eastern Bering Strait, continuing south through Shpanberg Strait along the eastern shore of St. Lawrence Island. This ribbon-like feature aligns closely with a horizontal oceanic density gradient. Schumacher et al. (1983) and Danielson et al. (2006) show that brine flux from local ice formation is accompanied by eastward transport along the south side of the island. Locally-enhanced saline water is advected into Shpanberg Strait, where it encounters fresher coastal waters near mainland Alaska, aiding in the formation of a tight zonal density gradient (Danielson et al. 2011; Clement et al. 2005). The gradient results in a baroclinic jet, producing a strong northward component in near-surface seawater velocity. The surface currents influence the location of the ice edge and ice distribution, making predictability of ice concentration and location of the ice edge in the retreat season more challenging.

A second low-skill feature present in the ice concentration panels can be found across the eastern Bering shelf. This region coincides with the seasonal maximum extent in 2011. The belt of SFF < 0.7 stretches from Bristol Bay along the shelf break south of St. Mathews Island, terminating near Navarin Canyon. The ice edge remained near-stationary in this location for multiple weeks during the retreat season, challenging the model system to produce accurate forecasts where warm waters can melt ice (Hendricks et al. 1985) and strong along-isobath currents can displace ice (Kinder et al. 1975).

3.2.2 Sea-Ice Thickness Forecasts Relative to Climatology

The center panels in Figure 3.3 show the seasonal SFF for sea-ice thickness relative to the PIOMAS climatology. An appreciable loss of information exists along the Bering Sea coastline due to the 1x1° resolution the climatology. While an evaluation of sea-ice thickness forecasts using the skill score methodology is acceptable for identifying spatial patterns of model performance, the method is a broad measure and does not delineate between dynamic or thermodynamic contributions to error in thickness.

The 24-hour predictions of sea-ice thickness (Figure 3.3c) are less skilled than ice concentration forecasts at the same lead-time. Lower skill is particularly evident over much of the Bering shelf where SFF is around 0.6 - 0.7. The SFF remains high in areas where sea ice commonly undergoes deformation. This includes areas north of St. Lawrence Island, St. Matthews Island, and Norton Sound. Strong northerly winds that persist through the winter and into the beginning of the retreat season drive sea ice into the northern shores of landmasses in the region. SFF approaching 1 in these zones may be explained by the ACNFS accurately capturing deformation features at a higher resolution than what is seen in the course resolution on the output grid of the PIOMAS climatology. SFF greater than 0.7 in Bristol Bay suggests that the ACNFS captured thermal growth in the 2011 season with higher precision than a climatological average could provide.

High SFF (>0.8) north of landmass features described in the 1-day thickness predictions remain for the 5-day forecasts. However, a second familiar pattern emerges to the south and east of St. Lawrence Island in the 5-day SFF panels. A linear feature defined by SFF between 0.2 and 0.4, as seen in the area ice concentration panels is present, suggesting that this feature is linked to ice concentration. While both thermal and dynamic processes are affecting sea-ice thickness during the breakup season, the presence of a velocity jet in the underlying water mass indicates that incorrect placement of sea ice contributed most to low-skill forecasts created for Shpanberg Strait rather than in-situ melt.

3.2.3 Sea-Ice Drift Speed Forecasts Relative to Climatology

The SFF for sea-ice drift speed (Figure 3.3e-f) has less pronounced spatial features when compared to that of sea-ice concentration and thickness but a few notable patterns do exist. For example, the near-shore areas off the northern coastlines of Cape Navarin, St. Matthews and St. Lawrence Islands, and Norton Sound are all marked by reduced SFF compared to the offshore regions. Alternatively, sea-ice drift over the central Bering shelf has higher SFF since it is impacted less by interaction with the coastlines has a higher SFF, suggesting that the magnitude of ice drift is predicted more accurately when sea-ice is closer to the mode of free drift. A second low-skill region exists that follows the shelf break in the Bering Sea. This narrow belt of low predictive skill is related to errors in the forecast ice extent but may also result from difficulties in capturing the Bering slope current.

3.3 Spatial Verification Results with Persistence as a Reference Forecast

The regional forecast skill of the ACNFS has been assessed with persistence as the reference forecast (Figure 3.4). Overall, spatial patterns in SFF are not as strong when compared to a climatological reference. The key differences between the 1-day and 5-day forecasts are increasing SFF for sea-ice concentration and thickness and decreasing SFF for sea-ice drift speed. The shift to higher SFF from 1-day to 5-day forecasts agrees with the typical time rate of change for each variable. On a spatial scale the size of the Bering shelf, both sea-ice concentration and thickness are slowly changing over the timescale of less than or equal to five days. Therefore, a persistence forecast is likely to be a good predictor on such a short timescale. The decrease in SFF from 1- to 5-day forecasts, however, likely reflects the reduction of predictive skill over time of highly variable wind speeds in the atmospheric forcing model.

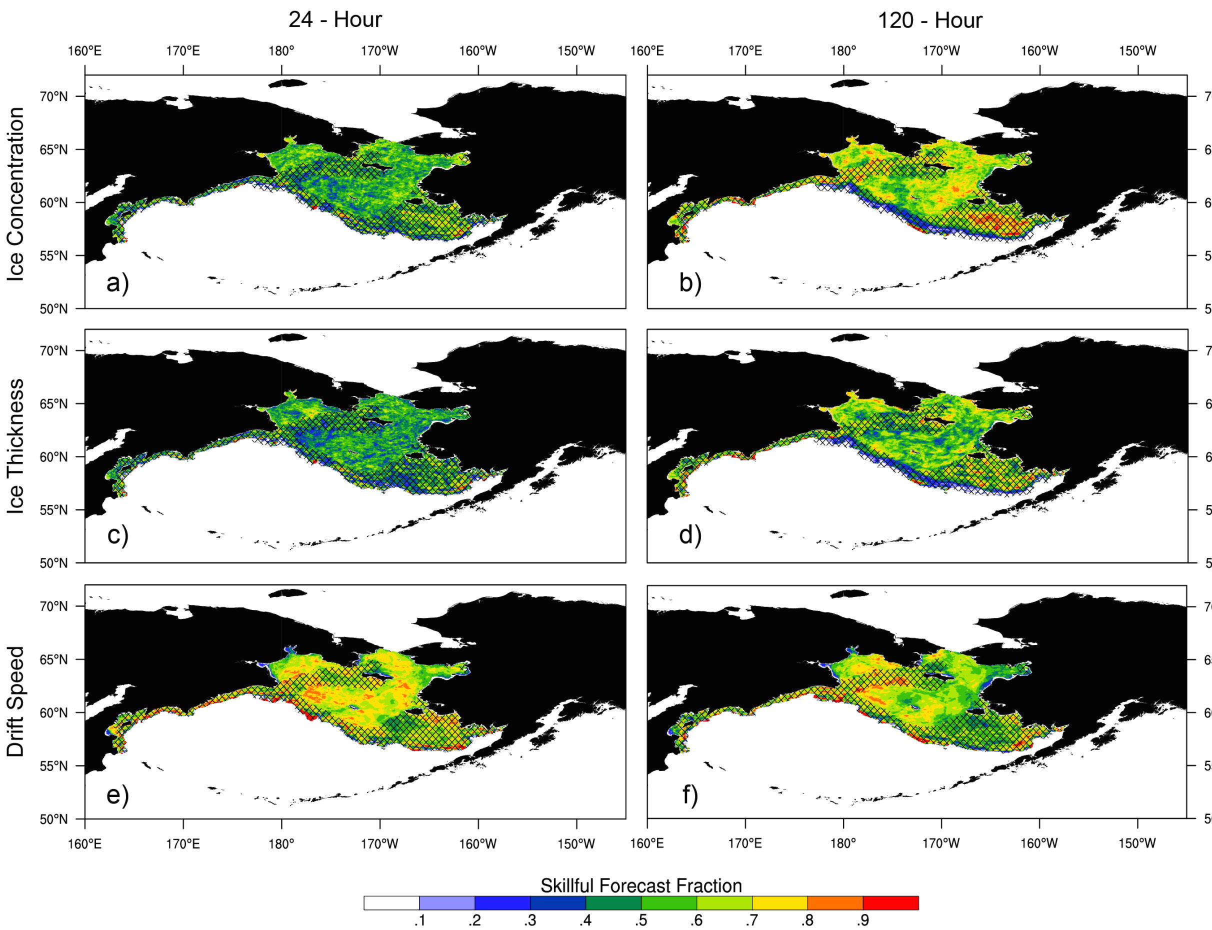


Figure 3.4. Skillful forecast fraction (SFF) with persistence set as the reference forecast. Cross-hatching indicates the area where sea-ice was present for less than 30 days. Panels on the left show the seasonal summary of 1-day forecasts and the panels on the right show the summary of 5-day forecasts. Ice concentration (a, b), ice thickness (c, d), and ice drift speed (e, f) are ordered in rows from top to bottom, respectively.

3.3.1 Sea-Ice Concentration Forecasts Relative to Persistence

The 1-day SFF values for sea-ice concentration (Figure 3.4a) are similar (0.3 – 0.5) across the sea-ice extent domain in the 2011 retreat season with only a few small areas of higher SFF. However, in the 5-day SFF for concentration (Figure 3.4b) displays a strip of low SFF (<0.4) along the edge of the ice extent domain. The most significant changes in ice concentration can be expected to occur near the ice edge. Generally, the ice edge is where the smallest floes can be found with floe size increasing towards the interior of the pack (Squire et al. 1995). The direction of wind, wave, and current forcing becomes critical when forecasting changes in the location of the ice edge.

3.3.2 Sea-Ice Thickness Forecasts Relative to Persistence

There are no distinct patterns that emerge in the map of SFF for sea-ice thickness (Figure 3.4c-d). Most of the ice extent domain has SFF > 0.5, while values below 0.4 are visible along the Bering shelf in the 120-hour panel, suggesting forecasts of ice thickness near the edge have less consistent skill. This feature may be closely related to sea-ice extent. If the ice extent is forecast incorrectly, then any variable dependent upon ice present in a particular location will also be forecast incorrectly. Overall, there is a shift to higher SFF from the 1-day to 5-day prediction of sea-ice thickness in the region.

3.3.3 Sea-Ice Drift Speed Forecasts Relative to Persistence

SFF decreases from the one to five day forecasts of drift speed (Figure 3.4e-f). However, the shift to lower SFF is not uniform across the domain. There is higher SFF near the Gulf of Anadyr and lower SFF in Bristol Bay. The composite mean sea level pressure (MSLP) for the 2011 retreat season (Figure 3.5) has a gradient in MSLP oriented from the southwest Alaskan mainland to the

Chukotka Peninsula. Lower atmospheric pressure in the eastern Bering Sea is consistent with stormier conditions, which is inherently more difficult to predict and is consistent with forecasts having less skill.

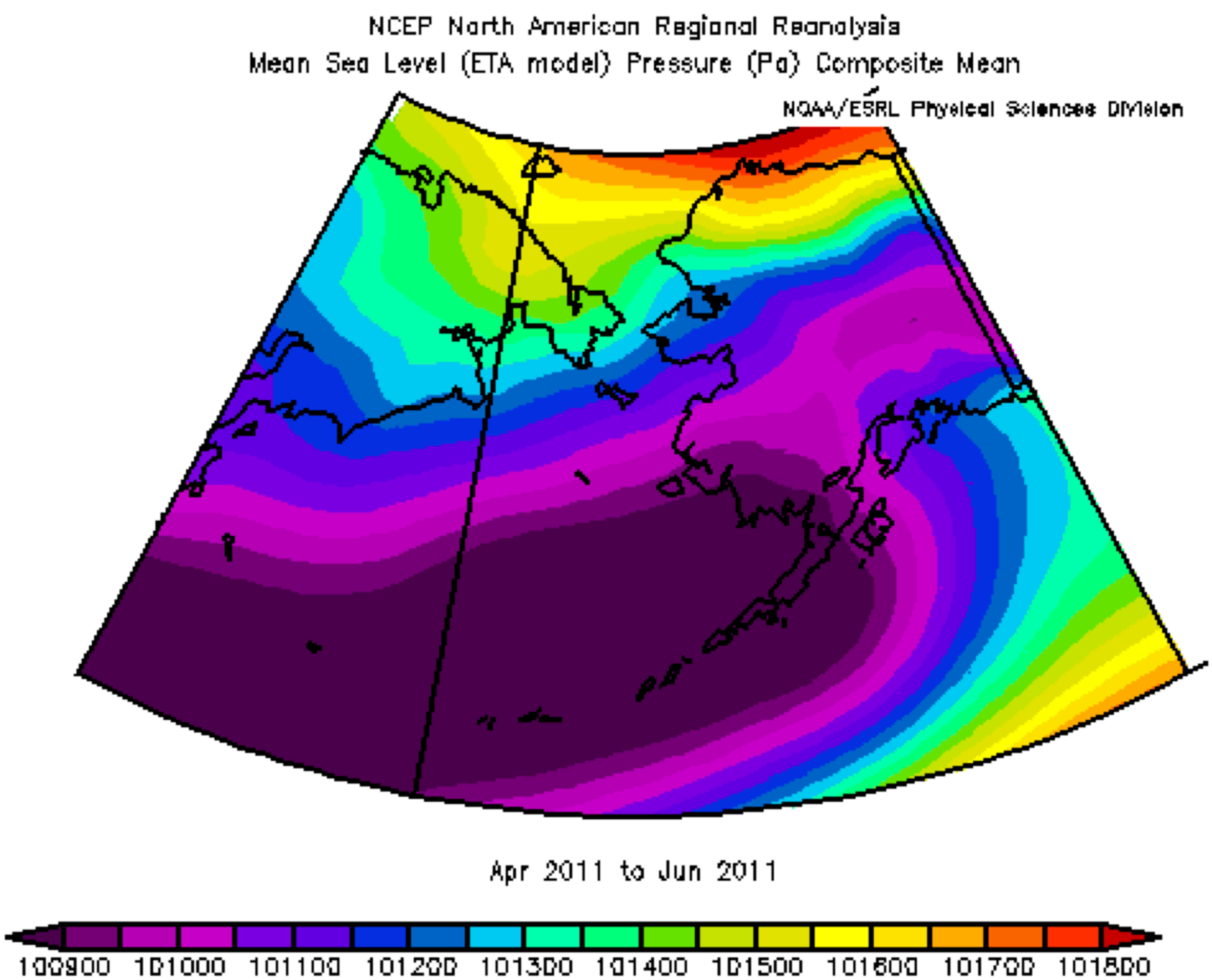


Figure 3.5. Mean sea level pressure over the Bering Sea, AMJ 2011.

3.4 Trends in Skillful Forecast Fraction Over Forecast Lead Time

A summary of SFF with respect to climatology and persistence for all forecast periods is presented in Figure 3.6. When climatology is set as the reference forecast, SFF decreases with increasing forecast length for all variables. Prediction of sea-ice concentration is most skilled while sea-ice drift speed and thickness are forecast with less skill.

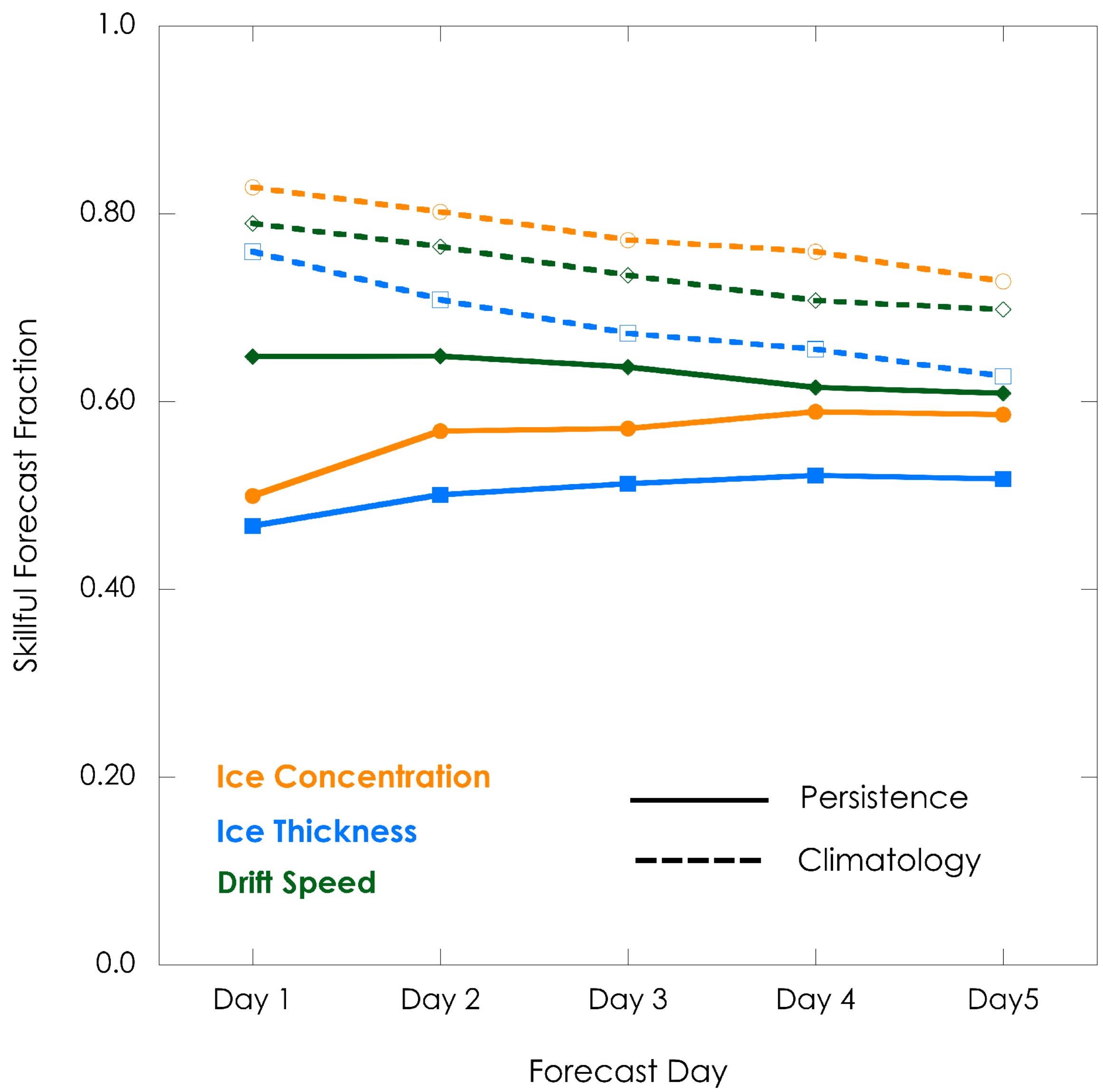


Figure 3.6. Trends in skillful forecast fraction with increasing forecast lead-time. Data points plotted represent a mean value across the ice extent within the Bering Sea.

There is no common trend in SFF with increasing forecast length when persistence is set as the reference. Forecast skill from the 1- to 5-day span increases for ice concentration and ice thickness and decreases for ice drift speed. These findings are consistent with the shift in SFF seen in the spatial plots in Figure 3.4. Ice concentration and thickness are predicted with increasing skill relative to persistence, while the ice drift speed is influenced most by error in the atmospheric forcing. An intriguing result that requires further investigation is the unchanging bulk skill score from 4-day to 5-day forecasts for persistence as the reference forecast.

3.5 Time Series Verification Results

Figure 3.7-Figure 3.9 show the forecast skill as a time series relative to two reference forecasts. The top panel in each time series is calculated with persistence as the reference. The bottom panel is calculated with climatology as the reference. Each data point is a domain-wide average, dependent on the ice extent. The calculated skill score for both 1-day and 5-day forecasts are represented with data markers on the day that the forecast verified. The forecast production date will precede the skill score marker by the prediction timespan. Decreasing sea-ice extent during the 2011 retreat season is plotted as a dashed line in both the climatology and persistence time series.

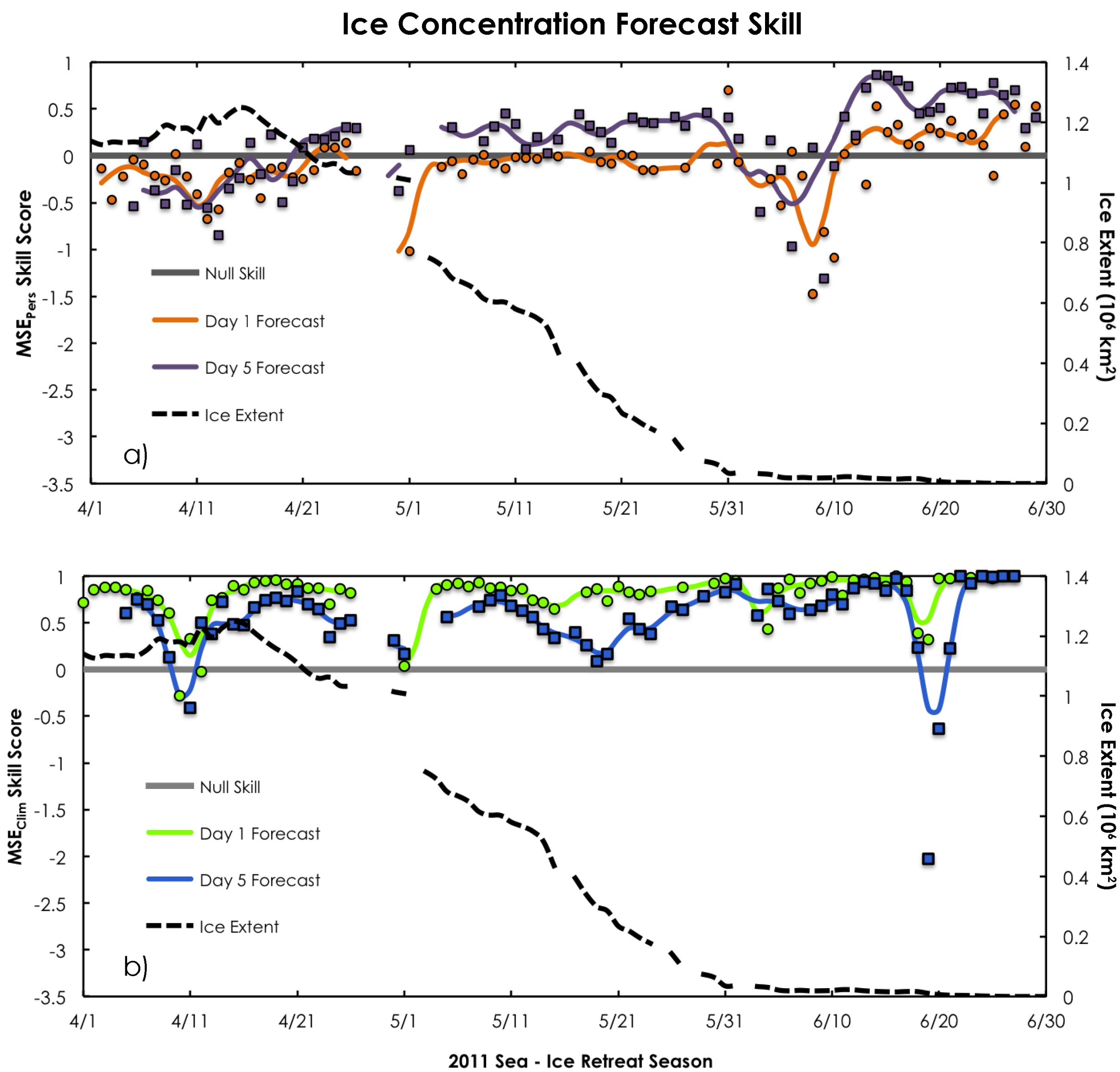


Figure 3.7. Time series of forecast skill for ice concentration. The reference forecast is set to a) persistence and b) climatology. Calculated MSE skill score is plotted as a marker for each day. A solid line connects the data with a 1:2:1 smoothing. Ice extent in each plot represents the 2011 retreat.

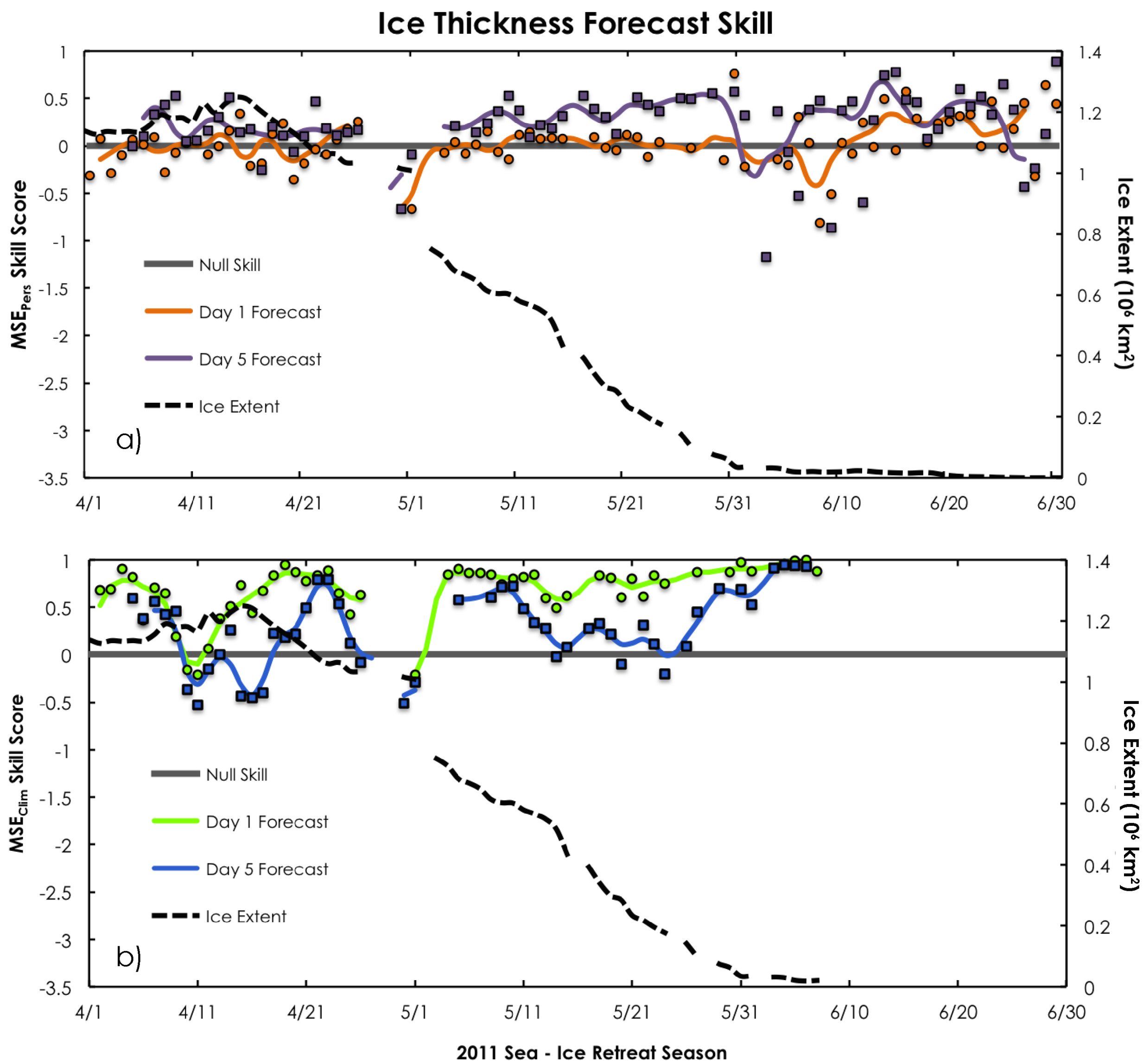


Figure 3.8. Time series of forecast skill for ice thickness. The reference forecast is set to a) persistence and b) climatology. Calculated MSE skill score is plotted as a marker for each day. A solid line connects the data with a 1:2:1 smoothing. Ice extent in each plot represents the 2011 retreat season.

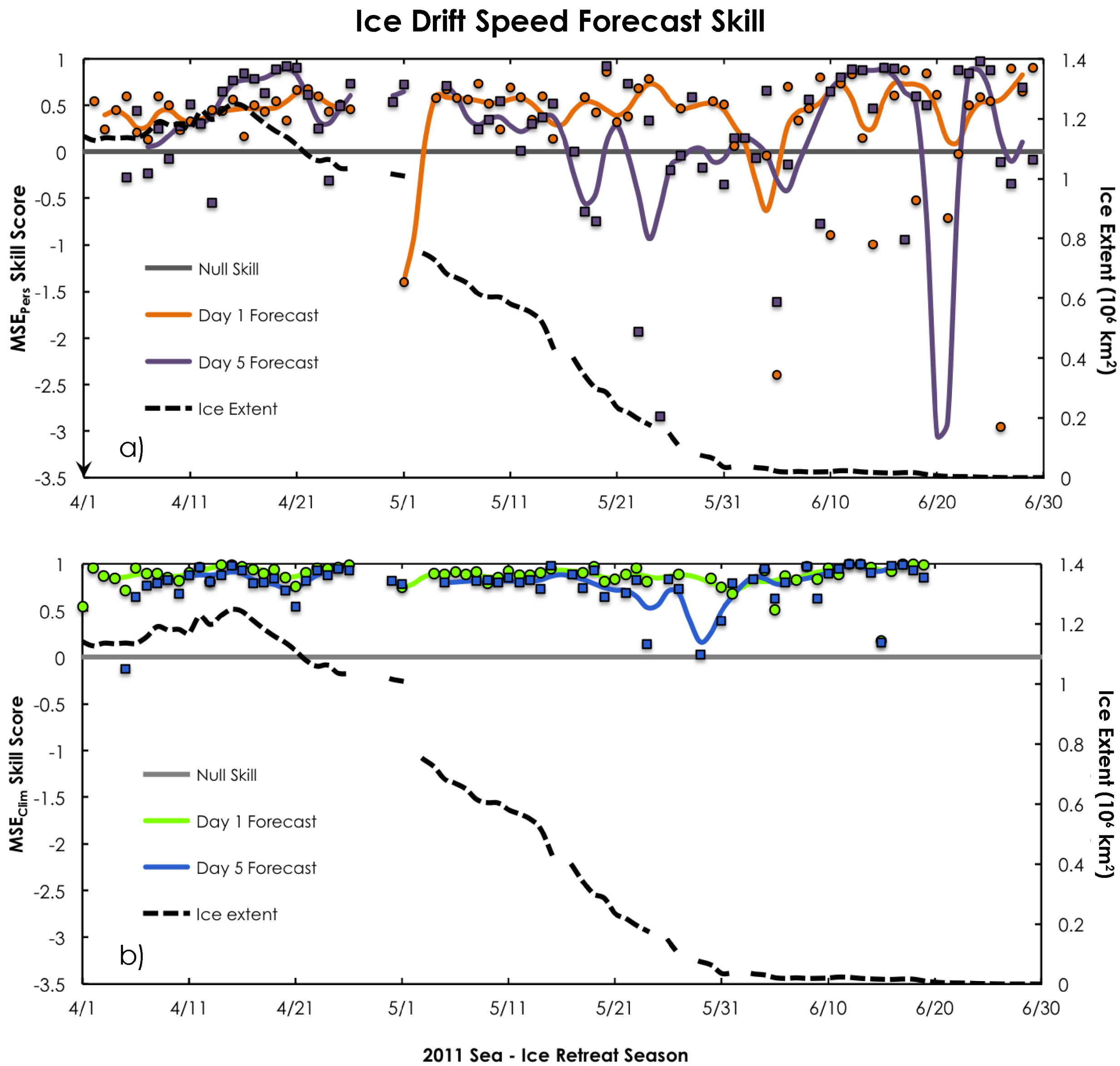


Figure 3.9. Time series of forecast skill for ice drift speed. The reference forecast is set to a) persistence and b) climatology. Arrow on MSE axis in a) indicates some daily skill score markers are out of range. Calculated MSE skill score is plotted as a marker for each day. A solid line connects the data with a 1:2:1 smoothing. Ice extent in each plot represents the 2011 retreat season.

It is important to note the difference in the expected relationship between the skill of a 1-day forecast and a 5-day forecast in the time series. When persistence is the reference, the expectation is for the 5-day forecast to have higher skill than the 1-day forecast. This is because a persistence forecast should represent conditions for the following day better than the five days into the future. The opposite relationship holds true when climatology is used as a reference value. The 24-hour prediction should show the highest skill since the modeling system is expected to predict conditions with the highest precision at short lead times. At a longer forecast range of five days, the model is subject to decreasing skill through systematic error. In summary, the 5-day forecast produced by the modeling system is expected to have the more skill when persistence is the reference forecast and less skill when climatology is the reference forecast.

3.5.1 Persistence as the Reference Forecast

The skill of the ACNFS relative to persistence can be seen in the upper panel of each time series plot. One common pattern in the persistence panels is an increasing variance of skill score over the season, which reflects the decreasing sea-ice extent and sample size reduction from 10^5 to 10^2 grid points from 01 April to 30 June.

All variables evaluated show similarities in skill during April. Neither forecast lead-time has consistently higher skill. The prediction of sea-ice drift speed is most skillful during the first month of the time series when nearly all forecasts fall above the null-skill line. Predictive skill of the modeling system appears to be largely unaffected by extreme synoptic weather in April. During the second week of April, an extratropical cyclone entered the southern Bering Sea from the western North Pacific. The low-pressure system then went through explosive cyclogenesis on 07 April, as it remained on a northeasterly track in the central Bering Sea. The feature later filled over the next 48 hours. Despite surface winds above gale force during the short lifetime of the storm, there is little response in the bulk skill score for all three variables.

Ice concentration and thickness forecasts in May have a higher bulk skill than those produced in April. The bulk error in the 1-day prediction is indistinguishable from persistence for concentration and thickness since the skill score is near zero. Prediction of drift speed becomes less consistent in May and 5-day forecasts are commonly without skill. Synoptic weather in May was quiescent when compared to the preceding 30-day period with the exception of one event. An occluded cyclone entered the Bering Sea in the first week of May when model forecast skill appears to degrade, but lack of model output from this time period prevents further analysis.

A common decline in forecast skill for all variables occurs during the first week of June. Both 1- and 5-day forecasts become unskilled when a large storm developed and intensified in the central Bering Sea before stalling, maturing, and lifting within a few days. Following this event, atmospheric pressure gradients relaxed. Ice-covered ocean in June is confined to the Gulf of Anadyr. Forecasts for concentration and thickness become skillful again in June. Skill scores for drift speed over the waning ice extent is noisier as a result of the small number of grid cells that went into the calculation.

3.5.2 Climatology as the Reference Forecast

The bulk skill is higher when climatology is set as the reference forecast. All three variables display the expected pattern when using a climatological reference value, where 1-day forecasts outperform 5-day forecasts. The length of the three time series is unequal, resulting from coarse land mask resolutions in the climatological data sources. The skill score for ice concentration and thickness vary over the retreat season while the drift speed skill score remains near unity.

Forecast skill for thickness and concentration is commonly greater than zero but becomes unskilled during a few key events in the 2011 retreat season. A reduction in forecast skill, centered on the early April storm can be seen in the two time series. During the final week of April, predictive skill for both concentration and thickness decrease but remain positive. Following a period of missing data at the beginning of May, the bulk 24-hour skill score for ice concentration and thickness in the Bering Sea is high. The 5-day forecasts are less skilled during this time. The 120-hour predictions for ice thickness do not perform well when compared to climatology, indicating that model-generated forecast error is comparable to the error in a climatology-based prediction.

3.6 Discussion of Time Series Verification

3.6.1 Skill Relative to Persistence

Overall, ice concentration is represented well by persistence on short time scales. Given a limited dataset, the ACNFS has difficulty outperforming persistent concentration when ice extent is at or near the maximum (about 1.0 million km sq) in April. Sea ice has limited places to travel in the Bering Sea when winds blow from the south in the early part of the retreat season. Advection towards the south offers the path for ice moving from the north. A southern migration of sea-ice over the Aleutian basin was observed following a large April storm, but the expansion was short-lived since melt occurred quickly over warmer ocean waters. Open-water areas developed in response to strong offshore winds along western-facing coastlines, but the ability for the ACNFS to predict these features is not treated explicitly.

The cold, prevailing northeasterly winds that were responsible for driving the production of sea ice during the growth season relax during the spring, leading to variable wind patterns dominated by individual weather systems (Mesquita et al. 2010). Strong storms in the early days of the retreat season can lead to large deformation events along windward coastlines and the seaward landfast ice edge (Mahoney et al. 2005). The thickening of sea ice through ridging and rafting occurred near costal boundaries during strong storm events in the retreat season. Mechanical ice growth in the model increased the mean thickness on the order of meters. However, the horizontal advection of different ice masses that followed deformation events in the Bering Sea is on the order of tens of kilometers. Therefore, in order to produce skillful forecasts of sea-ice thickness on the regional scale and in the marginal ice zone of the Bering Sea, the ACNFS must be able to capture the horizontal advection of ice better than persistence. 5-day sea-ice thickness forecasts are better than persistence in the 2011 retreat season, which indicates skillful advection of different ice masses within the Bering Sea.

For the Bering Sea shelf, surface wind stress will dominate the force balance equation of sea-ice drift on the weather time scale (Leppäranta 2011; Bond et al. 1994). However, local areas, such as the Bering Strait have a more energetic flow field where strong currents drive ice against the wind (Kozo et al. 1987; Pease and Salo 1987; Woodgate 2005). The 1-day sea-ice drift speed forecasts produced by the ACNFS are consistently skillful with respect to persistence throughout the first two months of the retreat season. There is also a slight upward trend in skill for the 1-day forecasts over the first 60 days. The model appears to predict drift with more skill in areas further from the coasts and when sea ice is closer to the mode of free drift. This supports results from the spatial verification study where higher SFF exists in the central Bering Sea. Increasing skill during the month of April suggests that as internal ice stress decreases in response to retreating ice cover, the model is able to capture the magnitude of ice drift with higher precision. The area of open water increases rapidly in May when the model is able to produce drift speed forecasts with the highest skill. In the final month of the time series, all sea ice in the Bering Sea is confined to the coasts along the Gulf of Anadyr, and the skill of drift speed forecasts become less consistent.

3.6.2 Skill Relative to Climatology

The exceptional skill of sea-ice drift speed forecasts with respect to a climatological reference value is an interesting result of the verification study. However, there may be some limitations in the climatology product used in this study region. The Polar Pathfinder II sea ice drift product (Fowler et al. 2013) is a multi-sensor derivation of sea-ice drift velocity over the polar regions that synthesizes drift estimates from passive microwave remote sensing, in-situ buoys, and surface wind forcing from climate reanalysis models. In the seasonal ice zone of the Bering Sea, there is an absence of in-situ drift data, causing drift estimates to be solely influenced by drift detection from coarse-resolution passive microwave imagery and atmospheric forcing from numerical models. The sea-ice retreat season poses many challenges for passive microwave sensors because of the increasing complexity of the ice surface. During more advanced stages of decay, surface melt ponds appear as open water in the microwave signal causing an underestimation in ice concentration (Markus and Dokken 2002). Algorithms for detecting sea-ice displacement from passive microwave scenes are established on the movement of large-scale lead systems and such features may not be present within the Bering Sea. The 22-year ice drift climatology spanning 1979-2000 produced at a daily resolution may have other limitations because of the short period of record. A daily temporal resolution may be strongly influenced by oceanic tides and the interannual variability of atmospheric low-pressure systems. A seven-day moving average applied to the climatology in this study removes some interannual variability, but will also affect drift magnitude giving the ACNFS an advantage in predicting periods of rapid drift in the 2011 case study.

Compared to climatology, sea-ice thickness is forecast well, but is also subject to rapid rates of change and brief periods of unskillful prediction. Both lead times represented in the time series respond to the strong storm in early April with a plunge in forecast skill. Strong winds during and in the wake of the storm system caused deformation along coastal boundaries. While the advection of deformed ice was predicted well compared to persistence at a 5-day time span, the total error during this period of rapid ice displacement has a similar amount of error compared to the climatological average. Most of the ice retreat during May was over the central Bering Shelf, leaving the remaining ice nestled in the coastal areas of Norton Sound and the Gulf of Anadyr. These coastal areas are unresolved in the climatological evaluation due to a coarse 1x1 degree resolution of the dataset.

The ACNFS can predict sea-ice concentration on the regional scale better than climatology. There are a few periods in the spring 2011 time series where the skill diminishes, but the majority of forecasts are skilled. High skill sores throughout the first 30 days may be attributed to the slow-changing interior of the ice pack. It is expected that the largest changes in concentration will occur near the ice edge, which is not explicitly addressed in this evaluation. The model skill drops during the large April storm, when rapid southward ice advection and coastal polynya opening occurred. The deep low-pressure center produced strong cyclonic ice motion in the Bering Sea. This regional drift regime drew the ice edge southward in the western Bering Sea while at the same time peeling sea ice away from the northern coastline of Nunivak Island and the Yukon-Kuskokwim river delta. The degradation in 5-day forecast skill for concentration in May is attributed to the complexity of the ice edge. The ice edge during this time challenged the model to predict the location of ice and led to more error. The final event with unskilled forecasts occurred in mid June, when the model consistently over-predicted ice extent, moving sea ice away from the coast while the analyses indicated sea ice remained closer the coast.

3.7 Closing Comments

The performance of ACNFS forecasts on the regional scale, during the 2011 retreat season can be summarized as follows. A greater number of skilled forecasts are produced when climatology is the reference forecast compared to when persistence is the reference forecast. The SFF for all variables decreases over increasing forecast lead-time when climatology is the reference forecast. When persistence is the reference, both concentration and thickness forecasts increase in SFF with increasing forecast length while the SFF in sea-ice drift speed trends negatively. The discrepancy in the trend in SFF over forecast length between the different variables is related to how quickly the variables change. For the slow-changing variables, persistence is a good representation of future conditions and error in persistence will be small. For the quick-changing variables, persistence will not be a good representation for long and error will increase.

Chapter 4

Incorporating Indigenous Observations in Operational Sea-Ice Information Products: Case Studies from Western Alaska

4.1 Introduction

Coastal communities in the high latitudes need operational sea-ice products for the purpose of keeping hunting crews and local residents safe. Compared to currently available operational tools and sea-ice products, these needs require enhanced spatial and temporal resolution. Therefore, new tools are required for operational sea-ice forecasters to meet these needs. This chapter explores the utility of new approaches, specifically in the form of community-based observations or advanced forecast model guidance to improve sea-ice information services. A guidance product in this context is a deterministic value or set of values produced by a numerical model that projects future conditions based on physical parameterizations. Forecasters use this guidance in producing a forecast product available to the public.

Subsistence hunting requires a keen understanding of physical-environmental variables in order to guarantee the safety of hunting crews and village residents. Environmental knowledge is passed down through the generations, with recognized observational experts who draw on indigenous knowledge as well as extensive personal experience (Krupnik et al. 2010). Thus, residents of indigenous communities have broad knowledge of their environment in the present as well as over multi-decadal timescales. The vocabulary of indigenous residents along the Arctic coast includes unique sea-ice terminology absent in non-Arctic languages (e.g. Weyapuk 2012). Native sea-ice terms describe processes in the ice cycle that include descriptions of ice attributes, and are often used to efficiently communicate during hunting and travel to ensure safety. Such detailed sea-ice observations in a polar marine environment are potentially valuable in expanding information available in operational sea-ice products

A sea-ice forecast model, such as the ACNFS, can potentially provide useful guidance to forecasters serving coastal hunting communities. An analysis focusing on the performance of the ACNFS on the regional scale has been presented in Chapter 3. Results give insight into how the forecast model performs in different regions and under transient synoptic weather systems. Forecasters armed with the knowledge of model performance in different regions and conditions are more confident in using the product. However, the question: "How can a new guidance product inform short-term forecasts needed on the local scale?" remains unanswered. Here, community observations, model guidance from the ACNFS, and current operational sea-ice forecasting practices are discussed in the context of forming a more integrated sea-ice forecasting system.

Two case studies that bring together model guidance from the ACNFS, community-based observations and operational sea-ice products during the spring retreat season in the Bering Sea are presented. Local observers, sea-ice users, and ultimately, the people making decisions based on forecasts for each case study are local hunters and ice experts from coastal communities. The objectives of the case studies are to: a) Discuss how local indigenous knowledge can be woven into operational sea-ice information products, and b) explore how community-based indigenous observations might be paired with standardized equipment to ensure that the context and terminology in indigenous, narrative observations are fully translated.

4.2 Methods

4.2.1 Community Observations Database

The community observations in this study are part of the Local Observations database of the Seasonal Ice Zone Observing Network (SIZONet). The Local Observations database was developed to record, archive, and share indigenous sea-ice knowledge and expertise. When using this information, it is crucial to understand not only what is being observed but also why and how these observations are being made; context is important, especially as longer-term records of local observations are maintained (Druckenmiller et al. 2009). The community reports archived in the database are centered on ice uses and information about ice conditions, weather, ocean state, and animal behavior relevant to hunters and to community members (Eicken et al. 2014). Observations of sea ice and weather during the spring breakup season studied in this thesis are typically recorded once per day and often include a summary of spring subsistence activities from returning boat crews. Specific observations will be shown and discussed in the case studies.

4.2.2 Extracting Information from Community Reports

Local observations contain information about a broad range of environmental variables (Eicken 2010). The reports are non-standardized and may not consistently mention the same variables. The extraction of environmental information from the context of hunting reports into ground-truth, qualitative data for discussion in operational sea-ice information products was performed. Days with active hunting were selected from reports of boating crews out in the ocean during the traditional hunting season. Observations were limited further by selecting only the reports containing sea-ice information. Sea-ice observations are taken by an onshore observer and describe ice conditions as they appear from the village. Local reports can also include offshore sea-ice information relayed to the observer from boating crews returning to the community.

Operational sea-ice products were used to extract sea-ice information from community-based observations and refine the case study selection criteria. The primary variables in operational sea-ice analyses, forecasts, and text discussions are sea-ice concentration and spatial extent. A nominal concentration as calculated by satellite detection algorithms or an observer, trained using standardize methods, will not be reported by indigenous ice users. Rather, observations typically mention how tightly spaced ice floes are in the context of navigability. Therefore, community-based observations that mention the local distribution of sea ice were selected. Observers who document the distribution of sea ice often mention the orientation of pack ice relative to coastlines, how defined or diffuse the edge of the pack is, the distance between the community and offshore pack ice, expanses of open water, the ice edge, or other features that help to define the local icescape.

4.2.3 The Setting of Gambell, AK and Case Study Selection

Winter ice conditions at the village of Gambell are generally characterized by heavy, deformed pack ice along the northern and western shoreline, with hunters active among the drifting offshore ice floes. Almost all adult men in the St. Lawrence Island community of Gambell hunt in their spare time or year-round. During the spring hunting season in April–May, as many as 200 men and teenage boys may be boating in the drifting ice (Krupnik et al. 2010). Kapsch et al. (2010) have reviewed the success and effort of Gambell hunters in relation to the physical-environmental variables of ice concentration, wind speed, temperature, and visibility over a 29-year timespan. Results show safe, successful hunts are related to sea ice concentrations ≤ 30%, wind speeds between 5 and 9 m s^{-1}, temperatures from -5°C to +5°C, and visibility > 6km. The typical maximum distance traveled from the village in pursuit of marine mammals is approximately 75km (Figure 4.1), but changing ice conditions in a warming climate are causing an increase in distance traveled (Lovecraft et al. 2013).

The Gambell case study serves as a test case for synthesizing different components of an integrated sea-ice forecasting system. This case study falls within the 2011 sea-ice retreat season, when model forecasts are available from the ACNFS. Paul Apangalook, an indigenous sea-ice expert in Gambell, AK recorded observations during the breakup season as part of a long-term project with near-daily observations during the ice season beginning in 2006. Local observations were aligned with the verification dates of 5-day sea-ice forecasts from the National Weather Service after extracting sea-ice information from the written, local observations. The final constraint was ACNFS forecasts being available when ice concentration near Gambell was ≤ 30% based on an analysis of successful hunts from (Kapsch et al. 2010). May 07, 2011 was found to match all criteria.

4.2.4 The Setting of Wales, AK and Case Study Selection

The subsistence community of Wales, Alaska is located on the eastern side of the Bering Strait. The Bering Strait is a physically dynamic region. A strong northward sloping sea surface across the strait drives powerful ocean currents (Coachman and Aagaard 1966). Complex terrain impacts the atmospheric wind field. Local-scale forcing in the ocean and atmosphere complicates the drift of sea ice, raising safety concerns amongst a number of different stakeholders.

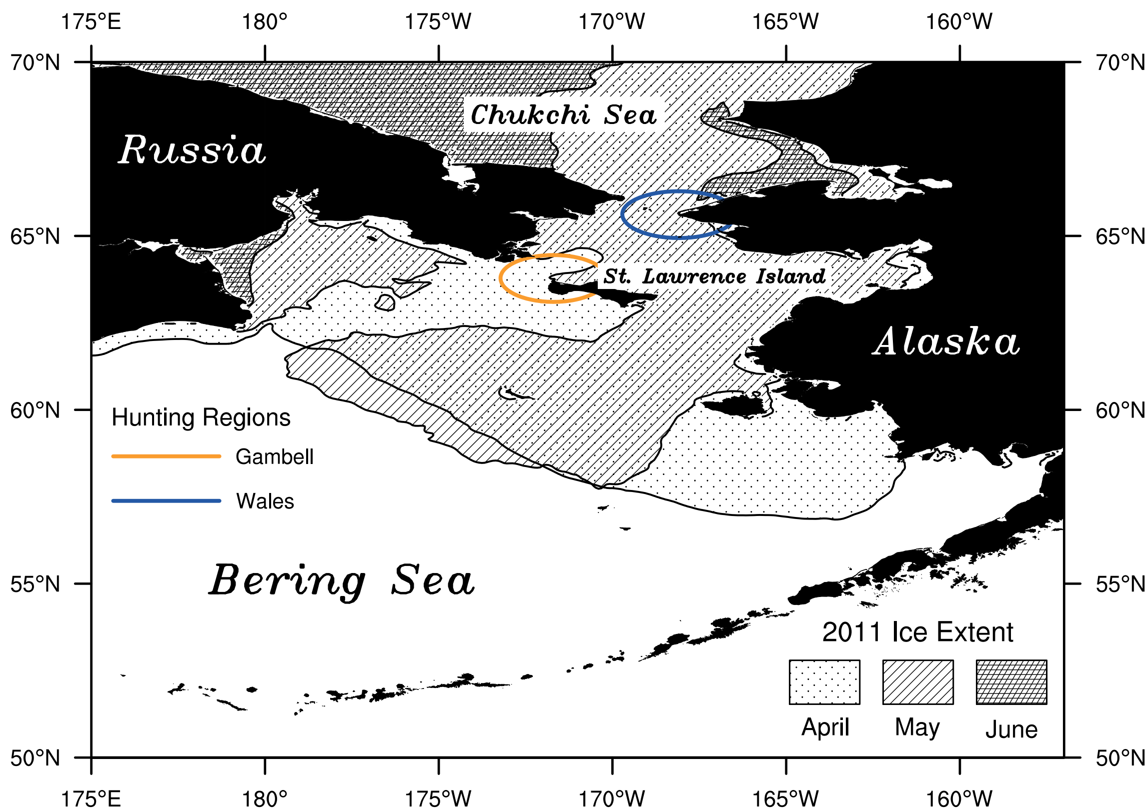


Figure 4.1. Monthly sea-ice extent during the 2011 sea-ice retreat season. The average sea-ice extent for the first week of each month is plotted using a 15% concentration threshold. The circles around Gambell (63.8N, 171.7W) and Wales (65.6N, 168.1W) represent a region with a 75km radius typical of the maximum distance traveled from the village during the hunting season (Kapsch et al. 2010).

The Bering Strait (~85km in width) is a major corridor for vessels in the Arctic. A rise in traffic associated with offshore resource development, pan-Arctic commercial shipping, and tourism (Arctic Council 2009) will impact the narrow waterway. Additionally, the creation of near-shore protected areas and designated shipping routes in the strait (Johnson 2012) increases the local institution density and bring challenges similar to those faced on Alaska's northern coastline (Lovecraft et al. 2013).

The winter sea-ice environment at the village of Wales is more representative of coastal communities in northern Alaska (Stringer 1980). A stable, landfast ice cover shoreward of grounded pressure ridges supplies a stable surface for hunting and fishing. During the spring retreat season, hunters navigate within the drifting ice pack and typically operate in a 75km radius from the village (Figure 4.1). The hunting crews track a broad range of sea-ice variables (Eicken 2010), some of which may be useful for operational forecasters.

Forecasting for dynamic region of the Bering Strait is challenging. Accurate translation of sea-ice reports from the area is needed. An exploration into supplementing community-scale observations through the addition of technical equipment is performed. In this study, purpose-built observation kits (Appendix) were distributed to the community of Wales and Shishmaref, AK in the spring of 2012, 2013, and 2014. A total of four kits were handed out in the community of Wales and one in the village of Shishmaref over the three field seasons. The kits included instrumentation for recording geographic location, taking photographs and videos, measuring wind speed, and logging observations by hand.

The purpose of distributing instrumentation to local ice experts is not intended to enroll collaborators into the position of a citizen scientist. A citizen scientist is a volunteer who simply collects and/or processes data as part of a scientific enquiry (Silvertown 2009). Our collaborators are recognized sea-ice experts who have spent years studying the complex properties and behavior of sea ice near their community (Krupnik et al. 2010).

The suggested observation schedule was left open-ended and at the convenience of participants. There was no formal training given to community-based observers, which differs from other cooperative observer programs that support operational forecasting efforts (NOAA 2010). Instruction was given to participants using cameras to document ice features they believe would present a navigational hazard. If an anemometer was used to collect wind speed, the observer was asked to record for two minutes or until the measured wind speed stabilized. Observers were encouraged to use the equipment in conjunction with their traditional observation techniques and standards. The information sought is indigenous sea-ice expertise with supporting measurements relevant for multiple stakeholders in the Arctic.

The case study was selected on the following criteria. Photographs, audio, video, and/or wind speed measurements taken by an observer narrowed the range of dates in the 2012 – 2014 retreat seasons. The local-scale observations include evidence of potentially hazardous ice features were selected first. Secondary criteria specify that the observation should overlap with an ice analysis created by the NWS. Additionally, the date of the observation must have aligned with a village-based report from Winton Weyapuk, who has been providing near-daily observations as part of a longer-term record that began in 2006. June 17, 2013 met all qualifications. The ACNFS nowcast from the selected date was available, but forecasts were not.

4.3 Case Study Results

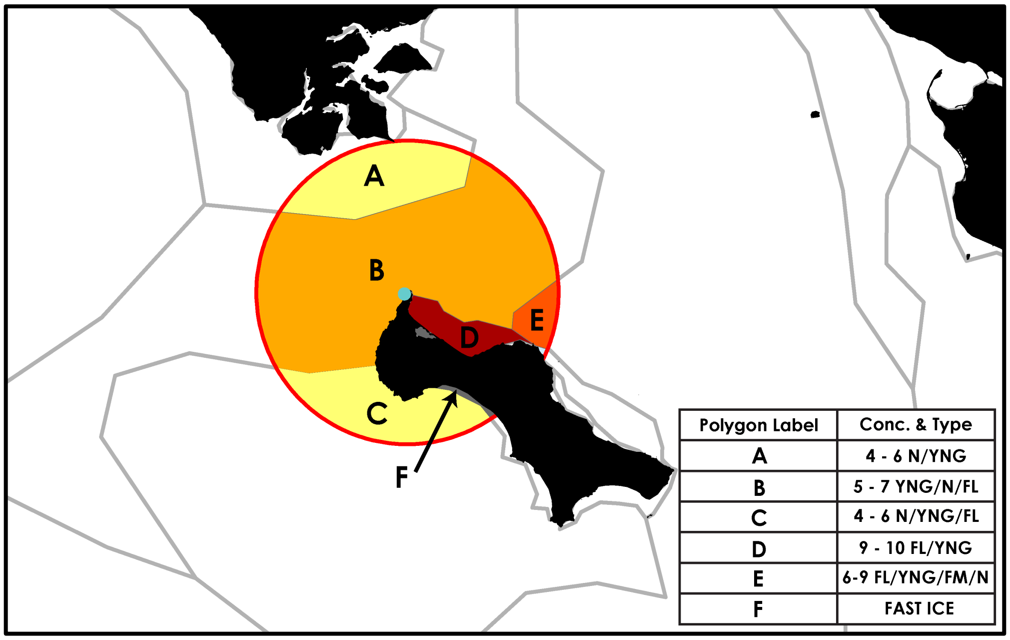
4.3.1 Gambell, Alaska 07 May 2011

A ground-based observation from Gambell declaring a successful hunting day on 07 May is in agreement with favorable, safe hunting conditions of Kapsch et al. (2010). Weather leading up to and on 07 May was benign, as a weak surface high-pressure center was entrenched over the Chukotka peninsula. Light winds, temperatures around the freezing point, and clear skies led to consecutive days of hunting success among the drifting ice floes.

> 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 - 23km] west southwest and at least one boat 30 miles [48 km] southwest of the village. Paul Apangalook Gambell, AK 07 May 2011." (Apangalook et al. 2013)

The public operational forecast for 07 May 2011 became available on 02 May 2011 (Figure 4.2a). The ice edge on 02 May, as analyzed by the National Weather Service, was nearly 500 km south of Gambell. A marine text advisory (Figure 4.2b) called for the ice edge to retreat 20-30 nautical miles to the North over the next five days. Forecasters followed procedure and focused on predicting the movement of the ice edge, leaving the rest of the Bering Sea ice pack to persist and become the forecast for 07 May (Figure 4.2a).

a.



b.

-BERING SEA-

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

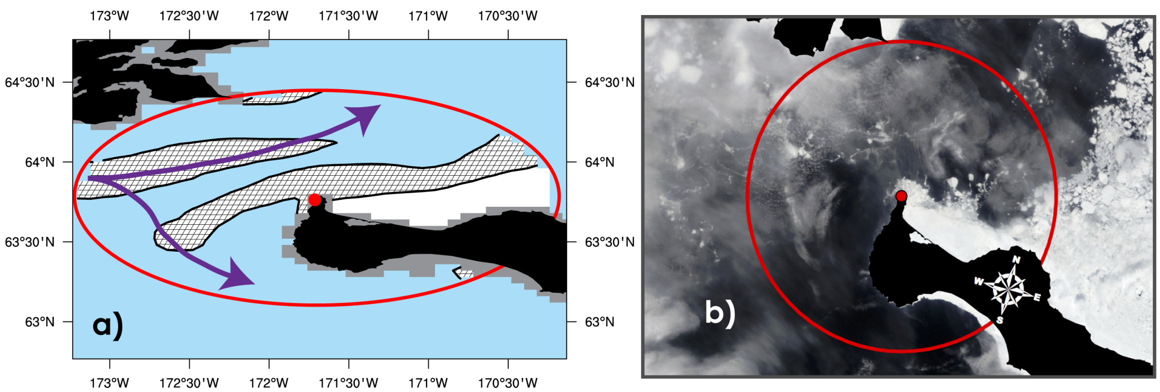
THE ICE EDGE LIES FROM CAPE NEWENHAM TO 58.8N 163.7W TO 57.6N 163.9W TO 57.1N 166.5W TO 58N 168.6W TO 57.9N 173.2W TO 60N 177.4W TO 57.8N 177.7E AND CONTINUES ALONG THE RUSSIAN COAST. THE ICE EDGE WEST OF 168W IS 6 TO 9 TENTHS YOUNG...NEW AND FIRST YEAR THIN ICE IN STRIPS. THE ICE EDGE EAST OF 168W IS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

Figure 4.2. NWS Anchorage Sea Ice Program 5-day forecast created 02 May 2011, valid 07 May 2011 at 1600 AKDT. Plot shows a subset of the NWS ice forecast chart. Grey lines denote deemphasized polygon boundaries. The plot legend gives concentration in tenths. Ice type dominance within each polygon reads left to right. N = New, YNG = Young, FL = First Year Thin, FM = First Year Medium sea ice. Supporting text is from the sea-ice advisory product generated 1600 AKDT, 02 May 2011.

The 02 May analysis, and thus the forecast for 07 May near Gambell shows sea-ice concentrations of 50% - 70% blanketing much of Anadyr Strait to the North and West, and concentrations approaching 100% east of the village. The polygons in the NWS chart used to describe ice conditions near Gambell extend over a much broader area in the Bering Sea and may smooth-over details that are of interest to hunting communities. A local observation from Gambell the following day (Figure 4.3c) provides more detail for the near-shore region and mentions a larger area of open water separating the village from the sea ice.

A model analysis produced by the ACNFS near Gambell on 02 May indicates two linear bands of pack ice with $\leq$ 30% concentration to the North and West of the village (Figure 4.3a). The local observation is in agreement with the orientation of the ice features produced by the model. However, there is less near-shore ice mentioned by the observer (Figure 4.3c) and a concurrent MODIS image (Figure 4.3b) offers additional insight into the near-shore ice conditions. The evolution of the two ice masses over the days leading up to 07 May is attributed to in-situ melt and drift in the Anadyr current. In the absence of strong wind forcing, the Anadyr current tends to fork with one branch flowing north towards the Bering Strait and the southern branch flowing to the South of St. Lawrence Island (Figure 4.3a). The northern ice pack is maintained by a source of ice floes being drawn from the Gulf of Anadyr. The near-shore ice pack is advected towards the East and forms an isolated patch of ice on the south side of the island. The isolated area of sea-ice, with a concentration $\leq$ 30%, is present during the verification time of May 08 2011 00Z. The net ice movement predicted by the model during this case study brings the northern ice pack closer to the shores of Gambell.



c) *Local Observation from Paul Apangalook, Gambell, AK*

May 03, 2011

Light winds from the north, 30 f, overcast. There is ice to the northwest at the closest point at about 13 miles. 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.

Figure 4.3. Ice conditions for Gambell, AK around 02 May 1600 AKDT. Red marker and ring in a) and b) marks the village of Gambell, AK (63.8N, 171.7W) and a 75km radius is representative of the typical maximum distance traveled by hunters. a) ACNFS model analysis for 03 May 0000z. The hatched area represents ice concentrations ≤ 30%; white area is >30% concentrations. Purple arrows depict the bifurcation of the Anadyr current around St. Lawrence Island, b) 250m resolution MODIS image from Terra platform 02 May 2318z, and c) a ground-based observation from Paul Apangalook taken some time on May 03, 2011.

The ability of the ACNFS to correctly forecast changes in the local ice edge and ice extent near Gambell is investigated (Figure 4.4). Model forecasts for both ice extent and ice area are quantified in terms of absolute error and percent difference from persistence. Ice extent plotted in the top five panels displays guidance for where the closest piece of sea ice is located, and the ice area product provides information on the ice surface area that may be useable by stakeholders that view ice as a platform. Maps displaying the distribution of sea-ice extent favorable for safe hunting in Figure 4.4 show sea-ice extent consistently predicted too close to St. Lawrence Island. Interestingly, at lead times less than or equal to 96 hours the model captures the low-concentration, isolated patch of ice south of the island. Percent difference from persistence forecasts improves leading up to the verification date, indicating that the model is able to predict the overall ice extent and ice area within the analysis region with less error than if the sea-ice extent areas were held in steady state.

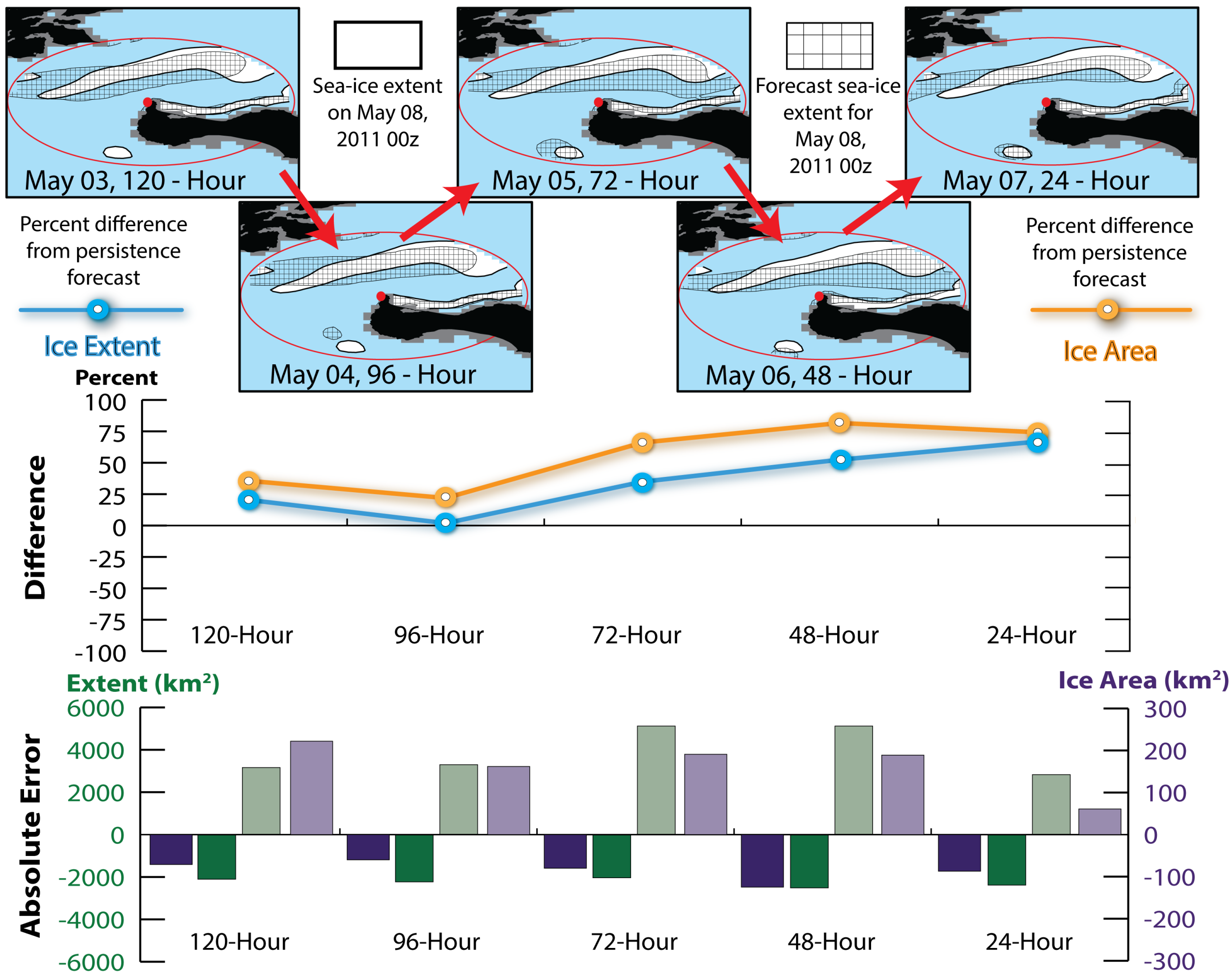


Figure 4.4. ACNFS sea-ice forecast guidance for 08 May 2011 00Z (07 May 2011 1600 AKDT) near western St. Lawrence Island. The five upper panels show the forecast ice extent for 08 May 00Z at different lead times. Red dot and ring in forecast panels are same as in Figure 4.4. Ice information outside of the ring masked. Grey grid cells near coastlines show 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 75km 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.

4.3.2 Wales, Alaska 17 June 2013

On Monday 17 June 2013, local hunters from the village of Wales were boating and had the purpose-built observation kits in-hand. A local report of environmental conditions on the morning of 17 June reports calm conditions, active ice users, and the location of drifting sea ice in the area:

> "8:15 A.M. Skies are overcast, wind N at 15 mph [25 kmph], temperature 37 F [3 C], visibility 10 miles [16 km]. There is pack ice drifting north one mile [<1 km] offshore. There were two boats out hunting yesterday - Winton Weyapuk Jr. Wales, AK 17 June 2013" (Apangalook et al. 2013)

The local text observation, ACNFS model analysis (Figure 4.5a), and NWS Ice Analysis (Figure 4.6) are in agreement with near-shore sea ice present on 17 June 2013. The model analysis suggests ice concentrations ≤ 30% where operational ice analysts bound the near-shore region with 3-5 tenths concentration. The operational ice chart also indicates near-shore sea ice consisting of ice new (0-10cm), young (10-30cm), and first-year (30-70cm) thin ice. However, categorical ice thickness describes only the level "pan" ice thickness inferred by an analyst from satellite remote sensing products. Deformed sea ice is undocumented in the operational product.

Figure 4.5b gives an example of a deformed sea-ice feature near the village of Wales. Local hunters using observation kits on 17 June 2013 captured the image. The hunters were positioned atop a stable, solitary ice floe a few miles south of Wales. The ice floe provided a safe platform for hunting while also serving a means of transportation. Hunters were adrift on the sea-ice floe in a strong, northward-flowing surface current (Figure 4.7a). Evidence of north-setting, swift ocean current in the eastern Bering Strait is also documented using portable instrumentation (Figure 4.7b).

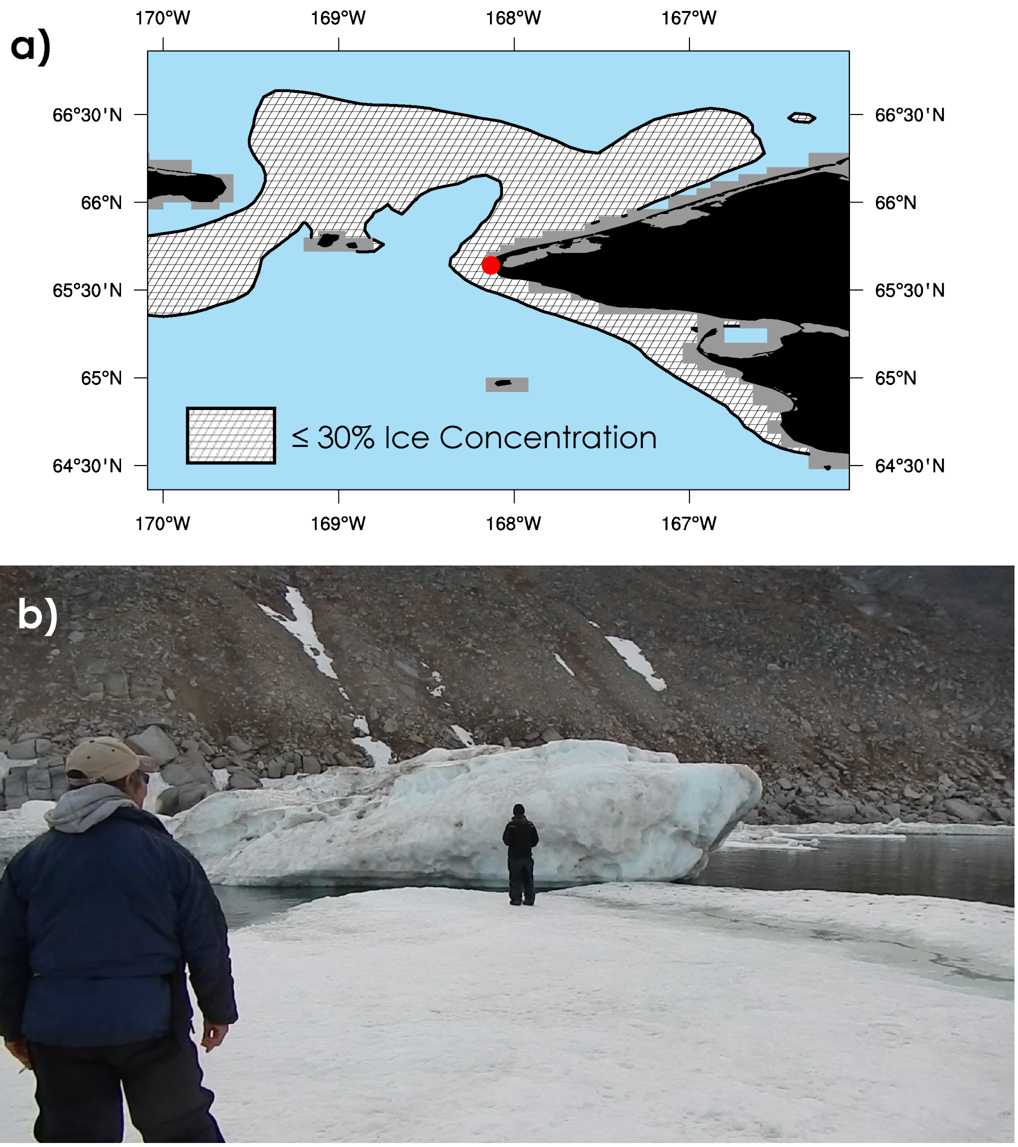


Figure 4.5. Sea ice in the eastern Bering Strait 17 June 2013. a) ACNFS analysis showing ice concentration. Red dot shows the approximate location of the village of Wales, AK. b) Hunters using a drifting sea-ice floe as a hunting platform and transportation. Photo: A. Oxereok. Image taken within the area of the red village marker, looking east. Large deformed, grounded sea-ice feature with adult male hunters in the foreground for scale.

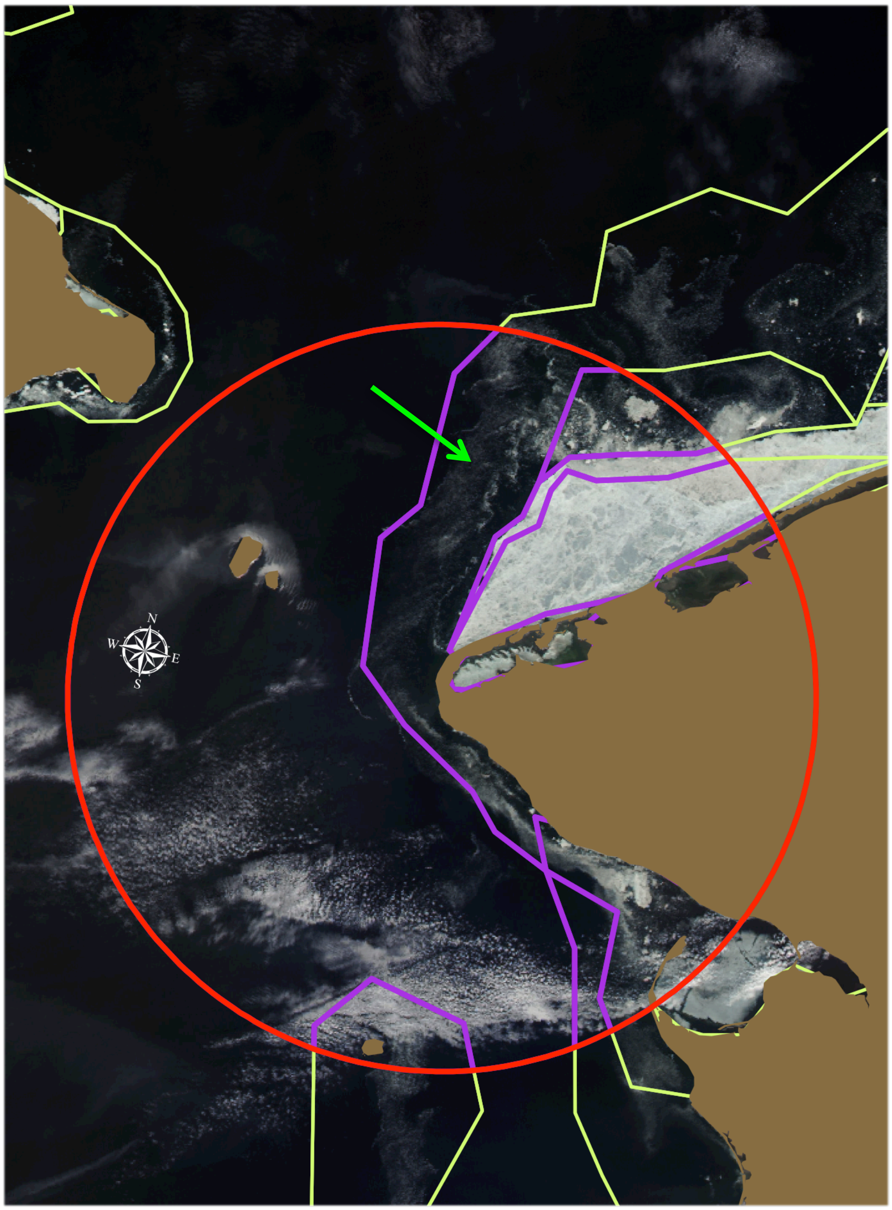
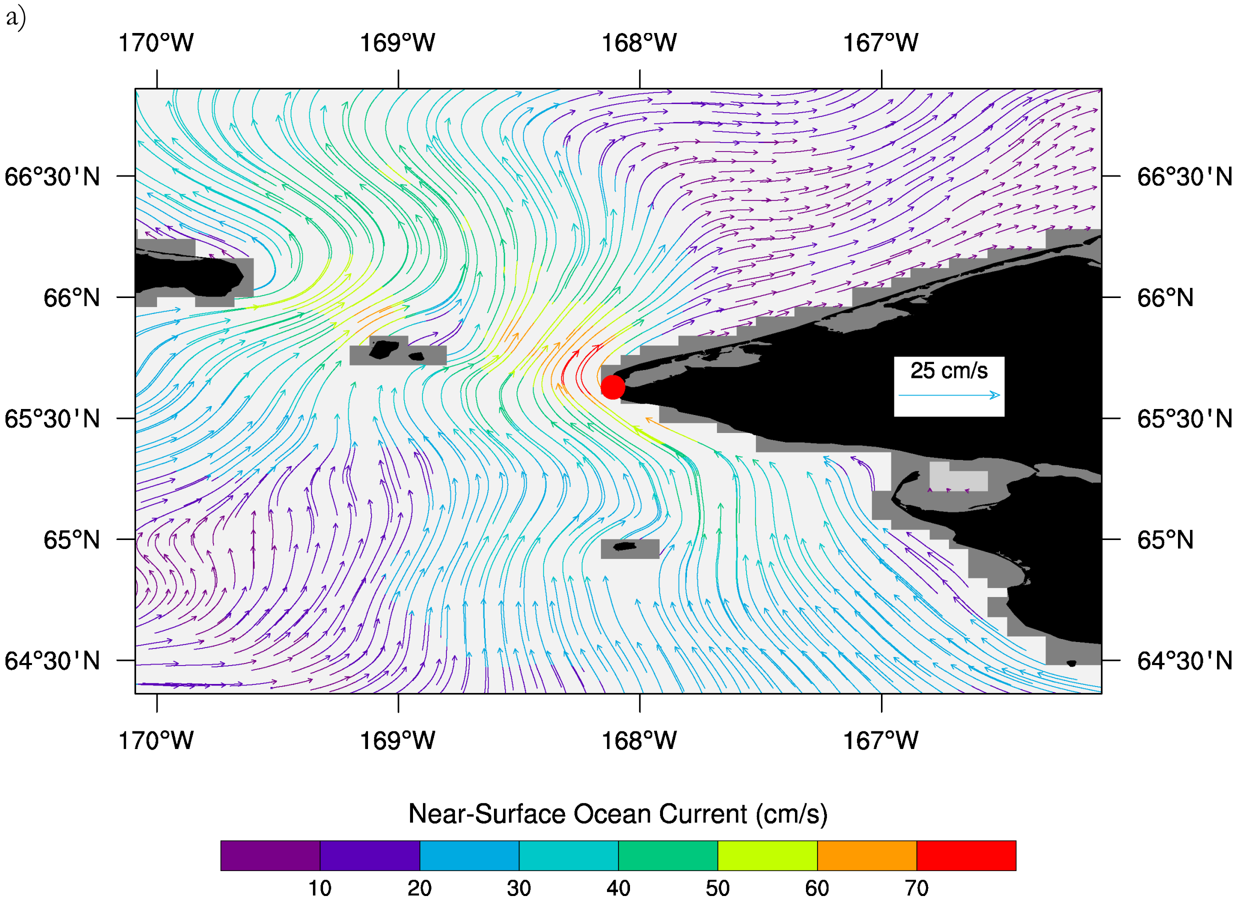


Figure 4.6. June 17 2013 NWS ice analysis and MODIS imagery for the hunting region near Wales, AK. Operational analysis issued July 18 2013 00Z. A red ring defines the typical hunting are area. Green arrow point to the near-shore polygon categorizing ice concentration and ice type discussed in the text. MODIS image at 250m resolution June 17 2013 2326Z.

a)



b) See supplemental video file entitled: 17Jun2013_DeformedIce_WalesAK.mov

Figure 4.7. A qualitative comparison of surface currents (1-3m depth) near Wales, AK with the use of community observations. Location of Wales, AK approximated with red dot. a) ACNFS analysis of near-surface (1-3m depth) ocean currents 17 June 2013 and b) Ground truth video showing speed of ice drift near shore, captured within the area of the red dot.

4.4 Discussion

4.4.1 Gambell Case Study

Forecasters with access to new tools like the ACNFS and community-based observations can provide clarity to operational discussions and spatial forecast products for a broad variety of stakeholders. For example, a forecast discussion strengthened by the addition of local observations and model guidance within the hunting region of Gambell, AK could read similarly to Figure 4.8. In the sea-ice forecast discussion, ground-based observations and a numerical sea-ice prediction model work together to provide a more detailed sea-ice advisory with information relevant to multiple stakeholders.

Subsistence hunting communities need forecasts of the local sea-ice edge, extent, and drift. Some hunting strategies are planned around distance to safe and reachable sea-ice. For example, the crew of Raymond Seetook Sr., a veteran hunter and environmental expert in the Bering Strait village of Wales, AK only plans for traveling 25 round-trip miles (40 km) (Raymond Seetook Sr., personal communication 2014). Knowing if a safe and accessible sea-ice pack is in the forecast will help crews prepare.

Huntington et al. (2013) evaluated environmental variables and hunting effort (hunting trips taken) in the context of hunting success for communities on St. Lawrence Island. Hunting effort explains a majority (i.e. >50%) of the variability in hunting success. As the number of favorable hunting days are becoming fewer in a warming Arctic (Eicken et al. 2014) and weather becomes less representative of historical norms (Jolly et al. 2002), it is important for communities to put forth the appropriate effort when safe hunting conditions are in the forecast.

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SEA ICE ADVISORY FOR WESTERN AND ARCTIC ALASKAN COASTAL WATERS
NATIONAL WEATHER SERVICE ANCHORAGE ALASKA
400 PM AKDT MON MAY 2 2011, UPDATED TUE MAY 3 2011

FORECAST VALID . . . SATURDAY MAY 7 2011

ANALYSIS CONFIDENCE - HIGH
.
- BERING SEA –
- WATERS NEAR GAMBELL ALASKA AND ANADYR STRAIT –

CURRENT SYNOPTIC CONDITIONS IN THE AREA ARE CALM. HIGH PRESSURE IS
ANCHORED OVER GAMBELL AND SIBERIAN CHUKOTKA. WINDS LIGHT AND VARIABLE.
COMMUNITY OBSERVATIONS FROM GAMBELL MENTION THICKER FLOES . . . WILL
ADVISE NON ICE-STRENGTHENED WATERCRAFT TO AVOID THE AREA.

- FORECAST IN RELATION TO LOCAL SEA ICE MOVEMENT –

ATMOSPHERIC MODELS CAPTURING CONDITIONS WELL AND IN AGREEMENT THROUGH
FRIDAY. WINDS IN THE AREA WILL REMAIN CALM WITH A FEW BRIEF PERIODS OF
WIND SPEEDS ELEVATED ABOVE 10MPH AS MULTIPLE LOW PRESSURE SYSTEMS
TRANSIT ALONG THE ALEUTIAN CHAIN. EXPECT MOSTLY CLEAR SKIES WITH SOME
THIN CLOUDS ALOFT. NO CHANCE OF PRECIPITATION. DOMINANT ICE DRIFT WILL
FOLLOW THE ANADYR CURRENT AND NEAR-SHORE CURRENTS AROUND WESTERN ST.
LAWRENCE ISLAND.

SOLUTION FROM THE ARCTIC CAP NOWCAST FORECAST SYSTEM SHOWING TWO BANDS
OF 1-3/10 PACK ICE ORIENTED SOUTHWEST TO NORTHEAST ACROSS THE AREA.
MODIS IMAGERY AND LOCAL REPORTS FROM GAMBELL AGREE WITH LOW-
CONCENTRATION ICE PACK NEAR CHUKOTKA. HAVE DECIDED NOT TO GO WITH
GUIDANCE ON NEAR SHORE ICE BARRING GROUND-TRUTH VALIDATION. GUIDANCE
SUGGESTS STRENGTHENING IN THE ANADYR CURRENT FROM 20 CM/S TO 40 CM/S
OVER NEXT FIVE DAYS. WILL AGREE WITH STRENGTHENING, BUT WILL BACK OFF
TO 30 CM/S IN THE ABSENCE OF SOUTHERLY SURFACE WINDS IN THE FORECAST.
HEAVY ICE CONCENTRATION EAST OF GAMBELL IN AGREEMENT WITH ANALYSIS AND
ACNFS . . . WILL PERSIST THROUGH THE PERIOD. SEA ICE CHART HAS BEEN
UPDATED ACCORDINGLY.

EXPECT OVERALL MOVEMENT OF 1-3/10 ICE EXTENT FEATURE ORIGINATING IN
THE GULF OF ANADYR TO SLIDE 5 MILES CLOSER TO THE VILLAGE OF GAMBELL.
MOVEMENT OF ICE FLOES WITHIN THE EXTENT FEATURE WILL MOVE TO THE NORTH
AND EAST AT A RATE OF 15-20 MILES PER DAY.

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Figure 4.8. A hypothetical sea-ice advisory discussion for the community of Gambell, AK. The text is augmented with local observations and forecast model guidance. The discussion aided by the ACNFS is in blue and red text indicates information added by a community-based observation.

Operational forecasting is a fast-paced environment. Observations that come in must be quickly interpreted and folded into products for forecast customers. Quick decisions made by forecasters using community-based observations can result in observations being out of context. Observations that were taken in the context of hunting and are relevant to the needs of other hunting communities may not be directly translated into the information needs of other stakeholders. Additionally, valuable detail from text observations might be lost in translation. For example, the hypothetical forecast discussion (Figure 4.8), guided by local sea-ice observations at Gambell, incorporates the term "thicker floes". Using the information, a decision was made by the forecaster in advising ice-sensitive vessels to avoid the area. However, forecasters will need more descriptive ice thickness information relevant to commercial forecast stakeholders. Indigenous hunters commonly observe ice thickness in the context of safety rather than a nominal thickness range. Druckenmiller et al. 2013 performed a study of the landfast ice offshore Barrow, AK and show that trails chosen atop the ice for access to open water and favorable whale hunting areas are strategically chosen based on the ability of the sea-ice to support a taken whale. Thick pack ice as reported by Paul Apangalook in his May 08, 2011 observation from Gambell, AK may be referring to floes capable of supporting Walrus or a boating crew. One approach to supplementing indigenous observations through the use of observation packages distributed to coastal communities is discussed in the context of the Wales, AK case study.

4.4.2 Wales Case Study

A sea-ice mass documented by local hunters from the community of Wales, AK on 17 June 2013 (Figure 4.5b) is a hazard if it were to enter a shipping lane. The feature is a consolidated shorefast sea-ice ridge. The ridge fragment was grounded and stationary when photographed. The grounding strength and fate (in-situ melt or drift out) of the feature are unknown. The addition of local indigenous knowledge in this type of observation can add valuable detail. Hunters with local knowledge of the area may be able to comment if the feature is anomalous or perennial and provide information on where the feature would likely drift if it broke away.

In-situ, near-time observations of surface currents and sea-ice drift in the Bering Strait are current unavailable. Presently, acoustic Doppler current profiler arrays span the Bering Strait, but data is unavailable in real time. Additionally, subsea moorings with upward-looking current profilers often fail to capture near-surface currents due to wave contamination (RD Instruments 1989). Observations of ice drift accompanied by indigenous knowledge of local currents (Raymond-Yakoubian et al. 2014) would provide useful ground truth of forecast guidance products (Figure 4.7a).

Observations of weather conditions are equally important in the Bering Strait. Strong orographic steering in the local wind field impacts currents, ice drift, vessels, and aircraft. Indigenous hunters in the region have a keen understanding of local wind patterns. Many offshore maneuvers while hunting involve positioning the crew in areas where the wind flow is blocked by topography. Such knowledge of wind bias and orographic steering is relevant not only for days when hunters can travel in small watercraft but also during extreme events that are of interest to industry stakeholders. Knowledge of common nuances in wind velocity and the gradient, dependent on the distance from topographic obstacles, can advise forecasting efforts for the Bering Strait. In operations, meteorological observations are needed in real time. However, hand-held weather meters given to local environmental experts lack a direct transmission link to operational forecast desks. The inadequate infrastructure and equipment might be resolved in a more general sense with local knowledge in-hand. Instrumentation can be helpful in providing locals with a quantitative metric such that they may then be able to indicate whether wind forecast biases are consistent or have any seasonality.

Sea ice, and in particular, deformed sea-ice features that present a significant hazard for maritime navigation, change on a longer timescale compared to local weather conditions. As a result, depreciation in the value of sea-ice observations occurs more slowly. Current operational sea-ice forecast products from the NWS are issued on the sub-weekly timescale. Therefore, community-based observations of sea-ice relevant to commercial stakeholder needs are useful even at transmission lag times of a few hours to days.

4.5 Conclusions

This chapter provides an example of how community-based collaboration in operational sea-ice forecasting could operate. The current forecast products, new sea-ice prediction modeling tools, and observations from local indigenous sea-ice experts were brought together to discuss the potential in adding needed detail for improving sea-ice prediction and information services in the Arctic. Two case studies focusing on the sea-ice retreat season in the Bering Sea provide a practical guide for how the cross disciplinary components of forecaster heuristics, numerical forecast guidance, and indigenous sea-ice observations can be used, in an integrated sense, to improve operational sea-ice monitoring and prediction.

Distributing instrumentation for sea-ice and weather observation to local sea-ice experts had success and shortcomings. The instrumentation has utility, but communicating and exchanging information with observers in the field was challenging. Data transmission and communication with coastal observers was best performed with social media outlets such as Facebook. Through the Facebook interface, observers have the ability to upload imagery along with captions. If numerous pictures or videos needed to be shared at a single time, connecting with the observer through a cloud-based file syncing application such as DropBox was successful. This methodology allowed for a more complete and direct flow of information that is unachievable with social media sites. However, the expertise of the observer was not always available when images were supplied without written descriptions to accompany them. Methods for combining local and traditional sea-ice knowledge with standardized instrumentation still need to be developed. Videos such as the one captured in Figure 4.7b may provide the best means for local experts to share their perspectives on sea-ice and weather conditions on the local scale. A more descriptive narration of the videos may be the best means of sharing local knowledge. Videos with vocal descriptions of processes or features being observed would be an ideal method to informing forecasters and would reduce the risk of misinterpreting local observations. Connecting misalignments in sea-ice observation by combining new instrumentation with indigenous sea-ice knowledge should help in developing new forecasting products based on stakeholder needs.

Chapter 5

Conclusions

5.1 Summary

With the possibility of an Arctic devoid of perennial sea ice looming in current climate projections and observations outpacing modeled trends, the now ice-covered summer waters impeding marine navigation and offshore resource development may soon be fully accessible. Consequently, increased congestion in the Arctic offshore environment will impact the safety of those involved in industrial activities. The livelihood and safety of Arctic residents has also been affected by changes in the seasonal ice cycle. The date of freeze-up, duration of stable ice cover, and breakup dates have become less consistent. The increasing variability in the timing and characteristics of sea ice at the local scale adversely affects locals whose lives are protected by knowledge of the ice. It is recognized that operational sea-ice prediction and information services must be able to meet the rise in demand for forecast products.

Operational sea-ice forecasting in the Arctic needs improvement. Unlike operational weather forecasters, who have access to proven prediction models, extensive monitoring networks, and standardized community observations such as the SkyWarn storm spotter network (Moller 1978) and Community Collaborative Rain Hail and Snow (CoCoRaHS) network (Cifelli et al. 2005), sea-ice forecasters are currently without sufficient model forecast guidance and ground-truth validation data. In this thesis, new lines were drawn that connect 1) numerical sea-ice prediction models, 2) operational sea-ice forecasting services, and 3) community-based sea-ice observations. The 2011 spring sea-ice retreat season served as a case study for evaluating the three components.

5.2 Conclusions from Regional Evaluation of the ACNFS

The Arctic Cap Nowcast/Forecast System, a coupled modeling system developed by the U.S. Naval Research Lab has drawn interest from the operational forecast community. In this thesis, the ACNFS has been evaluated using the concept of forecast skill. The three key sea-ice variables analyzed in the model predictions were concentration, thickness, and drift speed. Both climatology and persistence were used as reference forecasts in the evaluation. The objective was to determine differences in the forecast skill between 1-day and 5-day forecasts compared to the low-skill references. Overall, the model showed more skill when climatology was the reference. The skill in predicting all variables decreased with increasing forecast lead-time when compared to a climatology-based prediction. When compared to a prediction based on persistence, the slowly changing variables (concentration, thickness) were predicted with greater skill at longer lead times. Conversely, the prediction of sea-ice drift speed, which is influenced most by winds on the regional scale, became less skilled with increasing lead times when persistence was the reference forecast.

There were no strong spatial patterns that emerged as a result of the forecast evaluation when persistence was the reference. When climatology was the reference, there was more spatial contrast in the number of skilled forecasts produced during the 2011 sea-ice retreat season in the Bering Sea. Common spatial patterns in all three variables follow areas where the ice edge was located for at least a week or longer. These patterns are marked by a low skillful forecast fraction (SFF) produced over the season when compared to the SFF in the rest of the Bering Sea. More forecasts should be analyzed to determine if patterns are consistent between different seasons and years. Additionally, a similar evaluation of forecast skill should be confined near the ice edge, where the greatest changes are expected to occur and where operational forecasters place the most emphasis.

In the time series evaluation, the model had more skill when climatology was the reference forecast. However, during large storms, the model produced forecasts that were unskilled for ice concentration and thickness when compared to the climatological average. The Polar Pathfinder multi-sensor sea-ice drift speed climatology may be insufficient for analyzing weather-scale forecasts. The ACNFS produced near-perfect skill when evaluated against the climatology, which relies on detecting motion of large lead systems that might not be present in the Bering Sea. When persistence was the reference forecast, ice thickness and concentration forecasts had higher skill at longer lead times, which was consistent with spatially averaged SFF. More noise was produced when evaluating the skill of the model in forecasting sea-ice drift speed relative to persistence and neither forecast lead-time had more skill, consistently.

The forecast skill calculations were performed using the model analysis as ground truth. The error in the model analysis in the Bering Sea during this season is unknown. In order to determine the true accuracy of the model, it is recommended that the ACNFS analyses be subject to a validation study in the marginal ice zone. Results from such a study would give useful insights into the absolute error of the forecasts rather than error relative to the model analysis.

5.3 Conclusions from Community-Scale Observation Case Studies

Two case studies in the Bering Sea were presented in the context of bringing local observations into the toolbox of a public sea-ice information provider. One case study included written records of ice and weather made by indigenous experts in Gambell, AK and the other included both written observations and observations gathered with handheld sea-ice and weather instrumentation near Wales, AK. The study focusing on Gambell includes model forecasts from the ACNFS in 2011. The study from Wales only contains the model analysis available in 2013. Both case studies were chosen when hunters were active and sea ice in the region was in low concentration ($0 \leq$ concentration ≤ 30).

During the Gambell case study, the ACNFS consistently predicted sea ice to be closer to shore and in a broader extent than what verified. Both the model and local observations showed the ability to bolster a sea-ice advisory discussion for the near-shore region around the village. However, the model showed some skill and performed better than persistence. Skilled model solutions of future conditions can be useful guidance products. Observations mentioning the thickness of ice were useful in discussing sea ice properties relevant to other stakeholders, but some terms are in need of more clarity. Ice thickness in the context of indigenous observations often relates to the stability of ice with respect to how the ice can be used. Translating ice uses into a nominal thickness range would be more useful for other stakeholders of sea-ice forecast products that may view the ice as a hazard.

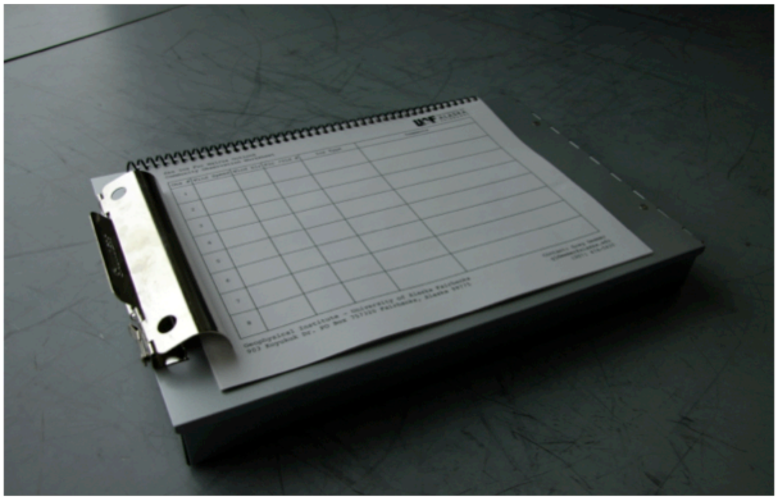
The effectiveness of having indigenous experts document sea ice and weather in the Bering Strait with the use of handheld instrumentation was explored with a case study near Wales, AK. Three field seasons during the years 2012 – 2014 supported this effort. Each year, success in the transmission of observations improved. A video captured in 2013 near the village of Wales, AK documents an ice hazard and nearby sea surface currents that can be distributed to operational forecasting centers. These observations may help validate the analysis field of numerical sea-ice models, which will improve forecaster interpretation of the guidance product. Measurements of weather variables taken by local community members may be useful in a research setting, but difficulties delivering data in real-time for the use of operational forecasters is troublesome. Nevertheless, this case study shows the utility of the equipment, which offers a way for locals to quantify their knowledge of forecast bias and improve short-term prediction of sea ice and weather within the Bering Strait.

Appendix

Presented here is a description of the community observation packages. The selection of instrumentation was governed by availability from local vendors in Fairbanks, Alaska. Despite small year-to-year differences, the packages included components for recording geographic location, taking photographs, measuring wind speed, and logging observations manually (Figures A.1 and A.2). The itemized cost of the observation kits delivered in 2014 is as follows:

- Heavy aluminum clipboard box: $50
- Nikon CoolPix AW100: $350
- Floating camera strap: $20
- 16Gb Flash Memory card: $37
- Kestrel 1000 Wind Meter: $99
- Rite in the Rain pen and float: $15
- Rite in the Rain paper: $40 (per 200 sheets, not per obs package)
- Spiral binding for obs booklets: $5 (FedEx Kinkos, Fairbanks)
- Return postage for instrumentation retrieval: $15

a)



b)

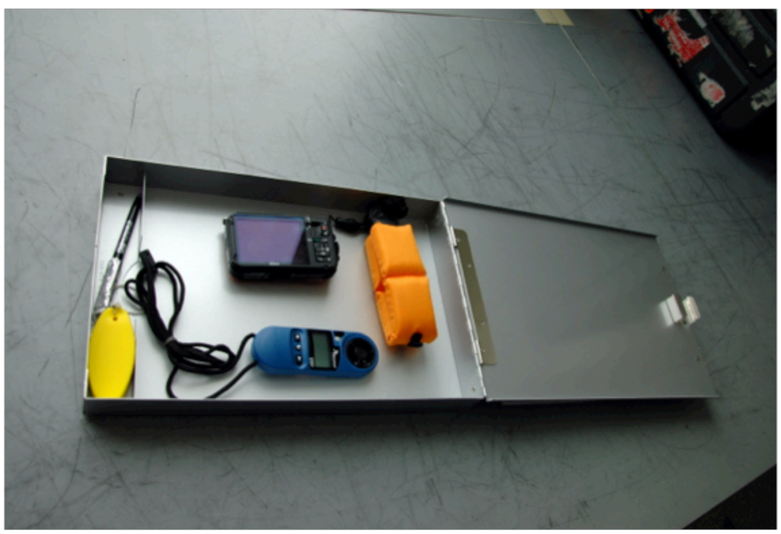


Figure A.1. Purpose-built observation package distributed to local observers. a) Closed kit with observation workbook clamped to writing surface and b) Open kit showing observational components.

Sea Ice For Walrus Outlook
Community Observation Worksheet

UNIVERSITY OF ALASKA FAIRBANKS

Obs #	Wind Speed	Wind Dir	Pic /Vid #	Ice Type	Comments
1					
2					
3					
4					
5					
6					
7					
8					

Geophysical Institute - University of Alaska Fairbanks
903 Koyukuk Dr. PO Box 757320 Fairbanks, Alaska 99775

Contact: Greg Deemer
gjdeemer@alaska.edu
(907) 474-5430

Figure A.2. Format of the community observation workbook.

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