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Impacts of a lengthening open water season on Alaskan coastal communities: deriving locally relevant indices from large-scale datasets and community observations

Rebecca J. Rolph[1]**, Andrew R. Mahoney**[1]**, John Walsh**[2]**, and Philip A. Loring**[3]

[1]Geophysical Institute, University of Alaska Fairbanks, P.O. Box 757320, Fairbanks, Alaska 99775-0001, USA
[2]International Arctic Research Center, Fairbanks, Alaska, USA
[3]School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Correspondence: Rebecca J. Rolph (rjrolph@alaska.edu)

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Abstract. Using thresholds of physical climate variables developed from community observations, together with two large-scale datasets, we have produced local indices directly relevant to the impacts of a reduced sea ice cover on Alaska coastal communities. The indices include the number of ”false freeze-ups” defined by transient exceedances of ice concentration prior to a corresponding exceedance that persists, “false break-ups”, timing of freeze-up and break-up, length of the open water duration, number of days when the winds preclude hunting via boat (wind speed threshold exceedances), the number of wind events conducive to geomorphological work or damage to infrastructure from ocean waves, and the number of these wind events with on- and along-shore components promoting water setup along the coastline. We demonstrate how community observations can inform use of large-scale datasets to derive these locally relevant indices. The two primary large-scale datasets are the Historical Sea Ice Atlas for Alaska and the atmospheric output from a regional climate model used to downscale the ERA-Interim atmospheric reanalysis. We illustrate the variability and trends of these indices by application to the rural Alaska communities of Kotzebue, Shishmaref, and Utqiaġvik (previously Barrow), although the same procedure and metrics can be applied to other coastal communities. Over the 1979–2014 time period, there has been a marked increase in the number of combined false freeze-ups and false break-ups as well as the number of days too windy for hunting via boat for all three communities, especially Utqiaġvik. At Utqiaġvik, there has been an approximate tripling of the number of wind events conducive to coastline erosion from 1979 to 2014. We have also found a delay in freeze-up and earlier break-up, leading to a lengthened open water period for all of the communities examined.

1 Introduction

1.1 Identification of metrics useful for describing climate change-related impacts on Arctic coastal communities

Community engagement and feedback are useful to identify the social relevance of climate system variables commonly used by scientists, as covered extensively by Krupnik and Jolly (2002). For example, sea ice concentration (fraction of an area of ocean surface covered by sea ice), thickness, and extent (ocean area within the sea ice edge) can be considered “primary” geophysical variables for an Arctic ocean study. However, for indigenous Arctic coastal communities, the timing of local freeze-up and break-up is among the most important characteristics of sea ice (Berkes and Jolly, 2002; Berman and Kofinas, 2004; Laidler et al., 2009). While the definition of freeze-up and break-up timing can vary based on data source (Johnson and Eicken, 2016), it is useful to evaluate these metrics in a way that can be applied across communities, as done in this study. Residents of Arctic coastal communities report that the sea ice is changing in many other ways, including increased presence of rotten (partially melted and weak) ice and the way the ice breaks up (Sarah Betcher, personal communication, 2013). While

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these changes are unlikely to be directly captured in climate-scale observations, local community members connect these changes with trends that can be indicated from the length of the transition season or number of false freeze-ups and false break-ups. In this study, freeze-up day and break-up are defined by the dates when the ice passes a sea ice concentration threshold. The timing at which freeze-up and break-up concentration thresholds are passed does not necessarily imply a phase change, but can depend on advection of ice driven by winds or currents. While it is difficult to determine the best thresholds in terms of ease of water or ice transportation because the grid cell area covered is larger than the smaller boats or snow machines, concentrations well below 50 % are required for navigation by small boats. Serreze et al. (2016) use a 30 % sea ice concentration threshold, and we adopt that threshold here. The freeze-up and break-up date trends are found in this study (Sect. 3.1) to be similar when the sea ice concentration threshold is 15, 30, or 45 %.

In an analysis framework based on large-scale climate observations, complex interconnections between communities and the environment can often be overlooked (Huntington et al., 2009). It is therefore important to include local experience when attempting to understand and quantify the impacts of environmental variations and changes (Huntington et al., 2009). As an example drawn upon in this study, Ashjian et al. (2010) interviews with Iñupiat whalers in Utqiaġvik (formerly Barrow) identified winds 6 m s^{-1} or higher as impediments to whaling because hunters consider the resulting wave conditions too unsafe to travel via boat. Alternatively, Atkinson (2005) used a 10 m s^{-1} wind speed threshold for a duration of 6 h of longer to produce a climatology of storm events. The 10 m s^{-1} threshold was based on the finding of Solomon et al. (1994) that winds of this magnitude or greater produce waves with enough power to do geomorphological work on the coastline or damage to infrastructure and habitats. Variations and trends in the number and timing of these events may give an indication of how climate change will impact coastal communities. In this study we present a time series of these indices from 1979 to 2014 (1953–2013 for freeze-up and break-up timing) for three coastal communities in Alaska.

1.2 Communities examined in this study

The communities examined in this study are Kotzebue, Shishmaref, and Utqiaġvik. While the locations of the communities vary, all are located along the Alaskan coastline (Fig. 1) and have community members who participate in coastal or offshore subsistence activities (reliance or partial reliance on marine mammals as a food source and a way of life) (Ashjian et al., 2010; Callaway et al., 1999). The village of Kotzebue is located on a gravel spit on the Baldwin Peninsula, and the population is over 3500 (NANA Regional Corporation, 2016). Kotzebue Sound has the Noatak, Kobuk, and Selawik rivers providing freshwater seasonally into the

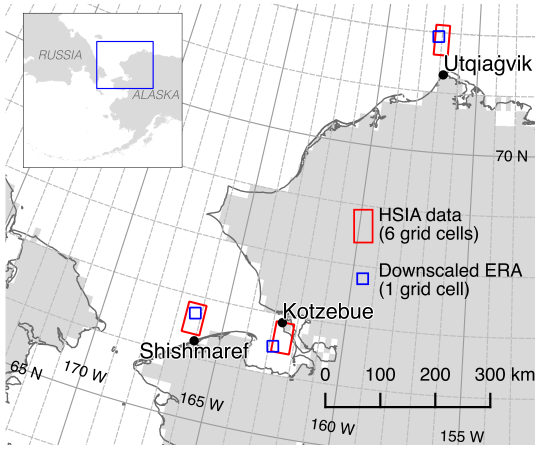

Figure 1. Selected grid cells from the Historical Sea Ice Atlas and WRF-downscaled ERA-Interim datasets used to extract sea ice concentration (also wind speeds from the WRF-downscaled dataset) offshore several communities.

sound. Uses of sea ice in Kotzebue include travel by snow machine and foot as well as subsistence hunting from the ice for marine mammals including sheefish and bearded and ringed seals (Georgette and Loon, 1993). Historically, the ice offshore has typically broken up in late June and reformed in October.

Shishmaref is located on a Chukchi Sea barrier island, about 0.4 km wide and 4.8 km long, slightly north of the Bering Strait and about 160 km southwest of Kotzebue. It is at the center of animal migration routes and is also the center of a complex food-distribution system based in subsistence hunting practices (Marino, 2012). It is highly vulnerable to erosion, which has been exacerbated by declining sea ice cover protecting the coastline (Barnhart et al., 2014). The members of Shishmaref have voted twice to permanently relocate the village due to this problem, but the funds are not available for doing so, even though the community will eventually have to move (Department of Commerce, Community, and Economic Development, 2017). The sea ice typically breaks up earlier than at Kotzebue, around May, and freezes up later, around November.

Utqiaġvik (formerly Barrow) officially reverted back to its original name in December 2016. It is the largest village on the North Slope Borough in Alaska and is located along the Chukchi Sea. Utqiaġvik is in a highly exposed position for drifting pack ice and also land-fast ice. Freeze-up has historically been in October or early November, and break-up can last from April through August (Johnson and Eicken, 2016). Sea ice in Utqiaġvik can be a hazard for commercial shipping, and it serves as a platform for the hunting of subsistence animals. Seal hunting can take place on the ice in winter, and bowhead whale hunting is done from the edge of land-fast ice in spring and from open water in fall (Gearheard et al., 2006).

1.3 Organization of this paper

This paper is organized into the following sections. First, we describe the data and methods, which are separated into subsections describing the Historical Sea Ice Atlas (HSIA) and downscaled ERA-Interim datasets, sources of community observations, the rationale for the selection of the study areas, and descriptions of the locally relevant metrics of the changing sea ice conditions in these communities. We then present the results showing how these metrics have been changing for each community. All the indices have been evaluated for the time period from 1979 to 2014. For the freeze-up and breakup dates, we evaluated a longer time period of 1953–2013. Next, the Discussion section links these indices to actual and potential impacts on the selected communities, including impacts on travel for subsistence hunting, prey availability, and erosion. Finally, the Conclusion section briefly summarizes our main findings.

2 Data and methods

2.1 The Historical Sea Ice Atlas

The HSIA for Alaska contains monthly gridded fields of sea ice concentration extending back to 1850. As described by Walsh et al. (2017), it is a synthesis of various datasets ranging from whaling ship logs to historical ice chart archive products to the passive microwave data for the more recent decades (1979–2017). A full list of all sources of data into the HSIA can be found on the Scenarios Network for Arctic and Alaska Planning (SNAP) webpage (http://seaiceatlas.snap.uaf.edu/about, last access: 1 September 2017). Temporal interpolation and analog reconstructions of months with missing data fill any gaps in the dataset. From 1953 through 2013, quarter-monthly sea ice concentration values are available and were used here to construct the sea ice indices and to analyze their trends along the coastlines of the selected communities in Alaska. The quarter-monthly grids were assigned calendar dates by the best approximation of the midpoint day of each quarter-monthly file. Use of HSIA data roughly doubles the timespan of the data available with sub-monthly temporal resolution compared with a reliance solely on the sea ice data derived from the satellite passive microwave record, which begins in 1979. While the satellite-derived (post-1979) portion of the dataset is less susceptible to heterogeneities arising from the use of multiple data sources, we do not find evidence for spurious discontinuities around 1979.

2.2 WRF-downscaled ERA-Interim reanalysis products

The European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim) dataset (Dee et al., 2011) has been dynamically downscaled using the Advanced Research version of the Weather Research and Forecasting (WRF) regional model (Bieniek et al., 2016). The dataset has an hourly temporal resolution (daily for sea ice) and a 20 km spatial resolution, from 1979 to 2014. It has been downscaled from a 0.75° (about 83 km) spatial and 6-hourly temporal resolution of the ERA-Interim reanalysis. The regional model simulation is observationally constrained by a reinitialization to the ERA-Interim reanalysis every 48 h. Sea ice concentration is prescribed (and spatially interpolated) from the ERA-Interim reanalysis, which in turn obtained its sea ice information from satellite passive microwave sources. The downscaling was performed in order to improve representation of temperature and precipitation around Alaska's varying terrain and to inform various stakeholders with higher-resolution climate and weather information. The WRF regional model uses a thermodynamic sea ice model of Zhang and Zhang (2001), together with the Noah land surface model, to simulate the surface fluxes over sea ice and land areas, respectively. As discussed in the following subsection, we used the sea ice concentrations and wind data from grid cells offshore the selected communities of Kotzebue, Shishmaref, and Utqiaġvik (Fig. 1).

2.3 Selection of grid cells representative of each study area

The communities of Kotzebue, Shishmaref, and Utqiaġvik were selected to represent a range of sea ice states and vulnerability to coastal erosion. The three communities have varying levels of reliance on subsistence activities and interaction with the offshore oil and gas industry. Figure 1 shows the grid cells selected for each community for comparison of sea ice metrics. To assess variability of ice conditions, we selected data near but not adjacent to the coastline of each community due to the fact that a large part of the sea ice dataset is derived by satellite. Satellite-derived sea ice concentration data have difficulty resolving sea ice in pixels immediately adjacent to the coastline. This can cause problems in obtaining accurate sea ice concentrations in the model grid cells adjacent to the coastline, as these grid cell values are interpolated from the satellite-derived concentrations prescribed from ERA-Interim. For example, there is a common flaw lead system south of the grid cells selected for Utqiaġvik, which develops during winter and spring (Norton and Gaylord, 2004). For the above reason, selecting "coastally contaminated" grid cells closer to shore would likely not improve representation of the sea ice conditions. The reliance on offshore ice concentrations highlights the need for across-community datasets containing reliable sea ice concentrations close to shore.

The maximum concentration (greatest fraction of sea ice per unit area) was extracted from a six-grid-cell area offshore of each community. The maximum (rather than the six-cell average) concentration was extracted because the grid cell with the highest concentration can serve as a "choke point" or hazard, while the other grid cells may not. However, in an

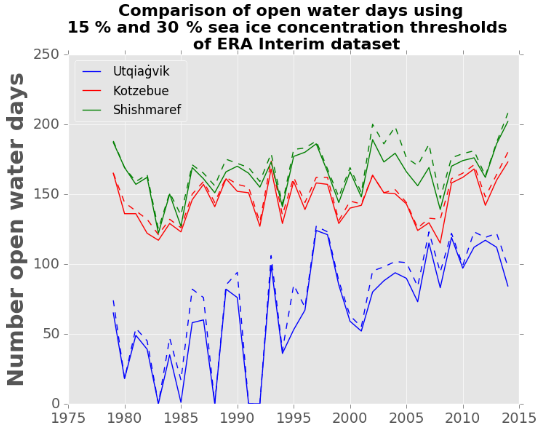

Figure 2. The number of open water days are similar when a 15 % (solid line) or 30 % (dashed line) sea ice concentration threshold is used. When the sea ice concentration (area of the grid cell) is lower than the threshold value, it is considered open water. Sea ice concentrations for the communities are extracted from the grid cells labeled as "Downscaled ERA" in Fig. 1.

analysis over the entire seasonal cycle, we found that neighboring grid cells offshore from the coast do not typically vary significantly in concentration. The location selected for the analysis of downscaled wind speed data were selected slightly further offshore in order to get a better representation of open ocean travel, but the results in terms of open water days are similar to those obtained from the HSIA analysis.

2.4 Indices related to freeze-up, break-up, and duration of open water period

In the analysis that follows, we define freeze-up and break-up as the seasonally "final" crossings of a given ice concentration threshold. The open water period is defined as the duration between freeze-up and break-up, when ice concentration stays continuously below this threshold. We experimented with different concentration values and found that the resulting dates of freeze-up and break-up are relatively insensitive to thresholds between 15 and 30 %. To illustrate this, we used a threshold of 30 % for the HSIA data, as used by Serreze et al. (2016), and a threshold of 15 % for the ERA-Interim data, as used by NSIDC (Fig. 2).

A "false break-up" is defined to occur when the ice concentration dips below the threshold before the final break-up prior to the open water season of that calendar year. Similarly, a "false freeze-up" is defined to occur when the sea ice concentration threshold rises above the threshold concentration between the final break-up and the final freeze-up of that calendar year. The numbers of false freeze-ups and false break-ups were also calculated for each community. The downscaled ERA-Interim data were used for these calculations because temporal resolution of ERA-Interim is finer than that of HSIA (daily instead of quarter-monthly). Because the ERA-Interim concentrations were used, the evaluation of false break-ups and false freeze-ups spanned the period 1979–2014.

2.5 Indices relating to open water wind events

The number of "boatable" open water days refers to the number of days that sea ice concentration is below 15 % while the winds do not exceed a 6 m s^{-1} threshold. This threshold is based on hunting success of whalers in Utqiaġvik (Ashjian et al., 2010). Higher winds speeds are usually considered by the hunters to be dangerous to hunt via boat. Ashjian et al. (2010) identified this wind speed threshold from interviews with 41 Iñupiat whale hunters and found that 86 % of fall whales in Utqiaġvik were landed on days when the wind speed was less than 6 m s^{-1}, while no whales were landed on days when winds exceeded 10 m s^{-1}.

Wind events exceeding 10 m s^{-1} for a duration of 6 h or longer have been found to have potential to cause geomorphological change or damage to coastal infrastructure or habitats (Atkinson, 2005; Jones et al., 2009). The number of these events was calculated for Kotzebue, Shishmaref, and Utqiaġvik from 1979 through 2014 using the WRF-downscaled output. Timesteps of lulls during "shoulder events" were counted as part of the geomorphologically significant wind event as long as the wind speeds did not dip below 7 m s^{-1}, which follows the same method as used in Atkinson (2005). We have also counted the number of high-wind events as defined by Atkinson (2005) (greater than 10 m s^{-1} for at least 6 h) but have an added restriction that winds conducive to erosion must be blowing from directions within a 90 arcdeg between normal to the coastline and alongshore with the coast to the right of the wind. High winds from these directions favor both wave generation and water setup along the coastline (i.e., increase in local sea level) and can therefore be particularly damaging to a community in terms of increasing erosion rates (Barnhart et al., 2014) and possible infrastructure damage due to flooding. Winds from between 225 and 315° satisfy both the alongshore and onshore requirements at Utqiaġvik. Winds blowing from directions between 180 and 270° satisfy the criteria for Kotzebue, while Shishmaref's quadrant ranges from 225 to 315°.

3 Results

3.1 Changes in timing of freeze-up and break-up and number of false freeze-ups and break-ups

The HSIA dataset was used in order to extend the time series of freeze-up and break-up timing for the communities of Kotzebue and Shishmaref 27 years prior to the starting date of purely satellite-derived datasets. For years which showed multiple freeze and/or break events, the final freeze-up and break-up date was used. The linear trend of the date of freeze-up is a delay of 2.2 day decade^{-1} for Kotzebue and

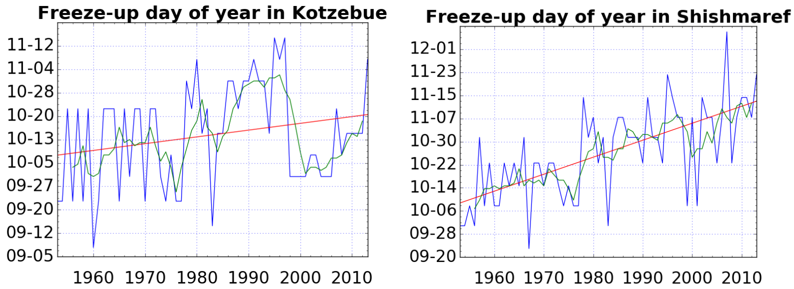

Figure 3. Trends in freeze-up day of year for Kotzebue and Shishmaref. Blue line is yearly freeze-up day, and green line indicates the 5-year running mean. Data are from HSIA.

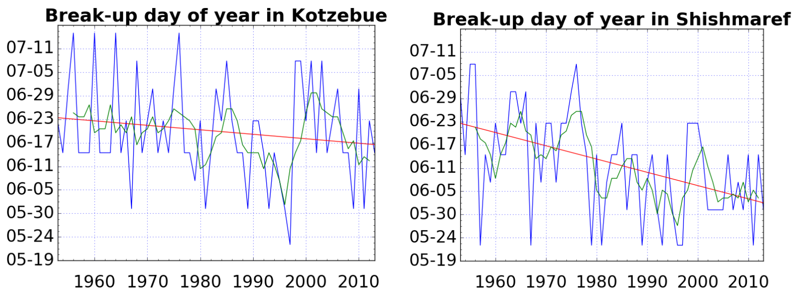

Figure 4. Trends in break-up day of year for Kotzebue and Shishmaref. Blue line is yearly break-up day, and green line indicates the 5-year running mean. Data are from HSIA.

6.0 day decade^{-1} for Shishmaref (Fig. 3). The freeze-up day for Kotzebue Sound shows a much weaker trend than the freeze-up days for Shishmaref. As shown in Fig. 4, break-up has occurred earlier by 3.4 day decade^{-1} at Shishmaref and by 1.1 day decade^{-1} at Kotzebue. However, the interannual variability of the freeze-up and break-up dates is sufficiently high that none of these trends are statistically significant at the 5 % level. Utqiaġvik's trends in freeze-up and break-up timing since 1953 (HSIA data) are not shown because there are a high number of years with no freeze-up and break-up date as defined by a 30 % threshold, since the sea ice concentration remained higher year-round.

Not only are there differences in the trends of freeze-up and break-up between the selected communities, but the variance is different as well (Table 1). The variance of the freeze-up date is 32 % larger at Kotzebue than at Shishmaref, and the variance of the break-up date is 8 % larger at Kotzebue than at Shishmaref. Fractions of the variance that are explained by the trend are 6 and 2 % for the freeze-up and break-up day of Kotzebue and much higher for Shishmaref: 44 and 20 % for freeze-up and break-up date, respectively. The smaller percentages at Kotzebue imply that the trend will be a poorer guide to future break-up and freeze-up dates than at Shishmaref.

There has been an increase in recent years of the number of false freeze-ups and false break-ups at all three communities (Fig. 5). There have been more false break-ups than false freeze-ups for both Kotzebue and Utqiaġvik. In contrast,

Table 1. Variance of freeze-up and break-up trends.

	Trend (day yr^{-1})	% variance explained by trend
Freeze-up Kotzebue	0.23	6
Freeze-up Shishmaref	0.60	44
Break-up Kotzebue	−0.10	2
Break-up Shishmaref	−0.34	20

Shishmaref shows many more false freeze-ups than false break-ups: 17 false freeze-ups from 2002 to 2014, with only 6 false break-ups. In prior decades (1979–2001), Shishmaref had only 2 false freeze-ups and no false break-ups. Kotzebue also shows an increase in the number of false freeze-ups and break-ups in recent years, with none prior to 2004. However, from 2004 to 2014, Kotzebue had 5 false freeze-ups and 9 false break-ups. Utqiaġvik shows 5 false freeze-ups in recent years (2002–2013), with 15 false break-ups. There were only 3 false break-ups prior to 2002, with 3 false freeze-ups. Dates of the false freeze-ups and break-ups are given for each community in Table S1 in the Supplement.

3.2 Changes in the number of days "too windy" for safely hunting via boat

The average number of boatable days (based on the definition provided by Ashjian et al., 2010) from 1979 to 2014 in

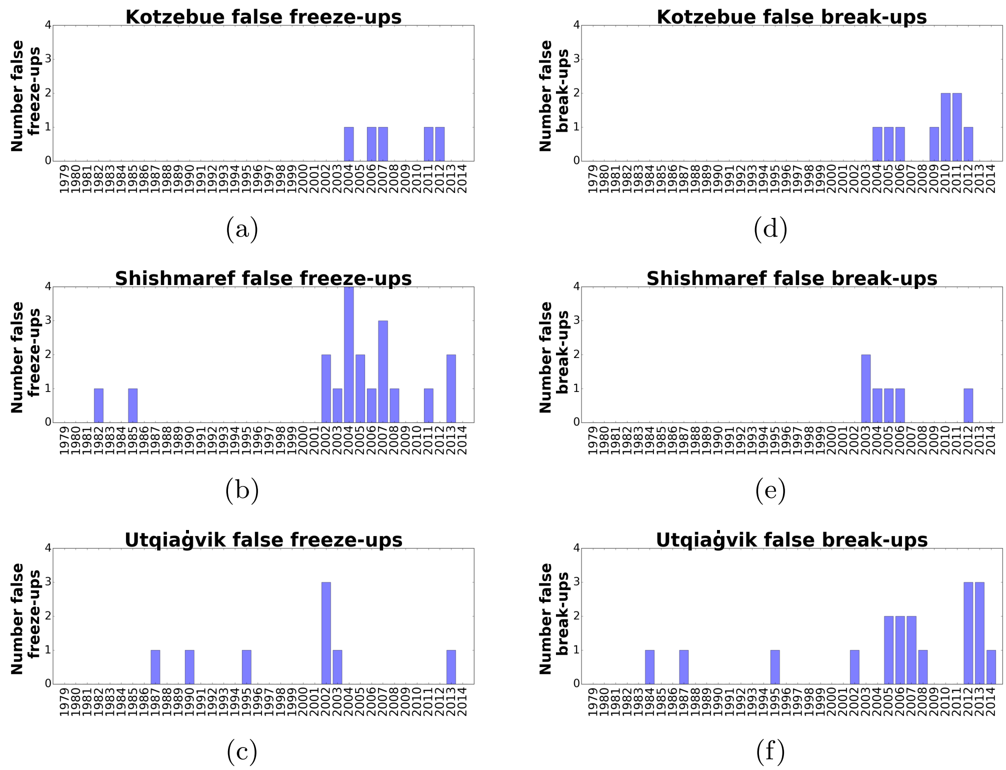

Figure 5. The number of false freeze-ups **(a–c)** and break-ups **(d–f)** per year, identified from ERA-I daily sea ice concentration data. False freeze-ups (break-ups) are defined as the number of times the ice concentration oscillated above and below the sea ice concentration threshold value of 15 % before the last freeze-up (break-ups) was finally achieved.

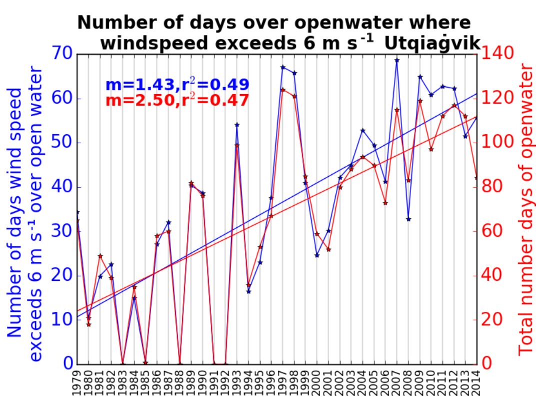

Figure 6. Annual time series from 1979 to 2014 of the number of days deemed too windy for boat travel for subsistence hunting ($> 6\,\mathrm{m\,s^{-1}}$; Ashjian et al., 2010) and number of open water days (number of days less than 15 % sea ice concentration). Data are from WRF-downscaled ERA-Interim.

Kotzebue is 87.0 days, while in Shishmaref the average number is 79.2 days. Utqiaġvik shows an average of 32.0 boatable days for the same time period. The number of "boatable" days in the open water period is not increasing as rapidly as the total number of open water days because some of the open water days have winds exceeding the $6\,\mathrm{m\,s^{-1}}$ criterion for safe boating. This is especially true at Utqiaġvik, where the number of unboatable open water days is increasing at a rate of $1.43\,\mathrm{day\,yr^{-1}}$ with an r^2 value of 0.49 (Fig. 6). The rate of total increase in open water days is $2.5\,\mathrm{day\,yr^{-1}}$ with a similar r^2 value of 0.47. The increases in both total number of open water days and unboatable days are statistically significant. Shishmaref and Kotzebue show only weak and statistically insignificant increases in the number of windy days over open water (Fig. 7). Kotzebue has a statistically insignificant increasing trend of the total number of days without ice cover ($4.2\,\mathrm{day\,decade^{-1}}$), while the trend in Shishmaref is statistically significant ($5.6\,\mathrm{day\,decade^{-1}}$). Shishmaref, on average, shows more unboatable days than Kotzebue, but Shishmaref also shows a higher number of open water days in general. Although Kotzebue has an overall lower number of days of open water, there is a higher number of days for community members to hunt via boat.

3.3 Increasing number of wind events with potential for geomorphological change

As described in Sect. 2.5, wind events exceeding $10\,\mathrm{m\,s^{-1}}$ for at least 6 h have the potential to cause geomorphological change (Atkinson, 2005; Solomon et al., 1994; Jones

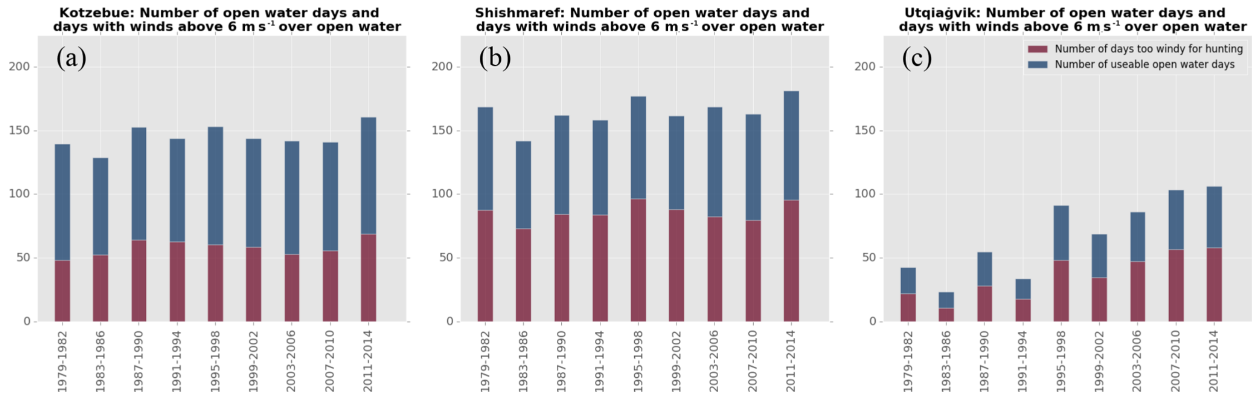

Figure 7. The number of days deemed too windy for boat travel for subsistence hunting ($> 6\,\mathrm{m\,s^{-1}}$, Ashjian et al., 2010) are increasing along with the increasing number of open water days (number of days less than 15 % sea ice concentration). Data are taken from the WRF-downscaled ERA-Interim reanalysis.

et al., 2009). The number of such events over open water have been increasing, particularly at Utqiaġvik (Fig. 8). The rate of increase in the number of geomorphologically significant wind events over open water near Utqiaġvik is about 1 every 2 years, with an r^2 value of 0.2, approximately tripling the number of wind events (10 to 30 events) over the 36-year time period from 1979 to 2014. There has also been a change in the character of the time series. Between 1993 and 2014, some years (e.g., 1983, 1985, 1988, 1991, and 1992) did not have any of these wind events over open water, because the ice pack did not recede far enough offshore in earlier years. At Kotzebue, there has also been an increase in geomorphologically significant wind events, but at a slower rate than Utqiaġvik, about 1 additional event every 5 years, leading to an increase of about 7.2 events over the 36-year time period (Fig. 8). Shishmaref shows the weakest increase in the total number of high-wind events (including all directions), about 1 every 10 years. Despite this weaker trend, Shishmaref has a higher number of such events than Kotzebue. Over the 36-year time period examined, Kotzebue has had an approximate increase from 39 to 46.2 total wind events, while Shishmaref has seen an increase from an average of 49 to 52.6 events.

In addition, wind direction is very important to determine whether a particular wind event is able to set up water along the coastline enough to cause flooding, increased coastal erosion, or infrastructure damage (Barnhart et al., 2014). The average number of high-wind events from the quadrant favorable for erosion at Utqiaġvik is approximately 4.61 with a significant increasing trend of 0.14 per year. The maximum number of these events is 14, and the minimum is 0 for Utqiaġvik. If we count only the number of wind events exceeding $10\,\mathrm{m\,s^{-1}}$ for at least 6 h, and coming from between 315 and 225°, the annual average of Shishmaref is 7.22, with a minimum of 1 and a maximum of 14, with no significant trend. At Kotzebue, the average number of onshore wind events is 6.61, with a maximum of 12.0 and a minimum of 2.0. At Utqiaġvik, the annual percentages of the total hours during these on- and along-shore high-wind events (between 225 and 315°; see Sect. 2.5) averages 21 %. At Kotzebue, an average of about 12 % of the winds above $10\,\mathrm{m\,s^{-1}}$ were onshore and between 180 and 270° during 1979–2014. An average of about 9 % of the total duration of the high-wind events in Shishmaref is between 315 and 225°, which are the directions conducive to increased levels of erosion and flooding.

4 Discussion: impacts and implications

4.1 Consequences of changes in the transition period between open water and ice: timing and number of freeze-up and break-up events

Our results show that in all three communities the annual number of open water days has increased in recent decades (Fig. 2) due to increasingly delayed freeze-up (Fig. 3) and earlier break-up (Fig. 4) of the ice cover. Additionally, the twice-annual transitions between open water and ice-covered seasons are becoming increasingly ill-defined and characterized by multiple "false" freeze-up and break-up events before the final, lasting transition occurs (Fig. 5). According to our definitions of these events (see Sect. 2.4), false freeze-ups and break-ups were non-existent in Kotzebue prior to 2004, after which they have occurred with some regularity (Fig. 5a, d). In Shishmaref, two false freeze-ups occurred in the 1980s, but since 2002 they have occurred more often than not and most often multiple times per year (Fig. 5b). False transition events appear to have been more common in Utqiaġvik overall (Fig. 5c, f), but there has been a marked increase in the number of false break-ups in the last decade. These results are in agreement with local observations by residents of Arctic communities, such as those of one community member from Kotzebue who reports the following: "we have a longer fall and a longer spring so it's warming on both ends and

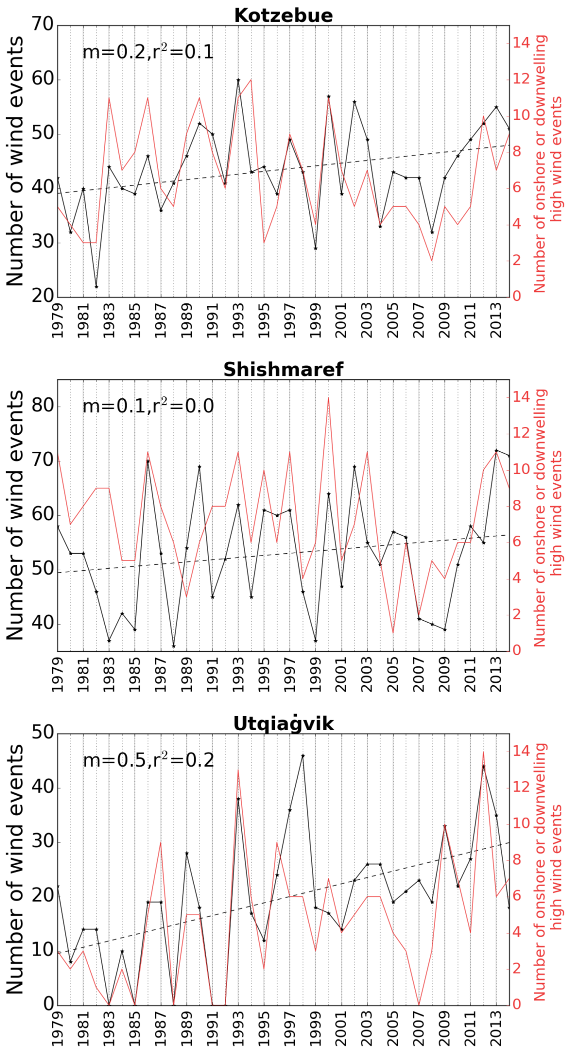

Figure 8. The number of wind events capable to cause significant erosion for Kotzebue, Shishmaref, and Utqiaġvik. Wind events were defined as being at least 6 h or longer of sustained winds exceeding $10\,\mathrm{m\,s^{-1}}$ including lulls of over $7\,\mathrm{m\,s^{-1}}$ shoulder events, as defined in Atkinson (2005). Also shown is the number of these events which have winds in the 90° window between the two directions of coming from alongshore (downwelling) and directly onshore toward the community from the ocean, setting up water along the coast. Wind data are from WRF-downscaled ERA-Interim; sea ice data are from ERA-Interim.

the winter is getting shorter … used to be everything would melt in one week" (Sarah Betcher, personal communication, 2013). Freeze-up and break-up represent important events in the cultural calendars of coastal communities in the Arctic (Gearheard, 2013) and these changes therefore have significant consequences for residents and their subsistence activities. However, the nature and severity of these consequences depends upon the local ice regime and cultural practices, and each community must therefore be considered individually.

Once the ocean surrounding the community starts freeze-up, transportation via small boats becomes increasingly difficult and risky. Hence, until a stable landfast sea ice cover forms (allowing the use of snow machines, dog sleds, or regular street vehicles in some cases) early winter travel to the mainland from villages on islands and peninsulas such as Shishmaref and Kotzebue can be extremely limited. The growing number of false freeze-up events each year extends this period of reduced accessibility and increases the level of uncertainty at this time of year. In the Canadian Arctic community of Igloolik, Laidler et al. (2009) report that "hunters are finding autumn sea ice travel more dangerous, travel routes must be altered, and people are essentially stuck in town" during this period. In Utqiaġvik, travel to inland hunting regions or other communities is not directly affected by sea ice conditions, but boating during the extended open water season has been impacted by winds and waves. This is discussed in more detail in Sect. 4.2.

Entrainment of sediments by sea ice commonly happens during the formation of sea ice in shallow water. Sediment entrainment could therefore potentially increase with an increasing number of coastal freeze-up events in a given year. The reduced albedo of sediment-laden ice (Light et al., 1998) promotes subsequent melt and early break-up the following year. Additionally, sediment by transport has been observed to be a significant mechanism for across- and along-shelf particulate flow (Eicken et al., 2005). Ice shove events, during which sea ice piles or rafts onto the shore, are another coastal process that may be impacted by the number of false freeze-ups. They occur most commonly in the fall and spring (Kovacs and Sodhi, 1980) and represent a significant hazard in some Arctic coastal communities. With an increasingly delayed freeze-up extending into the fall storm season (see Sect. 4.3), and a higher number of false freeze-ups happening at the same time, it seems possible that coastal communities may also experience more ice shoves.

The subsistence harvests of all Arctic coastal communities include ice-associated marine mammals such as ringed and bearded seals, walrus, belugas, and bowhead whales (Moore and Huntington, 2008). The availability and accessibility of each of these species, in terms of both the population size and proximity to hunting grounds, will be impacted by changes in the timing and persistence (number) of freeze-up and break-up events. Work done by Kapsch et al. (2010) identified optimal conditions for maximum walrus hunting success in St. Lawrence Island, Alaska, of 0 to 30 % ice concentration and specific windows of wind speeds, temperature, and visibility. This suggests that a delayed freeze-up will shift the optimal walrus hunting conditions to later in the year, though Kapsch et al. (2010) found that hunting success was more sensitive to ice conditions in spring than fall. Interviews collected by Krupnik and Jolly (2002) indicate that open water can be a driver of early break-up and can make walrus hunting difficult.

In Utqiaġvik, the spring whale harvest traditionally take place in the lead that forms at the seaward edge of the landfast ice with the butchering taking place on the landfast ice itself (e.g., Gearheard et al., 2013). Although the grid cells selected for our study do not capture landfast ice at Shishmaref and Utqiaġvik, Mahoney et al. (2014) found trends toward earlier break-up of landfast ice along the Alaska coast in agreement with those identified here. These changes reduce the time for which landfast ice is available as a platform for spring whaling. Without landfast ice, communities must butcher their catch on the beach, which creates additional challenges for disposal of the carcasses.

Ringed seals are associated with ice year-round, and breeding occurs on stable ice with good snow cover. When a delayed freeze-up (Fig. 3) or an increased number of freeze-up and/or break-up events (Fig. 5) means there is less time for the snow cover to develop, pups are more exposed to predators due to inability to construct an adequate lair (Kovacs et al., 2011). Ringed seals can be hunted for subsistence whenever ice is accessible, either on landfast ice or among loose floes by boat (Gearheard, 2013), but the overall accessibility to subsistence hunters is reduced by the shortening of the ice-covered season. Bearded seals are also likely to be negatively impacted by an earlier break-up (Fig. 4), because they require stable seasonal ice late in the spring for raising pups and molting (Kovacs et al., 2011). Ideal hunting conditions consist of loose floes accessible by small boats. These conditions typically occur as the ice is in the process of breaking up and hence the occurrence of multiple break-up events each year may potentially offer increased hunting opportunities. However, the overall earlier occurrence of break-up means an earlier start to the hunting season, which may conflict with other subsistence activities or become out of sync with the life events of the seals.

4.2 Increases in open water duration and the number of windy days over open water

As a result of a delayed freeze-up and early break-up, the open water season has lengthened at all three communities, though most rapidly at Utqiaġvik (Fig. 2). Using the HSIA dataset, we see that this change began abruptly in the late 1990s (Fig. 9), when the summertime sea ice edge first began retreating significantly to north of Point Barrow. As the northernmost tip of Alaska, once the sea ice has retreated beyond Point Barrow, navigation to points further east along the northern Alaska and Canadian coasts becomes possible. Consequently, the recent changes in the length of the open water season at Utqiaġvik (Figs. 6, 7, and 9) have led to a significant increase for maritime traffic destined for Utqiaġvik or locations further east (Smith and Stephenson, 2013). Longer navigation seasons along other Arctic coasts are leading to an increased use of coastal shipping routes and development of offshore continental shelves (Instanes et al., 2005). However, it should also be noted that

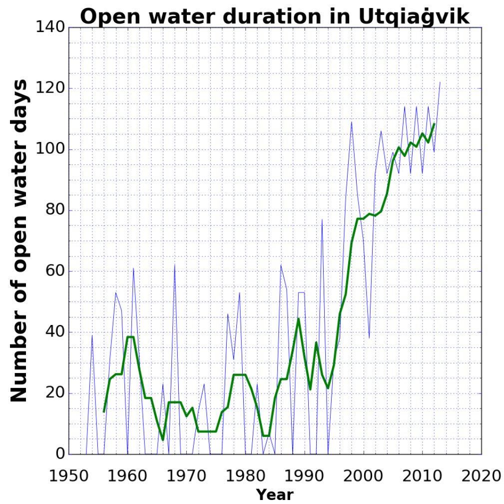

Figure 9. Number of open water days at Utqiaġvik, AK, has increased substantially since the dataset began in 1953. There has been a marked shift such that after 1992, Utqiaġvik has seen at least some days of open water. Bold green line shows the 5-year running mean of the number of open water days as defined by a 30 % sea ice concentration threshold. Data are from HSIA.

as sea ice retreats, the resulting larger fetch of open water is likely to lead to increased wave height (Thomson and Rogers, 2014). Additionally, without deep water ports, swell propagating through open water may prevent barges from offloading goods even under calm winds. Associated political, economic, and social consequences for residents of Arctic coastal areas could be significant and possibly outweigh direct physical impacts from global warming.

In addition to extending the navigation season, the lengthening open water season allows for more time for winds to impart momentum to mix the upper ocean and create waves. Wind waves represent a significant hazard for hunters in small boats, who may need to travel further from shore to obtain their catch in recent years. Aerial surveys in the western Beaufort Sea indicate that as the ice retreats further from shore, bowhead whales are traveling closer to the coast during their fall migration (Druckenmiller et al., 2017), but hunters in Utqiaġvik reported during interviews that they had to travel farther from land due to increased barge activity pushing whales out further from shore. This is an example of the complex interplay of social systems responding to environmental change. Hunters stress that whales should be harvested closer to the community so the meat does not spoil on the haul back to shore (Ashjian et al., 2010).

The problem of traveling further from shore is amplified by an increase in the annual number of high-wind events over open water (Figs. 6, 7c, and 8) which will lead to more days with high waves. The trends of number of boatable open water days in conjunction with the increase in total number of open water days should be taken into account when examining the impacts of climate change on subsistence activities taking place from boats. The open water season has increased 4.2, 5.6, and 25 day decade^{-1} for Kotzebue, Shishmaref, and Utqiaġvik, respectively, but the number of boatable days has increased by 1.2, 3.1, and 10.7 day decade^{-1} for each community, respectively. The increase in the number of open water days at all communities agree well with the results of Parkinson (2014). Greater wave heights caused by increased fetch can hinder hunting success much more than prey abundance due to lack of access to the prey. Hansen et al. (2013) examined threshold wind speeds reported by Wainwright hunters which were deemed unsafe hunting conditions; 11 % fewer boatable days were determined for bowhead whales in spring (15 April–15 June) and 12 % in summer (1 July–31 August) over the period 1971–2010. In terms of handling larger waves due to increased fetch and the increasing amount of time open water is exposed to storm activity, perhaps hunters can obtain access to more stable, suitable, and bigger boats. The impacts of climate change and changes in the timing of freeze-up and break-up might be less severe if communities were able to adapt their hunting practices effectively.

4.3 Increasing winds over open water: number of geomorphologically significant wind events and consequences for erosion

It is well documented that a lengthened period of open water leaves Arctic shorelines more vulnerable to erosion from fall storms (Barnhart et al., 2014; Overeem et al., 2011). Moreover, along the Alaskan coast during the open water period, we have found the number of wind events capable of doing geomorphological work or creating hazards to habitat or infrastructure (as defined by Atkinson, 2005) is increasing at all three communities in this study (Fig. 8). The trend is strongest along the northern coast near Utqiaġvik, although the number of events annually is significantly less than we find at Kotzebue and Shishmaref. Once we apply an additional wind direction criteria to count only those events likely to produce both waves and coastal setup, we see a substantially lower number of events and we find that Utqiaġvik is the only community to exhibit a significant increasing trend in these wind events. Shishmaref shows the highest number of the high-wind events coming from the direction allowing for water set up along the coastline; although no significant increasing trend was found, these events contribute to an already existing problem of shoreline erosion there. Kotzebue shows only a slightly lower annual average of these water setup events than Shishmaref, but differences in the geographical location of the communities should also be considered in terms of relative exposure to the open ocean and increases in fetch. Shishmaref is more exposed to the open ocean than Kotzebue because it is not geographically located within a Sound, and this might also contribute to differences in water setup along the coastline. Closely monitoring possible future trends in these events for all communities can provide a proxy for future shoreline erosion.

Parkinson and Comiso (2013) presented a quantifiable variation of coastline exposure due to inconsistencies in trends of the delayed freeze-up and earlier break-up of sea ice, but this study analyzed years starting with the satellite era in 1979. By using HSIA data, we were able to quantify changes in the duration of the open water period offshore Utqiaġvik since 1953 (Fig. 9), before the satellite data became available. Although there are other factors that influence coastal erosion rates (e.g., permafrost extent, surface geology), a change in the number of wind events able to geomorphological work, and how often the winds in these events have directions favorable to increased water levels, may also be an indicator of how vulnerable a particular coastline is to erosion. An increase in these wind events which can create significant storm surge can also be a threat to food security. For example, in Shishmaref, an October 1997 storm caused 9 m waves and swept away multiple families' winter supply of food, which was stored on top of permafrost but under sand. In addition to food storage locations, multiple homes have had to be relocated and school housing, a warehouse, and a tannery were also threatened (Callaway et al., 1999).

5 Conclusions

By applying simple thresholds identified using local observations, we have demonstrated that large-scale climate datasets can be used to assess the impacts of a changing climate to the three Alaska coastal communities of Kotzebue, Shishmaref, and Utqiaġvik. The methods used in this study can be applied to any Arctic coastal community, though the specific thresholds and impacts of changes are likely to differ. Our results show differences in changes of the sea ice regime across the three communities. Particularly Utqiaġvik is showing the most pronounced changes in terms of a lengthening open water season. However, changes in the open water period are not able to capture the full story of the impacts of changes in sea ice cover, as we have demonstrated in this study. Other indices specific to individual communities and informed by local knowledge must be used.

The number of "boatable" open water days is not increasing as much as one might expect from the lengthened open water period, particularly in Utqiaġvik. Some of the additional days in the open water period occur during the fall storm season when there commonly are days too windy for hunting or travel by boat. Therefore, lost days during the ice-covered season that might have been suitable for snow machine travel are not necessarily offset by an equal number of boatable days.

Lengthening of the open water season has been linked to increased rates of coastal erosion (Overeem et al., 2011). Our results show that the number of wind events capable of performing significant erosion (Atkinson, 2005; Solomon et al., 1994) scales with the length of the open water season. Accordingly, Shishmaref, which has an open water season approximately twice that near Utqiaġvik, also has approximately twice as many erosion-capable wind events. All three communities showed positive trends in the number of such events, but Utqiaġvik showed the strongest increase over the study period, with roughly three times the number of events in 2014 as occurred in 1979. The trend at Utqiaġvik is still apparent when we consider only those high-wind events coming from directions favoring both onshore wave generation and coastal set up (i.e., from the northwest and southwest). If this trend continues, erosion rates are likely to increase in the future at Utqiaġvik, placing the community's substantial (compared to the other Arctic coastal communities) coastal infrastructure at risk.

Along with the increases in open water season length, our results also show that the number of false freeze-ups and false break-ups has increased substantially in recent years. As a result, community members are finding it more difficult to change modes of transportation with the seasons. During the intervals between false transition events, coastal residents can be trapped without a reliable method of transportation (Laidler et al., 2009). Although Utqiaġvik is showing a greater increase in the number of open water days, Shishmaref has had the greatest increase in the number of false freeze-ups in recent years according to ERA-Interim data. Kotzebue experiences the fewest false freeze-up and break-up events, but they did not occur before 2004. If the patterns of the more recent years continue, the occurrence of false freeze-ups and break-ups could begin to define a new "normal" for the transition periods between open water and sea ice cover.

Indices such as those we have derived here show that the use of community observations and local knowledge in conjunction with large-scale climate datasets can be a powerful tool in evaluating the impacts of climate change at local scales. All of our results relied on the use of a sea ice concentration threshold to identify transitions between periods of open water or ice cover. For further research, it would be useful for individual communities to report when freeze-up and break-up occur. If every community provided this information, choosing a threshold for sea ice concentration may not be required in terms of comparing analysis of large-scale datasets across communities.

Data availability. The Historical Sea Ice Atlas is available for download at http://data.snap.uaf.edu/data/Base/Other/Historical_Sea_Ice_Atlas/ (last access: 1 September 2017, SNAP, 2017). The WRF-downscaled ERA-Interim dataset was made available by Peter Bieniek at University of Alaska Fairbanks.

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