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

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

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

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

Abstract. Using thresholds of physical climate variables developed directly from indigenous knowledge, and two large-scale datasets, we have produced locally-relevant indices demonstrating how a reduced sea ice cover impacts Alaska coastal communities' way of life. We utilize large-scale datasets to identify locally-relevant impacts because the methods used here can be applied to any Alaskan coastal community. We have chosen three Arctic rural communities of Kotzebue, Shishmaref, and Utqiaġvik (previously Barrow) as examples to show changes in these indices from 1953-2014. The indices chosen in this study are: the number of 'false freeze-ups' (times sea ice concentration oscillated above and below the threshold value before freeze-up was finally achieved), 'false break-ups', timing of freeze-up and break-up, length of the open water duration, number of days where the winds are too strong to hunt via boat (wind speed thresholds from Ashjian et al. (2010)), and number of wind events capable of performing geomorphological work or damage to infrastructure from creation of waves and storm surge (using the definition of these wind events from Atkinson (2005)). We demonstrate how indigenous knowledge can inform use of large-scale datasets to form locally-relevant indices describing change in sea ice conditions, which also leads to changes in the duration and strength of winds over open water. The Historical Sea Ice Atlas (HSIA) and WRF-downscaled ERA-Interim datasets are used jointly to assess the potential direct impacts from sea ice change for selected Alaska coastal communities. We have found that there has been a marked increase in recent years for all communities, especially Utqiaġvik, in the number of combined false freeze-ups and false break-ups, and number of days too windy for hunting via boat. In Utqiaġvik, there has been an approximate tripling of the number of wind events capable of significant coastline erosion from 1979-2014. 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 interaction and feedback is 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 open water covered by sea ice), thickness, and extent can be considered “primary” geophysical variables for an Arctic ocean study, but for indigenous Arctic coastal communities, timing of freeze-up and break-up are among the most important criteria that define the state of the sea ice locally (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 (Betcher, personal communication). While 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.

When trying to downscale large-scale climate observations, complex inter-connections between communities and the environment can often be overlooked (Huntington et al., 2009). We therefore recognize the importance of incorporating local knowledge in understanding and quantifying the impacts of such direct changes(Huntington et al., 2009). For example, from interviews with Iñupiat whalers in Utqiaġvik (formerly Barrow) Ashjian et al. (2010) identified winds 6 m/s or higher to be linked to less successful whaling because it is deemed by hunters too unsafe to travel via boat. Alternatively, Atkinson (2005) used a 10 m/s wind speed threshold for a duration of 6 hours of longer to produce a climatology of storm events. Atkinson (2005) used this threshold wind speed because it was found by Solomon et al. (1994) to produce waves with enough power capable of doing geomorphological work or damage to infrastructure and habitats. For these indices, identifying long term trends in conjunction with changes seen in recent years may give an indication of how climate change can be expected to impact coastal communities. Here we present a timeseries of these indices from 1979-2014 (1953-2013 for freeze-up and break-up timing) for the communities of Utqiaġvik, Kotzebue, and Shishmaref.

1.2 Characterization of communities examined

The communities examined in this study are Kotzebue, Shishmaref, and Utqiaġvik (previously Barrow). The geographic location of the communities examined are varied, but all are located along the Alaskan coastline (Figure 1) and have community members who participate in offshore subsistence (reliance or partial reliance on marine mammals as a food source and a way of life) hunting activities (Ashjian et al., 2010; Callaway et al., 1999). Kotzebue Sound has the Noatak, Kobuk, and Selawik rivers providing freshwater seasonally into the Sound. The ice typically breaks up around late June and freezes around October. The village of Kotzebue is located on a gravel spit on the Baldwin Peninsula, and the population is over 3,500 (NANA Regional Corporation, 2016). Sea ice use in Kotzebue includes travel by snowmachine and foot, as well as subsistence hunting from the ice for marine animals including sheefish, bearded and ringed seals (Georgette and Loon, 1993).

Shishmaref is located on a barrier island in the Chukchi Sea, about 0.25 miles wide and 3 miles long, slightly north of the Bering Strait and about 100 miles southwest of Kotzebue. It is at the center of animal migration routes and also a center of a complex food-distribution system based in subsistence hunting practices (Marino, 2012). It is highly vulnerable to erosion in part to declining sea ice cover protecting the coastline (Barnhart et al., 2014). The members of Shishmaref have voted twice previously to relocate due to this problem, however the funds are not available for doing so, even though they will eventually have to move (Department of Commerce, Community, and Economic Development, 2017). The sea ice typically breaks up earlier than Kotzebue, around May and freezes up later, around November.

Utqiaġvik (previously Barrow) officially reverted back to its original name in December 2016. It is the largest village in the North Slope Borough in Alaska, and is located along the Beaufort Sea. Utqiaġvik is in a highly exposed position for drifting pack ice and also land-fast ice. Freeze-up is typically around November and break-up can last from April through August (Johnson and Eicken, 2016). Sea ice in Utqiaġvik can be a hazard for commericial shipping but also as platform for hunting subsistence animals. Seal hunting can take place on the ice in winter, and bowhead whale hunting is done from the edge of shore-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 including descriptions of the Historical Sea Ice Atlas and WRF-downscaled ERA-Interim datasets, sources of indigenous knowledge, as well as the selection of the study areas and detailed descriptions of the metrics used to evaluate the changing sea ice conditions in these communities. Second, the Results section describes what we have found in terms of how these metrics have been changing for each community. For each index, we have evaluated the time period from 1979-2014, and earlier (1953-2013) for the freeze-up and break-up dates of Kotzebue and Shishmaref. Next, the Discussion section links these indices to what they could mean in terms of impacts for the communities selected, 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 Historical Sea Ice Atlas extends back to 1850 with monthly resolution, incorporating various datasets from whaling ship logs taken at that time to historical ice chart archive products. Analog representations of a given month fill any temporal or spatial gaps, which assume no large jumps in the sea ice concentration between the first and the last timestep of the HSIA dataset (Walsh et al., 2017; Scenarios Network for Alaska and Arctic Planning, 2015). From 1953 through 2013, quarter-monthly sea ice concentration values are available and were used here to investigate trends in changes in sea ice concentration along the coastlines of selected communities in Alaska. Use of HSIA data roughly doubles the timespan we can consider as compared with relying only on the sea ice data derived from the passive microwave satellite record, which begins in 1979. The HSIA has a 0.25 x 0.25 degree resolution, and is a compilation of a different number of sea ice concentration data. 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). While the quarter monthly data starts in 1953, monthly data in the HSIA goes back to 1850. One caveat to including multiple data sources is that there are a different the number of observations that have gone into each time segment of data. For example, the frequency of ship-based of observations was not consistent throughout the record and the number of available observations increased dramatically with the advent of the satellite era. However, with regard to the latter, we do not find evidence for anomalous discontinuity in trends around 1978-79, when the passive microwave satellite data are incorporated into the dataset.

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 (updated daily for sea ice) and a 20 km spatial resolution, from 1979-2014. It has been downscaled from a 0.75 degree (about 83 km) spatial and 6 hourly temporal resolution. It was developed 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), coupled with the Noah land surface model used within the WRF model to accurately simulate the thermal conditions over sea ice.

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, with varying levels of dependence on subsistence activities, susceptibility to coastal erosion, and interaction with the offshore oil and gas industry. In addition, an offshore area was analyzed in the Bering Strait. Fig 1 shows the grid cells selected for each community and offshore areas used to analyze ice concentration. The HSIA includes a land-mask, so grid cells near the coastline can be readily identified. To assess variability in ice conditions most immediately relevant to the secu of coastal communities (Loring et al., 2013), we selected data near the coastline of each community. The maximum concentration (greatest fraction of sea ice per unit area) was extracted from within this area. The maximum concentration was extracted and not the averaged because if one grid cell in this area was higher than the others, it could serve somewhat as a 'choke point' or hazard while the other grid cells do not. In order to capture this, we decided to take the maximum value of these several grid cells, although the neighboring grid cells do not typically vary significantly in concentration. The entire sea ice cycle was examined. For the offshore area analyzed (Bering Strait), the maximum ice concentration from a 0.75 degrees longitude and 0.5 degrees latitude box was examined. Quarter-monthly data provided by the HSIA were assigned a calendar date by the best approximation of the midpoint day of each quarter-monthly file. The selection of the location for the analysis of downscaled ERA-Interim sea ice concentration and 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

The open water period is defined as the duration between the assigned calendar days in the summer season where the ice concentration stayed below 30% for the HSIA data and 15% for the ERA-Interim data. The freeze-up and break-up day trends are similar if the sea ice concentration threshold that defines them is increased or decreased by 15% from the 30% threshold used in this analysis. Freeze-up day and break-up day are defined as the time when the ice passes the concentration threshold. The timing at which freeze-up and break-up concentration thresholds are passed does not necessarily imply a phase change, but also can include advection of ice in terms of shifts in winds or currents. The slightly higher threshold of 30% has been used for the HSIA data because it provides a quantitative value for comparison between communities. It is difficult to determine what the best thresholds are in terms of ease of water or ice transportation are because the grid cell area covered is larger than the smaller boats or snow machines. Serreze et al. (2016) also uses a 30% sea ice concentration threshold, because it allows more years to be included in the dataset which do not dip below the usual 15% threshold used by studies of sea ice extent. We chose the 15% threshold for the ERA-Interim to highlight that the number of open water days between the two datasets roughly compare even if the threshold differs by 15%. 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.

The number of ’false freeze-ups’, or the number of times the ice concentration trend oscillated above and below the sea ice concentration threshold value before freeze-up was finally achieved, were calculated at a point offshore each community of Kotzebue, Shishmaref, and Utqiaġvik. The number of false break-ups were also calculated for each of these communities. The downscaled ERA-Interim data was selected to evaluate the number of false freeze-ups and false break-ups for each community examined because the temporal resolution of that dataset is higher than that of HSIA (daily instead of quarter monthly). A false break-up is defined as the time when the ice concentration dips below the threshold before the final break-up prior to the open water season of that calendar year. A false freeze-up is defined as when the sea ice concentration threshold rises above the threshold concentration between the last break-up and the last freeze-up of that calendar year.

2.5 Indices relating to open-water wind events

The number of ’boatable’ open water days refers to the number of days of sea ice concentration is below 15% while the winds do not exceed a 6 m/s threshold. This threshold was found to be related to hunting success of whalers in Utqiaġvik, because higher winds speeds are usually considered by the hunters as too dangerous to hunt via boat. Ashjian et al. (2010) identified this wind speed threshold, and from interviews with 41 Iñupiat whale hunters, found that 86% of fall whales in Utqiaġvik were landed on days where the wind speed was less than 6 m/s, and that no whales were landed on days where winds exceeded 10 m/s. Wind events exceeding 10 m/s for a duration of 6 hours of longer have been identified to have potential for geomorphological change, or to cause damage to coastal infrastructure or habitats (Atkinson, 2005; Jones et al., 2009). The number of these events were calculated for Kotzebue, Shishmaref, and Utqiaġvik from 1979 through 2014. 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, which follows the same method as used in Atkinson (2005).

3 Results

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

The timing of freeze-up and break-up has changed for the communities examined. The HSIA dataset was used here in order to extend the timeseries freeze-up and break-up timing 27 years prior to the starting date purely satellite-derived datasets (1979 versus 1953). The final freeze-up and break-up date was taken for those years which showed multiple freeze/break events. The freeze-up day for Kotzebue Sound shows a much weaker trend than the freeze-up days for Shishmaref (Figure 3). The linear trend of the date of freeze-up is a delay of 2.2 days per decade for Kotzebue and 6.0 days per decade for Shishmaref.

Considering break-up timing, Shishmaref again shows about a three times stronger trend than Kotzebue, with Shishmaref seeing an earlier break-up by 3.4 days per decade, and Kotzebue at 1.1 days per decade (Figure 4). The significance of the freeze-up and break-up trends were evaluated and we found to have p-values above 0.05, and so are considered to not be statistically significant. This reveals that the interannual variability is high for freeze-up and break-up timing.

There has been an increase in recent years of the number of false freeze-ups and false break-ups (Figure 2) for the communities examined of Kotzebue, Shishmaref, and Utqiaġvik (previously Barrow). False freeze-ups and false break-ups are defined as the number of times the sea ice concentration threshold was passed before the ’true’ freeze-up and break-up date. There have been more false freeze-ups than false break-ups for all communities examined, but in particular Shishmaref shows many more false freeze-ups than false break-ups (Figure 2B). Shishmaref shows a total of 22 false freeze-ups from 2000-2014, with only 1 false break-up. From 1979 through 1999, there are only 2 false freeze-ups, and no false break-ups for Shishmaref. Kotzebue also shows more false freeze-ups and false break-ups in recent years, with no false freeze-ups or break-ups prior to 2004. From 2004-2014, Kotzebue had 10 false freeze-ups and 4 false break-ups. Utqiaġvik shows 9 false freeze-ups in recent years (2002-2013), with 11 false break-ups. There are only 5 false freeze-ups prior to 2002, with 1 false break-up.

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). Kotzebue shows more variability in the timing of freeze-up than Shishmaref, with 132% of the variance of freeze-up timing for Shishmaref, and 108% the variance of break-up timing. 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 at 44% and 20% for freeze-up and break-up day respectively. It is important to understand how much the variance plays a role in the trend because this can give indication of the strength of the trend. If the variability is not large relative to the observed trend in break-up and freeze-up day, then we have a better chance for determining how much change we can expect to see at any particular time.

3.2 Increase in number of days ’too windy’ for safely hunting via boat: the ’boatable’ open water period is not increasing as fast as one might think

We have found this ’boatable’ open water period is not increasing as fast relative to the increase in total number of open water days (Figure 5. In other words, the boatable open water period is not increasing as much as one might think, given the recent increases in open water duration. Kotzebue and Shishmaref (Figure 5A and B) do not show as strong of trend in the increase in number of windy days over open water as Utqiaġvik, although they show an increasing trend of the overall number of days without sea ice cover.

The number of unboatable open water days in Utqiaġvik is increasing at a rate of 1.4 days/year with an r^2 value of 0.4 (Figure 6). The rate of total increase in open water days is approximately 1.8 times this at 2.5 days/year with a similar r^2 value of 0.47.

The annual percent change in Utqiaġvik of number of boatable to total open water days (days over open water where the winds are lower than the 6 m/s wind speed threshold) from 1979-2014 is only slightly negative at -0.002 % per year, meaning that the number of boatable days is decreasing only slightly relative to the number of days too windy for subsistence hunting via boat. The average number of boatable days from 1979-2014 is roughly half (48%) of the total number of open water days (this can be visualized by noticing the red and blue stacked bars are roughly equal in length for each year bin in Figure 5C).

Kotzebue and Shishmaref show a negligible trend in the fraction of boatable to total open water days from 1979-2014, but the mean fraction of boatable to total open water days in Kotzebue is 60%, about 20% higher than that seen in Utqiaġvik. Shishmaref, like Utqiaġvik, has roughly half of the number of boatable to total open water days (Figures 5B and C).

3.3 Increasing number of wind events with potential for geomorpholgical change

Wind events exceeding 10 for at least 6 hours have been identified to have potential for geomorphological change (Atkinson, 2005; Solomon et al., 1994; Jones et al., 2009). The number of such events over open water have been increasing, particularly at Utqiaġvik (Figure 7). The rate of increase in the number of geomorphologically significant wind events over open water in Utqiaġvik is about 1 every 2 years, with an r^2 value of 0.2, approximately tripling the number of wind events from 10 to 30 events over the 36 year time period from 1979-2014. There has been a shift such that before the time period between 1993-2014, some years did not have any of these wind events over open water, because the ice pack did not recede far enough past our selected location offshore in earlier years (1983, 1985, 1988, 1991, and 1992). In Kotzebue, there has also been an increase in such events, but at a slower rate than Utqiaġvik at about 1 more event every 5 years, leading to an increase of about 7.2 events over our 36 year time period (Figure 7A). Shishmaref shows the weakest increase in such events at about 1 every 10 years, but has a higher number of such events than Kotzebue (Figure 7B). Over the 36 year time period examined, Kotzebue has had an approximate increase from 39 to 46.2 events, while Shishmaref has seen an increase from an average of 49 to 52.6 events.

For Kotzebue, the first ten years of the dataset (1979-1989) show about 3% less geomorphological wind events over open water than the last 10 years. In Shishmaref, the fraction of erosion-capable wind events to total open water period compared between the first and last 10-year periods of the dataset are roughly equal. Utqiaġvik, in contrast, shows an approximate 6.5% decrease in the number of wind events over open water to total open water period between the first 10 and last 10 year periods. This could be due to the large contrast in the total number of open water days between the first 10 and last 10 years, which is not as large as observed in the other communities.

4 Discussion

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

For Kotzebue and Shishmaref, the delayed freeze-up (Figure 3), and earlier break-up (Figure 4) can impact coastal erosion rates (Overeem et al., 2011) and change when different modes of transportation are used. During the spring transition period (the time window after the ice-covered period and transition into the open water season) an earlier break-up (Figure 4) means an earlier transition from snow machine to boat travel. However, there has also been an increase in the number of false freeze-ups and false break-ups for three separate communities examined (Figure 2), which has consequences for the operations of communities during these transition periods between sea ice cover and open water. For subsistence communities, the start of the freeze-up transition period means a closing window for safe transportation via small boats. After the freeze-up transition and once landfast sea ice has formed, travelling becomes safer to hunting areas or other communities by snow machine, dog-sled, or regular street vehicles. The changing shoulder seasons (time period between open water and ice cover) interfere with the subsistence way of life by altering travel routes, leading to less predictable sea ice conditions which could impact safety of the hunters. The number of false freeze-ups has increased in recent years more than the number of false freeze-ups (Figure 2). This suggests impacts relating to ice cover changes can be more profound in fall rather than spring, especially when the false freeze-ups are occurring during the fall storm season. Shishmaref in particular shows the highest number and greatest increase of false freeze-ups in recent years when compared to the other communities examined. A high number of false freeze-ups during the fall storm season could have implications for coastal erosion rates (Overeem et al., 2011), or the number of ice shove (ivu) events onto the shore, which is also a hazard. The number of false break-ups in Shishmaref is very low for all years examined, with 1 false break-up in 2012 (Figure 2). The high number of false freeze-ups and low number of false break-ups in Shishmaref suggest that impacts of the transtion period between ice cover and open water (for example changing the mode of transportation) during the break-up season in Shishmaref might be more predictable. Kotzebue shows an increase in recent years with the number of false freeze-ups with no false freeze-ups prior to the year 2004. False break-ups are less in number for Kotzebue and start in 2005. The variability of the river outflow in conjunction with changing air temperatures could be factors which contribute to the number of false freeze-ups and break-ups in the Sound. The recent increase in the number of false break-ups in Utqiaġvik is a further indicator of how ice conditions are changing and how this community must adapt their modes of transportation during a more turbulent break-up season. The two years with the highest number of false freeze-ups occur in the last 13 years of the 36 year dataset.

Reports of a longer transitional period, or time of uneven ice deterioration which can alter travel routes, can cause people to be “stuck” in town longer with hampered access to hunting grounds (Laidler et al., 2009). There has been much anecdotal evidence from community members across the Arctic that ~~suggest~~ the transition periods are becoming more prolonged. A community member from Kotzebue observes “we have a longer fall and a longer spring so it’s warming on both ends and the winter is getting shorter ... used to be everything would melt in one week” (Betcher, personal communication).

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 of each of these species, in terms of both the population size and proximity to hunting grounds, is likely to be impacted by changes in ice conditions related to 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. Waves generated from open water offshore have been shown to accelerate the break-up of sea ice (Squire et al., 1995).

“The fast-shore ice was broken up in early May or mid-May—about a week or even two weeks earlier than usual. I guess it was because of so much open water around. This open water in spring is the main thing that affects the ice. Spring walrus hunting here lasted much shorter, because the ice moved up north very quickly. Hunters had to go much further to get the walruses in late May, and then they just stopped going, because the ice was so far away” (Condrad Oozeva, October 2001 in Krupnik and Jolly (2002)).

Ringed seals are ice-associated year-round, and breeding occurs on stable ice with good snow cover. If a delayed freeze-up (Figure 3) or an increased number of freeze-up/break-up events (Figure 2) 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). Bearded seals are likely to be negatively impacted by an earlier break-up (Figure 4), because they require stable seasonal ice late in the spring for raising pups and moulting (Kovacs et al., 2011).

If the migration changes of animals that have been hunted for generations contribute to problems in number of catch, adaptation solutions must be found. It has been noted by communities in Nunavut, Canada that the delayed freeze-up results in thinner ice, delayed seal hunting, altered travel routes, and more difficulty locating the seals (Laidler et al., 2010). Travel between communities impacted by the timing of freeze-up could limit availability of subsistence animals which are not harvested from hunters of one particular community, but which must be traded between another community.

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

Following a delayed freeze-up and early break-up, the resulting lengthened open water season allows for more time for winds to travel over the open water, mixing the upper ocean and creating waves. Increases in the number of windy days means less time for hunters that might need to travel further from shore to obtain their catch in recent years. Hunters in Utqiaġvik reported during interviews that they had to travel farther from Utqiaġvik to harvest bowhead whales when barge activity pushed whales out further from shore. Hunters stressed 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 higher waves caused by an increase in the number of high wind events (Figures 5C and 6) over open water. 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. 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 wind speeds recorded at Utqiaġvik in conjunction with threshold wind speeds reported by Wainwright hunters which were deemed unsafe hunting conditions. An 11% shorter hunting season was determined for Bowhead whales in spring and 12% in summer since 1971. 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 are able to adapt their hunting practices effectively.

As with freeze-up and break-up timing (Figures 3 and 4), trends in open water duration vary considerably depending on location (Figures 5 and 6). Utqiaġvik shows the largest change between the first and last 10-year periods of the dataset (1953-1963 to 2003-2013). The next greatest increase in open water duration is Shishmaref, followed by Kotzebue. Due to the smaller trends in freeze-up and break-up timing, it follows that Kotzebue shows the least change in the number of open water days. Some variability in freeze-up and break-up dates has to do with changes in oceanic heat input. Since Kotzebue Sound is somewhat more isolated from the larger Bering Strait throughflow and changes there, this could be a reason Kotzebue Sound is showing less of a change than outside of the Sound. The changes in river discharge can also impact freeze-up date, because it can create a relatively stable buoyant freshwater lens over Kotzebue Sound, absorbing solar radiation with little heat loss from mixing from below. Ahlnäs and Garrison (1984) found the warmest water present in the Chukchi Sea in summer to be in Kotzebue Sound, and this warm water extends along the coast forming a tongue to Point Hope. Starting slightly further south, Wales is influenced by changes in the Bering Strait inflow and the Alaska Coastal Current (ACC). The ACC is relatively warm and fresh, is particularly pronounced in summer, and extends northwards from east side of Bering Sea to the east side of the Bering Strait surrounding Point Hope (Ahlnäs and Garrison, 1984). It has also been suggested there is an increasing mean northward warm water transport through the Bering Strait throughflow (Woodgate, 2012), and ice cover near Wales and northward may also be impacted by this. Utqiaġvik has seen a significant loss in multiyear ice in recent years (Drobot and Maslanik, 2003), which could be a major contributor to the abrupt change in number of open water days there.

Recent rapid changes in the length of open water season at Utqiaġvik (Figures 5, 6 and 9) have led to a significant change for maritime traffic destined for Utqiaġvik or locations further east (Smith and Stephenson, 2013). Although there is large interannual variability in the number of open water days, there is a marked increase in open water duration. Not only at Utqiaġvik, but longer navigation seasons along other Arctic coasts are very likely, which is 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 a larger fetch can lead to increased wave height (Thomson and Rogers, 2014), and can be a hazard to barges trying to offload goods. Associated political, economic, and social consequences for residents of Arctic coastal areas could be significant and possibly outweigh direct physical impacts from global warming.

The Bering Strait, which is a key area for Arctic shipping, also shows a significant upward trend in the number of open water days per year (Figure 8). The five-year running mean of open water days in the Bering Strait shows an approximately 70 day increase in the number of open water days from when the dataset began in 1953. The lengthened open water season has implications for vessel traffic because when the time window of open water is narrow, quick decision-making and accurate prediction of sea ice movement becomes vital for navigating through sea ice hazards (Whiteman, 2011). The break-up and freeze-up timing of the Bering Strait is important for vessel navigability, and when they can leave port for travel through the Strait.

The United States Coast Guard (2013) reports a 118% increase in maritime transit through the Bering Strait from 2008 to 2012. Recently, the US Coast Guard has released a recommended shipping route through the Bering Strait (United States Coast Guard, 2017), that can be used by vessels transporting goods, as well as a new tourist cruises made possible by the lengthened open water season. This defined shipping route away from the coastline could help alleviate hazards from potential oil spills, and make it easier to regulate speed limits and traffic numbers so as to minimize interference with the many marine subsistence mammals which use the Strait for their annual migration (Braham, 1980; Sakakibara, 2011). As mentioned prevously, whale hunters have reported as having to travel further from shore when the noise from barge traffic disturbs the whales (Ashjian et al., 2010). It is difficult to determine what impacts increased vessel traffic will have on the food, water, and energy security of coastal communities because the changes are happening very fast. Economically, increased shipping could enhance trade and reduce costs for Arctic communities, and increased development of resources can provide employment and income for Arctic residents (Ellis and Brigham, 2009). Food security could be impacted in the sense that any increases in goods delivery might influence certain coastal communities or individual members (for example, young people) of those communities to more heavily rely on outsourced food products, instead of relying on subsistence.

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 autumn 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 are hazardous to habitat or infrastructure are increasing, but particularly along the northern coast ~~in~~ Utqiaġvik (Figure 7). 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 along various areas of the coastline since 1953 (Figure 5), before the satellite data became available. Although there are other factors that influence coastal erosion rates (e.g. permafrost extent, surface geology, wind direction), changes in the number of wind events able to geomorphological work 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 30 ft 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 and indigenous knowledge, we have demonstrated that ~~to~~ 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 ~~(previously Barrow).~~ 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. Changes in the open water period are not able to capture the full story of the impacts of changes in ice cover, as we have demonstrated in this study. For example, if a time period of open water is too windy for hunting or travel by boat is now replacing a time period which would have in previous years been a stable ice cover suitable for snow machine, then hunting success due to ice change could decline. Along with the timing of the ’true’ freeze-up and break-up, the number of false freeze-ups and false break-ups are important to consider because a more turbulent change in the transition period between open water and ice cover also will impact how easy it is to change modes of transportation over open water and ice. A high number of false freeze-ups and break-ups during the shoulder seasons can make it more problematic and cause members of coastal communities to be trapped without a reliable method of transportation (Laidler et al., 2009). The more prominent recent increase in the number of false freeze-ups compared to the number of false break-ups (particularly in Shishmaref) might suggest the impacts during the freeze-up period are more profound and harder to predict than the impacts during the break-up transition. The number of ’boatable’ open water days is not increasing as much as one might guess from the lengthened open water period, particularly in Utqiaġvik. The number of wind events capable of performing significant erosion or destruction of habitat or infrastructure (Atkinson, 2005; Solomon et al., 1994) for Utqiaġvik again showed the strongest increase, with roughly three times the number of events since 1979 as occurred later in the record to 2014. Through these indices we have demonstrated that the use of traditional knowledge in conjunction with large-scale climate datasets can be a powerful tool in evaluating the impacts of climate change at local scales.

Data availability. The Historical Sea Ice Atlas, available for download at $http : //data.snap.uaf.edu/data/Base/Other/Historical_{Sea_{I}ce_{A}tlas}/$. The WRF-downscaled ERA-Interim dataset was made available by Peter Bieniek at University of Alaska Fairbanks.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was supported by National Science Foundation award 1263853 for the Sustainable Futures North Project. We would like to thank the reviewers for their constructive comments which helped to improve the manuscript.

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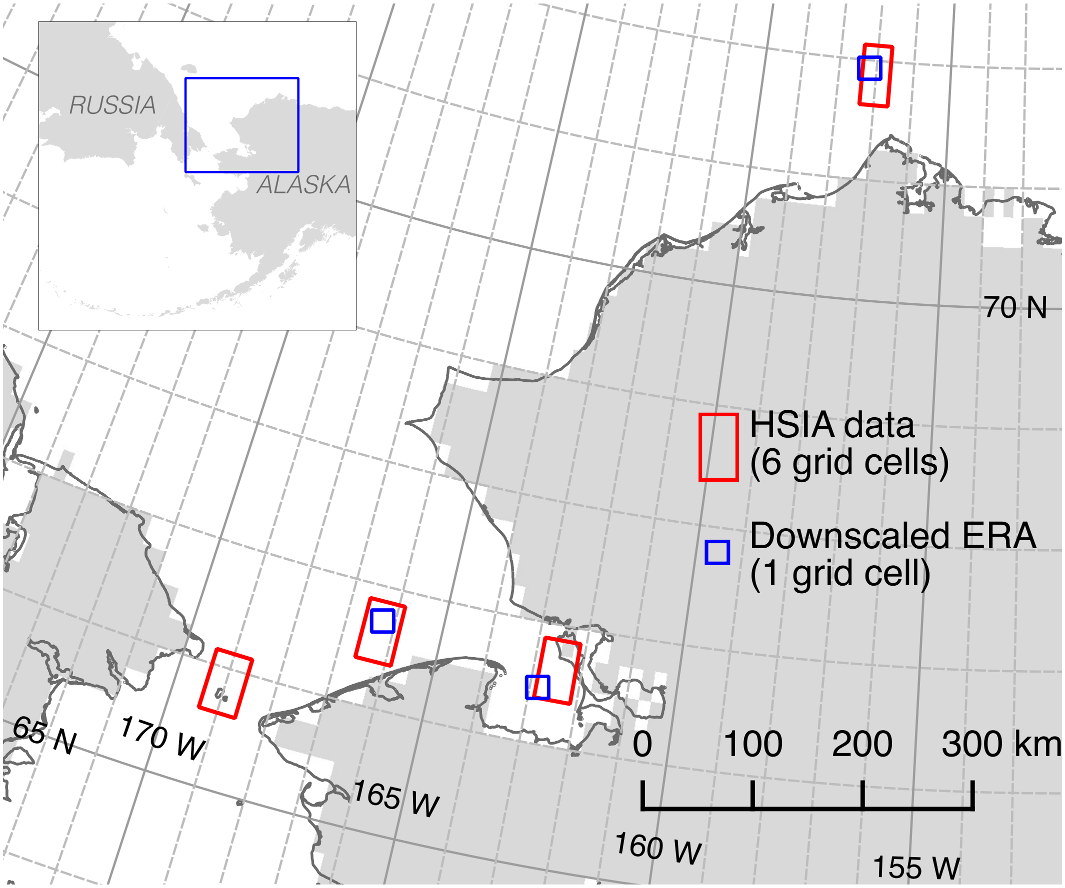
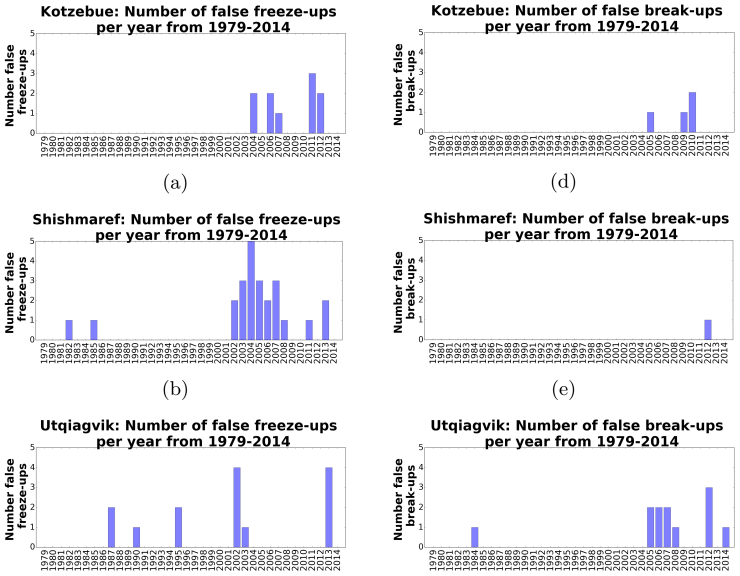


Figure 1. Selected grid cells from the Historical Sea Ice Atlas and WRF-downscaled ERA-Interim datasets used to extract sea ice concentration (also wind speeds from the WRF-downscaled dataset) offshore several communities and in the Bering Strait.


Kotzebue: Number of false freeze-ups per year from 1979-2014

Kotzebue: Number of false break-ups per year from 1979-2014

Shishmaref: Number of false freeze-ups per year from 1979-2014

Shishmaref: Number of false break-ups per year from 1979-2014

Utqiagvik: Number of false freeze-ups per year from 1979-2014

Utqiagvik: Number of false break-ups per year from 1979-2014

(a) (d)

(b) (e)

(c) (f)

Figure 2: The number of false freeze-ups and break-ups per year, identified by ERA-I daily sea ice concentration data. False freeze(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(break)-up was finally achieved.

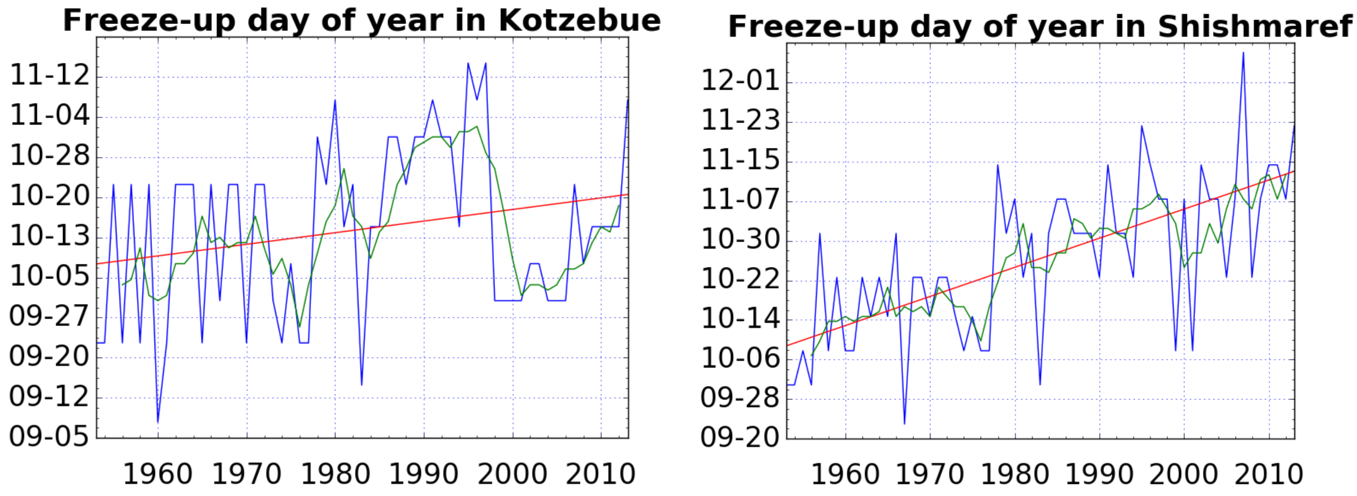


Figure 3. Trends in freeze-up day of year for Kotzebue and Shishmaref. Blue line is yearly freeze-up day, and green line indicates the 5-year running mean. Data from HSIA.

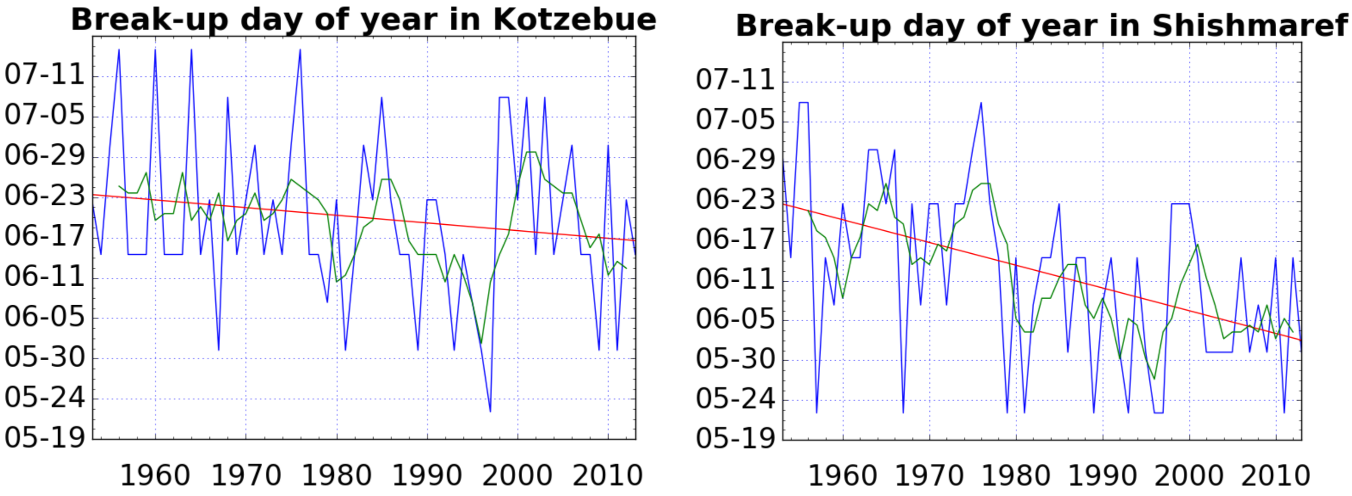


Figure 4. Trends in break-up day of year for Kotzebue and Shishmaref. Blue line is yearly freeze-up day, and green line indicates the 5-year running mean. Data from HSIA.

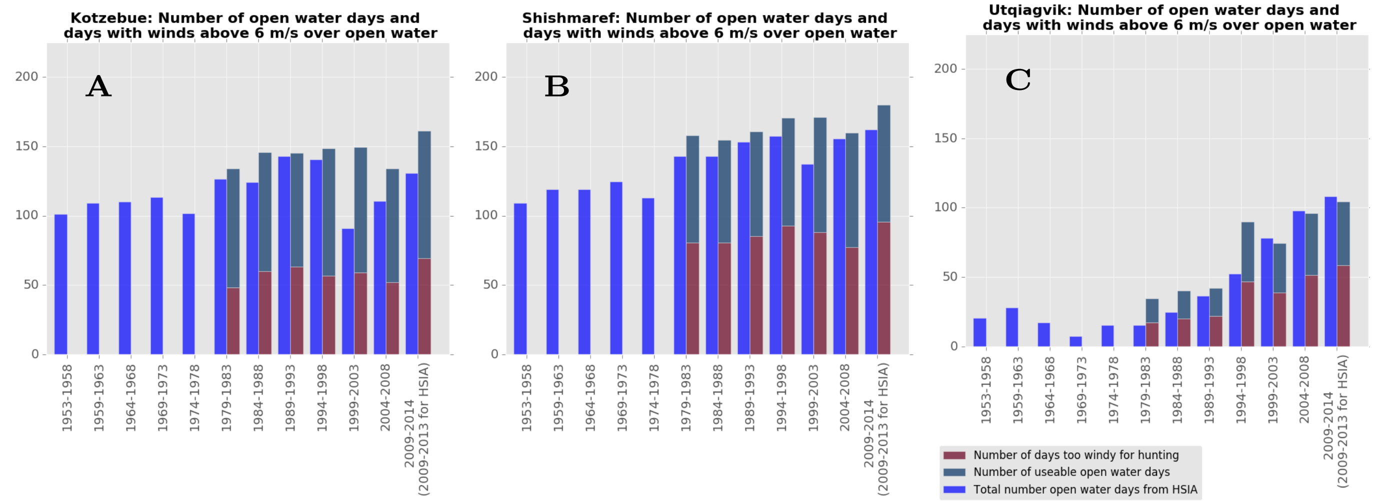


Figure 5. The number of days deemed too windy for boat travel for subsistence hunting (> 6 m/s, (Ashjian et al, 2010)) are increasing along with the increasing number of open water days (number of days less than 15% sea ice concentration).

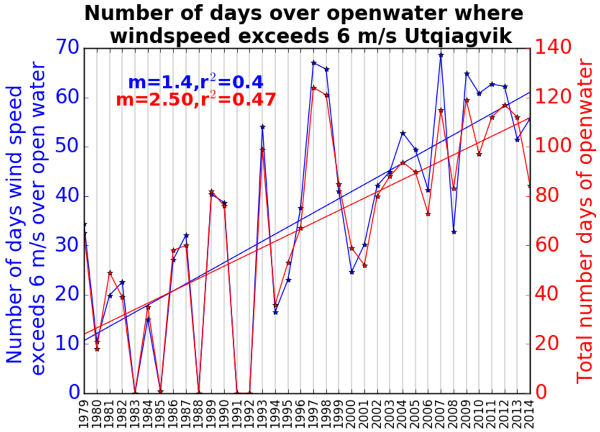


Figure 6. Annual timeseries from 1979-2014 of the number of days deemed too windy for boat travel for subsistence hunting (> 6 m/s, (Ashjian et al, 2010)) and number of open water days (number of days less than 15% sea ice concentration). Data from WRF-downscaled ERA-Interim.

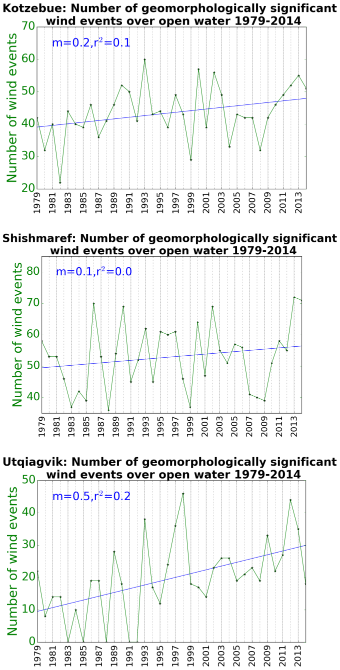


Figure 7: Number of wind events capable of geomorphological change (erosion) for Kotzebue, Shishmaref and Utqiaġvik. Wind events were defined as at least 6 hours or longer sustained wind events exceeding 10 m/s including lulls of over 7 m/s shoulder events, as defined in Atkinson (2005). Data from WRF-downscaled ERA-Interim.

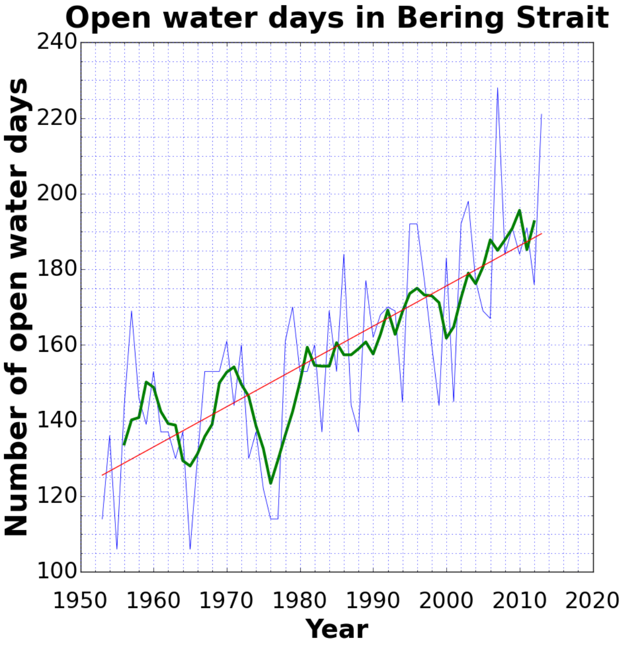


Figure 8. Number of open water days in the Bering Strait shown along with the trend line (red) and as a 5-year running mean (bold green line). Data from HSIA.

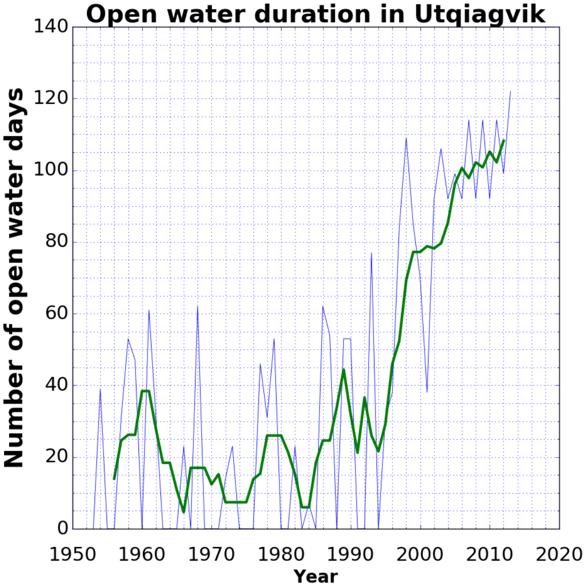


Figure 9. Number of open water days at Utqiaġvik, AK has increased substantially since the dataset began in 1953. There has been a marked shift such that after 1992, Utqiaġvik has seen at least some days of open water. Bold green line shows the 5 year running mean of the number of open water days as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

	Trend [days/year]	% 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

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