Author response to Reviewer #1

We thank Reviewer #1 for the thoughtful and helpful comments. The responses by the authors are written in blue.

The authors thoroughly responded to the first round of reviewer comments. The paper is now much more focused and better utilizes the data presented to draw conclusions. I have attached a pdf with many comments embedded. Most comments are minor. Below, I list the areas that I believe require a bit more attention before the paper is published.

1. The title references "community knowledge" and the first sentence of the abstract states that this study is "Using thresholds of physical climate variables developed directly from indigenous knowledge". I find these claims of using community and indigenous knowledge too generous in describing the approach of this study. There are references to wind thresholds that are dangerous, references to how hunting is impacted by barge noise and ice conditions, etc., but I think it is problematic to claim that this paper used "indigenous knowledge" in the study. This is not a critique of the study itself, but rather in how it is described. This is certainly a paper that is applicable to these communities and uses community "observations" in their methodoloy and discussion, but use of knowledge is a much different thing, especially as we are seeing the raising of the bar for what is classified as indigenous knowledge research and knowledge co-production.
Yes, we agree that our wording was misleading here, especially with the recent increase in the use of indigenous knowledge in Arctic studies. We have changed the title and the quoted sentence of the abstract (as well as some other related sentences in the manuscript) to reflect that the physical climate thresholds used in the study are made from local observations, rather than using the term 'indigenous knowledge'. In instances where the thresholds were obtained from community engagement reported in other published studies, we cite those studies.

2. Figure 1 shows the grid cells used to extract the sea ice concentration and weather data, which provides much of the basis for this paper's analysis. The large flaw lead system that develops off of Alaska's North Slope in winter and spring typically occurs south of the grid cells chosen to represent conditions off Utqiagvik. Therefore, I am concerned that the location for the ice analysis doesn't represent conditions near the village, especially in spring. This should be discussed in the paper, and the selection for grid cells better justified.
We see the need to justify the selection of the grid cells, especially in consideration of flaw leads and coastal polynyas that are common near Utqiagvik, and we thank the reviewer for his/her comment. We have made the subsection in the manuscript describing grid cell selection clearer about why we chose the grid cells. We have added the reviewer's valid point about the flaw lead system to the manuscript as well. Unfortunately, the interpolated ERA-Interim data used for lower boundary forcing is most accurate away from coastlines. This is due to the contamination of the sea ice signal by the land-ocean boundary. Because of this, moving the grid cells southward and closer to the coastline would likely degrade the analysis. We have also added a reference in Section 4.1, p. 9, L16, which states: "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."

3. The paper analyzes severe winds events capable of geomorphological change. In this regard, wind direction is of high importance, yet the authors only look at scalar values. For example, onshore and downwelling winds will have more potential for coastal sediment erosion and storm surge. At Utqiagvik, it is stormy winds from the West and NW that are most likely to cause coastal change or

damage. Why have the authors not looked at specific wind components to characterize sever wind events?

We thank the reviewer in particular for this comment, because it contributes to the practical aspects of the manuscript. We have computed the wind directions and the number of hours the winds are between two 'direction thresholds' defining the onshore/alongshore quadrant for each community. We then presented the number of these severe wind events (which the reviewer mentions above) that are composed of winds between these threshold directions. We have added the results as a second y-axis in Figure 8, and explained the method in the caption of that figure, and also in a newly added portion of the methods (subsection 2.5, p. 5 L30). The wind directions in the alongshore direction generally promote water setup along the coast, and promote water downwelling. Winds from this direction, as the reviewer mentions in his/her comment, have more potential for storm surge and coastal erosion. The inclusion of the resulting occurrences adds to the analysis of the data we have available by directly linking it to impacts on coastal communities. If we take Utqiaġvik as an example, we have presented the number of the severe wind events which have winds coming from the directions of Northwest (representing onshore towards Utqiaġvik) and Southwest (representing alongshore winds promoting downwelling). Kotzebue and Shishmaref, the other two communities examined in the manuscript, have different direction thresholds to calculate the number of the wind events that are between alongshore and alongshore/downwelling, due to their different orientations along the Alaska coastline. The directions for Kotzebue are between West and South, and for Shishmaref, between NW and SW. Please see the methods subsection 2.5 for further detail. We have added the results of this analysis in the Results subsection 3.3 (p. 7 L25) , and added discussion of these results in Section 4.3 (starting at p. 11 L8).

4. Lastly, I believe this paper will eventually make a nice contribution to the literature. Of greatest potential value (in my opinion) is the opportunity to illuminate the different ice regimes and conditions across these three communities. The differences are mentioned, but could be discussed a bit more in the conclusions, especially in the sense of what may be expected with further change. The paper makes a lot of general, broad comments on community impacts. It could be improved with a few more comments specific to these three communities.

Thank you for this comment. The addition of several statements in the conclusion section, comparing the differences in the indices across the communities has, we believe, improved the presentation. We have lengthened the conclusion section in the new version of the manuscript by comparing the indices across the communities and linking them to particular impacts associated with the three different communities. We have also added a statement that the increase in the wind events coming from the NW and SW in Utqiaġvik (new results added to the manuscript, based on the Reviewer #1's comment # 3 above) is likely to be a problem in the future if this trend were to continue in terms of erosion and the relatively greater amount of infrastructure present in Utqiaġvik.

The responses below pertain to the detailed comments marked within the manuscript by the reviewer. The author responses are in blue and the comments by the reviewer are in black.

p. 2 , L 23: Why not identify the location of these three communities in Figure 1?

In response to this suggestion, we have amended the map to include the community names and locations.

p. 2, L. 29: should be "sheefish and bearded and ringed seals"

Thanks, corrected

p. 2 L 34: Be more specific. They have voted to "permanently relocate the village"

Yes, this has been corrected

p. 3 L 4: The village is actually along the Chukchi Sea.
Thanks, this has been corrected.

p. 3 L 8: I suggest sticking with one term - either "landfast" or "shorefast"..
Agreed. We have gone with "landfast".

p. 3 L 20: Insert "(HSIA)" immediately after first use.
Thanks, this has been inserted at what is now p. 3 L25.

p. 4 L 4 You are getting sea ice concentration from this product correct? This though is not explicitly stated in this paragraph.
Yes, and we also obtained the wind data from this product. Although we did mention the use in the subsequent section, we did not explicitly state it in this section. We have added such a statement to this subsection (p. 4 L17) and provided further detail about the dataset.

p. 4 L 16 The large flaw lead system that develops off of Alaska's North Slope typically occurs south of the grid cells chosen to represent conditions off Utqiagvik. Therefore, I am concerned that the location for the ice analysis doesn't represent conditions near the village, especially in Spring.
This is an important point and we have added the description of the flaw lead in this subsection, because the reader should definitely be made aware of this flaw lead during Spring. The HSIA sea ice concentration data and WRF-downscaled ERA interim (used in this study) rely heavily on satellite-derived sea ice concentration products, which are problematic very close to the shoreline. Please see our above response #2 in the section "main comments". Due to limitations in the satellites' ability to distinguish land from frozen ocean near coastlines, moving the grid cells southward and closer to the coastline would reduce the accuracy of the concentrations. We have also added a reference (p. 9, L16) which mentions that the trends in landfast ice agree with our results presented in the manuscript. We have added a statement about the flaw lead in section 2.3, p. 4, L 27.

p. 4 L 18 "Security" is a vague term to use here. Why not just say "relevant to each community"?
Yes, agreed. We have changed the statement so that it now reads "To assess variability of ice conditions, we selected data near the coastline of each community but not too close due to the fact a large part of the sea ice dataset is satellite-derived." (Section 2.3, L23)

p. 5 L 5 Shouldn't these sentences which describe why the HSIA uses a higher threshold be immediately after the first sentence in this paragraph, which mentions the two different thresholds. Still, however, I am not clear how a higher threshold of 30% provides a "quantitative value for comparison between communities". Can't 15% also be the basis for comparison?
Yes, 15% can also be a basis for comparison. The point we were trying to make was that as long as a threshold is selected, the same threshold can be used across communities, thereby providing a basis for comparison. The statements here now read: "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% as used by NSIDC, for the ERA-Interim data (Figure 2)."

Figure 2 is a new figure added to the manuscript in response to this Reviewer comment (see response to next reviewer comment for p.5 L10). We have tried to make it clearer in the text that having a threshold provides a useful basis for comparison between communities, but the results of this comparison are relatively insensitive to the choice of threshold, since different thresholds produce similar results in number of open water days. We have also added in the conclusion section a statement that if enough community observations were available for freeze-up and break-up timing, then such a threshold may not be necessary.

p. 5 L 10 Instead of comparing HSIA at 30% and ERA-Interim at 15% to show that there is not a large difference in the number of open water days, why not compare ERA-Interim at 30% and ERA-Interim at 15%? That would make more sense scientifically. That comparison would provide a nice plot for the paper as well. The same could be included for comparing HSIA at 30% to HSIA at 15% concentration.
This comment indicates to the authors that we should have been more clear in the wording here, and we thank the reviewer for this comment. We have rearranged the text and added some clarifying statements in this section. Since the HSIA dataset does not contain any wind data, we have to use the WRF-downscaled ERA Interim wind and sea ice data to help evaluate the days which are 'too windy' for hunting and to identify the number of 'geomorphologically significant' wind erosion events. These events occur over open water, so the sea ice concentration had to also be utilized from the ERA dataset, in order to identify the high-wind occurrences over open water. Also in response to this comment, we have added a new figure (Figure 2) to support the statement that the 15% and 30% thresholds result in very similar numbers of open water days. We feel that a more extensive comparison of how open water changes across the two datasets with the different thresholds is a good idea, but also that a thorough evaluation of the sensitivity of the number of open water days to sea ice concentration thresholds across the two datasets is beyond the scope of the study.

p. 5 L 13 This is a good point, but these last two sentences should be included in the discussion, alongside some discussion of the challenges. Its important to recognize the challenges of getting communities to report freeze-up since there are many different ways that locals may define freeze-up.
Thanks, we agree that this statement is better moved somewhere else. We have moved it to the conclusions section, because we think that further exploration into how freeze-up is defined is also an important topic for future research. The statements regarding this topic in the conclusion section (p. 12 L 25) now read: "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 comparative analyses of large-scale datasets across communities."

p. 5 L 22 Correct to "refers to the number of days that sea ice concentration is below..."
Thanks, this has been corrected.

p. 6 L 4 Correct to: "..prior to the starting date of..."
Yes, thanks, corrected.

p. 6 L6 Figures 3 and 4 are referenced before Figure 2. Should the order be corrected?
Figures have been re-ordered, thanks.

p. 6 L20 This is interesting analysis. It would be valuable to know the weeks of year where these false-events took place, either in a plot or table.
We thank the reviewer in particular for this comment because it allowed us to better separate the time period of open water and to better distinguish between the false freeze-ups and false break-ups. We have also added a supplementary table to the manuscript which gives the month and day of each false

break up and false freeze-up, for each community. We have updated some of those results in Subsection 3.1 (p. 6, L 21) and Figure 5, based on the dates of the false freezeup/breakups. The supplementary table is mentioned in Subsection 3.1 (p.6 L28).

p. 6 L29 This is a long section title, and includes a conclusion. This is inconsistent with the other section titles in the paper. And having a conclusion in a results section title is a bit odd.
The title of the section has been renamed to “Changes in the number of days 'too windy' for safely hunting via boat”

p. 6 L29 See comment at Figure 5 below. . Comment at Figure 5: ‘Please clarify why the two parallel bars for each five year period are not equal in height. Is it because the blue is the HSIA data at 30% and the red/green is based on the ERA-interim at the15% threshold? It could be more informative to just show the red/green bars for each year (1979-2014), and leave off the blue. ‘
We had previously not included the HSIA-derived results (blue bars) but in the end decided to include them in order to show the longer timeseries alongside the ERA-Interim. However, due to the differences in the sea ice data incorporated into the HSIA and ERA-Interim, and sea ice concentration threshold, as well as the different grid cell area, we now see that the reviewer’s comment makes sense, so we have omitted the blue bars. This allows the reader to focus on the main point being conveyed in this figure: the comparison between the total number of open water days and the number of boatable days for each community. The blue bars (HSIA) are omitted in the edited Figure 7 in the most recent manuscript version (previously Figure 5).

p. 7 L9 The results reported appear correct, but it is a bit confusing/misleading. Increases in open water days in part drive the number of days that are too windy because there is a greater potential for days that are too windy with more open water days. Isn't the number of total boatable days (not expressed in relative terms) what is ultimately important?
The changes were presented in relative terms to show that just because there is a rate of increase in the number of open water days, there is not necessarily the same rate of increase in number of boatable days (due to high wind over open water). However, we do agree that the number of boatable days is ultimately what is important, so, based on this reviewer comment, we have removed the statements explaining the relative percentage changes. We have also added a few statements in this subsection about the rates of changes in the total number of boatable days between the communities. These changes are in section 3.2, p. 7, L4 and section 4.2, p. 10, L23.

p. 7 L10 Note that you are using a mix of both 6-year and 5-year bins in the figure. Clarifying why or finding a more consistent approach is needed.
Thanks for pointing out the potential confusion. We have changed Figure 7 so that each bin now includes 4 years of data. This results in a total of 9 bins for our 36-year timeseries. As suggested by the reviewer in a previous comment, we have also omitted the blue bars (HSIA) from this figure.

p. 7 L15 Wind direction is ultimately of high importance to the potential for geomorphological change. For example, onshore and downwelling winds will have more potential for coastal sediment erosion and storm surge. (At Barrow, it is stormy winds from the West and NW that are most likely to cause coastal change or damage.) Why not look at specific wind components instead of the scalar value?
This is a very good point. In response, we have augmented this section to include the relevant information on wind direction. We have added a second y-axis to Figure 8 in order to capture the number of those high wind events which are onshore and alongshore (downwelling). We have added a description of the procedure for identifying onshore/downwelling high-wind events in the Methods

subsection 2.5 (p. 5 L 30). Please also see our response to the Reviewer comment above, which is related to this one (Reviewer #1 main comment #3).

<u>p. 7 L32</u> Again, it is not clear why the relative number of high wind events to the total number of open water days is important. Isn't the TOTAL number of high wind events (during periods of open water) what is ultimately important, especially considering that this paper is looking at local community impacts?

The authors somewhat address the value of the relative value in the discussion (windy days of open water versus being able to travel by snowmachine on the ice) but it is not clear here.
We now state the results in terms of the absolute wind events.

<u>p. 8 L13</u> It seems that the underlying premise here is linked to uncertainty. With an expanding transition season, characterized by variability, the communities may have a harder time deciding on when and how to change their modes of transportation and hunting. If the authors agree, I think seasonal uncertainty is an important point to elaborate on.
Yes, this is exactly the point we were trying to get across in this subsection. In response to the reviewer's comment, we have added the following statements to this section:
p. 8 L7: "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 (Figure 5)."
p. 8 L 11: "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 about land at this time of year."

<u>p. 8 L18</u> It is not clear why the number of false freeze-ups has implications for coastal erosion rates. There may be a realationship but it is not well expressed here. Isn't it just the presence of open water (ice concentration) that is ultimately important? For example, a year with many false freeze-ups could have more ice in a region over the fall period compared to a year with very few false freeze-ups but with a very late date of freeze-up.
We have added a more detailed explanation in this section. We think this addition contributes to the discussion of why the recent increase in number of false freeze-ups is important for erosion. We have also added a reference here (Eicken et al., 2005) to explain that the increase in the number of false freeze-ups could increase sediment load transport (Section 4.1, p. 8, L 33).

<u>p. 8 L26</u> Correct to: "...false break-ups at Utqiagvik…"
This statement now refers to all three communities.

<u>p. 8 L27</u> "turbulent" is an very imprecise word choice. I suggest "more variable".
This section has been revised and the statement containing "turbulence" no longer exists.

<u>p. 8 L 29</u> It is not clear what "uneven" refers to. Is there a more precise word?
"Uneven ice deterioration" here was referring to the spatial variability in sea ice melt. We have changed the statements here to refer to the reduced accessibility of sea ice travel (section 4.1, p. 8 L30)

p. 11 L26. replace ‘in’ with ‘near’
Replaced, but this statement is now found at p. 11 L7.

p. 12 L04. Remove ‘to’
Thanks, removed.

p. 12 L06. Remove ‘previously Barrow’
Removed.

Author response to Reviewer #2

Author response is written in green, and Reviewer #2 comment is written in black.

While somewhat improved over the previous version this manuscript still suffers from a lack of clarity and concision in its description of the objectives, explanations of analyses and results, and poorly-proofed writing. The manuscript is still so far from being in at least in ‘near-final’ condition that I cannot recommend publication.

We thank the reviewer for his/her perspective, and we have made extensive editorial revisions to the manuscript with this in mind. We have enlisted a former editor for assistance in revising the presentation for clarity and technical correctness. The description of the objectives mentioned above by the reviewer is provided at the start of the manuscript: “Using thresholds of physical climate variables developed directly 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.” To address the reviewer’s comment about the “explanation of the analyses and results”, we note that in response to the comments of the other reviewer, the results of the indices are now given in separate subsections, which are ordered (numbered) consistently throughout the methods, results, and discussion sections. We believe that the organization of the manuscript has been improved from the initial submission by switching to this section/subsection structure. Concerning the “poorly-proofed” writing, we have proof-read the text, double checked all Figure references, and revised the wording based on the specific comments and line numbers given by Reviewer #1 (see responses to Reviewer 1).

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New Document:	**Old Document:**
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26 pages (5.73 MB)	25 pages (5.79 MB)
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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

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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 where 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 set-up 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 are 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 (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. 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 also 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 (Section 3.1) to be similar if the sea ice concentration threshold is 15%, 30% or 45%.

In an analysis framework based on large-scale climate observations, complex inter-connections 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 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 wind speed threshold for a duration of 6 hours of longer to produce a climatology of storm events. The 10 m/s threshold was based on Solomon et al.'s (1994) finding 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 timeseries of these indices from 1979-2014 (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 (Figure 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 3,500 (NANA Regional Corporation, 2016). Kotzebue Sound has the Noatak, Kobuk, and Selawik rivers providing freshwater seasonally into the Sound. Uses of sea ice in Kotzebue include travel by snowmachine 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 0.25 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, which has been exacerbated by declining sea ice cover protecting the coastline (Barnhart et al., 2014b). The members of Shishmaref have voted twice to permanently relocate the village due to this problem, however 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 commericial 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 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 1979-2014. For the freeze-up and break-up 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 Historical Sea Ice Atlas (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). 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 1979-2014. It has been downscaled from a 0.75 degree (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 hours. 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 (Figure 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 activites 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 a large part of the sea ice dataset is satellite-derived. 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-gridcell 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 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% as used by NSIDC, for the ERA-Interim data (Figure 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 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. 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 where the wind speed was less than 6 m/s, while 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 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 were 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, 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 for at least 6 hours), but have an added restriction that winds conducive to erosion must be blowing from directions within a 90-degree arc 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., 2014a) 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° and 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 timeseries 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/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 days per decade for Kotzebue and 6.0 days per decade for Shishmaref (Figure 3). The freeze-up day for Kotzebue Sound shows a much weaker trend than the freeze-up days for Shishmaref. As shown in Figure 4, break-up has occurred earlier by 3.4 days per decade at Shishmaref, and by 1.1 days per decade 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 (Figure 5). There have been more false break-ups than false freeze-ups for both Kotzebue and Utqiaġvik. In contrast, Shishmaref shows many more false freeze-ups than false break-ups: 17 false freeze-ups from 2002-2014, 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 2004-2014, 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 Supplementary Table S1.

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 1979-2014 in 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 m/s 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 days/year with an r^2 value of 0.49 (Figure 6). The rate of total increase in open water days is 2.5 days/year 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 (Figure 7). Kotzebue has a statistically insignificant increasing trend of the total number of days without ice cover (4.2 days per decade), while the trend in Shishmaref is statistically significant (5.6 days per decade). Shishmaref, on average, shows more unboatable days than Kotzebue, but Shishamref 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 geomorpholgical change

As described in Section 2.5, wind events exceeding 10 m/s for at least 6 hours have the potential to cause 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 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 1979-2014. There has also been a change in the character of the time series. Between 1993-2014, 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 (Figure 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 if 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., 2014b). 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 m/s for at least 6 hours, 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 Section 2.5) averages 21%. At Kotzebue, an average of about 12% of the winds above 10 m/s 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 were from 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 (Figure 2) due to increasingly delayed freeze-up (Figure 3) and earlier break-up (Figure 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 (Figure 5). According to our definitions of these events (see Section 2.4), false freeze-ups and break-ups were non-existent in Kotzebue prior to 2004, after which they have occurred with some regularity (Figure 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 (Figure 5b). False transition events appear to have been more common in Utqiaġvik overall (Figure 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 "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, 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 section 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 section 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 Utqiġvik, 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 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 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 (Figure 4), because they require stable seasonal ice late in the spring for raising pups and moulting (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 (Figure 2). Using the HSIA dataset, we see that this change began abruptly in the late 1990s (Figure

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 (Figures 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 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 travelling 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 (Figures 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 days per decade for Kotzebue, Shishmaref, and Utqiaġvik respectively, but the number of boatable days has increased by 1.2, 3.1, and 10.7 days/decade for each community, also 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 was 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 are 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 autumn storms (Barnhart et al., 2014b; 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 (Figure 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, and 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 set-up events than Shishmaref, but differences in the geographical location of the communites 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 (Figures 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 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 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 NW and SW). 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, available for download at $http : //data.snap.uaf.edu/data/Base/Other/Historical_Sea_Ice_Atlas/$. 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.

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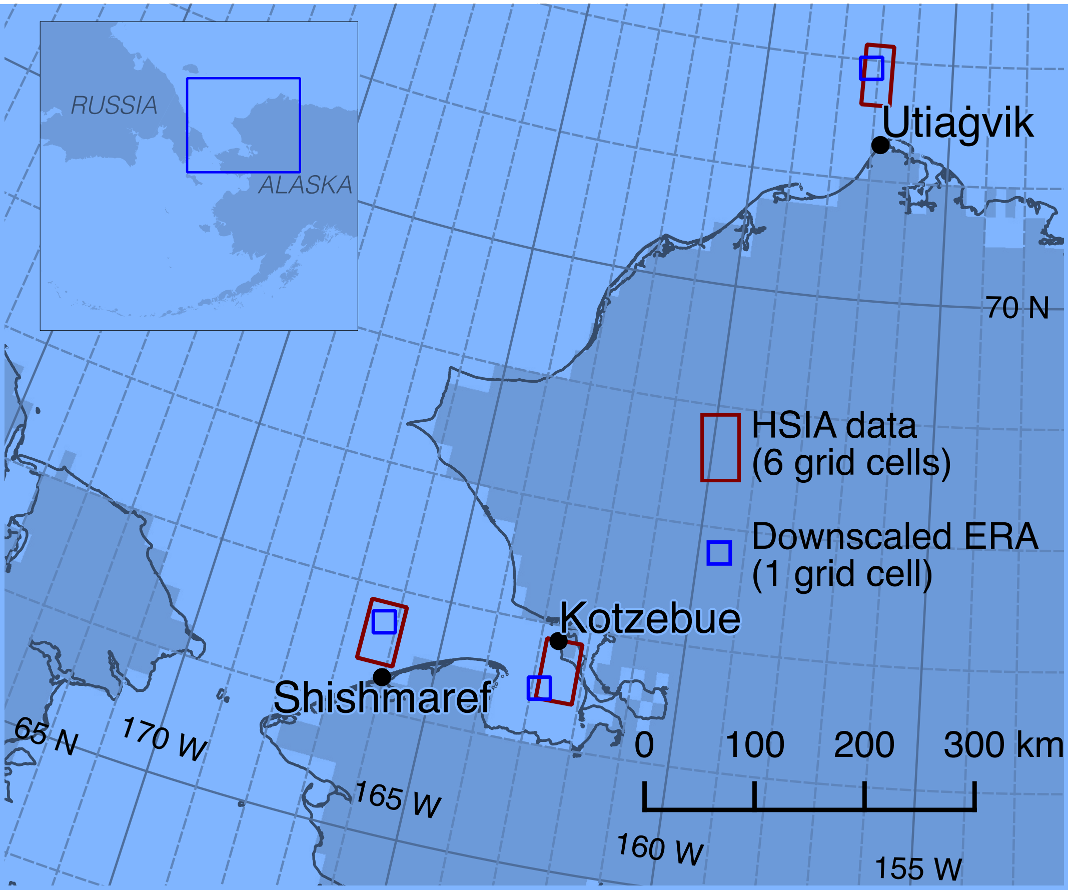


Figure 1. Selected grid cells from the Historical Sea Ice Atlas and WRF-downscaled ERA-Interim datasets used to extract sea ice concentration (also wind speeds from the WRF-downscaled dataset) offshore several communities.

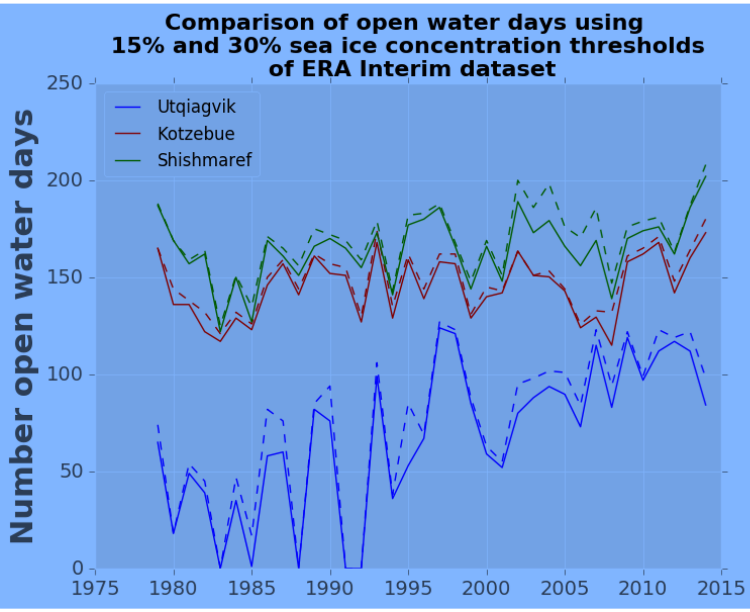


Figure 2. The number of open water days are similar if a 15% (solid line) or 30% (dashed line) sea ice concentration threshold is used. If the sea ice concentration (area of the grid cell) is lower than the threshold value, it is considered open water. Sea ice concentrations for the communities are extracted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

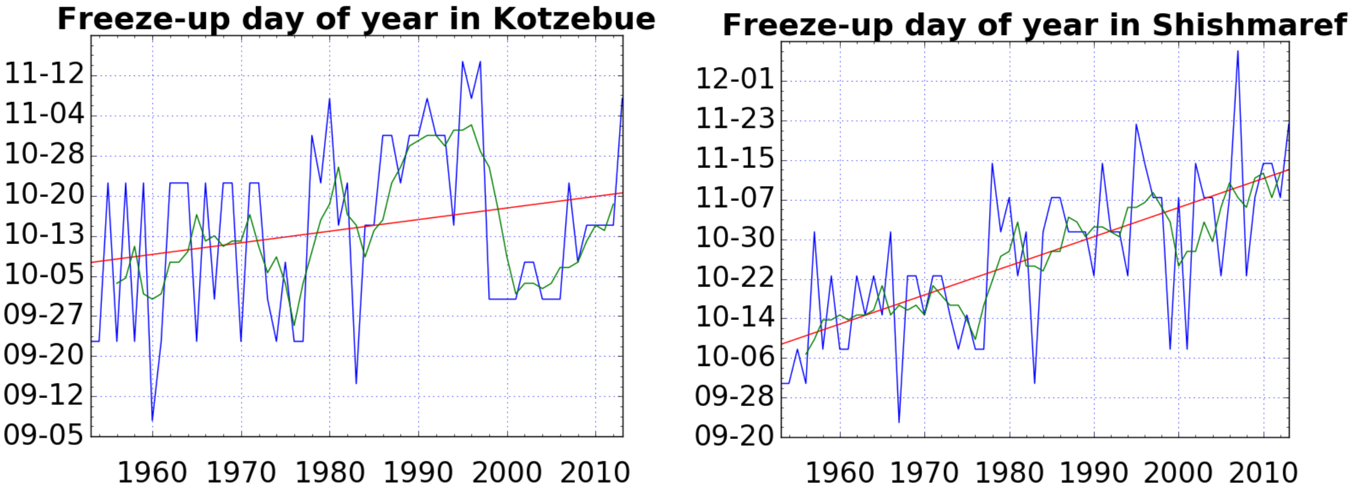


Figure 3. Trends in freeze-up day of year for Kotzebue and Shishmaref. Blue line is yearly freeze-up day, and green line indicates the 5-year running mean. Data from HSIA.

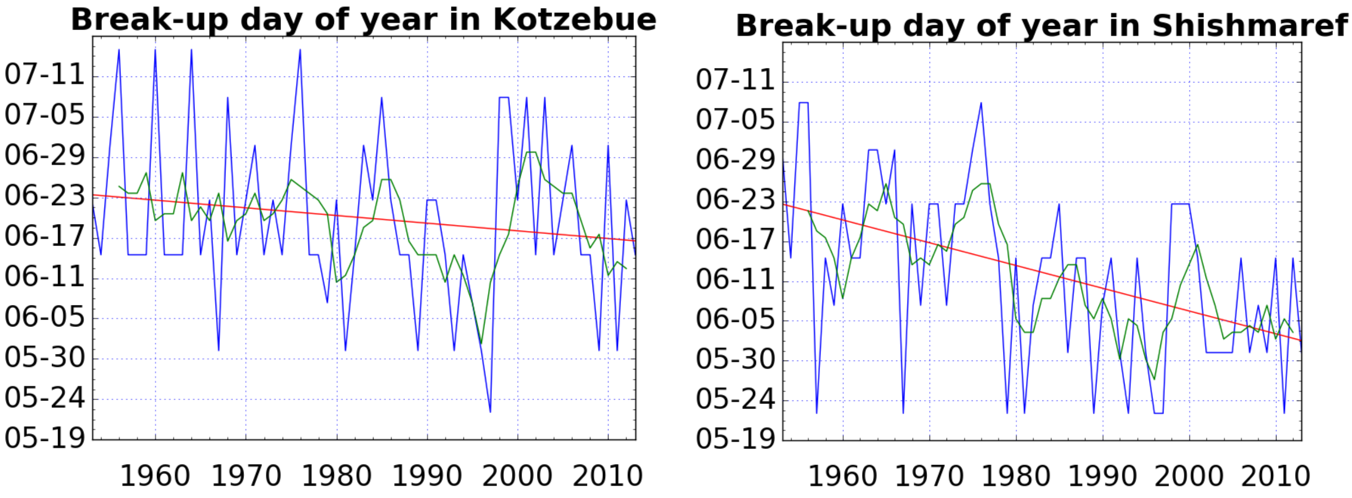
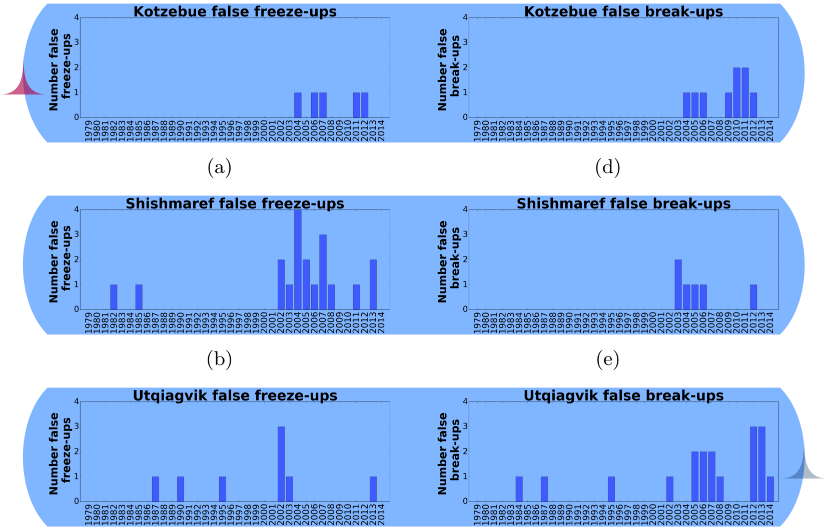


Figure 4. Trends in break-up day of year for Kotzebue and Shishmaref. Blue line is yearly break-up day, and green line indicates the 5-year running mean. Data from HSIA.



(a) (d)

(b) (e)

(c) (f)

Figure 5: 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.

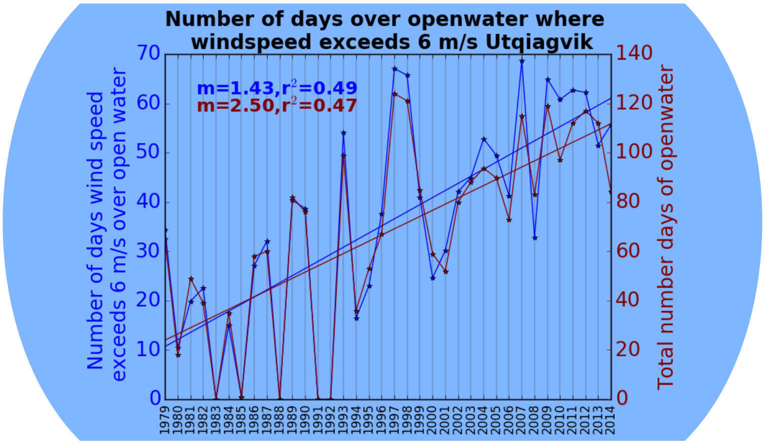


Figure 6. Annual timeseries from 1979-2014 of the number of days deemed too windy for boat travel for subsistence hunting (> 6 m/s, (Ashjian et al, 2010)) and number of open water days (number of days less than 15% sea ice concentration). Data from WRF-downscaled ERA-Interim.

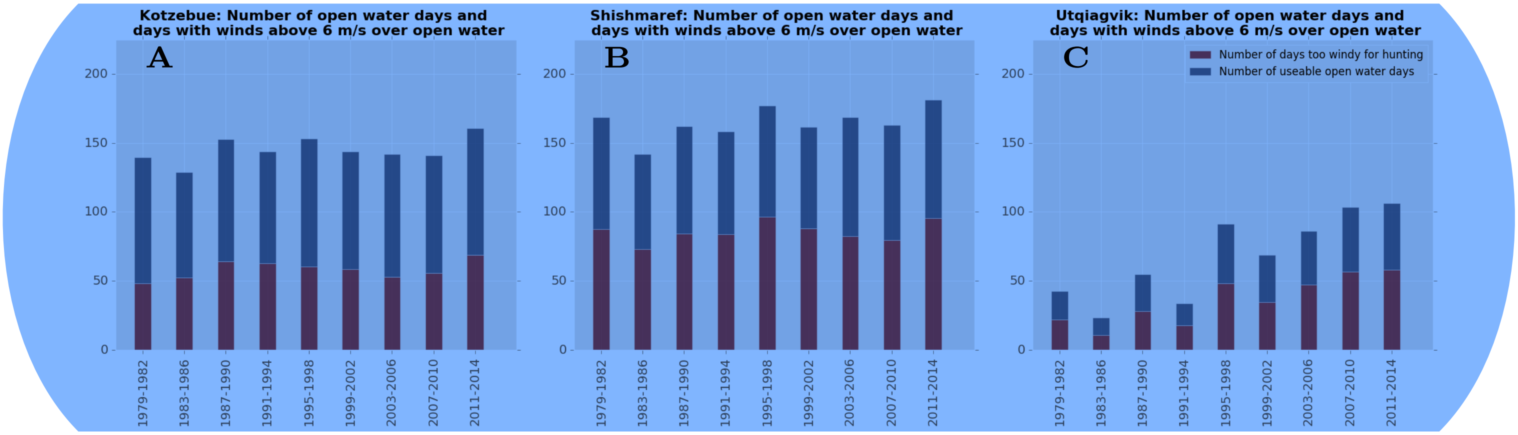


Figure 7. The number of days deemed too windy for boat travel for subsistence hunting (> 6 m/s, (Ashjian et al, 2010)) are increasing along with the increasing number of open water days (number of days less than 15% sea ice concentration). Data taken from the WRF-downscaled ERA-Interim Reanalysis.

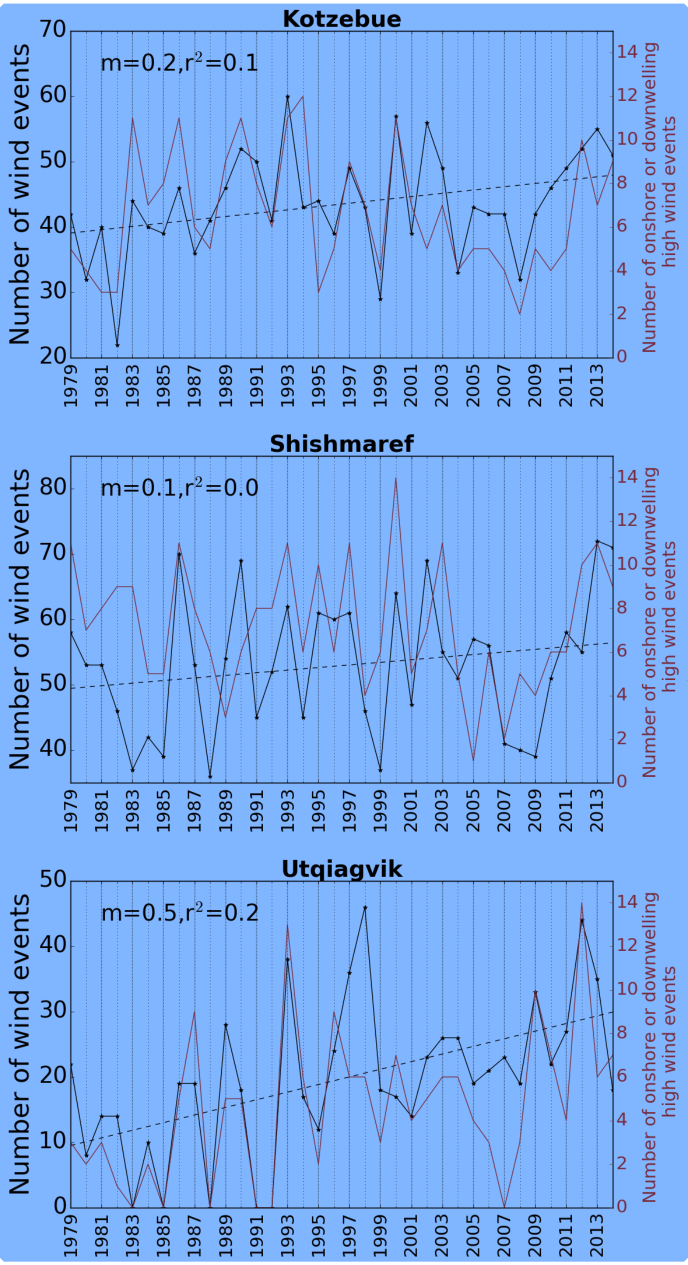


Figure 8. The number of wind events capable to cause significant erosion for Kotzebue, Shishmaref and Utqiaġvik. Wind events were defined as being at least 6 hours or longer of sustained winds exceeding 10 m/s including lulls of over 7 m/s shoulder events, as defined in Atkinson (2005). Also shown is the number of these events which have winds in the 90 degree 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 from WRF-downscaled ERA-Interim, sea ice data from ERA-Interim.

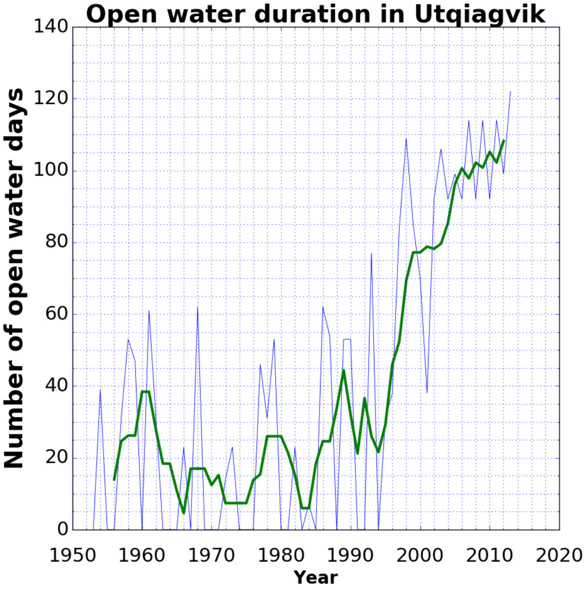


Figure 9. Number of open water days at Utqiaġvik, AK has increased substantially since the dataset began in 1953. There has been a marked shift such that after 1992, Utqiaġvik has seen at least some days of open water. Bold green line shows the 5 year running mean of the number of open water days as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

	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