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Reduced sea-ice protection period increases storm exposure in Kivalina, Alaska

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Abstract

On Arctic coasts, erosion is limited by the presence of nearshore sea ice, which creates a protective barrier from storms. In Kivalina, an Alaskan Inupiaq Inuit community, decreasing seasonal sea-ice extent and a lengthening of the open-water season may be resulting in fall storms that 1) generate higher, longer, and more destructive waves, and 2) cause damage later in the year, resulting in increased flooding and erosion. We assess trends in the duration of nearshore sea ice and their relationship with storm occurrence over the period 1979-2015 in Kivalina. Analysis of passive microwave sea ice concentration data indicates that the open-water season has increased by 5.6 ± 1.2 days/decade over the last 37 years, with moderate evidence that it is extending further into the fall than into the spring. This is correlated with an increased reporting frequency of high-damage storms; 80% of reported storms since 1970 occurred in the last 15 years. Each high-damage storm event occurred during the open-water season for that year. Our findings support Kivalina villagers’ assertions that climate change increases storm exposure and associated damages from flooding and erosion.

Key words: sea ice, storms, coastal erosion, Arctic coastal zone, Alaska
Introduction

On Arctic coasts, erosion is limited by the presence of nearshore sea ice, which creates a protective barrier from storms (Hume and Schalk 1967, Short and Wiseman 1984, Forbes and Taylor 1994, Urdea 2007). Sea ice reduces effective wave fetch by limiting the distance available for wave evolution (Barnhart et al. 2014, Thomson and Rogers 2014). While sea ice can also scour, mobilize, resuspend, and raft sediments (Reimnitz and Barnes 1987), the erosion caused by sea ice is relatively low, and the protective role of sea-ice cover as a barrier to wave action is typically the dominant control on coastal morphology (Forbes and Taylor 1994). Changes in sea-ice extent and duration are important in assessing the physical vulnerability of Arctic coasts (Overduin et al. 2014). Without a substantial concentration of sea ice, a larger spatial extent of open ocean provides longer fetches over which winds can generate higher, longer, and more destructive waves. Additionally, a longer temporal duration of the open-water season, during which ocean and land can interact, can allow for open water during the stormy Arctic fall and therefore increased potential for damage from flooding and erosion (Overeem et al. 2011, Barnhart et al. 2014).

The Arctic climate is warming (Jeffries and Richter-Menge 2013); during the past century, the Arctic has warmed twice as fast as the global average, with multiple lines of evidence supporting very substantial Arctic warming since the mid-20th century (IPCC 2013). Global climate change has led to a significant decline in pan-Arctic sea ice extent and thickness, at a faster rate than predicted (Jeffries et al. 2013). Arctic sea ice extent over the satellite record shows downward trends in all months (Serreze et al. 2007), with acceleration due to external atmospheric forcing (Stroeve et al. 2012). Cavalieri and Parkinson (2012) conclude that, from 1979 to 2010 on average, the rate of decrease in sea ice areal extent was $51.5 \pm 4.1 \times 10^3 \, \text{km}^2 \, \text{per year}$ across the entire Arctic. IPCC (2013) reported that annual sea ice extent decreased over the period 1979-2012, with the rate of decrease being $3.7 \pm 0.4\% \, \text{per decade}$.

Moreover, as the Arctic environment warms, the frequency and intensity of storms is anticipated to increase (Manson and Solomon 2007). Rising temperatures are causing deeper thawing of permafrost along the coast (ACIA 2004). Reduced sea ice allows higher and more frequent storm surges to reach the shore (Thomson et al. 2016) and the thawing permafrost makes the shoreline more vulnerable to erosion (Jones et al. 2009). The thermal energy of the sea water is compounded with the mechanical energy of waves, in a process termed thermo-abrasion (Are 1988). Global climate change leads to higher coastal landscape exposure and vulnerability (ACIA 2004).

Indigenous communities are at risk of damage that Arctic storms inflict upon the nearshore environment (Forbes 2011). The US Government Accountability Office determined that flooding and erosion affect 184 of 213 of Alaska Native villages to some extent (GAO 2009), damaging or destroying infrastructure such as schools and health clinics, and jeopardizing residents’ livelihoods as modes of transport and traditional hunting practices become increasingly untenable.

In Kivalina, an Inupiaq Inuit community on Alaska’s western coast, observers hypothesize that severe autumn storms are now more likely to occur during ice-free conditions due to a lengthening of the open-water season, resulting in higher physical vulnerability. While the relationship between sea ice and wave action has been studied in other parts of the Arctic (Overeem et al. 2011) and has been mentioned in the scientific and popular literature, no quantitative analyses of nearshore ice conditions have been carried out in Kivalina to date. From on-the-ground accounts, storm surge flooding and erosion threaten residents’ well-being and
impact infrastructure that is essential to Kivalina’s viability. Examples of infrastructure include the community’s single water source, its sewage containment area, and the gravel airstrip and summer barge landing, which are the only means of access to the community (City of Kivalina 2007). These consequences have prompted residents to seek relocation, voting to relocate in 1998 and 2000 (Bronen and Chapin 2013).

The goal of this study is to characterize how changing sea-ice temporal patterns have manifested in nearshore conditions along the western Alaskan coast. We assess trends in the duration of nearshore sea ice and their relationship with storm occurrence over the period 1979-2015 in Kivalina. We hypothesize that climate change is reducing the extent and duration of Arctic sea ice, and that shorefast sea ice - solid ice which forms along the coast and remains attached to the shore (WMO 2014) - is forming later in the year than in previous decades, leaving the village without protection from fall sea storm flooding and erosional wave action.

Materials and methods

Study area

Kivalina is located at the tip of a narrow 10-13 km-long barrier island in the Chukchi Sea, 130 km north of the Arctic Circle (67.727° N, -164.533° W; Figure 1). The island is 3-4 m above sea level at its highest point (City of Kivalina 2007, USACE 2007) and up to 0.4 km wide. Two tidal inlets define the island: the Wulik River flows from Kivalina Lagoon to the Chukchi Sea through the Singuak Entrance on the southern end of the island, and Kivalik Inlet is found northwest of the village. The Wulik River and Chukchi Sea shape the geomorphology of the area about the Singuak Entrance, as evidenced by erosion of bars and shoals (USACE 2007). Beach berms have accreted due to ice and storms, and are higher than the tundra further inland. Berms consist of washed sand and gravel with material added by longshore drift and sediment transported by rivers (Moore 1966) and provide the coastal tundra with some protection during storms (USACE 2007).

Kivalina was home to 374 people in the 2010 census, and 576 in the 2015 census (US Census Bureau 2015). Residents live in houses clustered around the southern end of the island. Inupiaq families remain engaged year-round in traditional hunting and gathering of foods.

Data description and processing

Sea ice concentration data were derived from Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR), Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I), and DMSP Special Sensor Microwave Imager/Sounder (SMMIS) passive microwave measurements, provided by the National Snow and Ice Data Center (NSIDC), based on the National Aeronautics and Space Administration team algorithm (Cavalieri 1992). The data have a spatial resolution of 25 x 25 km, with data collected every other day (26 October 1978-20 August 1987 using Nimbus-7 SMMR) or daily (21 August 1987-present using DMSP SSM/I and SSMIS). In a similar analysis, Overeem et al. (2011) validated the accuracy of this low-resolution passive microwave data against more detailed operational ice charts and MODIS remote-sensing imagery. They determined that, for the nearshore zone of the Drew Point coast along the Beaufort Sea, the NSIDC data were adequate for the assessment of long-term trends in break-up and freeze-up days.

We selected six ocean grid cells adjacent to the Kivalina coastline, as defined by the NSIDC land mask, from the data archive, covering a 125 km stretch of coast (Figure 2). Due to limitations from sensor resolution and the algorithm used, some land-to-ocean contamination is

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inherent, which may factor in the accuracy of the final analysis. To process the data, we extracted the fractional sea-ice concentration (SIC) for each cell for every day data were taken over a given year, over the period 1979-2015 for which the satellite record is complete. For each cell, we determined first and last days of open water in a given year, defined as the first and last days for which SIC was less than 15%; <15% SIC is commonly used as a marker of an ice-free area (Cavaliere and Parkinson 2008, 2012; IPCC 2013; Meier and Stroeve 2008). The length of the continuous open-water season can be quantified in a number of ways, as in some cases sea ice retreats rapidly, while in others sea ice may retreat and be blown back in repeatedly. For the purposes of this analysis, the open-water season was calculated as the last day minus first day of open water. We adjusted for the change in sampling rate from every two days (1979-1987) to every day (1987-2015), and for several presumed data errors in 2005 and 2006 (days during the ice-covered season when the SIC was reported as 0%).

Qualitative evaluation of observed storm trends

A faster expansion of the open-water season into the fall may coincide with increased fall storminess, leading to an increased likelihood of damage to Kivalina buildings and infrastructure as rapid erosion along shoreline segments with high ice content and long open-water seasons will only occur if a storm occurs. To assess changes in storm vulnerability over the time period 1970-2015, we conducted a literature review of peer-reviewed papers, government reports, news articles and eyewitness accounts to construct a summary of the incidence and duration of reported storms.

Results

Changes in the open-water season

Inter-annual differences in the pattern and timing of sea ice break-up off the Kivalina shoreline are considerable (Figure 3). However, there is no significant trend in the timing of the first day of the open-water season over the 37-year record ($R^2=0.005$, $p=.31$) (Figure 4). In contrast, the last day of the open-water season has been occurring later at a rate of 4.7 days/decade ($R^2=.19$, $p<.001$). According to the linear regression, on average, the autumn freeze-up has been delayed by more than 2 weeks over the observation period.

Overall, there is a clear positive trend in the length of the open-water season (OWS) over the last 37 years, increasing by 5.6±1.2 days/decade, based on linear regression (Figure 4, Table 1, $R^2=0.087$, $p<.001$). As an illustration, there were 173 days of continuous open-water on average across the six grid cells in 1987, whereas there were 184 in 2015.

Storm trends

The results of the literature review can be found in Table 2, which identifies and describes every documented major storm that occurred in Kivalina from 1970 to 2015. Of the reported storms since 1970, 80% occurred in the 15 years after 2000. Major recorded storms always occurred during the open-water period (Figure 5).

Discussion

The observed nearshore sea ice trends for Kivalina agree with a number of other studies, which report declining Arctic sea ice to varying degrees. In general, the trends we observe are consistent with, but not as pronounced as, other analyses. Cavaliere and Parkinson’s (2012) pan-Arctic study using the NSIDC passive microwave data showed that all months exhibited negative
trends in sea ice extent, with a minimum trend magnitude in May and maximum trend magnitude in September. Barnhart et al. (2014) also conducted a pan-Arctic sea ice analysis using the NSIDC passive microwave data and found that the median length of the 2012 open-water season, compared to 1979, expanded by between 1.5 and 3-fold across Arctic Sea sectors; Hufford and Partain (2005) found that since the 1980s, Arctic seas have remained ice-free 3 weeks longer into the autumn. Overeem et al. (2011) found that the duration of open-water conditions for the period 1979-2009 expanded faster into the autumn than into the spring at Drew Point. Brubaker et al. (2011) determine from anecdotal accounts that since the early 1980s, the time between spring break-up and autumn freeze-up along Arctic shorelines has increased from barely three months to as much as five months. Not all studies found that the open-water season extends more into the fall than the spring. Stammerjohn et al. (2012) found that in the eastern Siberian, Chukchi, and western Beaufort region, the day of spring sea ice retreat was -1.5±0.2 days earlier per year, while the day of fall advance was 1.3±0.2 days later. Overall, remote sensing data indicate that sea-ice extent is declining across the Arctic, including along Alaskan coasts.

Varying results across the range of available evidence may reflect differences in methodology when processing the sea ice data. More importantly, changes in sea ice extent exhibit large spatial variability due to the complexity of Arctic atmosphere and ocean circulation systems (Jeffries et. al 2013). For example, in an analysis of breakup and freeze-up dates for the Chukchi Sea as a whole, Serreze et al. (2016) showed that variations about the trend line are highly correlated with variability in the Bering Strait heat inflow, indicating that this inflow plays a major role in controlling the dates of spring sea ice retreat and autumn ice advance. When seasonal ice retreat occurs early, low-albedo open water areas are exposed earlier, which gain energy from the sun; with more heat in the upper ocean, autumn ice growth is delayed. The scatter about the trend lines in Figure 4, then, may to some extent be attributed to the highly localized spatial extent but broad temporal extent of our study.

The literature review (Table 2) suggests a correlation between increased open-water season and incidence of severe storms. As each high-damage storm event occurred during the open-water season for that year, three interpretations are possible: (1) storminess has increased; (2) the conditions in which damage occurs has changed; or (3) reporting frequency has increased. For the first possibility, we cannot confidently infer changes in storm distribution, because the data in Kivalina are limited to anecdotal accounts. Within the circumpolar sector, Atkinson (2005) found that the Chukchi Sea experienced the highest-strength storms, with storm power (defined as wind speed^2 * duration) reaching a minimum in July and maximum in October; however, observed storminess was characterized by large inter-annual variability, and no long-term trends were detectable in wind records from 1950-2000. Thus, we lack strong evidence that storminess has changed significantly. This shifts emphasis to the second possibility: Kivalina’s physical vulnerability to impacts has increased due to an extended open-water season.

The third interpretation implies a change in risk perception, and increased urgency to leave. This may also be the case, as the correlation between reduced sea ice and more frequent severe storms reported here confirms local anecdotal observations. According to Colleen Swan, a tribal administrator, “In the past the sea would freeze without fail (beginning in October)...protecting it from the vicious fall and winter storms...[now] the seas are sometimes not completely frozen even in the middle of December. Thus, the land has become vulnerable to
the pounding forces of the storm-swept seas. As a result, the people have become fearful...it’s been most devastating since 2004” (quoted in Calvert 2008).

A consequence of a lengthened open-water season is a shorter season for over-ice travel and hunting, an essential aspect of Kivalina residents’ livelihoods. Kivalina is the only community in the Kotzebue Sound region where the bowhead whale is still hunted (City of Kivalina 2007). Kivalina hunters depend on sea ice as a work platform and as a pathway to ocean hunting grounds. In winter, if snow and ice conditions are good, travel is possible in all directions across the frozen land and sea. With thinner and sparser ice, Kivalina hunters cannot travel safely to look for bowhead whales, walruses, and seals. In addition, increased fetch may make travel in small boats more dangerous. Kivalina households report a decline in sea mammal harvest; in 2007, 26% of households did not get enough sea mammals, citing poor ice conditions (Magdanz et al. 2007).

Erosion has always been a concern in Kivalina. The island is subject to severe erosion on three sides: along the ocean side, near the Signauk Entrance at the south tip of the village, and on the lagoon side where the flow from the Waulik and Kivalina Rivers converge. From the first years of occupation by the village, whose settlement was mandated by the US Bureau of Indian Affairs in 1905, concerns have been raised about its location and vulnerability to flooding. In a letter dated June 30, 1911, schoolteacher Clinton Replogle wrote about the risk of flooding and talk among residents about moving the village inland (Brubaker et al. 2011). In the 1990s, residents realized that the safety and sustainability of the community were at stake, and responded by reinforcing the lagoon shore with sandbags. Erosion has been occurring steadily for over two decades, with signs of acceleration in recent years (City of Kivalina 2007). According to Swan, in 1953 the size of the village was roughly 22 ha (54 acres), but due to accelerating erosion activity, the area had declined to 11 ha (27 acres) in 2007 (Calvert 2008).

In addition to humanitarian consequences, this erosion comes with economic costs; traditional methods of erosion control and flood protection have proven insufficient in protecting the community. Erosion control efforts by the state from 1985 to 2002 totaled $477,000, while from 2005 to 2006 emergency efforts cost about $850,000 (USACE 2006); the money was used to construct temporary erosion protection devices. In 2006, federal government leaders arrived in Kivalina to celebrate the completion of a multimillion-dollar, 550 m long seawall; however, before the beginning of the celebration, a storm damaged 50 m of the wall and forced officials to cancel the celebration (Bronen and Chapin 2003). In 2009-10, the US Army Corps of Engineers (USACE) installed a rock revetment that reduced the village area, but bought the village time to make a relocation decision; its anticipated lifespan is 10-15 years (USACE 2007).

In the press, reporters have dubbed the residents of Kivalina, along with those Newtok and Shishmaref, as “America’s first climate change refugees” (Wernick 2015). Kivalina received attention for filing a lawsuit against 20 fossil fuel companies, claiming monetary damages under public-nuisance law (Barringer 2008). However, the suit was dismissed in September 2009, when the US district court ruled that greenhouse-gas emissions were a political, rather than legal, issue.

While historically, native communities could easily move away from eroded areas, their reliance on built infrastructure now ties them to the land. The USACE estimated in 2006 that Kivalina has 10-15 years to relocate, after which they predict a complete disappearance of usable land (USACE 2006). Residents have advocated for relocation on numerous occasions (Bronen 2013). However, these efforts have stalled, due to lack of institutional framework and perceived high costs. According to the Government Accountability Office (2009), no government agency
has the authority to relocate communities, and no funding exists specifically for relocation. The cost of future erosion protection is $15 million (USACE 2006), while the cost to relocate is $95-125 million. Without clear guidelines for choosing a relocation site, Kivalina voted in 2000 to relocate to Kiniktuuraq, a site on the beach about 1.5 km south of Kivalina. The USACE, however, later determined that the site was unsuitable due to the existence of permafrost, which would not have been able to support buildings if warming trends continued.

Ultimately, as the open-water season continues to increase, community relocation may be the only long-term adaptation strategy that can protect Kivalina from the effects of flooding and erosion.

**Conclusions**

We conclude the following based on an analysis of sea ice change and on published reports concerning storm erosion at Kivalina, Alaska.

- The open-water season (OWS) has increased by \(0.56\pm0.12\) days/year over the last 37 years.
- The OWS now extends two weeks later into fall than it did four decades ago.
- The longer open-water season has resulted in increased exposure to erosion and flooding, with an increased frequency of high-damage storms.
- Erosion has been a concern in Kivalina since its founding in the early 20th century.

**Relocation may be the only viable long-term adaptation solution.**

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### Tables
Table 1. Slopes of the linear regressions for the first and last days of open water, and for the length of the continuous open-water season, over the measurement period 1979-2015. There are two options given below for calculating the open water season: (1) computing, for each grid cell, the first day when sea-ice concentration (SIC) went below 15%; or (2) computing the first day within the year when the average SIC across all six grid cells went below 15%. In the figures and text we depict the first option as more data were preserved when considering each grid cell individually, with $R^2=.005$ (p=.31) for the change in the first day, $R^2=.185$ (p<.001) for the change in the last day, and $R^2=.087$ (p<.001) for the change in the overall length of the open-water season.

| Input                                      | Change in first day (days/decade) | Change in last day (days/decade) | Change in continuous open-water season (days/decade) |
|--------------------------------------------|-----------------------------------|---------------------------------|-----------------------------------------------|
| SIC of each grid cell on each day (Fig 3)  | -0.9                              | 4.7                             | 5.6                                           |
| Average SIC on each day                    | -1.5                              | 5.5                             | 7.0                                           |
Table 2. Summary of reported storms documented in Kivalina, 1970-2015.

| Date           | Description                                                                                                                                                                                                 |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1970           | A 13.57’ “storm of record” inundated portions of the community (Hayes 2006).                                                                                                                                   |
| Sept 1976      | Storm surge resulted in water inundating 20-30% of the town, likely due to wave runup (Brubaker et al. 2011).                                                                                                |
| Oct 8, 2002    | Reported to have been caused by a low-pressure system moving down from the Arctic Ocean, and settling over the Chukchi Sea and Kotzebue Sound, storm resulted in extremely high winds, strong tidal action, and seas of either 14’ (Glenn Gray and Associates 2010b) or 18-20’ (City of Kivalina 2007) at high tide in Kivalina and Shishmaref. It caused severe damage and coastal flooding, including damage to public roads and other public property. The Governor declared a disaster area for the cities of Kivalina and Kotzebue in the Northwest Arctic Borough. |
| Oct 18-20, 2004| Between Oct 18 and Oct 20, 2004, a severe winter storm with strong winds and extreme tidal surges occurred along the western Alaskan coastline. 40-knot southeasterly winds, gusting to nearly 60 knots, produced a 4’ storm surge, as measured at the Red Dog Mine dock (City of Kivalina). The storm resulted in flooding of the lower portions of town, which was recorded at the port site as 5.05’ above mean lower low water, likely from wave setup of 1’ and run-up of 6.5’ (Glenn Gray and Associates 2010b). It caused a loss of 40’ of shoreline and damage to some structures along the beach. The teacher housing building was relocated due to storm surge erosion that turned the formerly slow-sloping beach to a drop-off (City of Kivalina 2007, Glenn Gray and Associates 2010b). Storm surge also damaged the sewage drain field at the washeteria, closing the washeteria for 5 consecutive months in 2005 and continuing to contribute to declining days of washeteria operation over the next several years (Brubaker et al. 2011). The 2004 Bering Strait Storm was declared on Oct 28 by Governor Frank Murkowski; a Major Disaster Declaration was made on Nov 15 by FEMA (DR-1571), which extended the incident to Oct 24. |
| Sept 22-26, 2005| This storm was estimated to have a storm surge height of 8.5’ above mean sea level; the average elevation of the village is 9-10’ above mean sea level. It eroded 25-30’ of beach (Glenn Gray and Associates 2010b). |
| Oct 2005       | This storm resulted in 70’ of erosion near the school and erosion of the beach to within 12’ of the airport. Residents placed 55-gallon drums and sandbags in front of the principal’s house and used scrap metal to protect the airstrip, including metal from fuel storage tanks and the fuselage of an abandoned cargo plane |
Governor Murkowski declared the 2005 West Coast Storm on Oct 24, and FEMA issued a disaster declaration (DR-1618) on Dec 9.

| Date   | Event Description                                                                                                                                                                                                 |
|--------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oct 12, 2006 | Federal government leaders had arrived in Kivalina to celebrate the completion of a multimillion-dollar, 1800’ seawall composed of one-meter square metal baskets (gabions) filled with sand and rock. However, before the beginning of the celebration, a storm with winds exceeding 40 mph damaged 160’ of the wall and forced the officials to cancel the celebration (Bronen and Chapin 2013). The storm eroded 50’ inland, exposing permafrost in some areas. |
| Sept 12, 2007 | A severe storm with waves up to 8’ forced 221 residents to evacuate the village in search of safety (Gorokhovich and Leiserowizi 2012). Village leaders told the US Government Accountability Office that the evacuation was so dangerous that they would never again attempt an evacuation (Bronen and Chapin 2003). Following this storm, the US Army Corps of Engineers approved the construction of a large rock revetment project, rising 13’ above sea level, with a design life of 15-20 years. It was built in 2009-10. |
| Nov 8, 2011 | A hurricane-strength storm occurred, causing 135 people to evacuate to the village school. However, the rock revetment succeeded in keeping out flood waters, so no flooding occurred, and no water damage was sustained. |
| Sept 24, 2015 | A surging storm moved the shoreline 10 feet closer to the Kivalina airport, eroding the shore in a scalloped pattern (Restino 2015). |
Figure captions

Fig 1. Map of Kivalina’s location (67.727°N, -164.533°W). Kivalina is located on a narrow 10-13 km-long barrier island in the Chukchi Sea, 130 km north of the Arctic Circle; the nearest major city is Kotzebue.

Fig 2. Grid cells used in analysis of sea ice off the coast of Kivalina. NSIDC sea ice concentration data on October 26, 1978, rendered in Quantum GIS version 2.14.2-Essen. The figure directly represents the NSIDC data product, which has been packed into one-byte integers representing sea ice concentration values. A black pixel indicates zero sea ice, grey represents some fractional sea ice concentration, and a white pixel represents the superimposed land and coastline mask. A numerical grid system was used to obtain coordinates; grid cells are outlined and labelled by coordinate in inset. These cells cover a 125-km stretch of coast.

Fig 3. Aerial images demonstrating changes in the extent and pattern of sea-ice cover between two consecutive years. The top image is from 07/06/2006, and the bottom image is from 10/06/2007. The figure is intended to illustrate the manner in which ice floes melt and recede from the shoreline, not to assert long-term trends in the shoreline. (Images courtesy of Google Earth / DigitalGlobe).

Fig 4. (a) Changes in the length of the continuous open-water season (OWS) off of Kivalina. The length of the OWS was defined for each grid cell (n=6) as the time difference between the first and last days of open water (SIC < 15%). Each marker shape represents a different grid cell. The linear equation was calculated using OWS length for each grid cell for each year, over the measurement period 1979-2016 (37 years). Table 1 shows the results of the linear regression.

(b) Changes in the first and last days of open water. The first and last days (lower and upper lines, respectively) were defined as the first and last days for which that grid cell's SIC was below 15%. The results for all of the grid cells are plotted, with each marker shape representing a different grid cell, over the measurement period 1979-2015. Table 1 shows the results of the linear regression.

Fig 5. Time series of sea ice concentration across the six grid cells for the year 2002, with a vertical bar representing the timing and duration of the major storm event that year, based on anecdotal reporting. All major recorded storms in Kivalina occurred during the open-water period.
**Figures**

Fig 1.
Fig 3.
Fig 4.

(a) Change in the number of continuous open-water days over the years.

(b) Change in the last day of OWS over the years.
Fig 5.