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Corresponding author:
Nathan P. Kettle; Email: nkettle@alaska.edu

Sea ice and socio-economic impacts from extreme events in Nome, Alaska

Nathan P. Kettle[1], Zav Grabinski[1], Richard L. Thoman[1], John E. Walsh[1] and Ryan Owens[2]

[1]University of Alaska Fairbanks, International Arctic Research Center, Fairbanks, Alaska and [2]University of Alaska Fairbanks, College of Natural Science and Mathematics, Fairbanks, Alaska

Abstract

Changing sea-ice conditions have significant societal impacts and implications across Alaska and the Arctic. This research examined the relationship between sea ice and extreme weather events with socio-economic impacts in Nome, Alaska (1990–2020), a community that has experienced notable changes in sea ice and impacts from extreme weather events. The research is based on the analysis of sea-ice concentrations from passive microwave data, socio-economic impacts of extreme weather events from an archival analysis of newspaper coverage, and an examination of the relationship between sea-ice concentrations and impacts. We found that sea-ice concentrations at the time of the reported socio-economic impacts were all characterised by ice-free conditions. Additionally, extreme events linked to socio-economic impacts occurred when sea-ice concentrations were at or below their historical (1979–2000) median for the day. Key implications for the observed increased probability of ice-free conditions in the autumn include a greater likelihood that a given coastal storm from November to mid-December may contribute to socio-economic impacts, which may have been mitigated by sea ice in the past, as well as an increased potential for impacts to occur when they have previously not been experienced.

Introduction

Arctic coastal communities are at risk to a multitude of climate-related environmental hazards, including coastal storms, flooding, erosion, high-speed wind events, and permafrost thaw (Walsh et al., 2020).These hazards contribute to significant socio-economic impacts to public health, food and water security, infrastructure, local economies, and cultural sites (Ford et al., 2021; Huntington et al., 2023).

Sea ice serves a key role in regulating ecosystem functions, provisioning food resources and cultural benefits, and supporting food webs and biodiversity across the Arctic (Eicken et al., 2009). For example, sea ice moderates wave action and swell size, mitigates storm activity, and protects coastlines from erosion (Barnhart et al., 2014; Farquharson et al., 2018; Joyce et al., 2019; Nederhoff et al., 2022; Overeem et al., 2011). However, rapid changes in Arctic sea ice have been detected over the last few decades, as observed by Indigenous Peoples, meteorological agencies, and earth-orbiting satellites (Meier & Markus, 2015; Sandven et al., 2023; Slats et al., 2019). The decline in Arctic sea ice extent since the late 20th century is viewed as one of the most iconic and widely reported manifestations of environmental change (Fox-Kemper et al., 2021). Other observed changes include longer sea-ice-free seasons, with delayed freeze-up and earlier break-up), thinning sea ice and the loss of old ice (greater than 4 years), and changing seasonality of sea ice (Rolph et al., 2018; Thoman et al., 2023; WMO, 2023).

Changes in sea ice affect global ocean and atmospheric processes through multiple feedbacks involving physical, ecological, and human systems (McGuire et al., 2006). The loss of Arctic sea ice amplifies global warming by enabling more solar energy to be absorbed into the ocean (Riihelä et al., 2013). It is also related to enhanced winter storms over the Arctic Ocean (Valkonen et al., 2021) and possibly more frequent extreme weather events in the Northern Hemisphere that are linked to a waiver jet stream (Francis & Vavrus, 2015). Declines in sea ice are also associated with increased wave height, larger swell size, and longer fetch distances for winds to propagate waves, resulting in greater energy transfer in the ocean (Overeem et al., 2011; Vermaire et al., 2013). Other research highlights the positive link between sea ice decline and increased erosion (Barnhart et al., 2014; Farquharson et al., 2018; Nielsen et al., 2022).

Changing sea-ice conditions have further implications for socio-economic impacts across the Arctic (Hausner & Trainor, 2021; Huntington et al., 2022). Longer ice-free conditions and thinner sea ice have consequences for subsistence cycles, marine mammal and caribou hunting, and cultural practices (Druckenmiller et al., 2013; Erickson & Mustonen, 2022; Hauser et al., 2021; Huntington et al., 2016; Slats et al., 2019; Thoman et al., 2020). These impacts are driven in part from ecosystem-level impacts, including marine mammal die-offs and animals occurring outside of previous ranges (Duffy-Anderson et al., 2019). Other impacts linked to sea ice loss include increased shipping and maritime travel, including a longer operating season (Bennett et al., 2020; Huntington et al., 2015), accelerated coastal erosion and relocation (Bronen, 2015), damages to public and private infrastructure (Kettle et al., 2020), economic losses (Euskirchen et al., 2013), and implications for mental health and place attachment (Durkalec et al., 2015). As such, sea-ice conditions are a key element in assessing the physical vulnerability of Arctic coastlines.

The degree of impacts experienced within a community arises from a diverse array of cross-level interactions that affect vulnerability. Within coupled human-environmental systems, vulnerability is generally conceptualised as the interaction among sensitivity, exposure, and adaptive capacity (Turner et al., 2003). This includes a combination of climate and non-climate stressors that shape differential vulnerabilities. Climate impacts are experienced acutely by the 229 federally recognised Alaska Natives Tribes due to historical and ongoing legacies of colonisation and social injustice, their close connections to the land, animals, and waters, and limited resources to address climate hazards (GAO, 2009; Reibold, 2023).

Assessments of the linkages between extreme events and socio-economic impact offer the potential to support climate adaptation planning decisions (Clarke et al., 2021). Indeed, some research has examined the relationship between extreme temperature and precipitation and crop yield (Beillouin et al., 2020), extreme heat and mortality (Khatana et al., 2022), extreme temperature and health (Weilnhammer et al., 2021), and climate scale meteorology to human impacts (Overland et al., 2024). However, few studies have assessed the relationship between community impacts associated with extreme weather events and sea-ice concentrations, though the relationship is often asserted at regional scales. In the context of sea ice, some studies have discussed the multitude of social and ecological impacts associated with extremely low sea ice for individual years (Thoman et al., 2020). Other research has documented the linkages between low sea ice and significant erosion events in communities (Fang et al., 2018). A key challenge for these scientific assessments is limited documentation of community impacts across the Arctic.

This research assesses the relationship between sea ice and extreme weather events with socio-economic impacts. For this analysis, we investigate sea-ice concentrations during autumn coastal storms with socio-economic impacts, the historical sea-ice concentrations for each date when impacts were detected, and changes in the probability ice-free conditions. The research is based in Nome, Alaska, a community that has experienced notable changes in sea ice and impacts from extreme weather and climate events (Birchall & Bonnett, 2020; Kettle et al., 2020).

Nome, Alaska

Nome is located in northwest Alaska along the northern coast of Norton Sound (Fig. 1). Approximately 3,600 residents live in Nome, which serves as an economic hub for 16 surrounding communities (US Census Bureau, 2020). Alaska Natives are the largest ethnic group living in Nome, including Central Yupik, Inupiaq, and St. Lawrence Island Yupik, who rely heavily on local and wild food resources for cultural practices and food security (Braem et al., 2017; Gadamus, 2013; Metcalf & Robards, 2008). There are ongoing planning discussions to expand and upgrade the Port of Nome in order to attract revenue, support national security, and develop natural resources, though there are community and tribal concerns regarding public safety, lack of tribal engagement, long-term fiscal responsibilities, and protection of marine mammals.

Extreme weather events in Nome are often related to cold temperatures, sea storms, snow and snowstorms, and high-speed wind events (Kettle et al., 2020). Documented socio-economic impacts from these extreme events include transportation, community activities (e.g. subsistence, public and municipal closures, mining), utilities, and damaged buildings (Kettle et al., 2020). A sea wall constructed in the 1950s protects some of the community from storm surge and coastal erosion, though several of the nearby coastal lands of the Nome-based tribes are unprotected. Sea ice near Nome is dynamic as winds and currents constantly keep ice in motion. A strip of fast ice typically extends from the beach seaward to 0.5 to 3 km in most seasons. The timing of the formation of fast ice varies from year to year, with occasional false freeze-ups where the sea ice concentrations rise above a freeze-up threshold before the final freeze-up of the calendar year (Rolph et al., 2018). The arrival of ice in the autumn and ice loss in the spring are important events in the annual cycle for the regional ecosystem, societal activities, and modulation of risk to coastal flooding and erosion.

The Nome region has experienced notable climate shifts in the last several decades, as observed by Elders and climate science, including changes in the timing and quality of sea ice and changes in wind (Kettle et al., 2017). For example, community members have observed a shortening sea ice season, bigger storm surges, and the importance of ice in protecting the coast (Birchall & Bonnett, 2020). Other assessments highlight delayed freeze-up and break-up events as well as thinning of sea ice (Rolph et al., 2018; Walsh et al., 2017). Changes in sea ice across the Bering Strait have adversely impacted travel and traditional hunting and fishing activities (Erickson & Mustonen, 2022; Slats et al., 2019). Other projected changes in Nome include fewer days below −30°F, an increase in high-speed wind events (Redilla et al., 2019), and more winter days where temperatures are above freezing (Kettle et al., 2020).

Data and methods

Our assessment of the relationship between sea ice concentrations and socio-economic impacts from extreme weather events in Nome, Alaska, involved three major steps: assessing historical sea-ice concentrations, identifying extreme event impacts, and examining the relationship between sea-ice concentrations and impacts. The data and methods associated with these three steps are discussed below. The analysis focused on assessing the relationship in the autumn between October 1 and December 31. Although Nome experiences sea-ice-related impacts in the spring, such as gold mining operations, crabbing, and rerouting dogsled racing routes (Kettle et al., 2020), these impacts are often related to sea-ice concentrations near the coastline, which are not reliably detectable in the multi-decade satellite record due to the underlying spatial resolution and land contamination of microwave readings of sea ice (Gentemann et al., 2010).

Assessment of sea-ice concentrations

Gridded daily sea ice concentrations (1979–2022) were derived from Nimbus-7 Scanning Multichannel Microwave Radiometer and Defense Meteorological Satellite Program Special Sensor Microwave/Imager Sounder passive microwave data, Version 2, provided by the National Snow and Ice Data Center (DiGirolamo et al., 2022). The construction of these data are based on the NASA

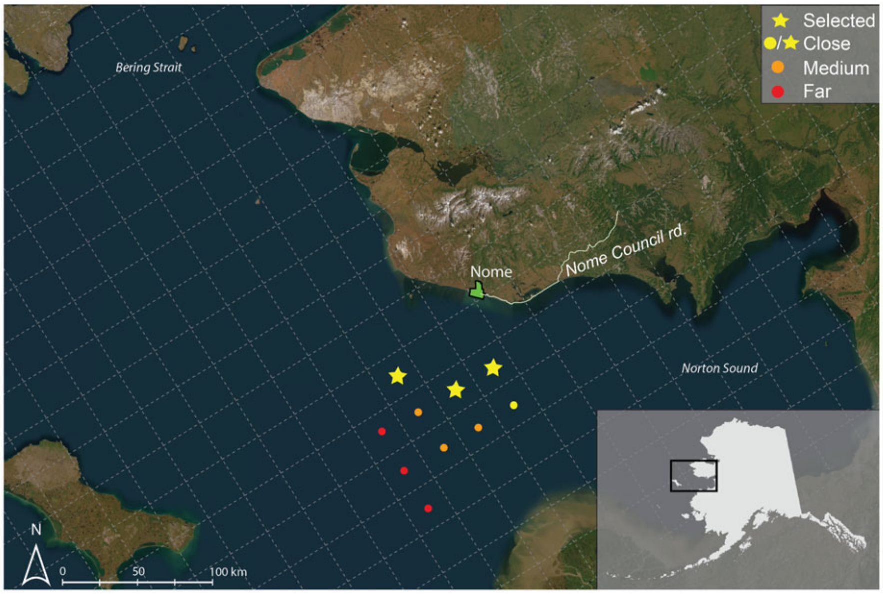

Figure 1. Grid cells used for sea ice analysis. Green triangle denotes location of Nome; Nome-Council Road is shown by thin line extending eastward from Nome.

Team algorithm to process microwave brightness temperatures into daily sea-ice concentrations (DiGirolamo et al., 2022). Although finer spatial resolution data are available than passive microwave (25 km × 25 km), such as the Advanced Microwave Scanning Radiometer (Lavergne et al., 2019), these data have shorter temporal data coverage that limits trend analysis over longer periods of time. Additionally, multi-frequency passive microwave instrumentation provides near-continuous daily observations, irrespective of daylight or cloud cover (Parkinson, 2022). Other datasets, such as the Historical Sea Ice Atlas provide sea-ice data back to the 1850s, though these data only provide monthly averages (Walsh et al., 2017). Validations of the accuracy of passive microwave data suggest they are sufficient for detecting long-term trends in freeze- and break-up in the Arctic (Overeem et al., 2011). Data on sea ice thickness were not included in the analysis as these data are only available from satellites since about 2011 (Ricker et al., 2017).

The median value of three 25 km × 25 km grid cells was used to represent the sea-ice concentration in Nome, Alaska (Fig. 1). A sensitivity analysis was conducted for different sets of grid cells at varying distances from the coastline on Nome, including 15 km (close), 50 km (medium), and 75 km (far). July and August were excluded from the sensitivity analysis because there was no sea ice present. This approach reveals how grid cell selection affected sea-ice concentration and the duration of the sea-ice season (Walsh et al., 2022). Grid cells located within 25 km of coast were excluded due to issues associated with land contamination of microwave readings of sea ice (Gentemann et al., 2010). The sensitivity analysis revealed no significant biases in sea-ice concentration values across "near," "medium," and "far" pixels (Fig. 1). Comparisons of the 'close' and 'medium' distance pixels revealed a 10% absolute-value difference in median sea-ice concentration, with the length of sea ice season being on average 10 days longer for medium-distance pixels. Comparisons of the 'close' to the 'far' pixels unveiled a 12% absolute-value difference in median sea-ice concentration, with the length of sea ice season being on average 16 days longer for far-distance pixels. To further explore the sensitivity within the 'near' pixel set, a comparative analysis was conducted between an eastern and a western pixel. This internal examination revealed a 22% absolute-value difference in median sea ice concentration with the length of sea ice season being on average one day longer for the eastern pixel. This is expected in the autumn as sea ice first forms in eastern Norton Sound due to the constrained geography of the Sound, where the water is shallower and fresher than farther west (Zhao et al., 2022).

Sea-ice concentrations were available for every other day from October 1978 to August 1987 and everyday thereafter. Linear interpolation was used to calculate sea-ice concentration for the missing days in the data set. The sea-ice season was defined as the period when sea-ice concentrations were continuously greater than 15% (Cavalieri et al., 1991). A five-day centred rolling average was applied to help remove anomalies affecting sea-ice season length as sea ice in the Nome region can form, thaw, or get windswept within a short period of time (Walsh et al., 2022). Concentrations less than 15% were considered sea-ice-free, as this value is within the uncertainty boundary of coastal sea ice in the passive microwave dataset and provides agreement between satellite and aircraft observations (Cavalieri et al., 1991). Ordinary least squares regression was used to assess changes in the sea-ice season, break-up, and freeze-up.

Identification of extreme event impacts

Extreme events linked to socio-economic impacts and sea ice in Nome, Alaska, were identified by reviewing articles from the Nome Nugget Newspaper and NOAA StormData (1990–2020). The analysis of archived newspaper coverage is especially well suited for some regions of the Arctic, as this approach can provide sustained observations of locally relevant concerns and impacts. Potentially relevant articles in the Nome Nugget were identified by reviewing microfiche (1990–2009) and online archives (2010–2020). The titles of these articles were reviewed based on keywords identified in local planning documents and peer-reviewed literature, including terms related to adaptation, weather and climate, hazards, infrastructure, subsistence, and transportation (City of Nome, 2012; City of Nome, 2017; Kettle et al., 2017). The review of

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NOAA Storm Data entries included both paper publications (1990–1995) and an online database because prior to 1996 the online database only included convective events (NOAA, 2019). Two criteria were then used for inclusion in the database. First, extreme events must be related to coastal storms and sea ice, such as autumn coastal storms, on calendar dates when there has been a precedent for sea ice since the 1980s. Second, socio-economic impacts from autumn coastal storms must be identified and discussed. Identified extreme event impacts were coded based on the day of the event, rather than when the article was published. A discussion of the document identification procedures is detailed in Kettle et al. (2020).

Examining the relationship between socio-economic impacts and sea ice

Three methods were used to examine the relationship between sea-ice concentrations and extreme events with socio-economic impacts in Nome, Alaska. First, we assessed sea-ice concentrations for the day that socio-economic impacts from the extreme events were documented. Second, we compared sea-ice concentrations during the impact event to the historical average for that day (1979–2000). Third, we assessed changes to the probability that a given coastal autumn storm will land during ice-free conditions. Changes in the probability of ice-free conditions were assessed based on findings from a Wilcoxon rank sum test, which compared sea-ice concentrations between the historical (1979–2000) and current (2001–2022) time periods. The 15% sea-ice concentration threshold was used in this analysis as all events associated with socio-economic impacts were linked to ice-free conditions.

Findings

The duration of the sea-ice season in Nome, as observed from the satellite record, has declined significantly ($p \leq 0.01$) from 1979 to 2021, with an overall decline of 30.5 days (Fig. 2). The beginning of the sea-ice season is significantly ($p \leq 0.001$) later in the autumn, now arriving nearly 15 days later. Likewise, the end of the sea-ice season in the spring (break-up) begins roughly 16 earlier, though the change was not significant ($p \leq 0.05$). There was greater variability to the change in the end of the sea-ice season in the spring relative to the start of the sea-ice season, as indicated by the standard error of the ordinary linear regression (0.233 and 0.112, respectively). The length of the sea-ice season in Nome exhibited interannual variability between 1979 and 2021. For example, during the 2018–2019 season, sea ice formed unusually late in the northern Bering, with ice in Nome not appearing until early December. This was followed by only about a month of seasonably cold weather before the onset of prolonged storminess from mid-January into early March, resulting in the near complete loss of sea ice in the northern Bering Sea in early March and the unprecedented spectacle of ice-free conditions at Nome as Iditarod mushers crossed the finish line. In contrast, in the 1984–1985 winter, sea ice arrival in mid-November was more typical for the 1980s, but one of the coldest springs in the 20th century resulted in exceptionally late ice loss.

The greatest half-month change in sea-ice concentrations occurred primarily from early November to mid-December and early April to mid-May (Fig. 3). Sea-ice concentrations did not change significantly mid-December to early April. Analysis of daily sea ice concentrations (1979–2022) revealed additional insights into the nature and timing of change (Fig. 4). In the autumn, the interquartile range of sea-ice concentrations for the current period (2001–2022) is comparable to the historical period (1979–2000), with a lag of about 7–10 days from mid-November through early December. The outlier years with especially high ice (early November) or low ice (later December) are only weakly segregated by historical or current periods. However, the nature of sea ice change in the spring is different. Although there is little overall difference in the daily medians of sea ice concentrations between the current and historical periods in the spring, there was higher variability in the historical period, as indicated by the width of the interquartile range. Additionally, there is a collapse of variability in sea-ice concentrations between the historical and current periods, as indicated by the complete segregation of outlier years with high ice in late May and early June (Fig. 4b). While the median sea-ice concentrations were close to zero after May 24th in the historical period, there were several years of significant ice persisting into early June. In the 2001–2022 period, the outliers are not as extreme and do not persist as long as the high ice springs in the later 20th century.

Eight extreme events with socio-economic impacts linked to autumn storms and sea ice were identified in Nome between 1990 and 2020 (Table 1). All of the events occurred in October ($n = 3$) and November ($n = 5$). Impacts from extreme events are occurring later in the autumn throughout the dataset. For example, within the first half of the archival analysis (1990–2005), impacts primarily occurred during the first three weeks of October. In contrast, impacts occurred throughout the first three weeks of November in the second half (2006–2020) of the archival analysis. Documented impacts from these storms primarily centred on damage to the Nome-Council Road ($n = 6$), water and power utilities ($n = 5$), Port of Nome and City dock ($n = 4$), and public and private buildings ($n = 3$). Three of the storms were associated with Federal Emergency Management Agency disaster declarations.

Sea-ice concentrations at the time of the reported socio-economic impacts were all characterised by ice-free conditions. All eight extreme events linked to socio-economic impacts occurred when sea-ice concentrations were at or below their historical (1979–2000) median for the day. Seven of the eight days with impacts occurred when sea-ice concentrations were equal to the historical median. The 23 November 2015 extreme event, which contributed to debris covering Nome Port causeway, had sea-ice concentrations that were 39% lower than the historical median.

There was an increase in the probability of ice-free conditions in the late autumn between 1979–2000 and 2001–2022 (Fig. 5). Between 31 October and 14 December, all but six days had a significantly ($p \leq 0.05$) higher probability of being sea-ice-free. The two largest single-day increases in the probability of ice-free conditions occurred on 23 and 27 November (39% and 38% more likely, respectively). The largest window of change in the probability of ice-free conditions occurred in the second half of November, where there was at least a 19% increase (except 18–19 November, where there was a 12% increase). There was also an ~14% and 5% increase in the probability of ice-free conditions for the first and second weeks of December, respectively, a time when there was previously 100% chance of having sea ice.

Discussion

Our findings linking socio-economic impacts from autumn coastal storms to periods of ice-free conditions (<15% sea-ice concentration) provide a quantitative assessment of scientific observations and relationships that have been regionally asserted, but

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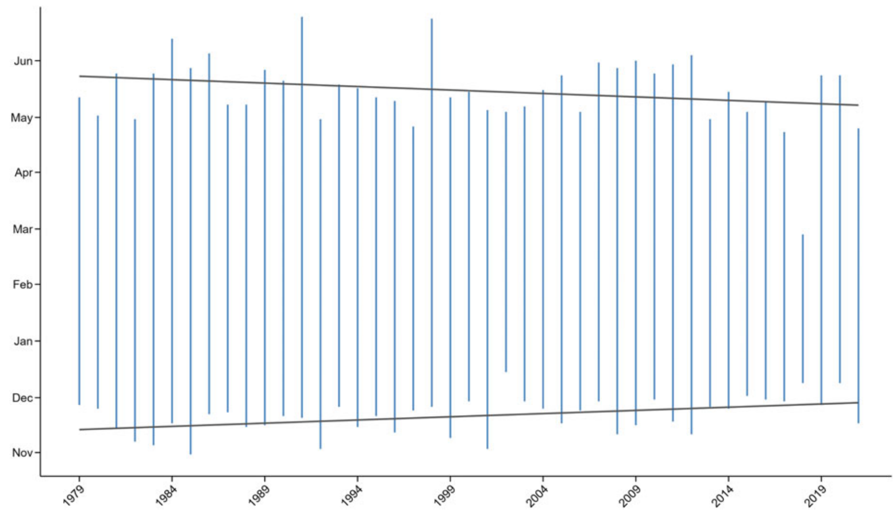

Figure 2. Annual sea-ice season in Nome, Alaska (1979–2022). Each year represents the beginning of the sea-ice season. The top and bottom lines represent trends in break-up and freeze-up, respectively.

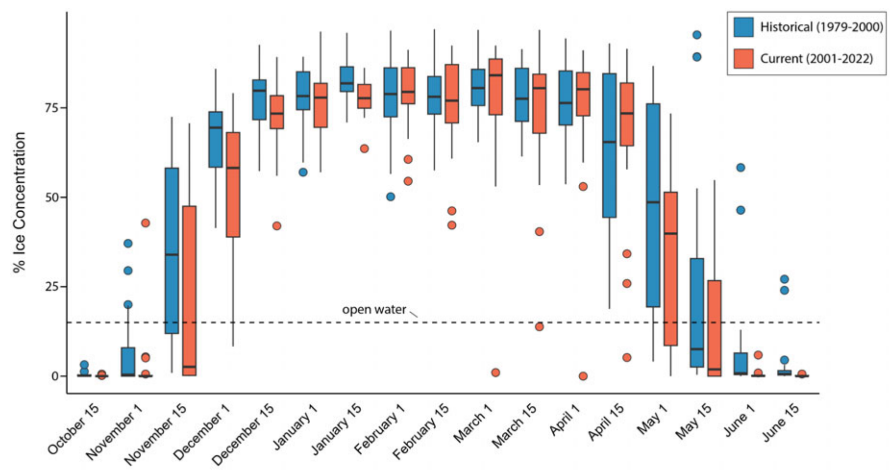

Figure 3. Half-month sea ice concentrations in Nome, Alaska (1979–2022). The box displays the middle 50% of sea-ice concentration values. The bar within the box is the median. The whiskers and outlying dots represent sea-ice concentrations that are 1.5 times within and outside the interquartile values, respectively.

rarely assessed at the community level. These findings cohere with local observations underscoring the importance of sea ice in protecting Arctic communities from storm surge and related coastal flooding impacts (Birchall & Bonnett, 2020). The observed relationship between ice-free conditions and socio-economic impacts also confirms the key role sea ice serves in regulating coastal hazards (Eicken et al., 2009).

The identified socio-economic impacts linked to autumn coastal storms and the absence of sea ice, including transportation impacts, loss of electricity, and damaged port infrastructure have notable societal implications for Nome and surrounding communities. Washouts and closures along the Nome-Council Road are especially significant, as they contribute to unsafe travelling conditions and limit access for harvesting salmon, plants, and other foods (Magdanz et al., 2003). Impacts on food security are further compounded by power outages, where the extended loss of electricity contributes to food spoilage in freezers. Such impacts were, and continue to be, experienced during Typhoon Merbok, which entered the Bering Sea in late September 2022. Impacts on food security from Typhoon Merbok were especially acute across western Alaska as the storm and loss of power occurred following summer and autumn harvest seasons when freezers were full of wildfoods (Rosen, 2022).

The observed increased probability of ice-free conditions in the autumn between 1979–2000 and 2001–2022 (Fig. 4) has implications for shifts in the timing of and potential for socio-economic impacts from extreme weather events, even if there is no systematic change in the number of coastal storms. First, there is a greater likelihood that a given coastal storm from November to mid-December may contribute to socio-economic impacts, which may have been mitigated by sea ice in the past. The change in November is especially significant as this occurs during the climatologically stormiest season of the year in the Bering Sea (Wicks & Atkinson, 2017). At the same time, the absence of sea ice in any given year does not guarantee that impacts will occur. For example, on 12–13 November 2023, a strong storm moved across the Russian Far East, with a large area of south to southwest winds across the nearly ice-free northern Bering Sea. At Nome Airport, 12-hour average sustained wind speeds exceeded 25 mph with a peak wind of 51 mph. However, the measured storm surge at Nome

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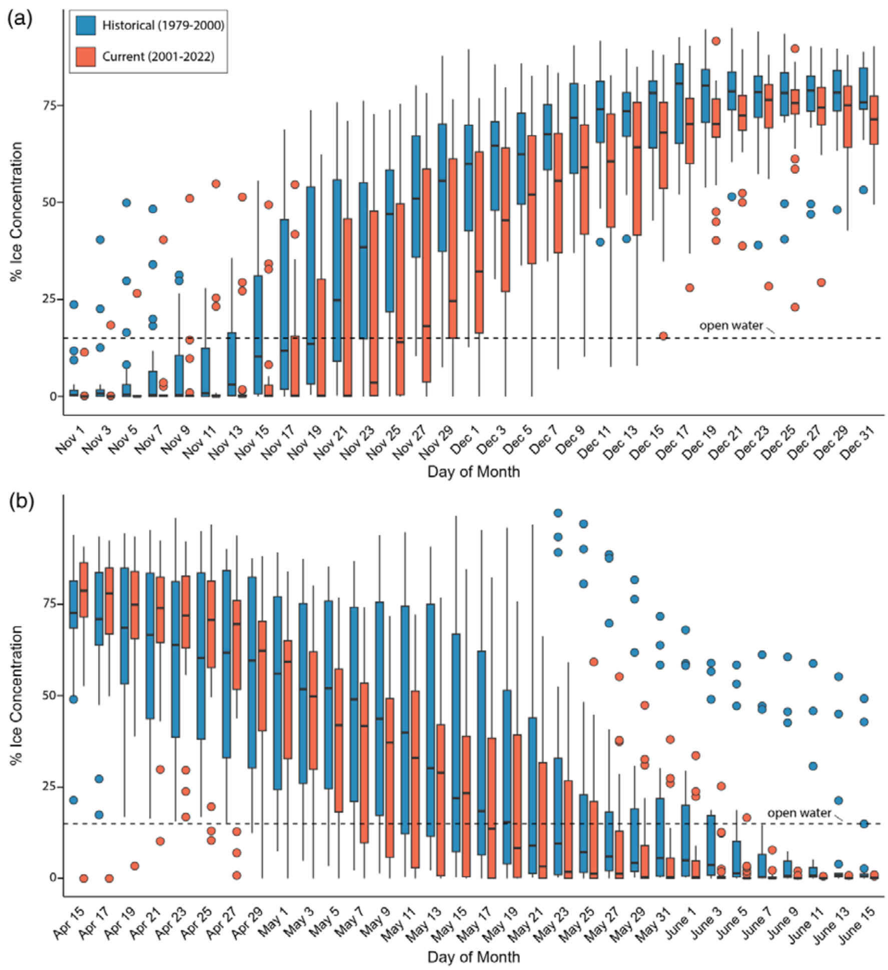

Figure 4. Daily sea-ice concentrations in Nome, Alaska (1979–2022). Top Panel November and December. Bottom panel April 15-June 15. The box displays the middle 50% of sea-ice concentration values. The bar within the box is the median. The whiskers and outlying dots represent sea-ice concentrations that autumn 1.5 times within and outside the interquartile values, respectively.

was less than 3 feet and there was no damage reported. A detailed examination of the meteorology of the event showed the wind fetch across the Bering Sea remained southeasterly longer than is historically associated with coastal flood events in Nome. So in spite of observed winds at Nome that looked favourable for flooding, the regional picture did not. This highlights that multiple factors in the ocean and atmosphere system must be aligned for coastal flooding to occur. Second, there is increased potential for impacts to occur in weeks when they have previously not been experienced, thereby extending the season when autumn storms may contribute to socio-economic impacts. Potential extensions to the season when socio-economic impacts may occur are greatest in the last week of November, though they also extend into December. The potential for impacts from coastal storms to extend later into the autumn season is consistent with the timing of the observed impacts (Table 1).

This research addresses detailed changes in the seasonality of sea-ice concentrations at one location in the northern Bering Sea. However, changing environmental conditions and the impacts of those changes to Arctic peoples have been recognised for decades (Krupnik & Jolly, 2002; Slats et al., 2019). Changing seasonality and quality of Bering Sea ice are important factors influencing Pacific Walrus, an important food resource for many communities around the Bering and Chukchi Seas (Ray et al., 2016).

Although multiple sources of data were used to identify socio-economic impacts from extreme events in Nome, Alaska, data limitations influenced our assessment of the relationship between sea-ice concentrations and socio-economic impacts. It's likely that the eight identified extreme events in the archival analysis underrepresented the full population of autumn coastal storm events with socio-economic impacts due to selection bias, a common challenge when mining newspaper text for historical events (Earl et al., 2004). Additionally, there are several sea-ice-related impacts that extend beyond community infrastructure, which were not included in our analysis that have significant implications for rural communities, including harmful algal blooms, mining, crabbing, and access to hunting and recreation. The inclusion of a broader set of impacts associated with sea ice may reveal additional insights into the relationship between sea-ice concentration and impacts. Counterfactual analysis, which examines how historical events and impacts might have occurred differently under different sea ice conditions, may offer the potential to further examine the relationship between sea ice and socio-economic impacts (Lin et al., 2020; Woo, 2021). However, such analysis would require a deeper understanding of the complex interactions among several variables, including the timing of shifting wind conditions and a regional-scale perspective of the ocean-atmosphere system. Future projections of ice extent in the

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Table 1. Socio-economic impacts from extreme events linked to sea ice in Nome, Alaska (1990–2020)

Date	Documented impacts
5 October 1992	Coastal storm knocked out power, washed out roads, damage to private homes (broken windows, roof damage), flooding; post office closed due to airplanes not able to land; interrupted dredging operations, evacuated households; damage to Nome-Council Road; damage to jetty and causeway (Source: Nome Nugget).
11 October 2004	Construction materials floated away, propane tanks damaged, and loss of power (Source: Nome Nugget).
18–19 October 2004	13 residences affected; loss of electricity; leakage from 1000-pound propane tanks; damage to Nome-Council Road; damage to private households; State building damaged, power lines downed; structural damage to water treatment system; damage to seawall; damage to the dock and jetty. Costs to the City of Nome included: $25K public facilities, $116k public works, $30K fire department, $6K museum, and $7K administration. $14K Port of Nome Causeway. $100K to remove sand from the jetty. Damage to subsistence camps (Sources: Nome Nugget and NOAA StormData). *FEMA-1571-DR
8–10 November 2011	Damage to Nome-Council Road (~$24M); City of Nome reported $580K in damages to Cape Nome Jetty and embankments. Other impacts included damages to Mini Convention Center, seawall, and private households; loss of power and telephone service; and cancelled public activities and incoming flights. Stormwater entered wastewater storage and overwhelmed pumps, which led to wastewater being released into the harbour (Sources: Nome Nugget and NOAA StormData). *FEMA-4050-DR. This storm also prevented a barge fuel delivery.
6–8 November 2013	Damaged utility poles and transformers; loss of power; damage to Nome-Council Road; cancelled flights; public events and activities cancelled (Source: Nome Nugget). *FEMA-4162-DR
13 November 2013	Extensive damage to Nome-Council Road (Source: Nome Nugget). *FEMA-4162-DR
9 November 2015	Damage to Nome-Council Road (Source: Nome Nugget).
23 November 2015	Rocks and logs deposited onto the Nome Port causeway (Source: Nome Nugget).

*FEMA declared disasters.

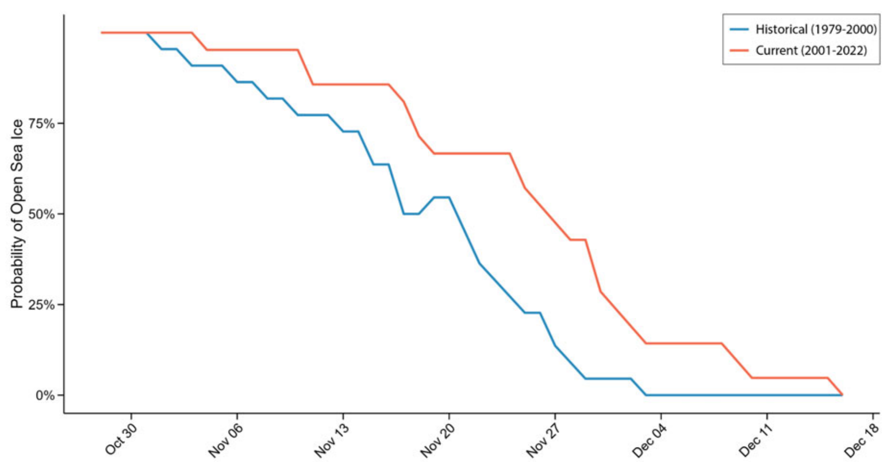

Figure 5. Changes in the probability of ice-free conditions (<15% sea-ice concentration) offshore of Nome, Alaska (1979–2022).

Bering Sea ice support the continued decrease of ice extent (Thoman et al., 2020), but lack the spatial and temporal resolution to directly address the evolution of changes in ice timing documented here.

Conclusion

This research provided evidence of an identifiable relationship between socio-economic impacts from autumn coastal storms and ice-free conditions in Nome, Alaska, a community that has experienced notable sea ice declines and impacts from autumn coastal storms. Each of the identified coastal storm events was associated with ice-free conditions at the time of the reported socio-economic impacts. The increasing probability of ice-free conditions in late November and early December has implications for understanding how the timing and probability of impacts may change in Nome as well as other Arctic coastal communities experiencing reductions in sea-ice concentrations. Assuming there are no changes in storminess within the Bering Strait, there is a greater likelihood that individual autumn coastal storms will be linked to impacts and a greater probability that impacts may occur later in the season when they have not previously occurred. In other words, we can't simply look at the past to understand the timing and frequency of future impacts. This research builds on previous studies documenting the importance of sea ice in mitigating coastal erosion and vulnerability.

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Competing interests. The authors report no conflict of interest.

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