Transformative Ecological and Human Impacts from Diminished Sea Ice in the Northern Bering Sea

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ABSTRACT: Our goal is to tie climate-scale meteorology to regional physics and ecosystem changes and demonstrate a few resulting impacts to which regional peoples are having to respond in the Alaskan Bering Strait region. The sea ice loss events in the winters of 2017/18 and 2018/19 initiated a series of marine environmental, ecological, and industrial changes through a chain of connected events from jet-stream meanders, storms, southerly winds, warmer sea temperatures, and minimum sea ice cover. Resulting impacts continue as coastal communities respond to ongoing nutritional, cultural, and economic challenges. Global warming potentially initiated these events through a weakened atmospheric Arctic Front. Ecological shifts included a transition/reorganization of the Bering Strait regional marine ecosystem. Subsequent changes included shifts in zooplankton species, increases in large-bodied, predatory fish species moving northward, an ice seal unusual mortality event, and seven consecutive years of multispecies seabird die-offs. These changes in the marine ecosystem create a serious food security concern. Ongoing impacts include large, toxic harmful algal blooms and coastal erosion. Recent changes to the maritime industries of the transboundary waters of the Bering Strait include increased industrial ship traffic, planned development of the Port of Nome, and northward proximity of foreign fishing activity. Projections for the next decades are for an increasing frequency of low sea ice years and continuing ecosystem and industrial transitions that contribute to increasing economic and food security concerns for the 16 coastal communities that compose the Bering Strait region.

SIGNIFICANCE STATEMENT: Extreme events in the atmosphere/oceans and resultant record sea ice minimums in 2018 and 2019 were manifested in marine ecosystem transitions and maritime industry impacts. This led to ongoing concerns over the food safety and food security of marine resources essential to the nutritional, cultural, and economic well-being of Alaskan coastal communities of the Bering Strait region. Persistent weakening of the Arctic Front may signal an increased frequency of low sea ice events into the next decades.

KEYWORDS: Arctic; Atmospheric circulation; Climate variability; Ecosystem effects; Societal impacts

1. Introduction

In the previous decade, there have been multiple extreme events in the Arctic that meet or exceed previous records (Moon et al. 2019; Walsh et al. 2020) and are often record-shattering (Fischer et al. 2021). Such extremes vary in type, location, timing, and duration. Landrum and Holland (2020) conclude that the Arctic is already transitioning from a system dominated by a stable cryosphere (sea ice, permafrost, glaciers) toward a different climate. In the Bering Strait region, major oceanographic extreme events occurred during the winters ending in 2018 and 2019 with ecosystem, fisheries, and societal impacts observed through at least 2021 (Siddon 2022). We draw connections from Arctic warming and north–south extensions of the jet stream, through record low sea ice, to a marine ecological reorganization due to the reduction in an oceanographic thermal barrier separating two distinct ecosystems, and to impacts on coastal communities. The Bering Sea historically grows sea ice from November through March. Such a pattern was absent during 2018 and 2019 with a major decrease in sea ice extent. As a result of these events and the trend for continued sea ice reduction, the Bering Strait region (>60°N) is a transforming ecosystem, in part shown by the northward migration of the southern Bering Sea ecosystem including large-bodied, commercially viable, predatory fish species (Stevenson and Lauth 2019; Eisner et al. 2020b) and marine mammals (Brower et al. 2018; Escajeda et al. 2020).

The risk of extreme weather causing an ecosystem transition is high for the Bering Sea (Hollowed et al. 2012; Duffy-Anderson et al. 2019; Wiese and Nelson 2022). As seasonal sea ice advances southward and thickens, brine rejection and associated stratification forms a more saline, cold (<2°C) bottom layer termed the "cold pool" that renews and maintains an oceanic thermal barrier between the northern and southern Bering Sea ecosystems. The cold-pool barrier affects the spatial distribution of groundfish and, thus, predator/prey dynamics

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within the food web (Mueter and Litzow 2008; Eisner et al. 2020a). The cold pool was almost completely absent in the summers of 2018 and 2019, as observed in the NOAA/National Marine Fisheries Service summer bottom trawl survey, extending to only 1% and 7% of its historical maximum observed size, respectively. During 2018/19, major components of the warmer-water ecosystem of the southern Bering Sea expanded their distribution into the Bering Strait regional ecosystem due to the lack of the cold thermal barrier (Thompson 2018). Juvenile snow crab abundance was negatively impacted by warm temperatures (Fedewa et al. 2020). A physical shock (i.e., change of winds, ocean temperatures, and anomalously low sea ice) impacted the marine ecosystem during 2018/19, causing a reduction in prey availability and/or carrying capacity (see Siddon 2022). It is not clear to what degree continuing ecosystem changes and coastal community impacts are due to persistent ocean warmth. One should not be surprised to see events such as 2018 and 2019 transpire during the next decades as the Bering Strait region ecosystem continues to respond to a changing climate (Thoman et al. 2020).

The occurrences of major sea ice loss in extent, duration, and quality during 2018 and 2019 were extreme events relative to reconstructions back to 1850 (Walsh et al. 2017) and were earlier than projected by climate models (Wang et al. 2018). It is difficult to explain their back-to-back occurrence given the normally large year-to-year variability in storm climatology. For new extremes beyond historical records, one cannot easily enumerate potential future states of nature that will arise using historical data, much less assign probabilities. An alternative is to concede that the new observations may have different underlying physics and biology, as opposed to a databased statistical model. Additional information can suggest processes that are nonstationary or that the event may be considered previously unimaginable. Arctic temperature increases and a weakening of the atmospheric Alaskan Arctic Front (AAF) due to global warming are candidates. The timing and magnitude of future events are uncertain with unpredictable consequences (Punt et al. 2014). A major tenet is that to support action, one cannot wait for complete understanding or to assume that such events will occur every year. The future environment of the Bering Strait region depends upon a combination of underlying warming, large interannual variability, and an increased frequency of extreme events.

Our goal is to tie climate-scale meteorology to regional physics and ecosystem changes that have direct impacts on the Alaskan regional coastal communities. We speculate on future decades and highlight the need for improved integration of communications and responses with and within the Bering Strait coastal communities, especially those that rely on the comprehensive use of the marine ecosystem for their nutritional, cultural, and economic well-being. Sections 2 and 3 discuss physical, ecological, and societal events of recent years. They are followed in section 4 by a discussion of external drivers causing such events: global warming, Arctic temperature amplification, and chaotic atmospheric interannual variability such as the position and resulting wind field of the Aleutian low pressure system. A way forward (section 5) notes the need for marine resource managers and researchers to integrate with existing regional communication networks, tribal governments, and the general public to improve the quality of marine science, improve the dissemination of research results, and thus provide much needed services to constituents adapting to a Bering Strait ecosystem undergoing unprecedented transition.

2. The winter 2018 and 2019 events and ecological impacts

Sea ice in the Bering Sea historically is present from November through March through freezing and transport of sea ice southward by cold northerly winds (Overland et al. 1984). Such a pattern was interrupted during winter (January–March) 2018 and 2019 (Fig. 1a). Sea ice reduction/absence and warm air temperature events were associated with an unusual southwest–northeast orientation of the jet stream that supported persistent warm, moist winds from the south and sea ice minimums (Fig. 1b). The jet stream shift can be considered as the ultimate cause of Bering Sea changes as a wavy jet stream, that is, an increased north–south orientation, steered warm air temperatures over the Bering Strait (Fig. 2). Stabeno and Bell (2019) and Thoman et al. (2020) discuss the ocean and sea ice physics of these events. They note that ocean warmth, late ice-cover development, and frequent atmospheric storminess were important factors. The unprecedented nature of the 2018 sea ice minimum extent is verified against reconstructed monthly sea ice extent since 1850 (Walsh et al. 2017). Also in Fig. 1a, we note other relatively low sea ice years since 2014, which all fall below the 1981–2010 climatological mean. The cold pool was nearly absent during 2018, 2019, and 2021 (Fig. 1c).

During 2018 and 2019 major ecologically and commercially important components of the southern Bering Sea ecosystem, such as large-bodied and predatory fish species, expanded their distribution northward into the Bering Strait region (>60°N) (Stevenson and Lauth 2019; Spies et al. 2020). Subarctic walleye pollock and Pacific cod experienced massive northward shifts in spatial distributions as the ocean thermal barrier of cold temperatures was not renewed/maintained due to the previous winter's reduction in sea ice quality, quantity, and duration. Their total biomass relative to 2010 (a comparatively cold year) increased 50 and 15 times, respectively (Table 1). Although numbers were less in 2021, they were still dramatically increased over 2010. Concurrently, there was also a lack of small-bodied forage fish species (Arctic cod, saffron cod, etc.) that reside in the colder-water northern Bering Sea ecosystem that are important noncommercial food species for peoples of the Bering Strait region. These forage fish species are essential prey for several seabird and marine mammal species/age classes that are harvested for subsistence purposes to feed families. These important endemic fish of the Bering Strait region subsequently either emigrated north to stay in cooler waters or were exposed to massive predation from an influx of predators from the southern Bering Sea (Mueter et al. 2020). Large-bodied adult pollock and Pacific cod are voracious and their movement into the Bering Strait region in high densities likely increased the predation pressure in the ecosystem. In an Eastern Bering Sea Ecosystem Status Report (Siddon 2022), and through Bering Strait coastal community

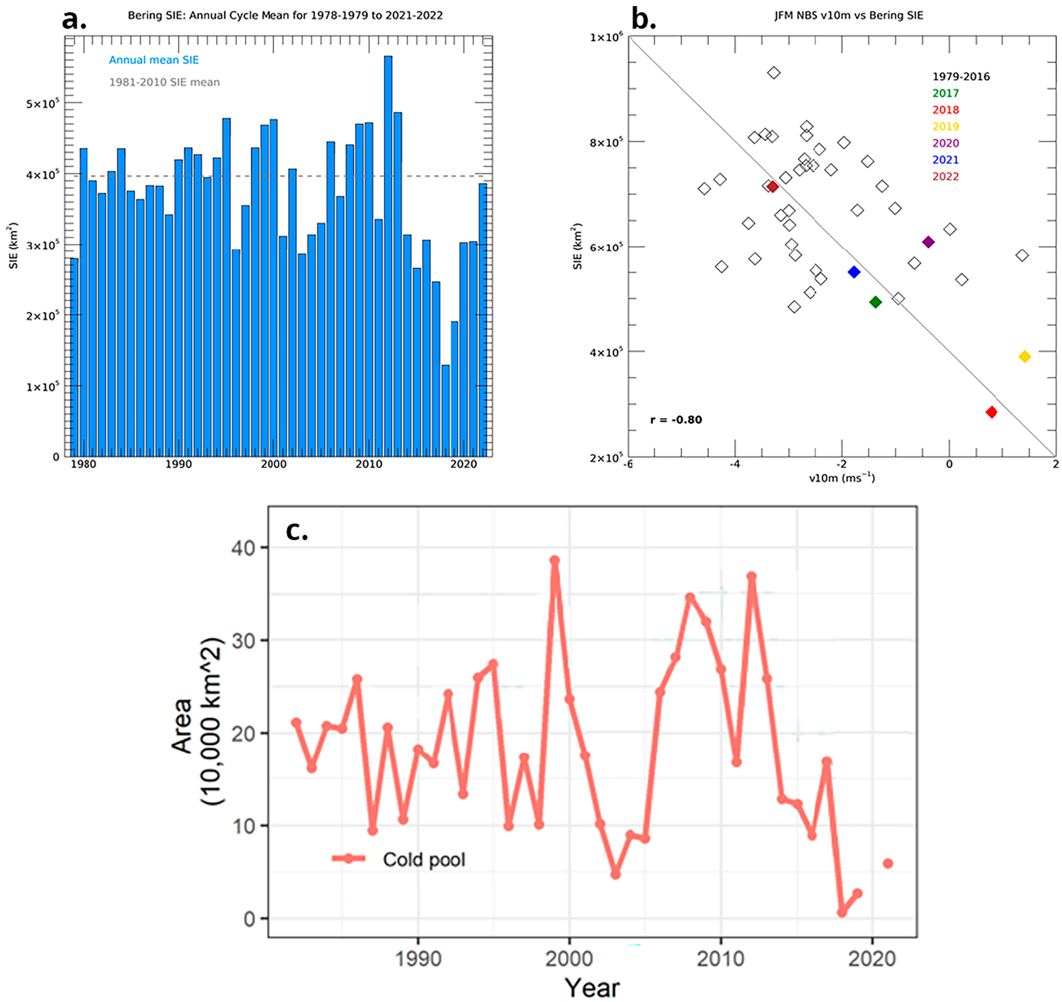

FIG. 1. (a) Bering Sea annual cycle (mean from November to the following July) sea ice extent (SIE; km^2) from 1978/79 to 2021/22. (b) Northern Bering Sea northward 10-m wind component (v10m; $m\ s^{-1}$)–SIE correlation, 1979–2022 ($r = -0.80$; $p < 0.05$). Minimum sea ice years are associated with more southerly (from the south) winds. Years since 2017 are shown by filled, colored diamonds and with the perfect line fit overlaid. Wind data are from the NCEP–NCAR reanalysis (Kalnay et al. 1996), and SIE data are from the National Snow and Ice Data Center Sea Ice Index (v3; Fetterer et al. 2017). (c) History of the Bering Sea cold-pool extent ($10^4\ km^2$) based on NOAA/National Marine Fisheries Service bottom trawl surveys (note that there are no data in 2020).

observations and subsequent responses to anomalous environmental changes as observed by the authors, multiple ecosystem impacts were noted through 2021 and beyond: juvenile crab population declines, consecutive multispecies seabird die-off events (2017–22) due to malnutrition (Kaler et al. 2022), and a 2018/19 federally designated, multispecies ice-associated marine mammal unusual mortality event most likely due to reduced prey availability (Siddon et al. 2020; Siddon 2022). The northern Bering Sea ecosystem's overall carrying capacity was likely reduced due to warming ocean temperatures setting a negative feedback loop that included, but was not limited to, reduction of sea ice algae, increased predation pressure by emigration of endemic southern Bering Sea fish predators and other marine taxa northward (e.g., sharks), a shift in zooplankton species (replacing endemic cold-water species with less nutritional warmer-water species), and an increased metabolic demand on cold-blooded taxa from warmer temperatures.

Warmer conditions impacted phytoplankton and zooplankton communities at the base of the food chain (Kimmel et al. 2023; S. Gonzalez 2023, personal communication). Lack of sea ice cover removed the platform for the development of ice algae. Warmer temperatures and increasing inflow of warm coastal water into the Chukchi Sea was associated with smaller sized phytoplankton (e.g., *Synechococcus*). The zooplankton community had higher abundances of small, less lipid-rich copepods and meroplankton, and reduced abundances of larger *Calanus* spp. These changes result in a planktonic food web with more trophic links that would have less energy available to upper trophic levels than under colder conditions, potentially impacting commercial and subsistence marine resources and benthic ecosystems.

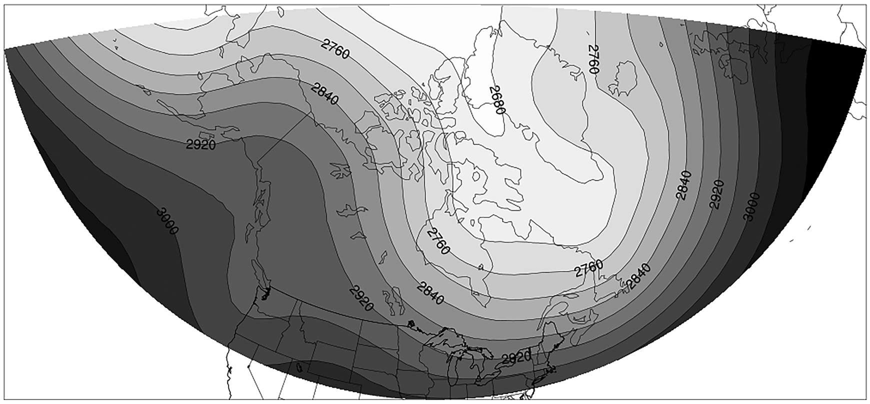

FIG. 2. The mean lower-tropospheric jet stream at 700 hPa (m) for winter (February–March) 2019. Lower geopotential height values (light shading) indicate lower pressure, and jet-stream winds follow the contours (i.e., mostly from west to east). Note the northeast tilt of the jet stream bringing warm air over the northern Bering Sea and Bering Strait region. Geopotential height data are from the NCEP–NCAR reanalysis.

3. Community, scientific, and regulatory adaptive responses to ecological events

The annual cycle of sea ice in the Bering Strait region defines the marine ecosystem that is comprehensively used by coastal communities for food. The changes in sea ice timing (i.e., delayed freeze-up and earlier ice breakup) and subsequent duration, combined with the reduction in sea ice extent and quality (thickness, distribution, and stability), are at the center of regional maritime social and industrial challenges. Recent dramatic sea ice changes have provided an ecological shock to the Bering Strait regional ecosystem that is superimposed on the longer-term warming trend of the northern Bering and Chukchi Seas. No coastal community in northern or western Alaska remains untouched by the recent suite of changes (Huntington et al. 2022). We present four examples of ecological impacts that require an integrated approach from all sectors (community, scientific, and regulatory) to respond to the immediacy of changes and adapt to the future.

a. *Shifting distributions of groundfish*

Unprecedentedly low sea ice and reduced spatial extent of the cold pool in 2018 and 2019 removed the thermal barrier resulting in northward distributional shifts of the southern Bering Sea ecosystem—most notably the commercially valuable groundfish stocks (e.g., Thorson et al. 2019; Thompson 2018)—and altered the food web through predation pressure and fishery species interaction (section 2). Indicative of the northward movement of southern Bering Sea fish species, there were northward shifts in U.S. commercial fishing vessel activity through 2020 (Lee 2021). Bering Strait regional coastal communities have observed increased presence of foreign fishing fleets in Russian waters on the western side of the Bering Strait. Within the Norton Sound region of the northern Bering Sea, the increase in the amount and quality of commercially viable adult Pacific cod during 2019 allowed for a novel fishing opportunity as a Bering Strait Community Development Quota was initiated, and the region had its first Pacific cod commercial season during 2021.

TABLE 1. Northern Bering Sea (>60°N) biomass, in metric tons (data are from the Alaska Fisheries Science Center of the NOAA/National Marine Fisheries Service; Lauth 2011; Markowitz et al. 2022a,b).

	2010	2019	2021
Pollock	21 000	1167 000	474 000
Pacific cod	29 000	365 000	228 000
Arctic cod	37 000	47 000	83 000

Observations by regional residents of multispecies ice-associated seal die-offs of predominantly juvenile bearded, spotted, and ringed seals primarily due to emaciation during 2018–20 resulted in a NOAA ice seal unusual mortality event (UME). Research documented the reduction in body condition of spotted and ribbon seals concurrent with sea ice habitat reduction (Boveng et al. 2020; Mahoney et al. 2021). Since 2018 additional die-off events included a gray whale UME and a short-tailed shear-water mass mortality event in the eastern Bering Sea (Siddon 2022). Communities of the coastal Bering Strait region documented examples of marine wildlife that had extended their northernmost range, for example, Stejneger's beaked whale (Savage et al. 2021) and invasive species, for example, the Hanasaki crab (Kent and Bell 2014).

The scientific response to northward shifts in marine species distributions included the extension of the eastern Bering Sea (EBS) bottom trawl survey to include additional stations in the northern Bering Sea (NBS; Lauth and Britt 2017). Since 2017 this NBS extension has become a more regular survey that informs crab and groundfish stock assessments and provides ecosystem-wide information to the Bering Strait communities that rely on the utilization of marine resources for nutritional, cultural, and economic well-being. The combined EBS and NBS bottom trawl survey provides an increased understanding of how crab and groundfish respond to environmental conditions over the shelf. The regulatory

FIG. 3. Noncommercial acquisition of marine resources is essential for nutritional, cultural, and economic well-being in the northern Bering Sea.

response includes improvements to stock assessment models to include the NBS survey data for an increasing number of federally managed fish, shellfish, and marine mammal stocks in the larger Bering Sea management region.

b. HABs

Warming ocean temperatures and subsequent reduction in sea ice coverage in the Bering Strait region have led to ocean conditions suitable to extreme growth events (e.g., a bloom) of a harmful algal dinoflagellate, *Alexandrium catenella*, that produces a neurotoxin, saxitoxin, responsible for paralytic shellfish poisoning (PSP). The PSP condition is potentially fatal in marine mammals, seabirds, and humans if saxitoxin is ingested in sufficient amounts. Persistent cyst beds of the harmful algal species *Alexandrium catenella* have been identified in the Bering Strait region and Chukchi Sea (Anderson et al. 2021) and the presence of algal toxins in several Bering Strait pinniped and cetaceans has been documented at levels that indicate potential health concerns/impacts (Lefebvre et al. 2022). During July–September 2022, the largest, most persistent, and highly toxic harmful algal bloom (HAB) event of *A. catenella* ever documented nationwide extended from the western northern Bering Sea to the southern Chukchi Sea (E. Fachon et al. 2024, personal communication). The size, high toxicity, and spatial extent of this event was unexpected (Gannon 2023), and it was a human/wildlife health threat, as well as a serious food security and food safety concern. The regional utilization of noncommercial taxa such as tunicates, marine worms, and the soft tissues and (biotoxin filtering) organs (e.g., liver, kidney, intestine) of seabirds and marine mammals consumed as food, poses novel health concerns to regulatory agencies and laboratories set up primarily for shellfish testing. The Norton Sound Health Corporation, the regional tribal health consortium of the Bering Strait region, and the Department of Public Health issued advisories about consuming shellfish, invertebrates, and the organs of seabirds and marine mammals to all coastal communities in the Bering Strait region. The response to this HAB event was collaborative in that it involved frequent communications at the regional hub community of Nome between HAB researchers/academia, healthcare entities (e.g., tribal and state), and government leadership (e.g., tribal, state, federal).

Bering Strait coastal communities are in need of real-time monitoring, surveillance, and the results of these efforts to better understand the rapidly changing environmental conditions and the risks to marine wildlife and people. Ongoing research projects under NOAA's Ecology and Oceanography of Harmful Algal Blooms (EcoHAB) program include transitory shipboard offshore monitoring efforts as well as limited nearshore efforts to follow the harmful algae species *A. catenella* and *Pseudo-nitzschia* and their biotoxins throughout multiple marine trophic levels. Limited sampling and analysis of nearshore marine resources utilized as food is under way. A more long-term regional monitoring/surveillance program, including soft tissues and organs of marine mammals and seabirds, is needed to provide risk assessments to the communities that are harvesting marine resources for food. Food security concerns due to a transitioning ecosystem have escalated steadily in the last 15 years resulting in threats to human health and safety, as well as conservation concerns for seabirds, marine mammals, and other marine taxa. Emerging threats such as HABs jeopardize people's nutritional, cultural, and economic needs (Fig. 3).

Although lags exist in disseminating research results, coastal communities have immediate and acute food security and food safety concerns. To address these concerns effectively, state and federal regulatory agencies with management authority of the marine wildlife resources would need to work closely and frequently with federally recognized comangement entities, tribal governments, consortiums, state and federal regional advisory councils, and their public constituents to help direct research, monitoring, educational materials, and other public support services to coastal communities.

c. Coastal storms and erosion

Coastal communities are increasingly subject to storm surge and coastal erosion due to a warming ocean and reduced sea ice. Increased storms and southerly wind events, as projected in the next section, will have future impacts on coastal communities and their infrastructure. Reduced sea ice allows higher storm surges to reach shore, diminishes the nearshore sea ice buildup that deflects high surf, and thawing permafrost makes the shoreline vulnerable to erosion. Delayed sea ice freeze-up during November has become common and is concurrent to the period of autumn storms. The village of Shishmaref located on Sarichef Island north of Bering Strait, inhabited at least for 400 years, is facing potential evacuation due to coastal erosion from rising temperatures that are causing a reduction in sea ice and thawing of permafrost along the coast (Willow 2022). The town's homes, water system, and infrastructure are being undermined. Another example is a major autumn storm during 2022, former Typhoon Merbok, that impacted a large number of western Alaska coastal communities. Storm surge forecasts were posted on Facebook, which is a widely available (as internet conductivity allows) communication system. Scientific meteorological advances will continue, with weather forecast model improvements and model initialization from satellite and surface observations. Servicing remote locations and having adequate internet coverage remain ongoing challenges as the National Weather Service has limited meteorological services in the Bering Strait region.

d. *Industrial development*

Vessel traffic increased through Bering Strait in 2023, with Russian officials claiming to have reached a record level of cargo moving along the Northern Sea Route. In 2023, 730 vessels were supported by the icebreakers, up from 653 in 2022 (https://maritime-executive.com/article/russia-claims-new-record-for-cargo-on-the-northern-sea-route). A significant step forward was made in 2018 when Russia and the United States established joint ships' routing measures through the International Maritime Organization. In anticipation of increasing industrial and maritime traffic (e.g., ships involved in research, pleasure cruises, fuel/freight, commercial fishing, and military) in the increasingly ice-free northern Bering Sea and Chukchi Sea, the U.S. Army Corp of Engineers and the city government of Nome have initiated the Port of Nome Modification Project that will enhance the only U.S. port on the Alaskan coast between the eastern Aleutian Islands and the eastern Beaufort Sea, providing improved access for anticipated industrial ships.

4. An external driver

It is important to tie the physical changes to the northern Bering/Chukchi Seas and subsequent ecological and human impacts to a larger, ongoing, global picture. The key factor is the warming of the whole Arctic at 2–4 times the global temperature increase, referred to as Arctic amplification. The regional impact is a warming of the northern Bering Sea that flows northward into the Chukchi Sea and the adjacent Beaufort Sea. An external driver of an accelerated local climate change for the Bering Strait region is the weakening of the atmospheric AAF. Historically, the AAF separates the cold and dry Arctic air mass from the southern Bering Sea moist and warm marine air mass (Fig. 4a). The contrast of the

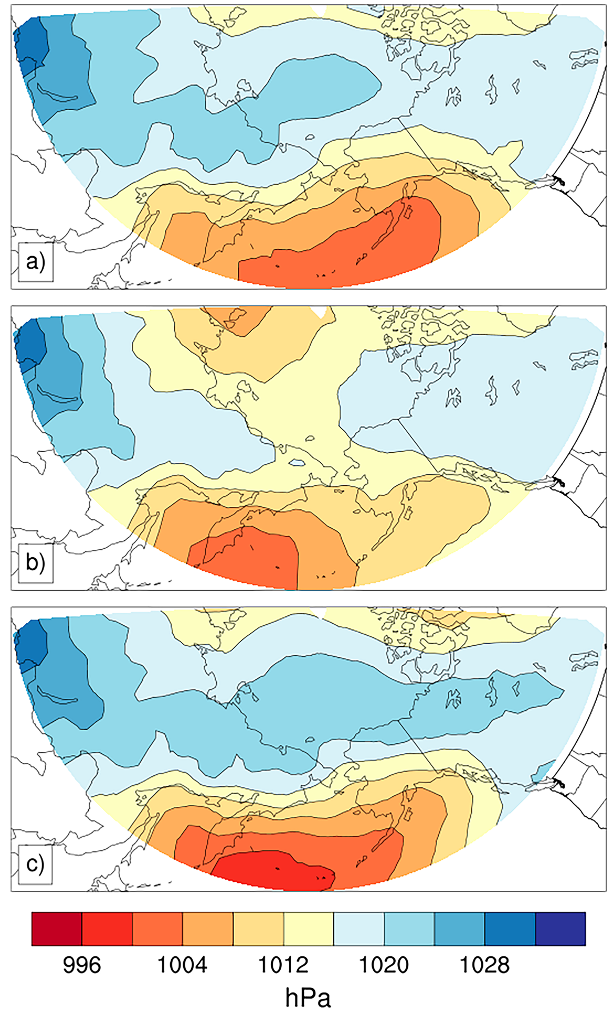

FIG. 4. (a) Winter (January–March) atmospheric AAF climatology for 2010–16 based on spatial differences in sea level pressure. (b) Weakened AAF for 2017–20. (c) AAF for 2022 with strong (low pressure) Aleutian low over Alaska. Sea level pressure fields are from the NCEP–NCAR reanalysis.

Beaufort high pressure system to the north and the Aleutian low to the south are key regional surface pressure features providing the setup and maintenance of the AAF. We propose that a new weakening of the AAF, and a more meridional (south–north) orientation of the jet stream supporting southerly winds, relates to overall western Arctic winter temperature increases due to Arctic amplification and global warming (Vavrus et al. 2022). Warmer Arctic winter temperatures resulted in a weakening of the AAF during 2017–20 (Fig. 4b). The degradation of this frontal structure was facilitated by the disappearance of the climatological Beaufort high and westward shift of the Aleutian low (Rodionov et al. 2007). The Arctic Front was subsequently strengthened during 2022 and 2023 by the Aleutian low pressure system having a more longitudinally expansive presence that extended to central Alaska, with easterly winds and colder Bering Strait

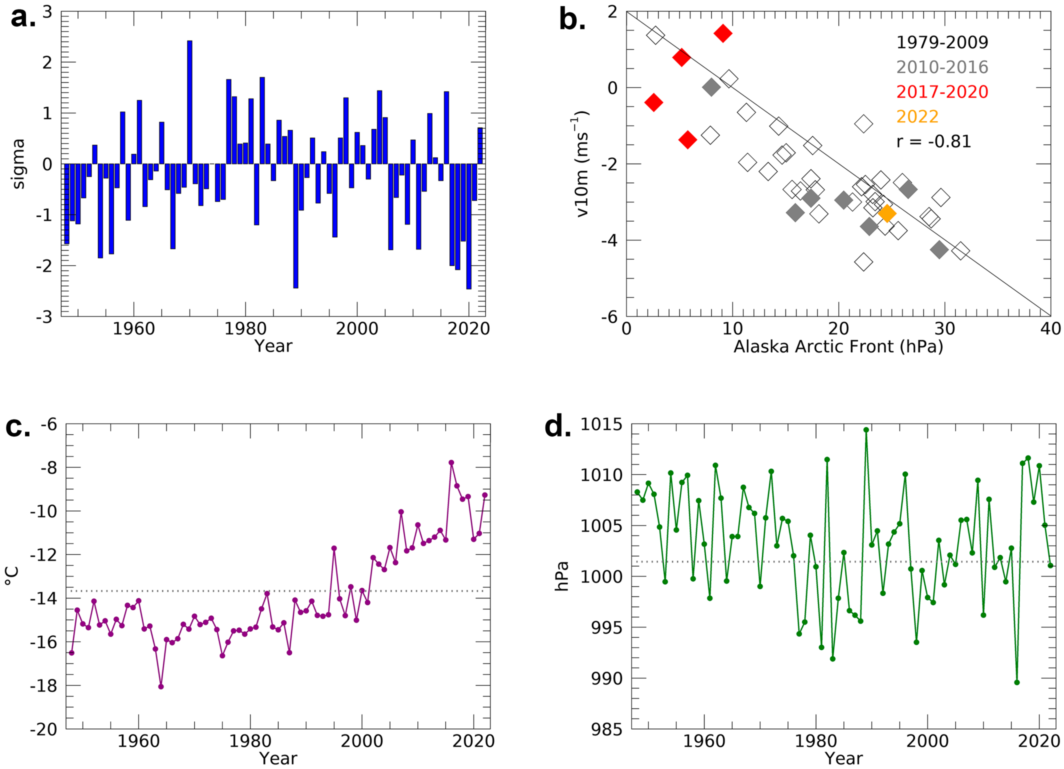

FIG. 5. (a) Winter (January–March) atmospheric AAF time series, 1948–2022. The AAF is calculated as the sea level pressure difference (hPa) between grid points representing the approximate climatological positions of the Beaufort high (75°N, 170°W) and the Aleutian low (50°N, 170°W) (i.e., Beaufort high winter grid point minus Aleutian low winter grid point). Note that five of the last six years show unprecedented persistence of below-normal winter-strength AAF values. AAF data are normalized by the 1981–2010 winter (January–March) mean and standard deviations. (b) Correlation between the strength of the AAF and the 10-m meridional wind near Bering Strait (m s^{-1}). A strong AAF corresponds to northerly winds (negative values). (c) Winter near-surface (1000 hPa) Arctic air temperatures at 77.5°N and 170°W, with warmer temperatures during 2016–19 and 2022. (d) Winter sea level pressure for southwestern Alaska (55°N, 160°W), showing an absence of low pressure in 2017–20 but a return to climatological conditions during 2022. The horizontal dotted lines in (c) and (d) represent the 1981–2010 air temperature and SLP mean, respectively. Data for all plots are from the NCEP–NCAR reanalysis.

temperatures (Fig. 4c). Winter sea ice and ocean temperatures in 2023 were similar to 2022 (R. Thoman 2023, personal communication).

Figure 5a captures the history of the winter (January–March) AAF at the surface [sea level pressure (SLP)]. The frontal strength is calculated from the difference between SLP values located near the climatological cores of the Beaufort high (75°N, 170°W) and the Aleutian low (50°N, 170°W), and represent distinctly different air masses (Ballinger and Overland 2022). The SLP gradient in recent years has been remarkably weak, reaching a 4-yr minimum during 2017–20, highlighted by a small difference in pressure between the Beaufort Sea and Bering Sea relative to most years of the atmospheric reanalysis era back to 1948. Figure 5b confirms the negative correlation between the strength of the AAF and the near-surface meridional (north–south oriented) wind near Bering Strait ($r = -0.81$; $p < 0.05$). Multiple cases since 2018 of weak northerly (slightly negative) and southerly (slightly positive) wintertime meridional winds are associated with the front's degradation. Figure 5c shows the history of near-surface temperatures north of the front (at 77.5°N and 170°W), highlighted by recent warmer conditions in all years; these warmer temperatures in the Beaufort high (Fig. 5c) contribute to the weaker AAF boundary, as in 2017–20 (Fig. 5a). A zonally (west–east) expansive Aleutian low pattern returned during winter 2022, as shown by near-normal North Pacific SLP at 55°N, 160°W (Fig. 5d), accounting for the stronger AAF in that year.

In summary, the atmospheric AAF is strong throughout the historical record before 2017. From 2017 through 2020 the Arctic Front is weak and corresponds to warmer Arctic temperatures. In 2022 and 2023 Arctic temperatures remain warm while the AAF is stronger because of the strength and northeast position of the Aleutian low, resembling mean conditions from 1981 to 2010, thus returning the Bering Sea to climatological mean sea ice extents. Thus, we do not expect to see record minimum sea ice extents in every future year.

5. A way forward

The minimum extent of sea ice in the Bering Strait region during winter 2018 and 2019 were unprecedented events. They manifested positive feedbacks between southerly winds, warm air and ocean temperatures, and opposition to the typical wind-driven southward advance of sea ice. A more north and south orientation of the tropospheric jet stream was important in initiating and maintaining the southerly surface winds and is in response to internal atmospheric variability and to the weakening of the atmospheric AAF. We draw a direct link from global warming, through changes in the jet stream and AAF, to sea ice loss and ecosystem transitions, wildlife health and conservation, resulting serious human health, food safety, and food security concerns, and loss of coastline such as at Shishmaref.

The climatic processes of the Bering Strait region are likely nonstationary (Shepherd 2021), and the recent events were previously unimaginable. An approach to investigate the future to make predications to prepare response efforts is through the use of climate models with a large number of possible future realizations, referred to as ensembles. Thoman et al. (2020) make an assessment based on use of the Community Earth System Model Large Ensemble (CESM-LENS) output to make such a calculation. They calculated the probability over 40 simulations, whether the 2018 minimum will be exceeded in each decade. The probability of occurrence is essentially zero through the 1990s but increases to a 29% chance of occurrence in the 2030s. Vavrus et al. (2022) used 50 independent realizations from the CESM, version 2, Large Ensemble (CESM2-LENS) to investigate future Bering Sea ice cover and North Pacific storm tracks. They conclude that there will be more minimum sea ice extents in the future due to increased northward propagation of storms. Both the weakening of the Beaufort high and the future variability of the position of the Aleutian low pressure system will contribute to new winter sea ice loss patterns.

The exact timing and magnitude of future events are uncertain with unpredictable consequences. Rather than explicit forecasts, scientists and communities should investigate a collection of possible future decadal scenarios and plan appropriate responses to worst case examples. Such scenarios represent a knowledge gap that can be supported by collaborative yearly biophysical–societal observational datasets and rapid analysis and understanding – at the ecosystem level. Our approach concludes that observations have new underlying physics and biology, such as atmosphere–ocean–sea ice feedbacks, resulting in extremes beyond previous records (Lloyd and Shepherd 2020). Based on recent multiple years of a weakened AAF, minimum sea ice years (2018/19), other recent years with a western location versus eastern location of the Aleutian low (2018–23), and the calculations of Thoman et al. (2020) and Vavrus et al. (2022), it is reasonable to project an increase in the frequency of future minimum sea ice years into the next decades, accompanied by impacts on ecosystems and societal systems. An important feature is that ecosystem and societal changes can be immediate and can lag the physical extremes by multiple years as suggested from Table 1 (Siddon 2022; Hollowed et al. 2012; Huntington et al. 2022).

The rate of environmental and ecological changes occurring in the northern Bering Sea ecosystem is increasing risks and stress because of the limited response capabilities of regional communities, scientists, and state and federal regulatory systems. Currently Bering Strait rural coastal communities, with active and essential maritime subsistence activities, typically are the first to discover anomalous events, alert partner institutions located in their regional communication/transportation hub community, and subsequently conduct and/or assist in regional responses (Bodenstein et al. 2015; Stimmelmayr et al. 2018; Sheffield 2019; Sheffield et al. 2021). Coastal residents provide observations, data, interpretation, and response on a largely volunteer basis using personal resources. Federal managers and researchers of the Bering Strait marine resources are typically located in urban hubs at least 500 miles from their coastal constituents, making communications and public service more difficult and infrequent. Regulatory response resources, including infrastructure for testing facilities (e.g., food safety), routine surveillance and monitoring of marine resources important as noncommercial and commercial foods, and collaborative education/outreach between regulators and their coastal constituents, are needed during rapidly changing environmental conditions. Starting in 2017, NOAA conducted offshore benthic research surveys in the northern Bering Sea and initiated a more collaborate approach with the regional hub entities of the Bering Strait region to increase two-way understanding of the offshore research, disseminate survey results, and engage with tribal leadership and the coastal regional public.

6. Summary

There was record minimum sea ice cover during winter 2018 and 2019 in the Bering Sea, with continuing multiyear impacts in the marine ecosystem and on human food safety, food security, and health concerns. Ecological shifts indicated ecological shocks to the northern marine food web as southern Bering Sea ecosystem taxa moved north and impacted lower trophic levels to top level species, including people. It is suggested that impacts included changes in food-web species composition and carrying capacity, resulting in increased emaciation and mortality in top level species that are commonly used as food in coastal communities. Global warming initiated these ecological events through the physical changes of warmer temperatures, loss of sea ice, and a weakened atmospheric Arctic Front. Harmful algal blooms, fisheries, food safety/food security, coastal storm erosion, and an increase of maritime industrial activities are of immediate concern to regional coastal communities' nutritional, cultural, and economic well-being and continue to compound.

The future climate of the northern Bering/Chukchi Seas will be impacted by a combination of underlying warming, large interannual variability, and an increased frequency of extreme events. Projections for the next decades are for physical changes to initiate a continuing ecosystem transition impacting essential marine wildlife resources and regional residents. Physical–ecological–societal observations, and rapid understanding and dissemination of information to communities, are not keeping pace. There remain community, scientific, and regulatory challenges in response to ongoing and anticipated rapid change.

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