Evidence suggests potential transformation of the Pacific Arctic Ecosystem is underway

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Abstract

The highly productive northern Bering and Chukchi marine shelf ecosystem has long been dominated by strong seasonality in sea ice and water temperatures. Extremely warm conditions from 2017 into 2019 - including loss of ice cover across portions of the region in all three winters - were a marked change even from other recent warm years. Biological indicators suggest this state change could alter ecosystem structure and function. Here we report observations of key physical drivers, biological responses, and consequences for humans, including subsistence hunting, commercial fishing, and industrial shipping. We consider whether observed state changes are indicative of future norms, whether an ecosystem transformation is already underway, and if so, whether shifts are synchronously functional and system-wide, or reveal a slower cascade of changes from the physical environment through the food web to human society. Understanding of this observed process of ecosystem reorganization may shed light on transformations occurring elsewhere.

The Pacific Arctic, composed of the Chukchi and northern Bering seas (Figure 1), is one of the world's most productive ocean ecosystems (1), characterized by high benthic biomass resulting from persistent, nutrient rich flow through the Bering Strait (2) that fuels high primary production (3). In summer and fall, the region is home to millions of nesting and migratory seabirds, with hotspots of foraging activity shared with marine mammals (4), supporting coastal Indigenous communities. The delivery of nutrients together with the extent and timing of sea ice (5) are dominant environmental factors structuring this ecosystem. Freeze-up in fall and winter eliminates large expanses of open water, causing whales, Pacific walrus (*Odobenus rosmarus divergens*), many seals, and seabirds to migrate southwards into the Bering Sea and beyond (6).

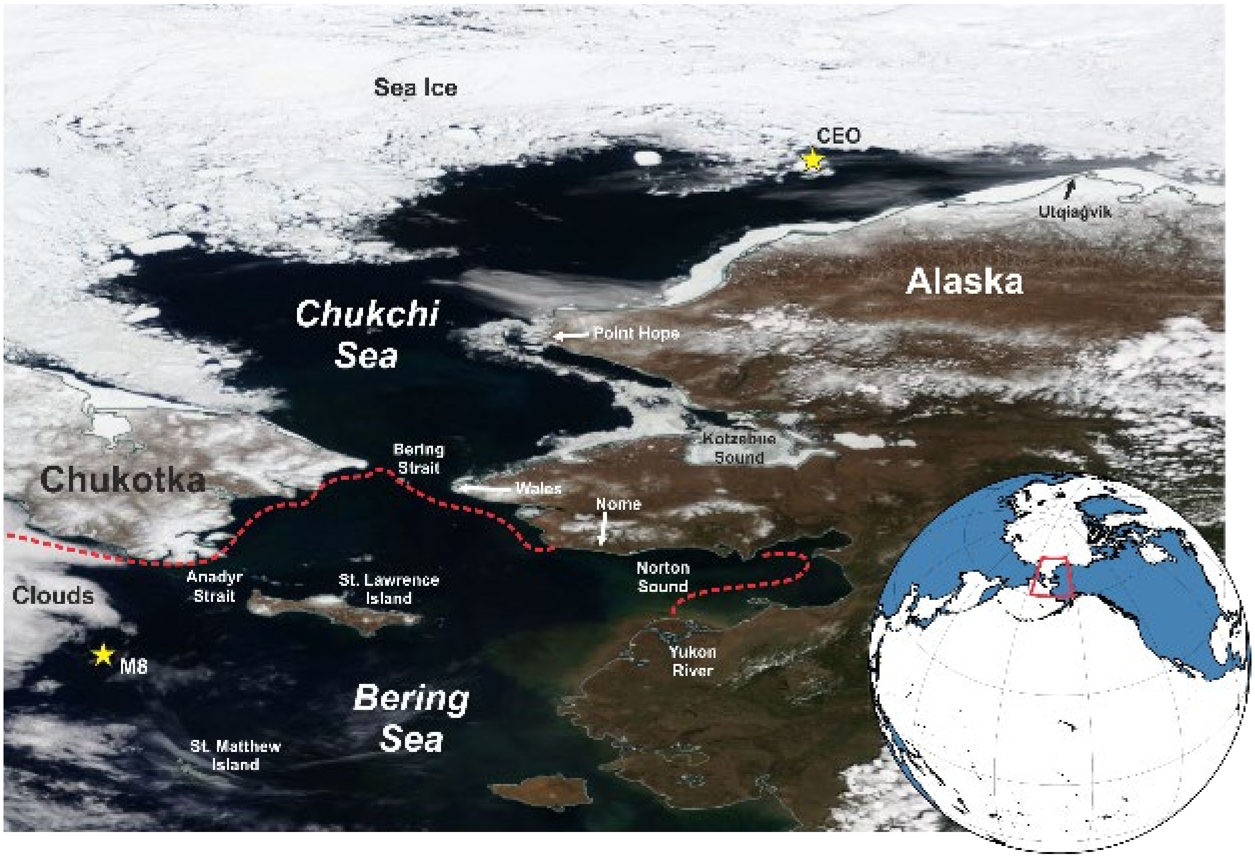


Figure 1. Sea ice changes in recent years. True-color MODIS satellite image showing northern Bering and Chukchi sea ice conditions on 2 June 2017. Red dotted lines denote the 1980-2010 ice edge climatology for June 2nd*. Yellow stars denote locations of oceanographic moorings M8 and CEO. Inset locates the study region. Image from NASA Worldview.*

In spring, the return of sunlight heralds snow melt, growth of sea ice algae, and a phytoplankton bloom that typically exceeds the consumption capabilities of pelagic consumers, resulting in carbon falling to the seabed, fueling rich benthic communities (7,8). Solar radiation and melting sea ice help stratify the upper water column, impeding the ability of winds to mix surface and subsurface waters. In summer, low-salinity surface waters near the pack ice remain cool relative to the shelf waters warmed by insolation. The Bering Sea cold pool, near-bottom shelf waters cooler than 2°C south of Bering Strait, has long served as a thermal barrier to northward migration of subarctic groundfish (9), which are major stocks for the southeastern Bering Sea's $2 billion fishery and account for about half the seafood landings in the United States (10,11).

Recent Changes in the Pacific Arctic Marine Ecosystem

Declining sea ice in this century has reduced surface albedo in spring and summer, accelerating oceanic heat uptake and causing earlier and more rapid sea ice melt (12). The pack ice and marginal ice zone has retreated north beyond the Chukchi shelf in recent summers, while warmer shelf waters delay sea ice formation in fall. Simultaneously, the northward flow of water through Bering Strait has increased, as has its temperature (2), so that it now delivers more heat, freshwater, nutrients, and biota northwards into the Arctic (13). Near-bottom water temperatures exceed 0°C for a larger portion of the year (Figure 2).

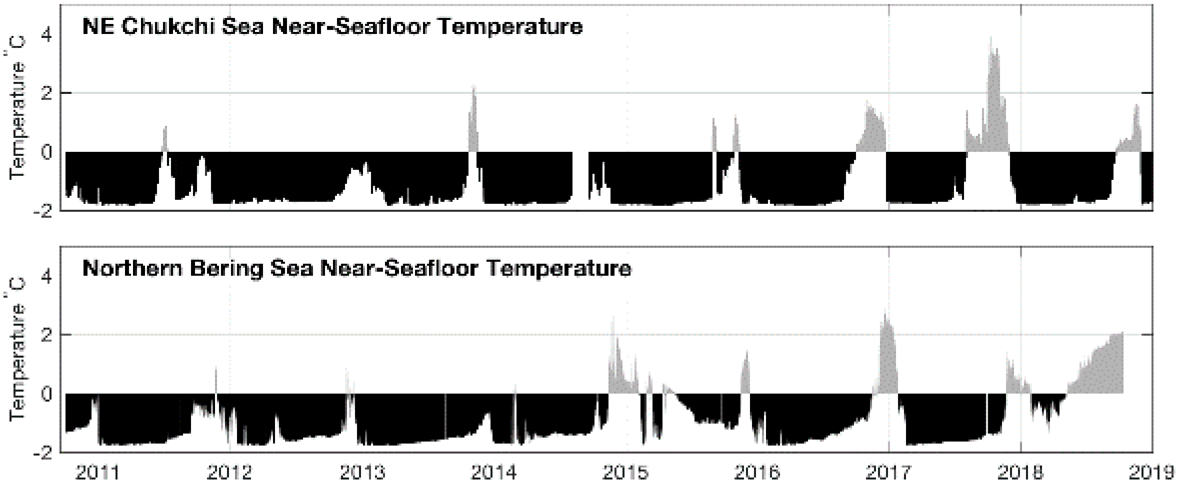


Figure 2. Near-bottom water temperatures. Previously, temperatures in important seafloor habitats remained below 0 ℃ for most of the year. In recent years, an increasing number of months exhibited temperatures well above 0 ℃. Mooring locations are indicated on Figure 1.

Ramifications of these physical changes have included more salmon in the Chukchi and Beaufort seas (14,15), walrus hauling out on shore in northwestern Alaska in late summer instead of on sea ice (16), an increase in the frequency and seasonal duration of killer whale (*Orcinus orca*) presence in the Chukchi Sea (17), an increase in planktivorous seabirds in the Chukchi Sea (18), and a northward shift in the distribution of other seabird species (19,20). For the Indigenous peoples of the region, spring marine mammal hunting opportunities dependent on the presence of sea ice have decreased and shifted in time (21), although the lack of sea ice has allowed additional whaling to occur in fall and early winter in the northern Bering Sea (22).

And Then Came 2017

In 2017, physical conditions in the Pacific Arctic marine shelf ecosystem of the Chukchi and northern Bering seas described above showed signs of a sudden and dramatic shift relative to historical means and even to other recent unusually warm years. In turn, these physical changes seemingly precipitated several significant ecological shifts, with consequences for the region's residents. Based on published and unpublished data from the authors, many changes persisted in 2018 and even into 2019, suggesting that 2017 was not a passing oddity of brief consequence to social-ecological systems, but a sign of what is to come.

In early January 2017, the sea ice edge had barely progressed south of Bering Strait and for the entire winter its extent remained at least $2x10^5$ km^2 below the long-term average. In June, ship-based observations found near-bottom ocean temperatures in Bering Strait of nearly 4 °C, over 3°C and four standard deviations warmer than the 1991-2016 June mean (2). Indeed, by June, the eastern Chukchi shelf was already mostly sea ice-free (Figure 1). In early December 2017, the ice edge was over 1000 km north of its climatological mean position near St. Lawrence Island. There was no sea ice in the Bering Strait in February 2018 and southerly winds forced a large ice retreat again in February 2019 (23). Waters in Norton Sound exceeded 10°C before the end of June 2018 and the cold pool was again minimal by late summer.

Reduced ice cover and warmer seas likely impacted primary production by influencing thermal, light, and stratification conditions. In spring of 2018, in the southern Bering Sea, the bloom was delayed due to a lack of freshwater input from melting sea ice, and chlorophyll concentrations were an order of magnitude lower than usual; however in the northern Bering Sea the ice-associated bloom was early and extensive (24). In addition, the detection of domoic acid in shipboard water samples (Figure 3) and saxitoxin in a few stranded and harvested walruses from Bering Strait villages led to concern about harmful algal blooms and food safety from Indigenous residents, though analytical challenges make the impact difficult to determine (25).

Changes in species distributions had already been observed this century, but not to the extent observed in 2017. The copepods *Calanus glacialis/marshallae* in 2017 were found to be remarkably low in abundance relative to 2012-2015 (Figure 4). Multispecies epibenthic biomass in the southern Chukchi Sea also exhibited a pronounced decline relative to comparable collections in 2004, 2009, 2012, and 2015 (Figure 4). In contrast, acoustic-trawl surveys indicate that age-0 Arctic cod abundance was dramatically higher in the Chukchi Sea in 2017 compared with previous surveys: backscatter in the northern Chukchi Sea (67 N to 71.5 N) was 5.6 times greater than in 2013, and 16.3 times greater than in 2012 (Figure 5), but the fish had low energy content. Juvenile pink salmon (*Oncorhyncus gorbuscha*) catch per unit effort in surface trawl surveys in the northern Bering Sea was two times greater during 2017 than previous years (Figure 4). Juvenile pink salmon return as adults the following year, and the adult pink salmon return to Norton Sound was much stronger than expected during 2018 (27). Adult walleye pollock (*Gadus chalcogramma*), Pacific cod (*Gadus macrocephalus*), and northern rock sole (*Lepidopsetta polyxystra*) biomass in bottom trawl surveys increased in the northeastern Bering Sea during 2017, likely due to northward movement of these fishes in the absence of the Bering Sea cold pool (28).

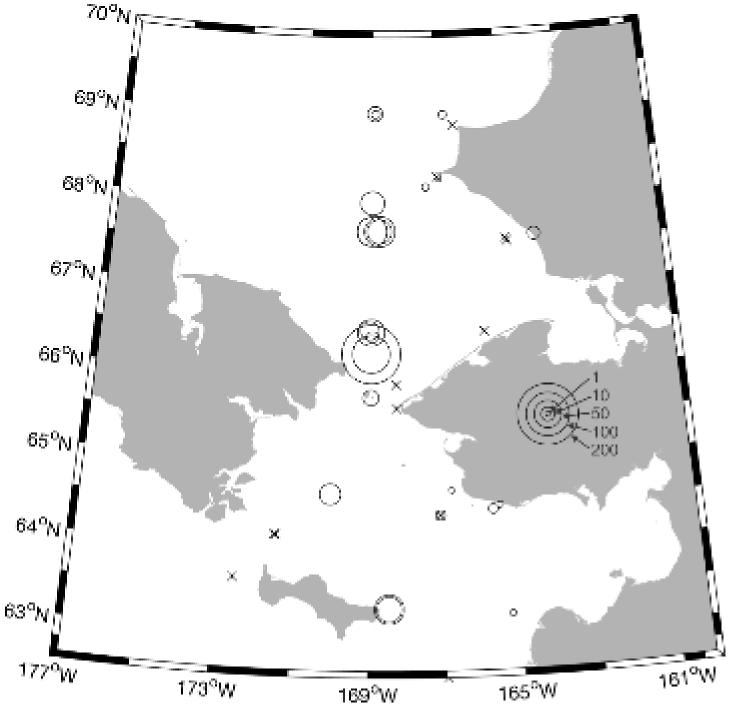


Figure 3. Seawater concentrations of domoic acid, June 2017. NTD = no toxin detected.

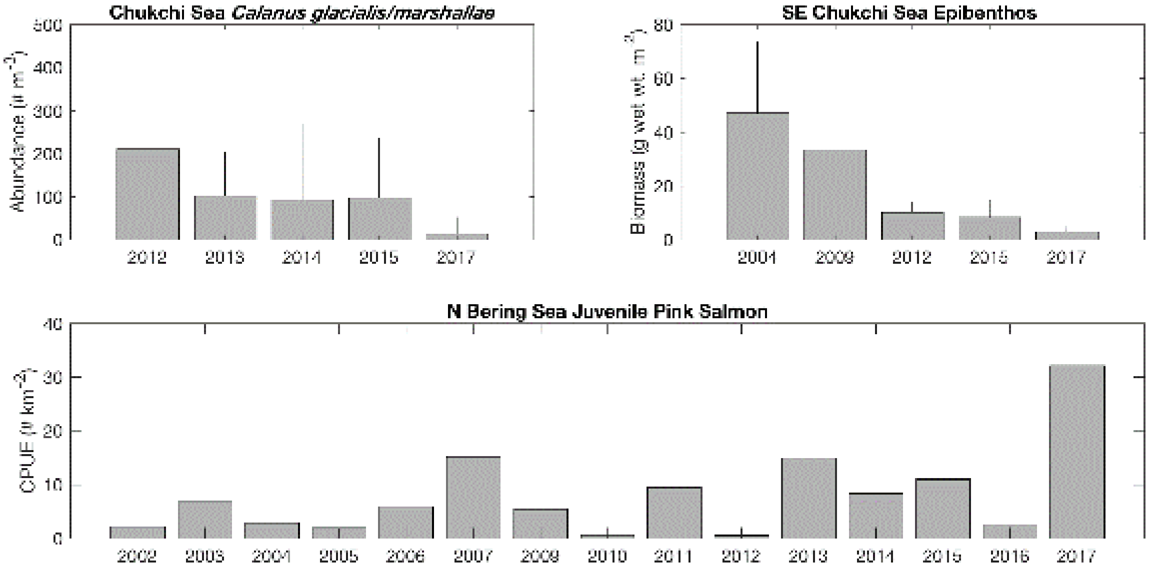


Figure 4. Biological changes in recent years. Observations show declines of Calanus glacialis/marshallae abundance (upper left) and epibenthic biomass (upper right) in 2017

relative to prior years, and an increase in juvenile pink salmon catch per unit effort (CPUE) (bottom). The graphs in upper left and upper right show simple means and standard deviation error bars.

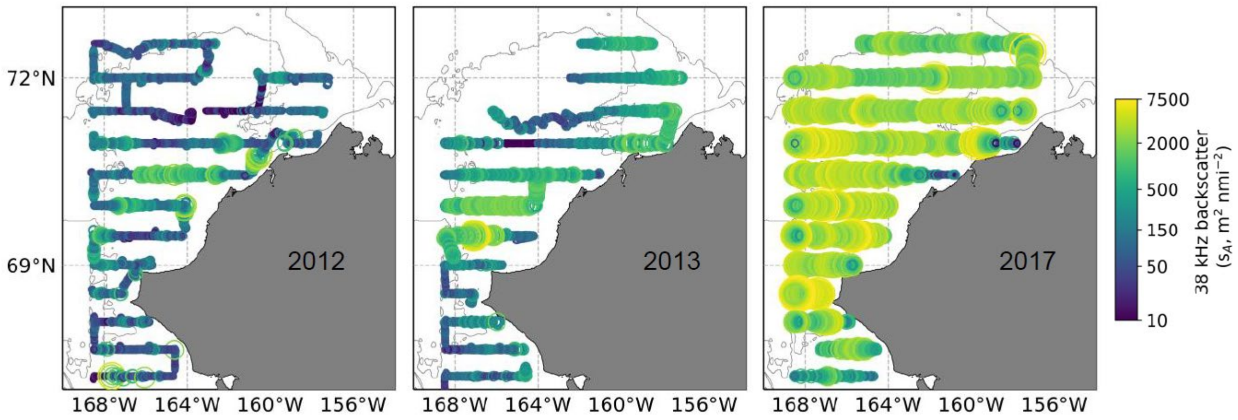


Figure 5. Arctic cod abundance change. Acoustic surveys indicate that the abundance of age-0 Arctic cod increased substantially in 2017 relative to 2012 and 2013. Trawl sampling indicated that Arctic cod dominated acoustic backscatter in this area in 2012 and 2013 (26). This was also the case in 2017: Arctic cod accounted for 95.4% of fish captured in 33 midwater trawl hauls.

In offshore waters, total seabirds declined from 2012-2017 in the southern and northern Bering Sea, but densities were above the long term mean in the Chukchi Sea during most of that period. The increase in the Chukchi Sea in 2015-2017 was primarily due to short-tailed shearwaters (*Ardenna tenuirostris*), which feed primarily on euphausiids, and less pronounced increases in piscivorous black-legged kittiwakes (*Rissa tridactyla*) and murres (*Uria* spp). In contrast, planktivorous auklets (*Aethia* sp.) had low densities in the Chukchi Sea in 2017 and 2018 but increased in the northern Bering Sea those years (24). Reproductive success was low for seabirds in the Bering Sea in 2017-2018, and there were mixed-species die offs there and in the Chukchi Sea (24,29;), with dead birds emaciated. Notably, numbers of murres and kittiwakes attending the large Chukchi Sea colony continued to increase (30) at a rate suggesting immigration of piscivorous nesting birds.

In the spring of 2017, bowhead whales, including females with calves, were seen near Utqiaġvik, Alaska, a month earlier than usual and the Utqiaġvik whale hunt recorded the earliest known landing, on 13 April. Four bowhead whales equipped with satellite transmitters all wintered (2017/18) in the Chukchi instead of their usual wintering area south of Anadyr Strait in the Bering Sea (31) and a bowhead was recorded singing near Utqiaġvik on 11 January 2018, something never recorded before at that time of year. In 2018/19, the bowheads were again north of Anadyr Strait in winter. Spotted seal (*Phoca largha*) pups in the spring of 2018 were found in poorer condition (less fat and lower mass/length) than in recent years, and almost no ribbon seals (*Histriophoca fasciata*) were seen during those same surveys, raising the specter of a failure in the 2018 year class. In the spring and summer of 2018 and 2019, more than 280 bearded (*Erignathus barbatus*), ringed (*Pusa hispida*), spotted, and unidentified seal carcasses, primarily young and many emaciated, were reported from beaches mostly of the northern Bering and southern Chukchi seas, nearly five times the annual average from 2014-2017, prompting the National Oceanic and Atmospheric Administration to declare an "unusual mortality event" (32).

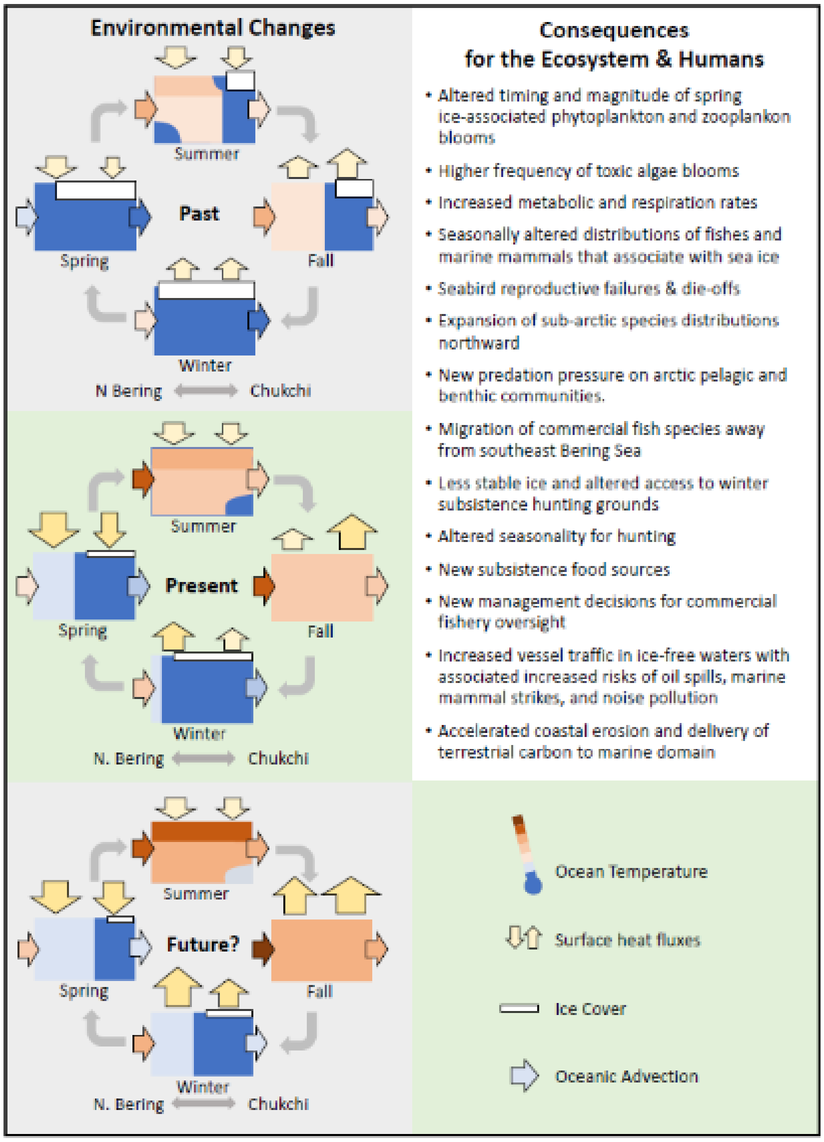
Anomaly or Transformation?

Changes in sea ice extent, water temperature, currents, zooplankton abundance, animal distribution and health, hunting success, and other aspects of the ecosystem are noteworthy in themselves, but such large-scale changes could conceivably occur without altering basic relationships among ecosystem components. The investigation of specific mechanisms underlying these changes were not part of the cited studies, however it is known from other areas, including the southern Bering Sea, that the spring sea-ice break-up spurs a productive phytoplankton bloom, and its timing together with ocean temperatures determines phytoplankton species composition, carbon export to the benthos, and food quality for zooplankton (24). Changes towards lower-lipid zooplankton reduces over-winter survival of fishes such as salmon and Arctic cod (33), even if they increase numerically in summer due to favorable thermal and oceanographic conditions. Lower zooplankton food quality and increased competition from predatory fish moving north from the Bering Sea might explain seabird and seal mortality.

The ecosystem-wide changes seen in 2017-2019 have the potential to fundamentally reconfigure the Pacific Arctic marine food web. An altered physical environment characterized by warmer waters and a longer open-water season is allowing subarctic species to establish themselves in the Chukchi Sea; seasonally for now, but possibly year-round in the future. Subarctic invaders such as walleye pollock and Pacific cod could fundamentally transform interactions among pelagic species, benthic invertebrates, groundfish, seabirds, and marine mammals by exerting strong predation pressure on forage fishes and benthic crab, worm, and shrimp communities (10). Predation pressure from these fishes adds top-down stresses to the bottom-up changes associated with altered temperature and primary and secondary productivity. Indigenous hunters may begin to find familiar species of fishes and marine mammals at unusual times of year or unfamiliar species during customary hunting and fishing periods (21).

An interdisciplinary look at the Pacific Arctic marine ecosystem as it changes may provide a rare opportunity to track ecosystem transformation in detail as it unfolds, rather than reconstructing details after the fact. The transformation of an ecosystem may reflect a cascade of sequential changes that take place over multiple years rather than a single shift or tipping point (e.g., 34), though changes to individual ecosystem components may be sudden and dramatic. For example, because of positive feedbacks in the climate system (e.g., 12) it is possible that 2017 marked the crossing of a threshold that precludes return to the system state common just a decade ago. We find that a closely coupled synergy between bottom-up and top-down factors (e.g., 35) appear to best characterize this system's transition, and the interactions among these multiple stressors have important implications for understanding any subsequent reorganization.

The result would be the transformation of an Arctic marine ecosystem into one characterized by subarctic conditions, subarctic species, and subarctic interactions (Figure 6). The Chukchi Sea may soon resemble the east-central Bering Sea shelf in condition, structure, and function, with annual sea ice, warmer bottom water temperatures, and ecosystem productivity derived from forage fishes and pelagic zooplankton rather than the benthos. Changes in the historically strong benthic-pelagic coupling have already been observed in the southeastern Chukchi Sea, where overall epibenthic biomass declined by an order of magnitude from 2004 to 2017; the fact that the most abundant taxa were consistent over time may hint at overall changes in ecosystem productivity or pathways rather than specific habitat changes (36,37). Yet this transformation is more complex than an ecosystem migrating north. For example, the Chukchi Sea would likely retain some characteristics distinguishing it from the Bering Sea shelf, due to higher latitude and downstream location relative to the Bering Strait nutrient supply. How these competing features will combine to create a new state of the Pacific Arctic ecosystem remains to be seen.



Consequences for the Ecosystem & Humans

- Altered timing and magnitude of spring ice-associated phytoplankton and zooplankon blooms
- Higher frequency of toxic algae blooms
- Increased metabolic and respiration rates
- Seasonally altered distributions of fishes and marine mammals that associate with sea ice
- Seabird reproductive failures & die-offs
- Expansion of sub-arctic species distributions northward
- New predation pressure on arctic pelagic and benthic communities.
- Migration of commercial fish species away from southeast Bering Sea
- Less stable ice and altered access to winter subsistence hunting grounds
- Altered seasonality for hunting
- New subsistence food sources
- New management decisions for commercial fishery oversight
- Increased vessel traffic in ice-free waters with associated increased risks of oil spills, marine mammal strikes, and noise pollution
- Accelerated coastal erosion and delivery of terrestrial carbon to marine domain

Figure 6. Environmental changes and related consequences. Observed and potential future changes in the physical environment (left panels) in the Northern Bering and Chukchi shelf systems (i.e., bottom-up forcing), along with observed and anticipated consequences for the biological and human components of the ecosystem (right panel).

In addition to its regional significance, the pattern of change underway in the Pacific Arctic may eventually shed light on the progression of ecosystem transformation more generally (38), which manifests as large-scale alterations in the connections and interactions among species and among physical and biological processes. Overpeck et al. (39) suggested the possibility of such a transformation resulting from the removal of perennial ice in the Arctic, though they focused on "before" and "after" states of the system without describing the transformation in between. The pioneering work of Gunderson and Holling (40) recognized that transformation and reorganization are less predictable and less well understood than a simple shift from stability to instability.

What To Expect Next?

The expectation is for the sea ice season to further shorten and sea ice coverage to diminish (41). Waters will become warmer and stay warm longer into fall and winter. How quickly these changes propagate through and persist in the system, and what additional sudden shifts may occur, are hard to predict. It is likely, however, that there will be differences in the temporal and spatial scales over which physics and biology change (42). Physical conditions that were once anomalous may become normal. The biological response will follow but may not carry over across years until species and behaviors that thrive in the new conditions are able to persist. Hunters and fishers will adjust to some degree but may find it necessary to switch the timing or targets of their efforts (43).

Specific trajectories of these changes and their implications for the Pacific Arctic ecosystem, including Indigenous coastal communities, are still unclear. To stay with or ahead of these system transformations rather than reacting to a new state some years from now, some critical unknowns, especially regarding ecosystem relationships, require further attention and continued monitoring at multiple scales. As sea ice retreats earlier, will some species cling to existing fixed habitats (e.g., depositional zones) and remain largely in place, while others follow shifting habitats (such as the ice edge)? Will subarctic species be able to flourish and persist in the Chukchi Sea year-round, transforming the ecosystem into a locus of groundfish or pelagic predator abundance? Will increased industrial activity such as shipping combine with climate-driven ecosystem changes in ways that amplify the consequences of either alone (44)? How can coastal communities adjust and adapt quickly enough to retain cultural and nutritional security (45)?

Even in this age of information overload, it is how remarkable how scarce (and thus how valuable) the available data are for making statistically robust comparisons of today's conditions versus yesterday's. For example, quantifying changes in primary and secondary productivity cannot immediately follow the spring retreat of sea ice because previously the ice itself precluded ship-based measurements at locations and times now ice-free. Across the study region, even 15 years of annually collected data is an unusually long time series, and for biological parameters most of these data are confined to summer months. Hence, it is important to learn to distinguish surprises from completely new observations.

A cascade of effects through an ecosystem may include tipping points governed by positive feedbacks for individual components, making recovery to the previous structure and function ever less likely (e.g., 34,46). Top-down changes such as increased predation may result from bottom-up changes such as the removal of thermal barriers to range expansion of predators. The experience to date in the Pacific Arctic by itself will not resolve these questions, but it does suggest that, with regard to cascades versus tipping points or top-down versus bottom-up controls (e.g., 47), ecosystem transformation may be a complex matter of “both and” rather than a simple dichotomy of “either/or.”

These questions are more than a curiosity (48). The well-being of coastal communities and the management of human activities in the region, including potential commercial fisheries, depend on reliable information and insight into what is likely to happen next. In Alaska waters, industrial and research activities are planned in ways to reduce interference with Alaska Native subsistence harvests, and conscientious vessel operators communicate with communities and adjust their plans to avoid areas where hunters are active (e.g., 49). Growing uncertainty about the timing of animal migrations and optimal harvest conditions increases the likelihood of conflict and concerns about food security. Coastal communities are likely to face difficult choices between capitalizing on increased economic opportunity and limiting industrial interference with subsistence activities.

The profound shift in ecosystem state and conditions suggest a new framework is needed to replace the paradigm that served well in recent decades. The Pacific Arctic marine ecosystem transformation is not an isolated case. Social-ecological systems worldwide are facing similar pressures from changing physical conditions, with implications that are increasingly uncertain as transformation propagates through the food web and to human outcomes (50). Long-term and multi-scale data are necessary to detect, examine, and respond to such changes. A better understanding of the nature of system transformation will help humans detect transformations earlier, perhaps in time for more effective response or adaptation, even if prevention may no longer be possible.

Data Availability

All data collected as a part of the North Pacific Research Board's Arctic Integrated Ecosystem Research Program (Arctic IERP) are being curated and preserved. Because the research is actively ongoing, the data are under program embargo through July 2021. At that time, all Arctic IERP data will be publicly released with a CC-0 license from the Research Workspace DataONE Member Node, and this paper will be cited in the DOI for those data, to create a formal link. In the interim, please contact the authors for access to Arctic IERP data.

In Figure 1, we acknowledge the use of imagery from the NASA Worldview application (https://worldview.earthdata.nasa.gov/), part of the NASA Earth Observing System Data and Information System (EOSDIS). Ice-edge marking is from Maslanik, J. and J. Stroeve. 1999. Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations, Version 1, F17. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/U8C09DWVX9LM. Accessed 12-December-2018.

2015 epifauna data are available at https://doi.org/10.25921/b2g4-bs86.

Other data are available on request, pending curation and archiving as part of ongoing studies.

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Author Contribution Statement

HPH, SLD, FKW, EF, CL, and KS developed the idea and contributed to writing and editing the paper. MB, PB, JJC, ADR, DD, JCG, KI, DGK, KK, RL, LQ, PS, DS, and CW wrote sections of the paper and contributed to editing of the manuscript. All authors provided data and reviewed the final manuscript and approved it for submission and publication.

Competing Interests

The authors declare no competing interests.

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