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SYNTHESIS

Multiple climatic drivers increase pace and consequences of ecosystem change in the Arctic Coastal Ocean

Mikael K. Sejr[1]*, *Amanda E. Poste*[2] *Paul E. Renaud*[3,4]
[1]Department of EcoScience, Arctic Research Center, Aarhus University, Aarhus C, Denmark; [2]Norwegian Institute for Nature Research, Fram Centre for Climate and the Environment, Tromsø, Norway; [3]Akvaplan-niva, Fram Centre for Climate and the Environment, Tromsø, Norway; [4]Department of Arctic Biology, University Centre in Svalbard, Longyearbyen, Norway

Abstract

The impacts of climate change on Arctic marine systems are noticeable within the scientific "lifetime" of most researchers and the iconic image of a polar bear struggling to stay on top of a melting ice floe captures many of the dominant themes of Arctic marine ecosystem change. But has our focus on open-ocean systems and parameters that are more easily modeled and sensed remotely neglected an element that is responding more dramatically and with broader implications for Arctic ecosystems? We argue that a complementary set of changes to the open ocean is occurring along Arctic coasts, amplified by the interaction with changes on land and in the sea. We observe an increased number of ecosystem drivers with larger implications for the ecological and human communities they touch than are quantifiable in the open Arctic Ocean. Substantial knowledge gaps exist that must be filled to support adaptation and sustainability of socioecological systems along Arctic coasts.

More than a third of the global coastline is found along the three continents that encircle the Arctic Ocean (Carmack et al. 2015). No single definition exists for the Arctic coastal ecosystem, but here we use the Riverine Coastal Domain (RCD; Carmack et al. 2015), defined as the contiguous ~ 15 km wide zone characterized by unique physical, chemical, and biological conditions driven primarily by input of freshwater from land. While there are obvious commonalities in ecological processes, we argue that there are important contrasts between the RCD and the open-ocean systems of both the Arctic Ocean and its broad continental shelves. This paper aims to review the specific processes driving ecological changes in the Arctic coastal ecosystem and to identify key knowledge gaps.

The classical view of the open Arctic Ocean marine ecosystem posits a short-lived spring bloom of primary production by microscopic phytoplankton, either associated with sea ice or in the water column, where a significant proportion of the total primary production can take place within a few weeks (Wassmann et al. 1999). This production relies on inorganic nutrients transported upward to surface waters. Phytoplankton near the sunlit surface is consumed by zooplankton, resulting in transfer to higher trophic levels and the sinking of fecal pellets and aggregates of organic matter to the seafloor where they sustain the benthic compartment (Wassmann and Reigstad 2011). Processes are highly seasonal, driven by light and nutrient availability and modified by the presence of sea

*Correspondence: mse@ecos.au.dk

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ice and snow cover. Thus, in open Arctic seas, climate change primarily impacts the ecosystem through warming and sea-ice loss, and their implications for light and nutrient availability (Ardyna and Arrigo 2020). Primary production in the coastal ocean ecosystem differs from offshore in that production in the water column is supplemented by producers on the sea floor. In the Arctic, light penetrates to the sea floor in many areas and biomass of macroalgae can exceed 30 kg wet weight m^{-2} (Sejr et al. 2021) with annual production rates of several 100s g C m^{-2} yr^{-1} (Pessarrodona et al. 2022), thus exceeding area-specific biomass and productivity of phytoplankton by orders of magnitude. The particulate and dissolved organic matter generated by benthic production enters coastal food webs and fuels biogeochemical cycles (Renaud et al. 2015*a*). Furthermore, significant quantities of organic matter originating from terrestrial ecosystems enter the coastal zone through river discharge and shoreline erosion. Hence, the coastal ecosystem relies on three main sources of organic matter (pelagic production, benthic production, and terrigenous input), each of which supports different types of consumers (Dunton et al. 2006; Harris et al. 2018; McMeans et al. 2013). The contribution from these two additional sources of carbon unique to the coastal ocean is substantial. The total net pelagic production in the Arctic Ocean by phytoplankton has been estimated from remote sensing to be 540×10^6 t C yr^{-1} (Babin et al. 2015). The gross annual benthic production of microphytobenthos is estimated at 115×10^6 t C yr^{-1} (Attard et al. 2016), while the potential net production by macroalgae is estimated to be 7300×10^6 t C yr^{-1} (combining potential macroalgae area in the Arctic (Assis et al. 2022) and the average Arctic macroalgal production (Pessarrodona et al. 2022)). The input from land has been estimated to be $18–26 \times 10^6$ t C yr^{-1} of dissolved carbon, $4–6 \times 10^6$ t C yr^{-1} of particulate carbon from rivers (Dittmar and Kattner 2003), and 6.7×10^6 t C yr^{-1} from coastal erosion (Semiletov et al. 2011). There are smaller but locally important contributions of organic matter from the Greenland Ice Sheet (Lawson et al. 2014) and groundwater (Connolly et al. 2020). All these estimates come with considerable uncertainty but show that (1) the contribution of carbon sources unique to the coastal ocean (benthic production and terrigenous carbon) equals or possibly exceeds that of pelagic primary production of the open ocean; and (2) for the coastal ocean there are periods and habitats where these carbon sources dominate. Thus, coastal ecosystems are sustained by organic matter whose bioavailability, phenology, and response to climatic impacts are vastly different than that of the pelagic ocean ecosystem.

At lower latitudes, it has long been recognized that estuarine-coastal ecosystems provide extensive ecosystem services for society but also are impacted by a unique combination of natural and anthropogenic forcings (Barbier et al. 2011). The concept of meta-ecosystems defined as a set of ecosystems linked by flows of energy, materials, and organisms has been applied to describe the connectivity between terrestrial processes and coastal ecosystems through the flow of freshwater into estuaries (Loreau et al. 2003). This connectivity can cause problems related to nutrient enrichment in lakes, rivers, and streams, with subsequent eutrophication of coastal waters being a key application (Cloern 2001). The lateral export of terrestrial matter by rivers into the coastal zone and subsequent horizontal gradients in density, light, and nutrient dynamics created by the freshwater input mean that focus is on lateral advection in coastal environments in contrast to the emphasis on the vertical fluxes in the open ocean. This is especially relevant in the Arctic where warming increases precipitation and snow and ice melt which increases freshwater input into the ocean and intensifies the land-coast coupling (Hernes et al. 2021). Taken together, these contrasts in key ecosystem services such as productivity, connectivity, harvestable resources, biodiversity, and uptake of greenhouse gases suggest that the coastal ecosystem will respond along a different trajectory and at a different pace than the open Arctic Ocean.

Coastal change is more pronounced

Warming temperatures, sea-ice loss, and the cascading effects on pelagic ecosystems are the "face" of Arctic Ocean change (Wassmann et al. 2020). But coastal systems are impacted by a broader set of drivers that are unique to, and/or magnified in, the coastal region (Table 1). Four such drivers are the modification of Arctic shorelines, glacial retreat, increased freshwater runoff, and increased human activity (Fig. 1). Each of these drivers, alone and in combination with other drivers, have manifold consequences for specific ecosystem changes. For example, in open-ocean systems warming and sea-ice melt influence pelagic primary production via impacts on stratification. Warming and melting throughout the cryosphere, combined with increased runoff from land, have arguably greater consequences for coastal primary production through their impacts on stratification, underwater light fields, nutrient concentrations, and acidification (Demidov et al. 2023; Etherington et al. 2007). Here, we argue that the limited evidence available suggests most changes in large-scale drivers and their ramifications for changes in environmental factors are more pronounced in coastal than in offshore systems (Table 1).

Warming

Seawater temperatures are impacted by increasing atmospheric temperatures and by local and regional processes, including advected heat from ocean currents and from atmospheric weather patterns. Modeling studies over the entire Arctic basin predict greater warming within the top 200 m of the water column will occur in nearshore regions (Renaud et al. 2015*b*). River discharge also contributes heat to the Arctic coastal zone, a mechanism that has contributed up to 10% of coastal sea-ice loss (Park et al. 2020). Suspended sediments in river water entering the sea absorb solar radiation, further warming coastal waters.

Table 1. Overview contrasting change in key environmental drivers, ecosystem structure and function and societal impacts in the near coastal zone and the offshore Arctic Ocean. Red shading indicates drivers or changes that are only (or primarily) relevant for the coastal zone. Yellow shading indicates ecosystem changes where the direction of change and key drivers differ between near coastal and offshore areas. Blue shading indicates a change that is occurring in the same direction in both near coastal and offshore areas, with darker blue indicating where observed/predicted change is higher. Select key references are included in the table, while additional references and details can be found in the main text.

	Coastal zone	Offshore
Environmental drivers		
Warming	Yes (IPCC 2019)	Yes: although less than along coast (Carvalho et al. 2021)
Changing cryosphere	Yes: permafrost thaw, glacial melt, loss of land-fast ice (Barnhart et al. 2014; Hernes et al. 2021)	Yes: sea-ice loss (Crawford et al. 2021)
Changing human activity	Yes: particularly relevant for coastal environment (Alvarez et al. 2020)	Yes: although less pronounced than for coastal regions (Bartsch et al. 2021)
Shoreline change/erosion	Yes (Irrgang et al. 2022)	
Increased runoff	Yes (Feng et al. 2021)	
Ecosystem changes		
Changing light availability	Yes: trade-off between sea ice loss and increased attenuation due to runoff (increased turbidity, cDOM (Singh et al. 2022)	Yes: increased light availability due to sea ice loss (Bélanger et al. 2006)
Freshening	Yes: driven by terrestrial runoff (including from glaciers) and sea-ice melt (Sejr et al. 2017)	Yes: driven by sea ice melt. Lower than along coast.
Acidification	Yes: driven by increased atmospheric CO_2 and terrestrial runoff (dilution and geochemical changes) (Henson et al. 2023)	Yes: driven by increased atmospheric CO_2 and less sea ice (AMAP 2018)
Changes in organic matter (OM) quantity and/or quality	Yes: driven by shifts in terrestrial runoff (Fichot et al. 2013)	*Likely, but less pronounced* (*driven by changes in primary production and OM mineralization*)
Nutrients	Increased due to terrestrial runoff (regionally variable) (Meire et al. 2017)	Decreased due to increased stratification. (Farmer et al. 2021)
Contaminants	Increased Hg due to permafrost thaw (Chételat et al. 2022)	*Likely, but less pronounced* (*broad-scale climate-driven changes in transport and cycling of contaminants*) (AMAP 2021*a*)
Ecosystem responses		
Pelagic primary production	Yes: observed and predicted increases (strongest along coast), due to riverine nutrients and sea-ice loss. However, an unclear impact of changing coastal light attenuation (Terhaar et al. 2021)	Yes: Observed and predicted increases, due to sea-ice loss (also attributed to changes in nutrient, and plankton biomass) (Lewis et al. 2020)
Benthic primary production	Yes: predicted strong increase (due to reduced land fast ice) (Assis et al. 2022)	
Changing species distributions	Yes: due to warming, arrival of boreal species, habitat changes. Risk for invasive species linked to shipping (Renaud et al. 2015*b*)	Yes: especially due to loss of sea-ice habitat (Michel et al. 2012)
Societal impacts		
Infrastructure	Yes: coastal erosion and permafrost thaw threaten coastal infrastructure (Nielsen et al. 2022)	
Safety	Yes: unsafe ice; increased shipping traffic and hazards; increasing trend in search and rescue activities in some Arctic coastal areas (Ford et al. 2021)	Yes: increased shipping traffic may increase risk of accidents (Fu et al. 2021)

(Continues)

Table 1. Continued

	Coastal zone	Offshore
Fisheries	Yes: increased risk associated with subsistence fishing from land-fast ice. Changing species distributions impact coastal fisheries (Galappaththi et al. 2019)	Yes: changing species distributions and sea-ice conditions impact fisheries (areas of activity and target species) (Van Pelt et al. 2017)

Cryosphere

The loss of sea ice, a key indicator of Arctic climate change, has been well documented (Kwok 2018). Remote sensing studies have revealed pronounced increases in the duration of the coastal open-water season, with typical increases ranging from approximately 10–25 d decade^{-1} (Barnhart et al. 2014), in contrast to the open Arctic Ocean with 5–6 d decade^{-1} (Crawford et al. 2021). Whereas the loss of sea ice has many of the same effects in both coastal and open-ocean environments, the coastal zone is also impacted by changes in glaciers

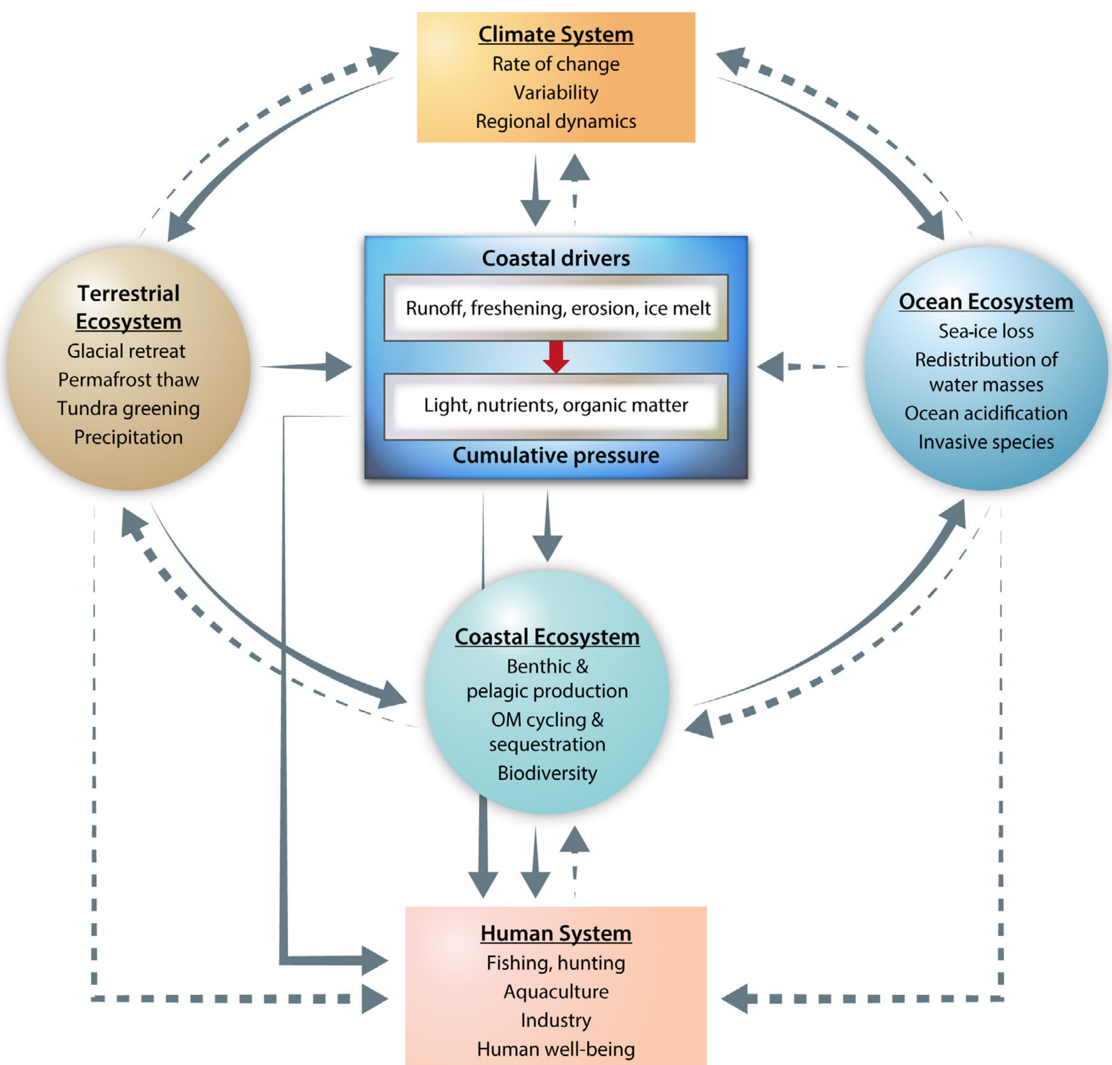

Fig. 1. Schematic representation of the how climatic driven changes in both the ocean and terrestrial ecosystems amalgamate in the coastal ocean with specific influence on the distribution and availability of light, nutrients, and organic matter which are key drivers of biogeochemical and biological changes. Note that most of the strongest impacts (solid arrows) originate in the coastal zone and not the terrestrial or open-ocean regions, where direct impacts are weaker (dotted arrows).

and permafrost. In Greenland (King et al. 2020), for example, the annual net mass-loss rate of the Greenland ice sheet has increased sixfold since the 1980s (Mouginot et al. 2019). Glacial meltwater entering the coastal region creates distinct physical and biogeochemical gradients (Meire et al. 2017), with subsequent impacts on ecosystem structure and function (Hopwood et al. 2020). With the continued retreat of glacial fronts, more glaciers will eventually change from having the glacial front in the ocean to having it on land. This change will profoundly alter the delivery of meltwater with consequences for vertical mixing, fjord circulation, and light and nutrient availability (Hopwood et al. 2020). Permafrost thaw is also accelerating in most Arctic regions and contributes to an increase in total river discharge and the delivery of both organic and inorganic materials to the coast (Hernes et al. 2021).

Human activity

Ship traffic through the Arctic breaks ice to make shipping lanes. A key emerging route is the northern sea route along the Russian coasts where the number of annual transits has been increasing exponentially, resulting in small-scale changes in ice distribution, heat exchange, and light penetration, as well as increasing vulnerability for introduction of non-native species from ship hulls or ballast water discharge (Miller and Ruiz 2014). This activity and its consequences are arguably more prevalent in coastal regions where ice-breaking is concentrated around ports and industrial installations. Coastal areas are also affected by other human activities, including both local and regional consequences of coastal infrastructure, fishing, tourism, petroleum, mining, and discharges of sewage (Vincent 2020), which result in a stronger direct human footprint compared to the open ocean. The continued loss of sea ice is increasing the accessibility to the Arctic and is projected to result in greater economic activity, with concurrent expansion of coastal infrastructures (Alvarez et al. 2020).

Shoreline change

Shoreline change includes both coastal erosion and other geomorphological dynamics, such as building and moving of river deltas (Bendixen et al. 2017). The latter is little studied, although changes in sedimentary environments can profoundly alter the Arctic coastal region where these habitats dominate. The erosion of Arctic coasts is accelerated by the loss of sea ice and land-fast ice. As sea ice disappears, wind generates bigger waves, while melting of permafrost makes coastlines more vulnerable to erosion. As a result, coastal erosion happens throughout the Arctic and with rates that have increased by a factor of 2–3 in recent decades (Nielsen et al. 2022). Erosion has strong implications for the coastal ocean through the delivery of both organic matter and nutrients, and through its impacts on coastal infrastructure. Coastal erosion delivers as much organic matter to the ocean as all Arctic rivers combined (Vonk et al. 2012; Wegner et al. 2015) and the nutrients released have been estimated to sustain about 20% of the coastal primary production (Terhaar et al. 2021).

Runoff

Freshwater runoff into the Arctic Ocean has been estimated to have increased by 0.22% per year since 1984 (Feng et al. 2021) but with substantial regional differences. Importantly, much of this runoff is retained within the RCD. Changing runoff patterns are strongly influenced by several of the drivers already mentioned (warming, cryosphere loss), as well as changes in precipitation patterns (Box et al. 2019). The input of freshwater affects the coastal ocean in several ways, including reduced salinities and increases in heat, nutrients, organic matter (OM) and contaminants (Hernes et al. 2021). The combination of these effects contributes to why the response of coastal ecosystems to climate change will follow different trajectories than those of the open ocean.

Light availability

Thinning and loss of both sea ice and land-fast ice will, all else being equal, result in increased light penetration into the water column, with profound consequences for marine primary producers. In nearshore habitats, however, increased input of sediments and colored dissolved organic material (cDOM) combined with resuspension and erosion may reduce light penetration. A remote sensing analysis covering the Arctic coastal ocean found that increased turbidity resulted in a 22% increase in light attenuation between 2003 and 2020, largely canceling out the light enhancement caused by decreasing ice cover (Singh et al. 2022). This provides a good example of how dynamics in a central parameter controlling ecosystem productivity are driven by different processes not only with different outcomes in the coastal ocean compared to open-ocean environments, but also with substantial local and regional variability along Arctic coasts.

Acidification

Acidification of the oceans is driven by the uptake of CO_2 from the atmosphere and can impact cellular processes, energy balance, and calcification potential in marine organisms. The loss of sea-ice cover increases the area and seasonal duration for air-sea exchange of CO_2, making the Arctic especially vulnerable to acidification (Terhaar et al. 2020). The solubility of CO_2 is temperature dependent and warming will moderate some of the acidification potential. Increased freshwater from riverine input and melting sea ice and glaciers decreases seawater alkalinity and substantially exacerbates acidification in coastal regions (Henson et al. 2023; Yamamoto-Kawai et al. 2009). Thus, models for the end of the 21st century predict declines in aragonite saturation state in the coastal Arctic to be at least a factor of 5 greater than in the open Arctic Ocean (Renaud et al. 2019). Photosynthesis, which takes up CO_2, and degradation of organic matter, which releases CO_2, contribute to significant spatial and seasonal variation in acidification in both habitats (Henson et al. 2023; Krause-Jensen et al. 2015).

Organic matter

Cycling of organic matter (OM) in offshore marine waters is dominated by pelagic primary production and subsequent food-web uptake, mineralization, vertical flux, and burial. In the coastal zone, benthic primary production and both particulate and dissolved OM from land represent additional sources of both autochthonous and allochthonous OM (Canuel and Hardison 2016; Sejr et al. 2022). These are likely to become increasingly important in response to climate change due to the mobilization and land-ocean transport of permafrost-derived OM (Frey and McClelland 2009; Wild et al. 2019). The coastal sources of organic matter are, thus, distinct in terms of their quantity and lability. Kelp forests can form extremely high standing stocks that produce substantial amounts of dissolved organic carbon with high content of humic-like components, which reduce the bioavailability compared to carbon from phytoplankton (Wada et al. 2008). However, kelp forests are also an important food source for pelagic and benthic food webs (Balmonte et al. 2020; Renaud et al. 2015*a*). The contribution of carbon from different sources with different degrees of bioavailability ultimately influences the production (via light availability; Fichot et al. 2013) and the fate of the organic matter. This has implications for how much of the organic matter produced and received in the coastal zone is sequestered and thus, contributes to mitigating anthropogenic emissions of CO_2 (Ager et al. 2023; Bélanger et al. 2006; Sejr et al. 2022). In particular, the fate of the large quantities of terrigenous OM delivered to Arctic coastal waters is largely unconstrained, including the potential for mineralization of terrigenous OM to lead to a positive climate feedback (Juranek 2022; Parmentier et al. 2017).

Nutrients

Increasing stratification from warming in many areas of the offshore Arctic Ocean is expected to reduce mixing of deep, nutrient-rich waters to the surface (Farmer et al. 2021). In the coastal zone, however, climate-change impacts on nutrient availability are likely to vary strongly in both space and time due to altered timing and magnitude of land-ocean nutrient transport (linked to heterogeneity in bedrock geology, catchment processes, and hydroclimatic conditions) (Speetjens et al. 2023), as well as coastal dynamics (including erosion, resuspension, stratification, and upwelling, Irrgang et al. 2022). Recent studies from Greenland suggest that the retreat of marine-terminating glaciers onto land will reduce fjord productivity as the entrainment of deep, nutrient-rich marine water into fjord surface waters by rising plumes of subglacial discharge will be replaced by particle-rich, low-nutrient surface runoff (Meire et al. 2023). In other areas, the importance of terrestrial runoff as a source of both organic and inorganic nutrients to coastal and offshore waters may be substantial (McGovern et al. 2020; Terhaar et al. 2021; Wadham et al. 2019).

Contaminants

Long-range atmospheric and oceanic transport of environmental contaminants has resulted in global distributions of persistent, bioaccumulative, and toxic compounds. Due to global distillation processes, the Arctic experiences particularly high deposition of semi-volatile chemicals transported from warmer regions, leading to high concentrations of, for example, polychlorinated biphenyls (PCBs) and mercury (Hg) in Arctic marine food webs (AMAP 2021*b*). The immense watersheds, lakes, and rivers surrounding the Arctic Ocean all serve to collect additional burdens of contaminants that are subsequently transported to the coastal ocean. Along the coast, thawing permafrost and melting glaciers represent a growing source of contaminants to food webs through increased mobilization and land-ocean transport (Chételat et al. 2022). Given that northern permafrost soils represent a globally significant Hg pool, the potential for permafrost thaw to lead to increased Hg contamination of the Arctic environment, including its food webs, is of great concern (Lim et al. 2020). Increasing human activity can also lead to significant point sources of contaminants (including contaminants of emerging concern) to the coastal environment, for example, from industry and shipping-related activities and the release of untreated wastewater (AMAP 2021*a*).

Coastal change has ecosystem consequences

Examination of key environmental drivers and their response to climate change shows that the coastal ocean is closely linked to terrestrial processes, which differentiates it from the open ocean (Table 1). The additional drivers and their rate of change warn that the accumulated pressure on the coastal ocean system exceeds that in both bounding oceanic and terrestrial systems. Disentangling the spatial and temporal mosaic of accumulated pressure from several drivers is a key challenge if we are to improve current understanding and capability to predict the response of coastal ecosystems to warming. We point to runoff, freshening, glacial melt, and coastal erosion (Fig. 1) as key drivers which, through impacts on the availability of light, nutrients, and organic matter, can alter coastal ecosystem structure and function. These bottom-up effects will be supplemented by top-down effects, for example, changes in the distribution and abundance of fish species or marine mammals responding to increasing water temperature and loss of sea ice (Heide-Jørgensen et al. 2023; Kortsch et al. 2015).

The productivity of an ecosystem is one of its key characteristics, and the projected changes in future conditions of both coastal and offshore environments include reduced ice cover, resulting in greater light availability. Remote sensing studies have confirmed a general increase in productivity driven by the loss of sea ice in offshore environments (Ardyna and Arrigo 2020). Indeed, increased primary production is both predicted and has been observed along the coast due to higher light levels and readily available nutrients from land and sediment (Assis et al. 2022). Whereas primary production in the open ocean is largely limited to pelagic phytoplankton, both macroalgae and benthic microalgae are abundant in coastal regions and are expected to increase their contributions to coastal primary productivity. As waters warm, ice retreats, and the inorganic nutrient supply remains sufficient, new habitats suitable for macroalgal growth can emerge (Kortsch et al. 2012; Krause-Jensen et al. 2012). Reductions in ice scour and increased light penetration have been observed to increase macroalgal distributions into both shallower and deeper waters, respectively (Castro de la Guardia et al. 2023; Krause-Jensen et al. 2020), although increased turbidity from glacial or riverine input may limit depth distribution locally (Niedzwiedz and Bischof 2023) and in the Arctic in general (Singh et al. 2022). Macroalgae are habitat-forming species and can enhance not only productivity but also biodiversity in areas where they expand. They also provide significant quantities of organic matter that are integrated into nearshore food webs (Renaud et al. 2015*a*), and potentially enhance carbon export and potential sequestration (Ager et al. 2023). Benthic microalgae in shallow, coastal habitats can be highly productive due to ample nutrients diffusing upward from the sediments. In one Arctic fjord, it was estimated that benthic microalgae in waters under 30 m depth exhibited primary production values at the same order of magnitude as phytoplankton (Rysgaard and Glud 2007). Benthic microalgae have also been estimated to have production rates up to 5× that of phytoplankton, and importantly, that the depth range over which they could be active may extend well over 100 m depth (Attard et al. 2016). These findings suggest that increased light availability along Arctic coasts can greatly enhance the net community primary productivity and local food-web subsidies by expanding the depth ranges, spatial extent, and total production of benthic microalgae and macroalgae (Attard et al. 2024). Local processes governing turbidity and the (changing) timing of turbidity events will, in part, determine the extent of productivity increases, and need further investigation. Sediments settling on the seafloor can change benthic habitats and bury sedentary organisms but also carry organic matter of varying lability that can be remineralized, buried in coastal habitats, or may be readily consumed by benthic organisms (Harris et al. 2018). It is increasingly clear that climate change effects at the base of the food chain may be much more complex and dramatic in the coastal oceans of the Arctic than in open waters. The contributions of benthic primary producers and terrigenous organic matter to coastal food webs need to be better constrained before we can fully gauge the impact of climate change on coastal ecosystems.

Climate drivers also directly affect community structure and functioning in ways that appear to be exacerbated in coastal waters. Establishment of boreal species via natural or human-facilitated introduction is likely (Cottier-Cook et al. 2024; Renaud et al. 2015*b*), although this may be less prevalent along interior Arctic coastlines than in areas with more direct linkages to temperate habitats. New community assemblages generated by the establishment of non-native species will have consequences that are difficult to predict (Williams and Jackson 2007). Since many species introductions take place via maritime transport vectors, coastal areas of the Arctic are more likely to be hotspots of invasions. That, combined with the high habitat complexity in the coastal ocean which provides more niches to potential invaders, suggests that the coastal ocean will be more susceptible to the establishment of alien species than the open ocean.

Warming will also lead to reductions and altered seasonality in shore-fast ice cover. This is likely to enhance scouring of coastal habitats as remaining drift ice becomes more mobile. Effects of ice scour are well documented, resulting in mosaics of communities under different stages of recovery, with impacts on both local structure and function, and enhanced regional biodiversity (Conlan and Kvitek 2005). Where ice scour is not relevant, warming can result in higher growth rates of benthic species (Ambrose et al. 2006; Sejr et al. 2009) and higher benthic biodiversity (Beuchel et al. 2006). The increasing frequency of marine and terrestrial heat waves has been linked to a range of biological effects, including a region-wide shift in intertidal community structure along Alaskan coasts (Weitzman et al. 2021). Metabolic rates within the water column and at the seafloor will also likely increase due to warming, resulting in higher carbon cycling rates and organic matter degradation, with knock-on effects on oxygen concentrations, nutrient regeneration rates, and the autotrophic/heterotrophic balance. Although these processes may also be enhanced in the warming open ocean, differences in habitat diversity and links with terrestrial processes and human settlements are likely to result in more pronounced impacts on current community structure, function, and services provided in the coastal system (Fig. 2). Few of these secondary impacts of climate change will be felt in the open ocean but may well characterize the changing coastal ecosystem. Species at higher trophic levels such as fish, marine mammals, and seabirds are concentrated along the coast and are especially affected by changes to primary producers, prey fields, and structural changes in the coastal ecosystem. And changes in distribution and abundance of these organisms will most directly impact human populations living in or using the resources of the Arctic coastal seas.

Coastal change impacts people

Changes in coastal ecosystems will impact people living there, but will also have far-reaching impacts. Arctic coastal communities are a key element of strongly coupled socio-ecological systems linking living resources from the coastal ecosystem to communities throughout the Arctic and beyond. Subsistence and commercial coastal fisheries and aquaculture are substantial components of the economies of Arctic nations

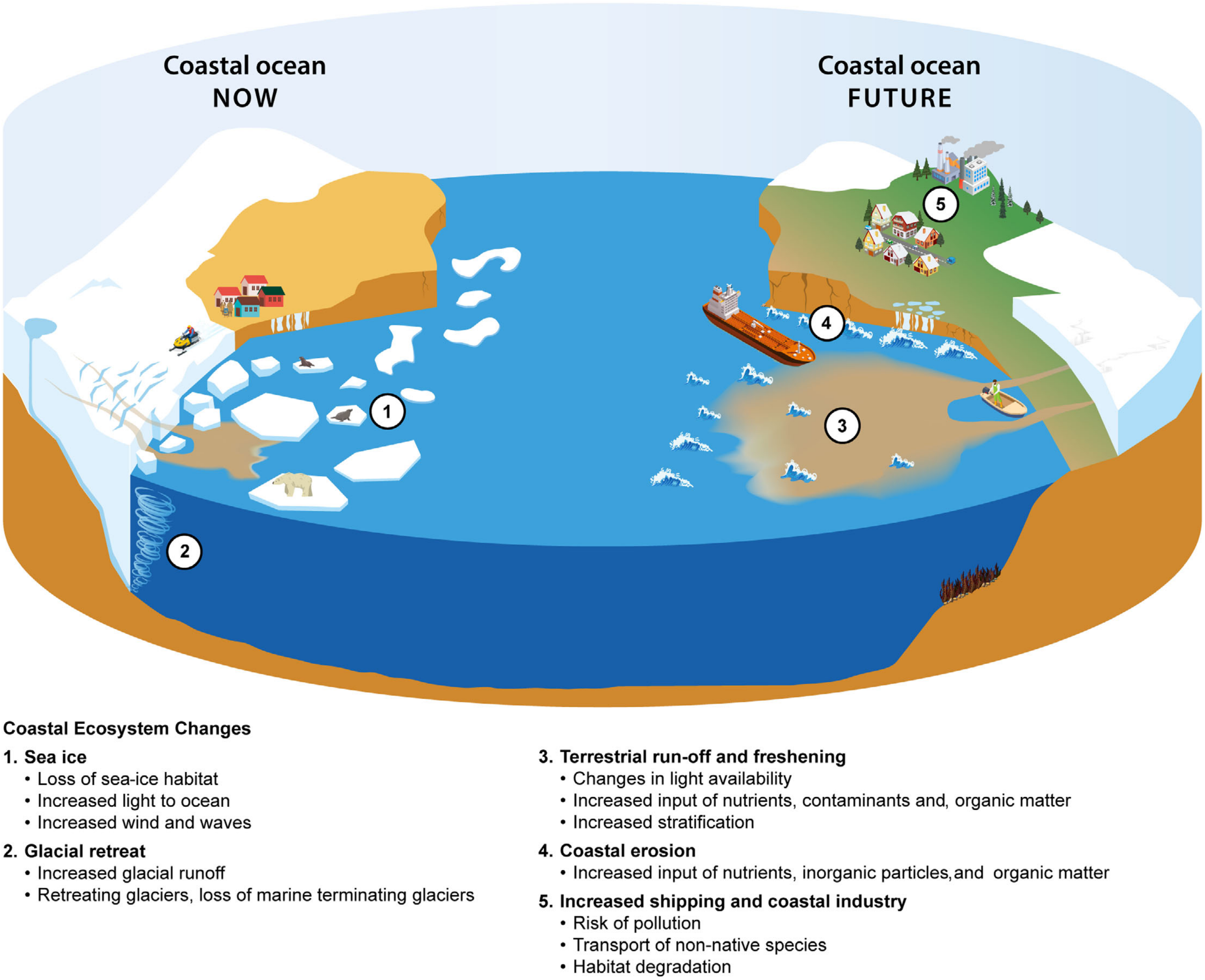

Fig. 2. Conceptual figure showing the transition of the Arctic coastal zone with emphasis on the impact of melting of marine and terrestrial ice and impacts on the coastal socioecological system.

and contribute significantly to national exports and value chains (Vincent 2020). Locally, many Arctic communities rely on coastal marine resources for subsistence and have strong cultural ties to the habitats and organisms present (Larsen et al. 2021). Changes in the coastal cryosphere will interfere with access to culturally and economically important hunting and fishing activities. Higher contaminant loads from industrial activities and mobilization following permafrost thawing will have profound impacts on communities that are strongly reliant on high trophic-level organisms such as fish, seabirds, and marine mammals. Furthermore, living conditions, cultural identity, and sense of place will be substantially altered by shoreline change, loss of land-fast ice, and changes in seasonality of key, culturally relevant species. If changes take place at an accelerated pace, they may exceed the ability of local communities to adapt (Hovelsrud et al. 2011). The open shelf and the deep Arctic Ocean stand in stark contrast by exhibiting few direct and indirect links with human populations. Coastal changes will, therefore, have more direct impacts on human societies than will changes in the open ocean or outer shelf.

Sustainable management and adaptation actions require better knowledge about how the accumulated pressures from climate change affect living resources that sustain local livelihoods and economies (Ford et al. 2021). As the melting of sea ice continues to make the Arctic coasts more accessible, increased activities related to aquaculture, shipping, tourism, energy production, and extraction of living and nonliving resources are expected (Hovelsrud et al. 2011). The opportunities of the new Blue Economy increase the need to expand infrastructures to support industry, search and rescue, and scientific activities, resulting in a larger human footprint in the coastal zone. This produces a feedback loop where environmental manifestations of climate change alter many aspects of coastal communities, resulting in further anthropogenic change—challenges that may compound environmental impacts. Similar to the ecological consequences of climate change, these complex societal implications have been little explored.

Conclusion

Above we review how climate change influences the coastal ecosystem and argue it leads to a substantial footprint along Arctic shores, impacting coastal ecosystems at a pace we hypothesize exceeds that in both terrestrial and open-ocean systems. This indirect human footprint is then combined with the direct physical human footprint from roads, structures, and industry, which has increased by 15% since 2000 (Bartsch et al. 2021). In addition to the local impacts these changes will have on Arctic communities, the vast geographic extent of the coastal Arctic means that changes here have global ramifications, including sea level rise, changes in ocean circulation patterns and atmospheric greenhouse-gas feedbacks. The Arctic has sustained humans for millennia and the ongoing transformation of the coastal ecosystem threatens many components of this socioecological system. We can no longer reverse the accelerating effects of climate change in the near future, which leaves adaptation as the inevitable alternative for communities living there. This requires the best possible prediction of what to expect and herein lies a clear challenge for the scientific community. Coastal change is not always well-represented in the dominant narratives of Arctic Ocean change (i.e., a polar bear on an ice floe). This is highlighted by the striking mismatch between the strong focus on open-ocean change in key international reports focusing on the physical, biogeochemical and ecological impacts of climate change on the Arctic Ocean (IPPC 2019), and reports highlighting the pressing need for knowledge related to climate change risks and adaptation needs for communities along the pan-Arctic coast (AMAP 2021*b*). Arctic coastal change is complex, pronounced and has profound impacts on those living along the pan-Arctic coast. Meanwhile, the ecosystem models and remote sensing approaches applied for the open Arctic Ocean are challenging to transfer to the dynamic coastal environment, where high spatiotemporal variability and interactions among multiple drivers complicate understanding of the compounding and amplifying effects of climate change. We argue that now is the time for a sustained effort to develop the tools necessary to improve our understanding and quantification of how climate change affects the services provided by the vast Arctic coastal ecosystem. Existing tools that should be enhanced include tailored coastal ecosystem models nested within larger regional domains, remote sensing products developed and validated for the coastal oceans, and use of drones to increase the spatial and temporal resolution when relevant. However, the biggest leap forward is likely to happen when efforts are co-developed with local communities and combine scientific approaches with residents' long-term ecological expertise of local ecosystems. The spatial heterogeneity and temporal dynamics of the coastal zone will require specific solutions for each question, emphasizing the need for improved pan-Arctic exchange of already existing knowledge and new data on Arctic coastal ecosystem change.

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