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Review Article

Possible future scenarios for two major Arctic Gateways connecting Subarctic and Arctic marine systems: I. Climate and physical–chemical oceanography

Kenneth F. Drinkwater [1,*], Naomi Harada[2], Shigeto Nishino[2], Melissa Chierici[3], Seth L. Danielson[4], Randi B. Ingvaldsen[1], Trond Kristiansen[5,6], George L. Hunt, Jr [7], Franz Mueter [8], and Jan Erik Stiansen[1]

[1] *Institute of Marine Research, Oceanography and Climate Research Group, PO Box 1870, Nordnes N-5817, Bergen, Norway*
[2] *Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natsushima-cho, Yokosuka 237-0061, Japan*
[3] *Institute of Marine Research, Oceanography and Climate Research Group, Fram Centre, Tromsø, Norway*
[4] *School of Fisheries and Ocean Science, Institute of Marine Science, University of Alaska Fairbanks, Fairbanks, AK 99775-7220, USA*
[5] *Fallon Institute, Petaluma, CA, USA*
[6] *Norwegian Institute for Water Research (NIVA), Gaustadalle´en 21, NO-0349 Oslo, Norway*
[7] *School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, USA*
[8] *College of Fisheries and Ocean Sciences, University of Alaska Fairbanks, Juneau, AK, USA*

**Corresponding author: tel: +47 9767552; e-mail: ken.drinkwater@hi.no*

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We review recent trends and projected future physical and chemical changes under climate change in transition zones between Arctic and Subarctic regions with a focus on the two major inflow gateways to the Arctic, one in the Pacific (i.e. Bering Sea, Bering Strait, and the Chukchi Sea) and the other in the Atlantic (i.e. Fram Strait and the Barents Sea). Sea-ice coverage in the gateways has been disappearing during the last few decades. Projected higher air and sea temperatures in these gateways in the future will further reduce sea ice, and cause its later formation and earlier retreat. An intensification of the hydrological cycle will result in less snow, more rain, and increased river runoff. Ocean temperatures are projected to increase, leading to higher heat fluxes through the gateways. Increased upwelling at the Arctic continental shelf is expected as sea ice retreats. The pH of the water will decline as more atmospheric CO_2 is absorbed. Long-term surface nutrient levels in the gateways will likely decrease due to increased stratification and reduced vertical mixing. Some effects of these environmental changes on humans in Arctic coastal communities are also presented.

Keywords: Arctic Gateways, Barents Sea, Bering Strait, Chukchi Sea, climate change, Fram Strait, hydrography, nutrients, ocean acidification, sea ice.

Introduction

For much of the last century the world has been warming under the influence of the greenhouse effect associated with human-induced increasing levels of atmospheric carbon dioxide (CO_2) (e.g. IPCC, 2013; Overland *et al.*, 2017). Interest in the Arctic has increased during the last few decades because of the extraordinary changes that are occurring there and the declaration by the Intergovernmental

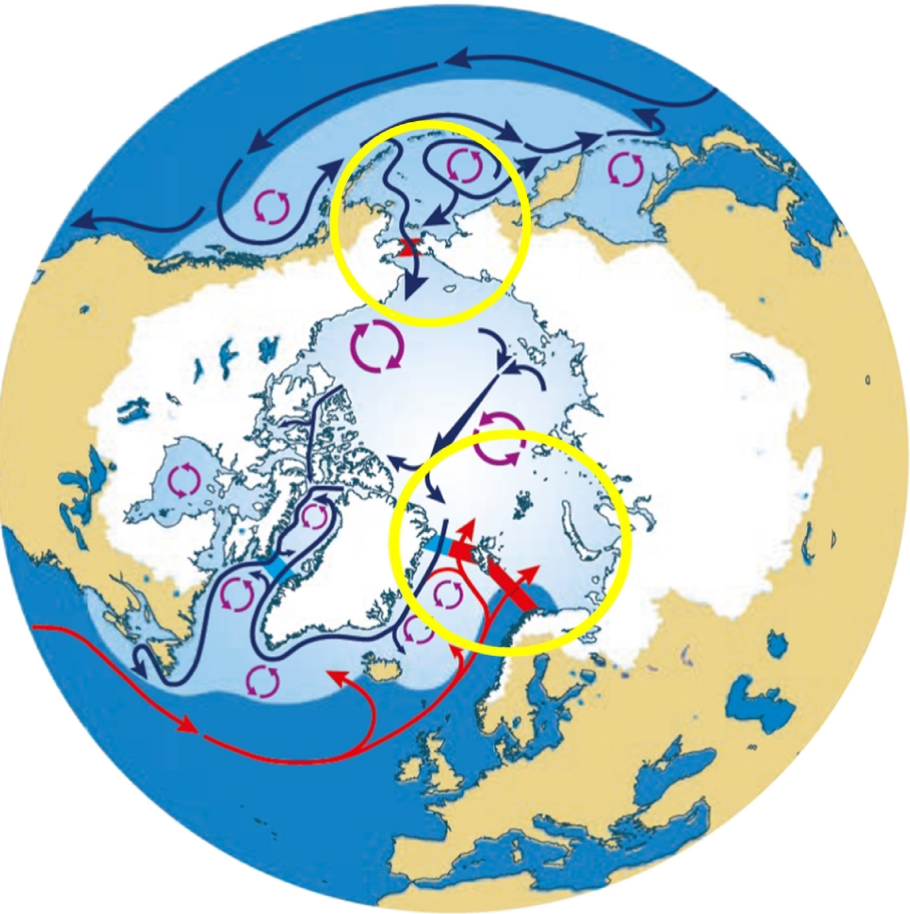

Figure 1. The Arctic Ocean showing the surface circulation patterns (red arrows denote relatively warm currents, blue colder currents). The red and blue bars denote the inflowing and outflowing regions of the major Arctic Gateways. The white regions show the catchment areas for the fresh water flowing into the Arctic. The yellow circles denote the primary study areas of the RACArctic project. (Modified from Prowse *et al.,* 2015). Image courtesy of the Arctic Monitoring and Assessment Programme (AMAP).

Panel on Climate Change (IPCC) that the Arctic region is one of the areas of the world most vulnerable to global warming (IPCC, 2013).

Indeed, within the Arctic, air and ocean temperatures have risen, sea-ice coverage has declined, and the area of open water in summer has increased, allowing greater exchange of CO_2 between the atmosphere and the ocean. The latter has led to an increased acidity (declining pH) of Arctic marine waters (ocean acidification). Understanding the impact of the combined warming, sea-ice loss, and ocean acidification (OA) on the organisms in the Arctic region is necessary to predict the changes in biological productivity (Mueter *et al.*, this issue).

The present paper reviews recent trends and projected future conditions of several physical and some chemical characteristics of the waters in the transition zones between the Arctic and Subarctic in the two major inflow regions to the Arctic (Figure 1), the Pacific Gateway (Bering Sea, Bering Strait, and the Chukchi Sea, Figure 2) and the Atlantic Gateway (Fram Strait and the Barents Sea, Figure 2). This study was undertaken as part of the Resilience and Adaptive Capacity of Arctic Marine Ecosystems (RACArctic) synthesis project.

The following sections summarize and discuss recent trends in major atmospheric and oceanographic features and expected changes under future climate change. Temporally, focus is on the near future (2050s) where possible, but we also consider likely scenarios out towards 2100. We discuss some climate impacts on Arctic residents as well as a few low probability events that if they did occur would have major ecosystem consequences.

The projections presented below are mostly from General Circulation Models (GCMs) or downscaled regional climate models (RCMs) from GCMS. The IPCC (2013) Representative Concentration Pathway (RCP) 4.5 and RCP8.5 are used for many of the projections of future greenhouse gas (GHG) emissions. The former represents an intermediate GHG scenario and the latter the highest, often referred to as the "business as usual" scenario. A few studies we cite use an earlier IPCC classification of GHG: A2 for high emission (low mitigation) scenarios and B2 for low emissions (high mitigation). We also present some results as part of CMIP6 (Coupled Model Intercomparison Project Phase 6) where future GHG emissions result from the world following the Shared Socioeconomic Pathways (SSPs) 245 and SSP585. SSP245 represents a middle of the road approach to mitigation and adaptation of climate change while SSP585 represents business as usual and suggests a carbon-fueled based economy (O'Neill *et al.*, 2017).

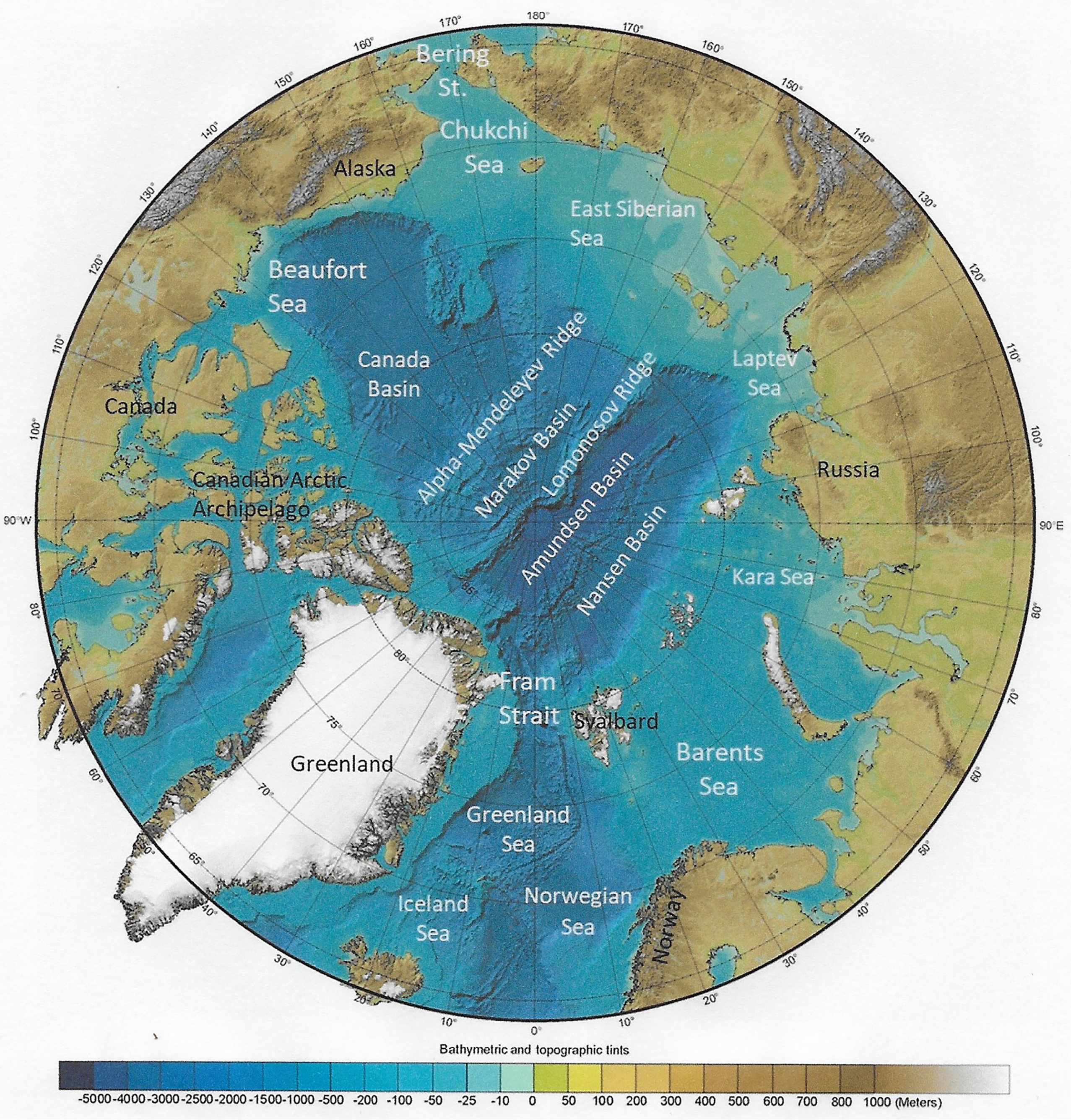

Figure 2. Topographic regions and bathymetry within the Arctic Circle.

Present trends and future climate

Atmosphere

Air temperatures

Between 1971 and 2019, surface air temperatures (SATs) in the Arctic increased at a rate approximately three times that of the entire globe (AMAP, 2021), a phenomenon termed Arctic amplification (Manabe and Stouffer, 1980). Ballinger *et al.* (2020) noted that the October 2019–September 2020 SAT above 60°N was the second highest since 1900, behind only 2016. They also pointed out that 9 of the last 10 years, SAT anomalies were at least 1°C warmer than the 1981–2010 mean. Such changes strengthen the conclusion that anthropogenic-induced warming is well underway (e.g. IPCC, 2013; Alexander *et al.*, 2014; Overland *et al.*, 2017).

Air temperatures have also increased within the Arctic Gateways. In the western Barents Sea (70–76°N, 15–35°E) surface air temperatures rose by approximately 2°C between the mid-1990s and 2016. They then declined but have remained above the 1981–2010 long-term mean through to 2020 (Trofimov *et al.*, 2020). The highest air temperature anomalies over the Arctic during October 2017 to September 2018 were in the Bering Strait–Chukchi Sea and the northern Barents Sea, with anomalies of 5°C in both regions relative to the 1981–2010 climatology (Overland 2020).

Model projections suggest that future air temperatures in the Arctic will continue to rise but the amplitude will vary spatially (Walsh, 2020). From CMIP6, we assembled multi-model averages of several climate variables for the Large Marine Ecosystems of the Pacific Gateway (LME54) that includes the northern Bering Sea, the Bering Strait, and the Chukchi Sea (Figure 3a) and the Atlantic Gateway (LME13) that includes the Barents Sea and eastern Fram Strait (Figure 3b). The number of models per variable ranged from 3 to 9 and the results are based on SSP245 (intermediate carbon forcing) and SSP585 (high forcing). The variables were averaged spatially before being averaged across models. The plots show the filtered mean (5-point annual running mean) as a function of time along with the 95th percentiles across models. The time series for air temperatures (Figure 3c and d) show rising temperatures throughout this century. The projected unfiltered air temperatures in the Pacific Gateway are expected to increase from around −9°C at 2020 to between −5 and −6°C by 2050 and between −3.5 and 3°C by 2100, depending on the SSP level (Table 1). In the Atlantic Gateway, temperatures are expected to increase from around −2°C at 2020 to between 0 and 2°C by 2050 and between 2 and 5.5°C by 2100, again depending on the SSP level (Table 1). Note the temperatures in the Pacific Gateway under SSP245 and SSP585 are similar through to about 2050, after which the SSP585 curve exceeds the 95th percentile of the SSP245 curve (Figure 3c). In the Atlantic Gateway, the year when the SSP585 curve exceeds the 95th percentile of the SSP245 curve does not occur until around 2070 (Figure 3d).

The rate of atmospheric warming varies seasonally. Seasonal projections of air temperature anomalies in the Gateways under RCP8.5 for the 2050s and 2080s relative to 1986–2005 means were obtained from Overland *et al.* (2017; their Figures 2.13 and 2.14). Strong seasonal dependence is expected to continue into the future, with maximum warming in winter, December to February (Table 2). Their model suggests that by the 2050s, summer (June–August) air temperature anomalies will be 1–4°C and in winter, 3–7°C. The spring and fall patterns resemble winter but with lower amplitudes. By the 2080s, summer anomalies were in the range of 3–7°C and winter anomalies of 11–12°C (Table 2).

The projected future Arctic warming is expected to result in an increased frequency of extreme high air temperatures and a decreased frequency of extreme low temperatures (ACIA, 2005; Landrum and Holland, 2020). The natural variability of stochastic weather and climate conditions are projected to drive alternating periods of warm and cool temperatures on top of the underlying warming trends (Medhaug *et al.*, 2017).

Precipitation and runoff

Precipitation averaged over the Arctic increased during 1970–2019 at an estimated annual rate of 9% (AMAP, 2021). Some have suggested this increase is due to a rise in the moisture content of the air transported into the Arctic (Zhang *et al.*, 2013; Screen *et al.,* 2018) while others have pointed to increased evaporation because of higher air temperatures and larger open water areas as the main cause (Carmack *et al.*, 2016; Bintanja and Andry, 2017).

With the increase in air temperature, less of the annual precipitation falls as snow and more as rain (Mård *et al.*, 2017). Indeed, the depth of the snow cover on the ice has been observed to be declining, especially in the Chukchi and Beaufort seas (Barber *et al.*, 2017; Bintanja and Andry, 2017). Despite this reduction in annual snow fall, the rate of snow fall in winter has increased, but accumulation through the winter season has decreased because of the shorter snowfall season (Brown *et al.*, 2017).

Projections indicate a further rise in precipitation in the Arctic including in the gateways, with generally slightly larger increases in winter than in summer (Table 3). Declines in snowfall are projected to be high within the gateways, e.g. −40% in the Barents Sea (Mård *et al.*, 2017).

On an annual basis, river runoff contributes an amount of fresh water to the Arctic that was estimated to be almost twice that of ice melt and six times the direct input from precipitation (Arnell, 2005). With warmer temperatures and higher rainfall, annual river runoff into the Arctic increased by approximately 9–12% between 1971 and 2017 (Box *et al.*, 2019). Future projections suggest it will continue to increase with higher runoff in winter and lower in spring, relative to present (Stadnyk *et al.*, 2021). At higher altitudes, much of the winter precipitation will continue to fall as snow, but with higher temperatures, the spring peak in runoff will occur earlier (Stadnyk *et al.*, 2021). Nummelin *et al.* (2016) suggest that an increase in runoff of around 10% by 2050 relative to 2000 and 26% by 2100 under high emission (A2) scenarios, but with high model-to-model variability.

Winds and storms

With the increase of Arctic air temperatures, the temperature gradient between the Arctic and the mid-latitudes decreases, resulting in a weakening of the upper-level zonal winds (Francis and Varvus, 2012; Vihma, 2014). Many studies have hypothesized that the weaker winds have allowed cold Arctic air to flow south into the mid- and lower-latitudes, accounting for the increase in cold outbreaks and snow during winter in southern Europe, North America and Asia (Overland *et al.*, 2011; Cohen *et al.*, 2018; Ma and Zhu, 2019).

Mean wind speeds in the central Arctic are projected to increase by 10–30% between 2000 and 2009 and the end of the century (2090–2099; Aksenov *et al.*, 2017). In Fram Strait, as well as the Barents and Bering seas, these same authors suggested that the winds will decrease or remain relatively unchanged under RCP8.5 with peak increases in mean wind speed (>2 ms^{-1}; 20–30%) likely to occur over the Chukchi Sea and north of Greenland. In areas where winds are expected to decrease, the changes were small (0–1 ms^{-1}, i.e. 0–12.5%). Our CMIP6 results generally support the conclusions of Aksenov *et al.* (2017), indicating the possibility of a slight increase in the winds over time in both gateways (Figure 3g and h). However, given the strong variability, we do not consider this increase statistically significant. Indeed, our air temperature results show large interannual to decadal variability (Figure 3e and f), the most of any of the other climate variables (Figure 3).

During the past decade or so, the passage of cyclones into the Arctic have become more common (Box *et al.*, 2019). Despite model uncertainty, future projections tend to support stronger Arctic cyclones during summer but a reduction in the number and intensity of storms in winter (Day *et al.*, 2018).

Clouds

Historically, Arctic cloud cover exhibits strong seasonal variability ranging from 40 to 70% in winter and from 80 to 95% in summer and autumn (Shupe, 2011). Based on recent observations during the period of rapid ice-cover loss, and projections of further ice losses, cloud cover during autumn is expected in several studies to increase

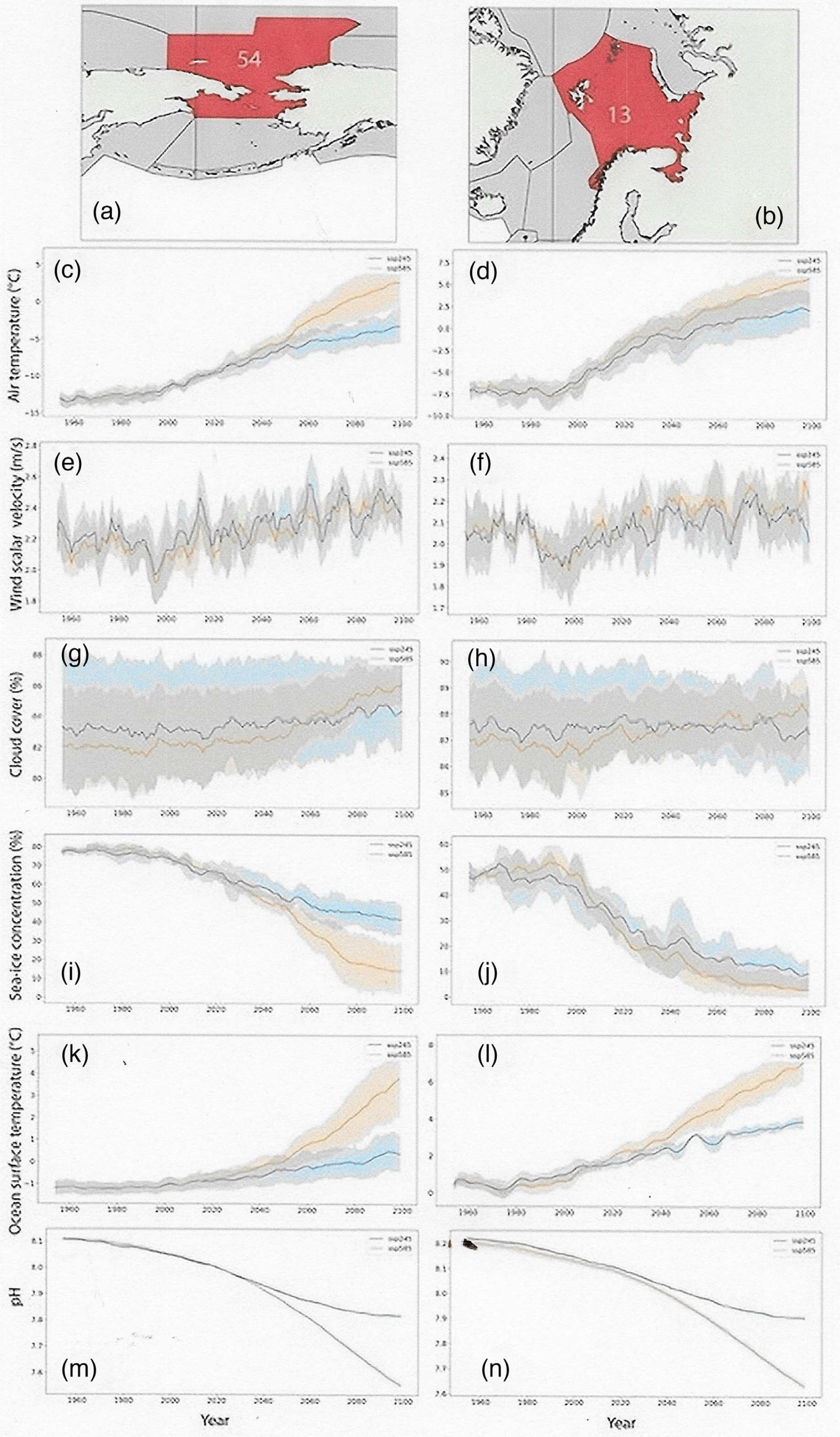

Figure 3. CMIP6 multi-model averages of climate anomalies for the Pacific (left panels) and Atlantic (right panels) gateways. The climate variables include: (c) and (d) surface air temperatures in°C; (e) and (f) cloud coverage in %age; (g) and (h) scalar winds in ms^{-1}; (i) and (j) sea-ice coverage in %age (k) and (l) surface ocean temperatures in°C; and (m) and (n) pH extracted from geographical boxes in the Large Marine Ecosystems (LMEs) taken as representative of (a) the Pacific and (b) Atlantic gateways. The data were averaged spatially and then averaged across models. The plots show the 5-year running means between the late 1950s and 2098 (solid lines) and the 95th percentile across models for two scenarios, SSP245 (blue) and SSP585 (red).

Table 1. The mean of the unfiltered climate variables considered in this study at 2020, 2050, and 2099 from the multi-model CMIP6 analyses for the Pacific and Atlantic gateways. The geographic areas for which the data were averaged are shown in Figure 3a, b. The number of models that were averaged for each variable and gateway are also listed. Values after ± signs are standard deviations based on the different models. The surface air and ocean temperatures are in°C; winds are in ms^{-1} and are scalar winds (sqrt of $u^2 + v^2$); clouds and sea ice are in % coverage of the LMEs; and pH are in standard pH units.

				2050	**2099**	**# Models**
Variable	**Gateway**	**SSP**	**2020**	**2050**	**2099**	**# Models**
Air Temp u	Pacific	245	−9.4 ± 1.6	−6.1 ± 2.0	−3.5 ± 3.0	5
		585	−9.3 ± 1.2	−5.0 ± 2.7	2.7 ± 5.0	7
	Atlantic	245	−2.4 ± 2.5	0.2 ± 2.8	1.7 ± 3.3	5
		585	−1.6 ± 2.1	2.4 ± 2.7	5.5 ± 3.8	7
Winds	Pacific	245	2.4 ± 0.3	1.9 ±0.3	2.0 ± 0.3	5
		585	1.9 ± 0.3	2.1 ± 0.3	2.2 ± 0.5	7
	Atlantic	245	2.0 ± 0.4	2.4 ± 0.7	2.2 ± 0.3	5
		585	2.1 ± 0.4	2.6 ± 0.4	2.7 ± 0,5	7
Clouds	Pacific	245	84 ± 5	84 ± 5	83 ± 5	5
		585	83 ± 4	86 ± 4	86 ± 2	7
	Atlantic	245	88 ± 2	88 ± 2	88 ± 2	5
		585	87 ± 2	87 ± 2	88 ± 2	7
Sea-ice	Pacific	245	65 ± 5	53 ± 3	43 ± 11	5
		585	64 ± 6	48 ± 7	14 ± 20	7
	Atlantic	245	29 ± 10	17 ± 9	9 ± 8	5
		585	22 ± 8	11 ± 7	4 ± 7	7
Sea temp	Pacific	245	−0.85 ± 0.64	−0.39 ± 0.85	0.32 ± 1.40	6
		585	−0.76 ± 0.52	0.10 ± 0.80	3.69 ± 2.69	9
	Atlantic	245	1.57 ± 0.64	2.96 ± 0.21	3.84 ± 0.68	6
		585	2.19 ± 0.72	3.97 ± 1.24	6.93 ± 1.64	9
pH	Pacific	245	7.998 ± 0.002	7.89 ± 0.01	7.82 ± 0.01	3
		585	7.994 ± 0.005	7.85 ± 0.01	7.57 ± 0.01	6
	Atlantic	245	8.092 ± 9.001	8.00 ± 0.01	7.91 ± 0.01	3
		585	8.067 ± 0.018	7.93 ± 0.02	7.65 ± 0.02	6

Table 2. The approximate surface air temperature changes in°C relative to the 1986–2005 mean for the Pacific and Atlantic gateways to the Arctic based upon RCP8.5 (taken from Figures 2.13 and 2.14 of Overland *et al.*, 2017). The estimated uncertainties, based on the model spread, are ±1 and ± 2.5°C for summer and winter, respectively. SWBS stands for Southwest Barents Sea.

	2050s				**2080s**			
	Pacific		**Atlantic**		**Pacific**		**Atlantic**	
	Bering Sea/Strait	**Chukchi Sea**	**Fram Strait**	**Barents Sea**	**Bering Sea/Strait**	**Chukchi Sea**	**Fram Strait**	**Barents Sea**
Summer June–August	1–2	1.5–3	2–3	2–4	1–3	1.5–3	2–5	4–7
Winter December–February	3–7	4–7	3–7	4–7 SWBS 3–5	11–12	11–12 SWBS 5–11	11–12	11–12

Table 3. Future precipitation increases in terms of % change for summer (April–September) and winter (October–March) under RCP585 obtained from Mård *et al.* (2017). Under RCP4.5, increases are about 10–30% less than those under RCP8.5. BeS-Bering Sea; NBa-Northern Barents Sea.

	Pacific		**Atlantic**	
	Summer	**Winter**	**Summer**	**Winter**
2050s	10–20%	10–40%	10–20%; (20–30% NBa)	10–40%
2080s	20–50; (20–30% BeS)	20–50%	20–50%	20–50%

over the Arctic, but not change much during summer. The latter has been attributed to the surface temperatures of the open water and sea ice being similar during the melting season (Vihma, 2014).

Using a 39-year data set (1971–2009), Eastman and Warren (2013) showed a trend of slightly increasing cloud cover in the Arctic. This is consistent with Nahtigalova (2013) who found that at Siberian land stations, there was an increase in the total lower level cloudiness from 1986 to the end of their record in 2012. Based on satellite data, Bélanger *et al.* (2013) observed an increase in cloudiness thoughout the Arctic, including in the Gateways, during May–September 1998–2009 that resulted in a decrease in photosynthetically active radiation (PAR) at the sea surface. The largest declines were in Subarctic areas, including the Barents and Bering seas of approximately −1 to −2% year^{-1}, which were considered statistically significant ($p < 0.01$). The authors noted that the increased cloudiness partly counteracts the positive influence of declining sea ice on light levels. On the other hand, Jun *et al.* (2016), investigating clouds over the Arctic Ocean in winter from satellite and reanalysis data, found that north of 67°N cloud amounts decreased from the late 1970s-early 1980s until the late 1990s, after which cloud coverage increased rapidly. These authors concluded that the increase was linked to the large reduction in sea-ice area.

Cai *et al.* (2018), as part of CMIP5 modelling studies, provided projections of cloud fractions in the Arctic out to 2050. Displayed as the change in the mean fraction over the period 2006–2050 relative to present day, the cloud cover was similar or decreased slightly in the Fram Strait recgion but increased in the Bering Strait area as well as thoughout the Barents Sea and the Bering Sea. Our CMIP6 analysis of clouds, showed no statistically significant trend in cloud coverage in either the Pacific or Atlantic gateways given the variability in the model results (Table 1; Figure 3g and h).

Large-scale atmospheric climate indices

Oceanographic and ecological changes in the Arctic are often related to large-scale atmospheric conditions, which are commonly condensed into climate indices that represent dominant modes of variability. The dominant atmospheric pattern in the far north is the Arctic Oscillation (AO; Thompson and Wallace, 1998). The AO is caused by the seesaw movement of air masses between the Arctic and mid-latitudes and results in cyclonic (counter clockwise) winds around the Arctic (the Arctic Vortex) with peak winds near 55°N latitude. The AO is linked to changes in the major pressure systems: the high pressure over the central Arctic, the Icelandic Low in the Atlantic region and the Aleutian Low in the Pacific. The AO Index, calculated as the first mode of an empirical orthogonal function (EOF) decomposition of the winter (November–April) sea level atmospheric pressure (SLP) fields in winter between the North Pole and 20°N latitude, accounts for 25% of the SLP variance (Thompson and Wallace, 1998). During a positive AO index, there is an intensification of the zonal (east–west) winds, which tend to confine cold Arctic air to the polar regions. During a negative phase, winds weaken and the cold air extends southward, often resulting in the increased storminess in the mid-latitudes (Overland *et al.*, 2015). The AO variability is closely related to that of the North Atlantic Oscillation (NAO; Ambaum *et al.*, 2001).

Wu *et al.* (2006) identified a second major atmospheric pressure pattern, the Arctic Dipole (AD). It is the second EOF mode of the winter (October–March) mean SLP above 70°N, which accounts for between approximately 13% (Wu *et al.*, 2006 during1960–2006) to 19% (Watanabe *et al.*, 2006 during 1900–2006) of the winter SLP variance. The AD is characterized by a high pressure over the North American Arctic region and low pressure over Eurasia, and is associated with meridional (north-south) winds. A negative AD is associated with the southerly winds, which transport warm southern air masses into the Arctic and reduces sea ice export southward through Fram Strait. The opposite occurs during a positive AD phase. The AD index was variable but principally negative from the 1930s to 2000. After 2000 it became mostly positive (Watanabe *et al.*, 2006; Wu *et al.*, 2006; Heo *et al.*, 2021). In the negative-AD decades (1979–1998), atmospheric circulation during summers of positive phase AD acts to reduce the sea ice extent (SIE) in the Pacific sector but increases it in the Atlantic sector. In the positive-AD decades (after 1999), the same atmospheric circulation pattern reduces the SIE in both sectors, resulting in enhanced sea ice melting across the entire Arctic region.

Since the late 1990s with the decline in sea ice and the increased open water in the Arctic region, the winter AO and the NAO indices relative to long-term mean 1960–1990 have been predominantly positive (http://www.climate4you.com/index.htm accessed 15.08,2021). However, summer indices of AO and AD tended to be negative (Cai *et al.*, 2018). CMIP5 modelling studies of future changes during summer indicate a switch to a more positive AO through most of the present century but a continuing negative trend in the AD (Cai *et al.*, 2018). These authors found that neither the AO nor AD contributed appreciably to future temperature and precipitation trends, but that the contribution of the AD was larger than that of the AO. Future changes of the large-scale pressure patterns include a likely intensification of the wintertime Aleutian Low and the Siberian High, but a weakening of the Icelandic Low (Screen *et al.*, 2018). Outside of summer, the effect of GHGs is dominant, leading to more robust projections of an increasingly positive AO (Screen *et al.*, 2018).

Sea ice

The Arctic annual mean sea-ice extent from 1979 to 2019 decreased at an estimated rate of 5×10^5 km^2 (4.7%) per decade (Figure 4a). The rate in summer (September at or near the sea-ice minimum) was in the range of −12% per decade (Figure 4b), much faster than predicted by most GCMs (Stroeve *et al.*, 2012). This rate of decline was greater than in winter (March), especially after 2006 (Figure 4b). The sea-ice coverage in September is now limited to the central Arctic north of Greenland (Figure 5). The 2 years of ice in the figure (2012 and 2020) are the minima in the satellite record.

Reductions in sea ice have been greater in the Arctic Gateways than in the central Arctic (Onarheim *et al.*, 2018; also, see Figure 6). In the Barents Sea, there has been a 50% reduction in the March sea-ice areal coverage over the past five decades (Docquier *et al.*, 2020) while some of the fastest declines in sea-ice cover across the Arctic have been observed in the Bering and Chukchi seas (Parkinson and Cavalieri, 2008; Cavalieri and Parkinson, 2012). The monthly mean variability in sea-ice cover in the gateways for the last three decades 1988–2019) are shown in Figure 6. These plots show the decline in sea-ice coverage through the decades.

The ice is melted by heat carried into the Arctic through the air, in ocean waters, and in rivers. The flow of warm air toward the Arctic, due in part to the AD, has contributed to sea-ice loss in both gateways, especially since 2000 (Budikova, 2009; Bi *et al.*, 2021; Wang, 2021). Increased inflows of warm Atlantic water through Fram Strait and the Barents Sea have also contributed to high melt rates there (Årthun et al., 2012, 2019; Polyakov *et al.*, 2017). Simi-

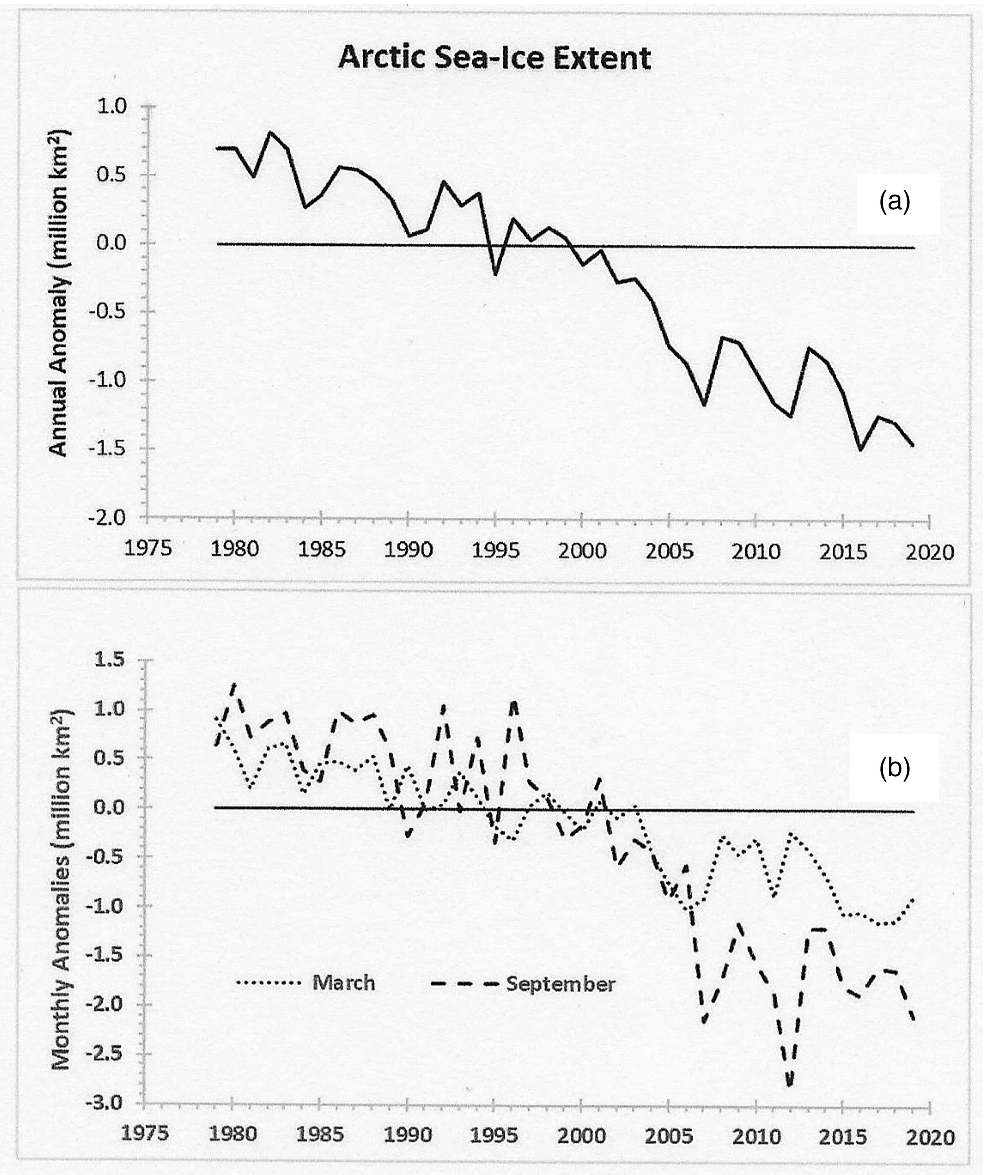

Figure 4. Time series of anomalies of Arctic sea-ice extent: (a) annual data; (b) March and September. The plots are based on NOAA data (https://www.ncdc.noaa.gov/snow-and-ice/extent/).

larly, inflow of warm Pacific waters through Bering Strait has been hypothesized to be responsible for the rapid reduction of summer sea ice in the Chukchi and Beaufort seas (Shimada *et al.*, 2006; Woodgate *et al.*, 2010). Moored current meter arrays in Bering Strait between 1990 and 2015 showed a general increase in heat fluxes into the Chukchi Sea, sufficient to melt 10^6 km^2 of 1-m thick ice (Woodgate, 2018). Still, in the Pacific sector, Tsukada *et al.* (2018) found that solar heating in summer during 1999–2015, was approximately twice that of the northward heat flux through the Bering Strait. Additionally, Arctic rivers carried enough heat to melt around 10% of the sea ice throughout the Arctic during 1980–2015 (Park *et al.*, 2020).

Coincident with the reduction in sea-ice coverage, there has also been a thinning of the ice with a significant loss of multi-year sea ice such that most of the ice is now first or second year ice (Lindsay and Schweiger, 2015). This has made the ice more mobile and responsive to wind forcing (Spreen *et al.*, 2011). Thinning sea ice also means an increase in the solar radiation reaching the sea surface (Barber *et al.*, 2017). Kristiansen (unpublished) estimated the increase in light levels due to changes in sea-ice concentration, sea-ice thickness, albedo, and snow depth for the Barents and Bering seas using the Norwegian Earth System Model (NorESM). He found an increase in surface light levels of 15% and 14%, respectively, by 2050 and 27% and 24%, respectively, by 2090. The same general rate of change in light was modelled for the entire Arctic Ocean in Varpe *et al.* (2015).

Sea-ice phenology has also changed. Analyses over a 32-year period, from 1979–1980 to 2010–2011, show that the Chukchi Sea and the northern Barents Sea have experienced a delay of the sea-ice formation of 1.0–1.4 months and an earlier retreat of sea ice by 1.6–1.9

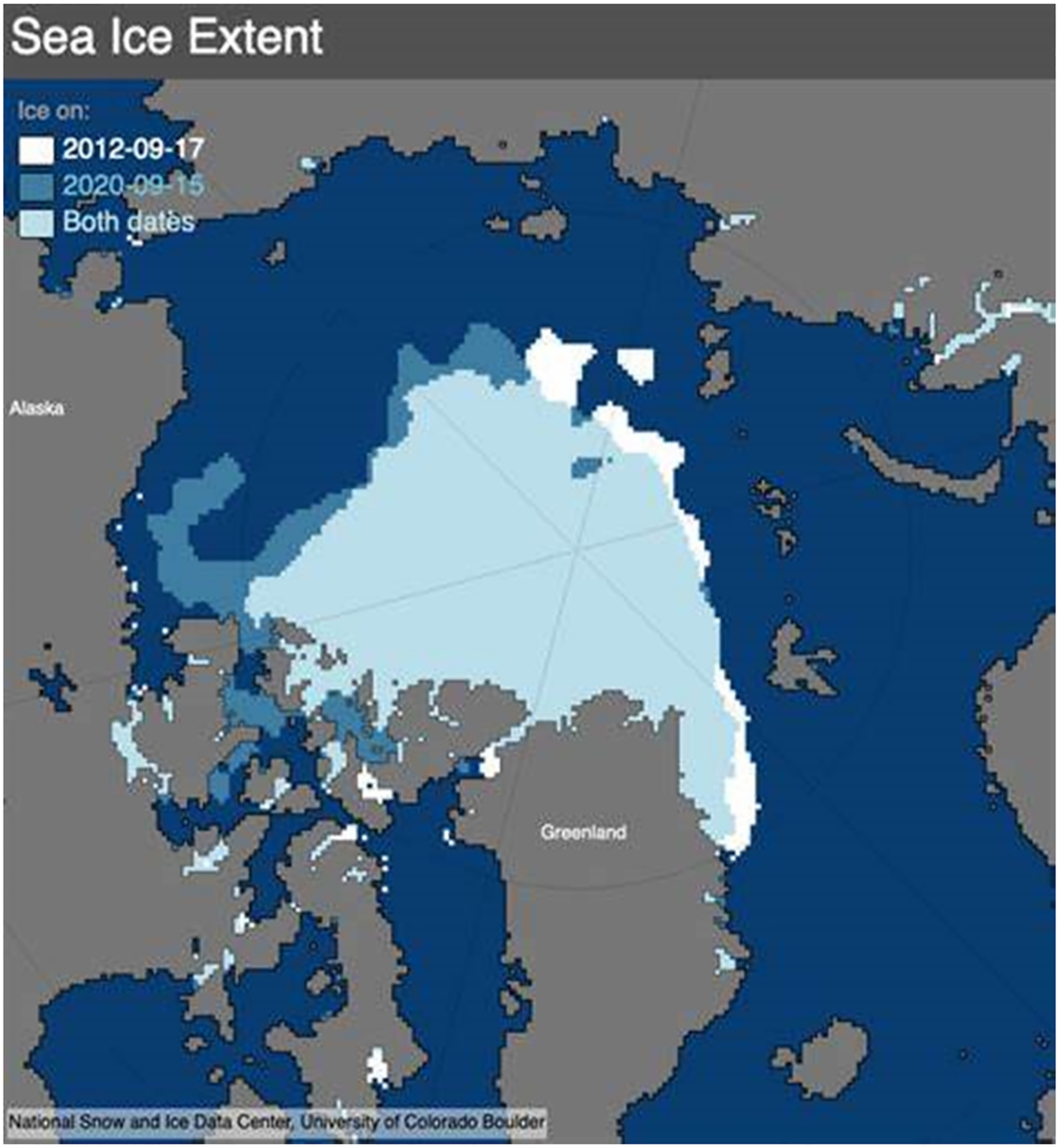

Figure 5. Comparison of the sea-ice minima for 2012 (September 17) and 2020 (September 15). Light blue indicates where ice occurred in both 2012 and 2020, while white and medium blue areas show ice cover unique to 2012 and to 2020, respectively. (Image courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder)

months, resulting in a reduction in the duration of the ice season by 3 months (Stammerjohn *et al.*, 2012). Throughout the Arctic, sea-ice melting has been occurring earlier in the spring (Stroeve *et al.*, 2014) while ice formation in autumn has been delayed (Barber *et al.*, 2017).

Although warming and sea-ice reductions are common in most Arctic areas, there has been spatial and temporal variability. For example, the Bering Sea had extended sea-ice cover and much colder temperatures in the winter and spring from 2006 to 2013 when most other Arctic regions experienced warming and retreating sea-ice cover (e.g. Overland *et al.*, 2012, 2014; Wood *et al.*, 2015). Since then, the Bering Sea has had warmer temperatures and decreased sea-ice coverage (Danielson *et al.*, 2020), with exceptionally low sea-ice cover in 2018 (Stabeno and Bell, 2019; Thoman *et al.*, 2020).

Projections are that the Arctic Ocean is likely to be nearly ice free in summer before the second half of this century or even sooner (Wang and Overland, 2009, 2012; Overland and Wang 2013). The projected trends are not monotonic and there could still be multi-year periods when natural variability forcing results in little to no loss of ice extent and even an increase (Barber *et al.*, 2017). Only in the Barents Sea, is the winter ice projected to disappear by the end of this century (Årthun *et al.*, 2021).

We assembled annual projections of average sea-ice coverage from CMIP6 models for the Pacific and Atlantic Gateways (Figure 3i and j). There appears to be much less ice coverage in the Atlantic compared to the Pacific but this is simply because all the southern Barents Sea has been, and is projected to be, devoid of sea ice while the Pacific Gateway is mostly ice covered. The projected decrease in

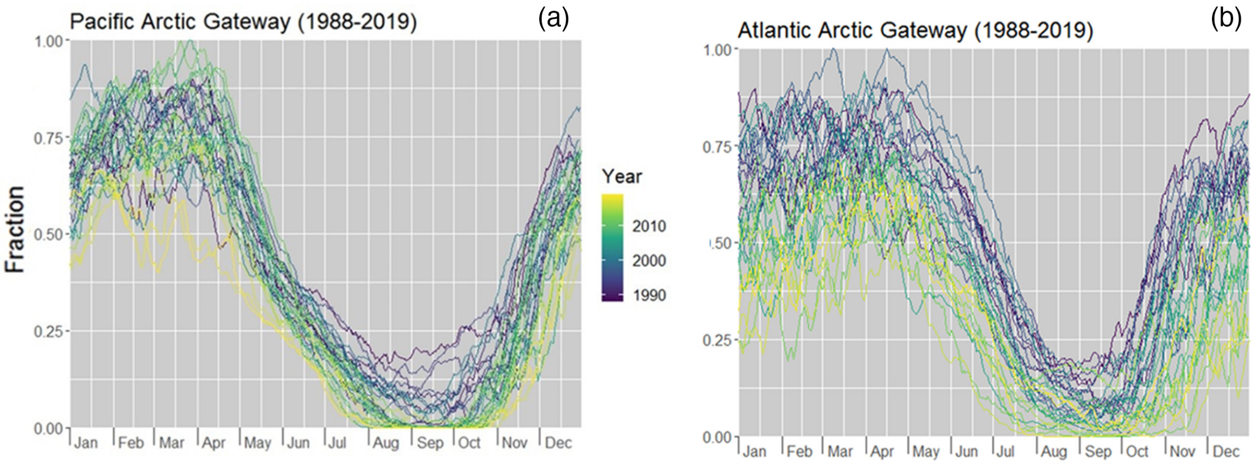

Figure 6. Seasonal trends in ice cover in (a) the Pacific Arctic and (b) Atlantic Arctic gateways from plots of daily sea ice for each year from 1988 to 2019. The Pacific Gateway covers the Bering and Chukchi seas and the Atlantic Gateway includes the Barents Sea. Daily concentrations are expressed as a fraction of the maximum daily extent of sea ice observed in each area over the time series. Data from the NOAA National Snow and Ice Data Center (Peng *et al.*, 2013; Meier *et al.*, 2017).

sea-ice coverage in the Pacific Gateway under SSP245 from 2020 to 2050 is around 12% and another 10% decrease by 2099 while under SSP585 the decreases are 16% and 34%, respectively (Table 1). In the Atlantic Gateway, the ice coverage under SSP245 fell from around 29 to 17% between 2020 and 2050 and then a further 8% by 2099 and for SSP585 the losses were from 22 to 11% between 2020 and 2050 and a further 7% by 2099 (Table 1). Given that the models are often underestimating the rate of sea-ice decline, our CMIP6 estimates may be slightly too conservative.

Physical oceanography

Ocean temperatures and salinities

Ocean temperatures have been increasing in both the Pacific and Atlantic gateways during recent decades. Moored current meter arrays in Bering Strait between 1990 and 2015 showed warm water (∼4–8°C) flowing from the Bering Sea into the Chukchi Sea (Woodgate, 2018), which eventually reached Barrow Canyon in the late 1990s (Itoh *et al.*, 2013; Williams *et al.*, 2014). Summer and fall warming trends over the Chukchi Sea for 1990–2018 were $0.43 \pm 0.35^{\circ}\mathrm{C}\ \mathrm{decade}^{-1}$, triple the rate during 1922–2018 (Danielson *et al.*, 2020). Timmermans and Labe (2020) showed that August sea surface temperatures (SSTs) during 1982–2020 from Bering Strait through the Chukchi Sea increased by approximately 0.5–1°C decade^{-1}. In the Bering Sea, water column temperatures (1966 to present) showed no statistically significant warming but SSTs did warm by $0.22 \pm 0.1^{\circ}\mathrm{C}\ \mathrm{decade}^{-1}$ (Danielson *et al.*, 2020). Recently, the latter authors estimated that the Chukchi Sea waters in autumn transferred enough heat to the atmosphere to warm the entire Arctic troposphere by 1°C.

In the Atlantic Gateway, SSTs warmed by $0.3^{\circ}\mathrm{C}\ \mathrm{decade}^{-1}$ during 1982–2013 in the Barents Sea (Jakowczyk and Stranska, 2014) and Atlantic waters in the northern Barents Sea warmed by $0.15^{\circ}\mathrm{C}\ \mathrm{decade}^{-1}$ between 1970 and 2011 (Lind *et al.*, 2016). In Fram Strait, the waters increased by $0.73^{\circ}\mathrm{C}\ \mathrm{decade}^{-1}$ during 1980–2016 (Goszczko *et al.*, 2018). Walczowski *et al.* (2017) reported that the temperature in the Atlantic waters off West Svalbard increased over the top 1000 m during the period 2000 to 2016, which ev.entually reached Fram Strait. A warming rate of $0.45–0.53^{\circ}\mathrm{C}\ \mathrm{decade}^{-1}$ was estimated for the inflow regions to the Barents Sea and Fram Strait during 1997–2015 (Gluchowska *et al.*, 2017).

Of the heat flux entering Fram Strait from the south, only approximately one third reaches the Nansen Basin, the rest being lost back to the south because of recirculation (48%), or to surface cooling (16%) (Kawasaki and Hasumi, 2017). Recently in the Barents Sea, there has been less ocean heat loss owing to the warmer atmosphere (Skagseth *et al.*, 2020).

Increased precipitation, river runoff, sea-ice melt (see above), and inflow of low salinity waters through the Bering Strait (Woodgate, 2018) led to a significant freshening of the Arctic from the mid-1990s (Proshutinsky *et al.*, 2009; Armitage *et al.*, 2016), peaking in the first decade of the 2000s (Proshutinsky *et al.*, 2015). The largest freshwater storage has been in the Beaufort Gyre (Carmack *et al.*, 2008; Proshutinsky *et al.*, 2015). In contrast, in the Amundsen and Nansen basins, salinity has increased due to a reduction in Pacific Water inflow there and an increase in salinity of the inflowing Atlantic Water (Wang *et al.*, 2019; Polyakov *et al.*, 2020a).

Projections of ocean temperatures using the model EC-Earth as part of CMIP5 indicated that the warming will continue through the 21st Century with maximum warming in the Barents Sea and vicinity (Koenigk *et al.*, 2013). Estimated heat and volume fluxes into the Arctic using the same model showed that an increasing flow through the Barents Sea will be a major contributor to warming of waters in the Arctic (Koenigk and Brodeau, 2014). The warming is primarily due to an increase in the Atlantic Water temperatures rather than a substantial increase in its volume flux. A future increase in Atlantic Water heat transports due to warmer, but weaker currents in the Barents Sea occurs in other climate model studies (Årthun *et al.*, 2019). Their study found that the warm Atlantic Water gradually spreads downstream from the Barents Sea and farther into the Arctic Ocean, leading to a reduced sea-ice cover and substantial changes in sea-ice thickness. Nummelin *et al.* (2016) suggest from models that there will be little to no change in the Atlantic inflow through Fram Strait. In contrast, the Bering Strait inflow may decrease owing to the reduction in the sea level pressure gradient caused by warmer and fresher water north of Bering Strait (Nummelin *et al.*, 2016). At this stage in the modelling, it is not clear what the resultant change in the inflows, and hence heat fluxes, into the Arctic will be.

Our CMIP6 results show increasing annual ocean surface temperature anomalies in both Bering and Fram straits, with little difference between the two regions (Figure 3e and f). A similar rise in SST anomalies of about 2°C occurs for both SSP scenarios until around 2050. After that, the temperatures increase significantly, reaching maxima anomaly values around 5°C near 2100.

Stratification

In much of the Arctic Ocean, there is a relatively cold and fresh surface layer above warm and highly saline Atlantic Water, between which lies an intermediate layer of cold but gradually saltier water, often termed the cold halocline (Rudels *et al.*, 2004). This halocline results in a strong vertical density stratification of the water column. River runoff, seasonal ice melt, positive net precipitation, and relatively fresh Pacific inflow contribute to the fresh surface layer (Polyakov *et al.*, 2020a). Seasonally, stratification is maximum in the summer and minimum in winter; the latter due to mixing by autumn winds and brine rejection during sea-ice formation. With warming temperatures and higher amounts of freshwater through increased precipitation and river runoff, the stratification in the Pacific Arctic has been increasing (Zhuang *et al.*, 2021). Increased stratification reduces the potential of vertical fluxes of nutrients reaching the euphotic zone (Carmack *et al.*, 2004; Tremblay and Gagnon, 2009), which seems to be borne out in the Pacific Arctic (Zhuang *et al.*, 2021). The increased stratification in the Pacific Gateway contrasts with what is happening in Fram Strait, where warming and shallowing Atlantic Waters are weakening the stratification as they enter the Nansen Basin (Polyakov *et al.*, 2020a). This leads to increased winter ventilation, further eroding the stratification and by the mid-2010s, the Atlantic Water heat began melting the sea ice (Polyakov *et al.*, 2020b).

Changes in stratification in the northern Barents Sea were considered by Lind *et al.* (2018) who linked recent changes in ocean temperature and salinity in the northern Barents Sea to declines in sea-ice import. They speculated that the northern Barents Sea may soon complete a transition from a cold and stratified Arctic to a warm and well-mixed Atlantic-dominated climate regime. Further studies are needed to determine the likelihood of such a scenario.

Circulation patterns and transports

Prior to 1996, the ocean circulation in the Arctic oscillated between cyclonic (counterclockwise) and anticyclonic (clockwise) circulation patterns approximately every 5–7 years (Morrison *et al.*, 2012; see Figure 7). During the former pattern, there was an increase in the freshwater flux out of the Arctic through Fram Strait while in the latter pattern it declined. However, from 1997 to present the Arctic has experienced a persistent anticyclonic circulation regime including the reduction in the outflow through the Fram Strait. (Proshutinsky *et al.*, 2015). Earlier, reductions in such outflow were ascribed to an increase in the southerly winds associated with a negative AD (Watanabe *et al.*, 2006). However, Proshutinsky *et al.* (2015) suggested the lower outflow through Fram Strait was due to a reduction in the sea level pressure gradient from the Arctic to the Nordic Seas caused by freshwater runoff from Greenland, although this is yet to be substantiated.

The present Arctic surface circulation is dominated by the transpolar drift, which crosses the Arctic Basin from the East Siberian and Laptev Seas to the Fram Strait and by the anticyclonic Beaufort Gyre in the Canada Basin. In the Pacific Gateway, the northward flow through the Bering Strait has been increasing during 1990–2019 at a rate of 0.01 ± 0.006 Sv year^{-1} (Woodgate and Peralta-Ferriz, 2021). In the Atlantic Gateway, Wang *et al.* (2020) suggested from modelling studies that the Atlantic Water inflow into the Arctic through Fram Strait increased though Nummelin *et al.* (2016), using the NorESM model, indicated that, in the future, the strength of the cyclonic circulation around the Arctic would increase.

Upwelling

Although wind-driven coastal upwelling in canyons had been observed in the Arctic, Carmack and Chapman (2003) were the first to point out the significant increase in upwelling when sea ice retreats seaward of the continental shelf. In such cases, upwelling favorable winds are better able to force shelf waters offshore through Ekman transport, which are replaced by deep off-shelf waters. For example, studies have described upwelling on the slope of the Beaufort Sea and its relationship to sea-ice conditions and the wind field (e.g. Pickart *et al.*, 2009, 2013; Schulze and Pickart, 2012). Woodgate *et al.* (2005) observed upwelling of Atlantic Water along the northern edge of the Chukchi Shelf/Slope. Upwelling was also observed north of Svalbard when the ice edge was offshore of the continental slope (Falk-Petersen *et al.*, 2015; Haug *et al.*, 2017). These results suggest that as the ice continues to disappear, upwelling will likely occur more often along the continental slopes in the Arctic (Lewis *et al.*, 2020). Shelf-edge upwelling is a more dominant process in the Pacific (western) side of the Arctic than in the Atlantic sector of the Arctic (Randelhoff and Sundfjord, 2018).

Chemical oceanography: nutrients and CO$_2$

Nutrients

Pacific waters that enter the Arctic from the Bering Sea contain high nutrient concentrations; e.g. in winter, nitrate concentrations are 20–25 μmol l^{-1} (Hunt *et al.*, 2013; Randelhoff and Sundfjord, 2018). These nutrients are advected north through Bering Strait into the Chukchi Sea where they sustain relatively high rates of primary production (Grebmeier *et al.*, 2006; Zhou *et al.*, 2021). Despite higher nitrate concentrations than in the Atlantic Waters (10–13 μmol l^{-1}), the total nutrient flux through the Pacific Gateway is only about one-quarter that of the Atlantic Gateway owing to the Pacific's smaller volume flux (Carmack and Wassmann, 2006; Torres-Valdes *et al.*, 2013). However, a large portion of the nutrients from the Atlantic Sector, through either Fram Strait or the Barents Sea, ends up in the deep waters of the Arctic, and thus is unavailable for biological productivity except over long-time scales.

Within the Atlantic Gateway, Rey (2012) noted a long decline in silicate concentrations in the Barents Sea beginning around 1990. Hátún *et al.* (2017) showed that this low silicate water originated from a weakened and retracted subpolar gyre south of Greenland with an associated increased influence of nutrient-poor subtropical waters. These authors concluded that the changes in the subpolar gyre were due to the reduction in vertical mixing through convection in the Labrador Sea. Oziel *et al.* (2017) observed a decline in nitrate concentrations of around 17% at the eastern entrance to the Barents Sea between the early1980s and 2010. In contrast to the Barents Sea, high nitrates were observed during late spring and summer in the Nansen Basin in 2014 and 2015 (Randelhoff *et al.*, 2016).

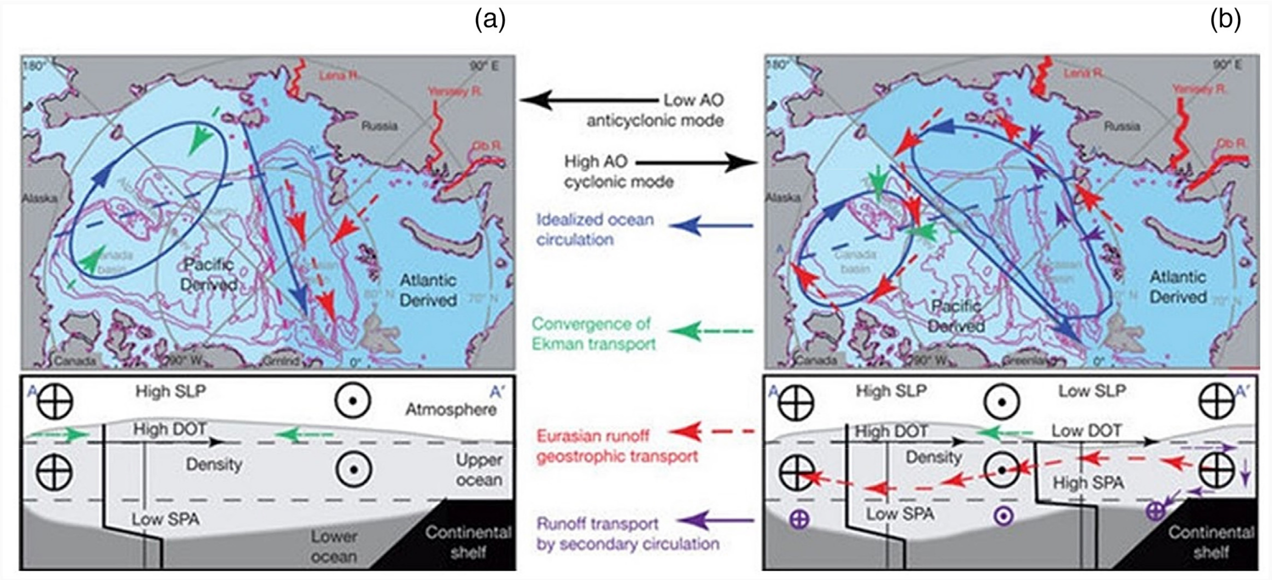

Figure 7. The Arctic surface circulation patterns taken from Morrison *et al.* (2012); (a) the anticyclonic mode and (b) the cyclonic mode.

Microstructure measurements indicated that these high nitrates were a result of increased turbulent mixing attributed, in part, to the recent shallowing of the inflow of Atlantic waters as they pass Fram Strait and enter the Nansen Basin north of Svalbard (Polyakov *et al.*, 2017). Henley *et al.* (2020) showed that the re-supply of nutrients was larger in the Atlantic Water north of Svalbard than in the Arctic waters in the northern Barents Sea.

The loss of sea ice and the accumulation of fresh water observed in the Canada Basin in the Pacific Sector of the Arctic discussed earlier, caused a deepening of the local nutricline and a reduction in the nutrient concentrations in the mixed layer (McLaughlin and Carmack, 2010; Nishino *et al.*, 2011b; Polyakov *et al.*, 2020a). However, in this region the role of eddies in supplying nutrients laterally from the shelf regions appears important (Nishino *et al.*, 2011b; Watanabe *et al.*, 2014).

The recent loss of Arctic sea ice increases the exposure of the sea surface to wind stress causing increased wind-driven vertical mixing and an upward supply of nutrients (Nishino *et al.*, 2015). This appears to be an important mechanism especially in the autumn throughout much of the Arctic. However, given that the projections of future wind changes in the gateways are relatively minor, increased upward nutrient fluxes in these regions are unlikely or will be small.

Nitrification is susceptible to changes in light levels. Shiozaki *et al.* (2019) conducted light control experiments in the Chukchi and Beaufort seas that showed nitrification was inhibited by a light intensity above 0.11 mol photons m^{-2} d^{-1}. Values exceeding this level extended to the shelf bottom and upper halocline layer, limiting nitrification in these waters. Satellite data indicate that the area where light levels inhibit nitrification has increased throughout the Arctic Ocean due to recent sea-ice reduction (Shiozaki *et al.*, 2019). This suggests that stronger light levels in the future Arctic Ocean as ice continues to disappear could further suppress nitrification and alter the composition of inorganic nitrogen (increasing ammonium-based nutrients), with implications for the structure of ecosystems (Shiozaki *et al.*, 2019).

The projected increased stratification in the future throughout the Arctic due to ice melt and increased precipitation would suggest that eventually, there will be less nutrients available in the surface layers. However, this will depend on the extent of vertical nutrient fluxes through increased wind mixing, especially in the autumn, and upwelling. Future nutrient levels in the surface layers of the Arctic are still under debate and remain highly uncertain.

CO_2 and OA

The Arctic plays an important role in the dynamics of the global carbon cycle. Yasunaka *et al.* (2016, 2018) estimated an annual CO_2 uptake by the Arctic Ocean during 1997–2014 of 180 ± 130 Tg C y–1 (1 Tg = 1012 g), almost 12% of the net global CO_2 uptake by the oceans (Gruber *et al.*, 2009; Wanninkhof *et al.*, 2013; Landschu¨tzer *et al.*, 2014). That the Arctic is such an effective sink for atmospheric CO_2 has been attributed to large spring phytoplankton blooms, strong cooling in the winter, the relatively high alkalinity of the Arctic Ocean, seasonal sea ice and freshwater additions (Takahashi *et al.*, 2009; Nishino *et al.*, 2011a).

The increased CO_2 in Arctic waters decreases the pH making the water more acidic, a process referred to as OA. Since the solubility of CO_2 is higher in colder water, this makes the polar regions more vulnerable to OA (Orr *et al.*, 2005). The addition of fresh water from sea-ice melt and river runoff reduces the ocean's buffering capacity further accelerating OA in the Arctic Ocean, especially on the freshwater-influenced shelf areas (e.g. Yamamoto-Kawai *et al.*, 2009; Chierici and Fransson, 2009).

The aragonite saturation state (Ω_{Ar}) is a measure of carbonate ion concentration and an index of OA. Ω_{Ar} greater than 1.0 (supersaturation) is required for marine calcifying organisms to form their skeletons and/or shells while if less than 1.0 (undersaturation), shells and other aragonite structures begin to dissolve. Recent studies (Baker *et al.*, 2021) have also shown that atmosphere acidification impacts the quantity and distribution of nutrients (nitrogen, phosphorus and iron) delivered to the ocean.

Although, the entire Arctic Ocean has naturally low Ω_{Ar} and pH relative to rest of the world's oceans, there are large regional differences within the Arctic (e.g. Bates and Mathis, 2009; AMAP

2013). Pacific Water, containing high CO_2 from remineralized organic matter, have the lowest Ω_{Ar} and pH values. The mean circulation carries this water into the central Arctic and eventually to western Fram Strait. In contrast, Atlantic water transports high anthropogenic CO_2 but with relatively high total alkalinity resulting in higher Ω_{Ar} and pH values relative to the Pacific Arctic.

In recent years, the aragonite saturation states have been declining in the Gateway regions and the Arctic in general. Corrosive events are already occurring in the Pacific Arctic (Cross *et al.*, 2018). In the Bering Sea, during 2003–2012, pH declined and the Ω_{Ar} showed high spatial variability with supersaturation of aragonite on the outer shelf due to high biological activity and undersaturation in nearshore waters due to freshwater runoff (Pilcher *et al.*, 2019). Yamamoto-Kawai *et al.* (2016) observed that the bottom waters on the Chukchi Shelf undergo intermittent aragonite undersaturation and calculated that the period of undersaturation has increased more than two times that in the pre-industrial times. In the Canada Basin, the area of Ω_{Ar} less than 1 expanded from 1997 to 2008 (Yamamoto-Kawai *et al.*, 2009; Qi *et al.*, 2017). On the opposite side of the Arctic, CO_2 concentrations have increased and pH decreased in the intermediate waters in the Amundsen and Nansen basins (Ericson *et al.*, 2014; Ulfsbo *et al.*, 2014). Chierici and Fransson (2018) suggested this was a result of the release of dense CO_2-rich brine during sea-ice formation from the shelf break and northern Barents Sea into the intermediate and deep waters in the Arctic Ocean.

Model projections for both gateways suggest that they will experience a reduction in pH in future under either SSP245 and SSP585 (Figure 5i and j) and that the duration, intensity, extent and frequency of undersaturation are likely to increase (Steinacher *et al.*, 2009; Mathis *et al.*, 2015; Skogen *et al.*, 2014). Undersaturation is projected to occur in the bottom waters in the northern Barents Sea by 2030 (Popova *et al.*, 2014). Future scenarios suggest a drop of 0.1–0.4 units in the surface pH by 2100, and in the worst case, the Barents Sea will be undersaturated with respect to aragonite (Fransner *et al.*, 2020). Chierici *et al.* (2019) showed that the Atlantic Arctic inflow area is a net annual ocean CO_2 sink, mainly caused by biological CO_2 uptake. Continuing sea-ice declines, with increased open areas exposed to wind as well as thinner sea ice as projected, ensures that the Arctic will remain a sink for atmospheric carbon dioxide into the future (Nishino *et al.*, 2011a; Fransson *et al.*, 2017).

Climate change impacts on humans

Changes in the physical and chemical characteristics of marine ecosystems have a profound effect on human activities in the Arctic, including in the gateways (e.g. Huntington *et al.*, 2020). For example, the loss of open sea ice and landfast ice impacts Indigenous peoples living on arctic coasts via shoreline erosion, interruption of transport on ice-covered waters, and less access for hunting marine animals. These losses also increase access for large vessels to transit the Arctic and for tourists to visit remote and fragile regions that are replete with wildlife.

Shoreline erosion is a major concern along the coasts of Arctic Alaska and the Yukon, where rates of coastline retreat exceed 5 m year^{-1} in places (Jones *et al.*, 2009). Two main factors are involved: (1) the length of the open-water season, which is increasingly extending into the stormy, fall season, and (2) the longer fetch as distances increase between the shore and the ice edge (Overeem *et al.*, 2011). The longer fetch allows increased wave heights and overall higher water levels, which in turn, increases coastal retreat. Increasing sea level elevation also occurs due to the steric effect from the warming and freshening ocean. Erosion has already caused infrastructure damage in several coastal communities and in some cases, has meant, or will mean in the future, that the communities must relocate (Fritz *et al.*, 2017). Such erosion can also destroy cultural heritage, through the loss of community lands and burial sites.

An additional impact of Arctic warming is the reduction and increased instability of landfast ice (Dumas *et al.*, 2006; Vermaire *et al.*, 2013). In combination with rising Arctic sea level, the loss of landfast ice has opened low lying arctic coastlines to inundation and inland flooding with seawater (ACIA, 2005; Manson and Solomon, 2007). These storm surges can damage terrestrial vegetation, and result in the salinization of near-coastal soils and freshwater lakes, thereby altering their ecosystems (e.g. Pisaric *et al.*, 2011; Deasley *et al.*, 2012; Kokelj *et al.*, 2012; Thienpont *et al.*, 2012).

Sea ice has traditionally provided access by humans for hunting marine mammals, sometimes at considerable distances from shore (Laidler *et al.*, 2009; Meier *et al.*, 2014; Huntington *et al.*, 2017). If there are large regions of open water, ice floes containing hunters may break away, thereby isolating them from a safe return to land (Gearhead *et al.*, 2006; Laidre *et al.*, 2018). Additionally, the loss of sea ice has reduced the extent of habitat available for ice-dependent pinnipeds and their polar bear predators (e.g. Kovacs *et al.*, 2011; Beatty *et al.*, 2016). These sources of food, fur, and skins are of great cultural importance to many coastal communities in the Arctic, and their reduction or loss has negative cultural and economic impacts (Himes-Cornell and Kasperski, 2015).

Another concern are contaminants that may affect food security. Rivers are the primary source of mercury to the Arctic Ocean (Fisher *et al.*, 2012). With melting permafrost, more mercury is released from the soil, and because of increased river runoff, more mercury will enter the Arctic Ocean. This could affect the health of those consuming marine resources such as fish, shellfish, marine mammals, and ultimately humans, as mercury can accumulate in the body as occurred in James Bay (Gorrie, 1990). This ultimately could lead to mercury poisoning and severe health issues. Toxins from harmful algal blooms have also been reported with increasing frequency in the Pacific Arctic (Natsuike *et al.*, 2013; Lefebvre *et al.*, 2016), posing additional health risks to coastal communities that depend on marine species.

In contrast to these detrimental impacts, the loss of arctic sea ice has meant opportunities for others. For example, the reduction in sea ice has opened transportation routes with increasing ship traffic through the Northeast and Northwest passages, and hence in the Arctic Gateways (e.g. Dawson *et al.*, 2018; Chen *et al.*, 2020). Tourist traffic has increased and is expected to increase even further as ice cover declines (Halliday *et al.*, 2018). This tourist traffic is problematic, as the visited sites are often to remote, fragile, and small Indigenous communities that can be negatively impacted. The decrease in sea ice also opens the Arctic up to oil and gas exploration, as well as mineral extractions, with the associated potential for environmental contamination (Kristoffersen and Langhelle, 2017). Already, in the National Petroleum Reserve-Alaska, some infrastructure has become subject to coastal erosion (Holland-Bartels and Pierce, 2011). Greater ship traffic also increases the possibility of oil spills (Nevalainen *et al.*, 2019) and the added need for facilities and personnel to deal with these, if they occur. Increases in marine activities pressure national governments to have search and rescue operations available (Ford and Clark, 2019).

The effects of climate change on the ecology in the Arctic and Subarctic including fish and fisheries are dealt with in Mueter *et al.*

(this issue). It will not only be fishers that will be directly affected but processors as well. For example, one of the important cod fish products in Norway is stockfish. The cod is dried on open-air timber racks, or "stocks" in northern Norway between February and May. The present climate is perfect for creating stockfish with the right balance of wind, sun and rain. However, with the anticipated increase in air temperatures and higher precipitation in northern Norway under climate change some communities and processors are concerned that drying conditions may deteriorate (Dannevig and Hovelsrund, 2016). This could limit or even possibly eliminate the stockfish product. Drying of salmon by Alaskan natives may also be compromised by increased precipitation and changes in air temperatures (Carothers *et al.*, 2014).

Low probability-high impact events

In addition to the above scenarios, as ecosystems move non-linearly into new and novel states there could possibly be some low probability events that would have high impact if they do occur. We provide two examples of such events. The first is the shutdown or precipitous decline of the North Atlantic large-scale ocean circulation, the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is the Atlantic portion of the global overturning circulation. In the upper limb of the AMOC, warm water flows northward into the subpolar North Atlantic and Nordic Seas, where it releases its heat, sinks and returns southward in the lower limb. The AMOC is primarily driven by density differences in the ocean and by winds. Rahmstorf and Ganopolski (1999) suggested the AMOC could shut down due to a freshening of the waters in the northern North Atlantic under global warming, causing extreme cooling in the northern North Atlantic, up to an estimated 11°C. Most modelling studies now suggest a cooling of northern Europe due to a reduced AMOC is unlikely to occur in the next 100 years and that a warming trend is expected to continue with increases of 2°C or more over this time frame (e.g. Vellinga and Wood, 2008). A recent study using various proxies suggests AMOC is presently at its weakest state of the last millennium (Caesar *et al.*, 2021). Such a weakening is consistent with models indicating a slowdown of the AMOC under climate change (IPCC, 2019).

A second major event that is unlikely but would have major consequences if it did happen is a reversal or significant reduction of the northward flow through Bering Strait. As previously discussed, this northward flow is presently driven primarily by a sea level elevation difference with the Arctic sea level being lower than the Pacific (Woodgate, 2018). However, the large warming and freshening of the Arctic and North Atlantic has resulted in regionally variable sea level rise thereby altering sea level elevation gradients and associated lateral pressure gradients. While it is unlikely for the gradient to reverse, if it did, the flow would be out of the Arctic into the Pacific, which would decrease the nutrient flux through Bering Strait and the highly productive Bering–Chukchi ecosystem would fundamentally reorganize.

Summary and discussion

In this paper, we have reviewed recent trends and projected future changes in the climatic conditions under anthropogenically-induced climate change with a geographic emphasis on the major gateways to the Arctic, specifically the Pacific Sector (Bering Sea, Bering Strait, and the Chukchi Sea) and the Atlantic Sector (Fram Strait and the Barents Sea). We have also discussed the physical or chemical mechanisms that are thought to be behind these changes. Many of the recent trends and projected future changes in the gateways are similar to those for the overall Arctic, e.g. increased air and ocean temperatures, higher heat fluxes into the Arctic, a loss of sea ice, etc. However, the amplitudes and rates of change have varied, and are projected to vary spatially.

One of the objectives of our study is to compare what has and will happen, in the Atlantic and Pacific Gateways of the Arctic. There are several major differences in the Atlantic and Pacific Gateways. In the Pacific Sector, the volume exchange with the Arctic is approximately nine times less than in the Atlantic Sector due to the much smaller cross sectional area of Bering Strait. Thus, the total nutrient flux into the Arctic from the Atlantic is about four times that in the Pacific despite the higher nutrient concentrations in the Pacific waters (Carmack and Wassmann, 2006; Torres-Valdes *et al.*, 2013). The Pacific Gateway is much farther south than the Atlantic Gateway and hence experiences more sunlight than the latter. Another difference is that the inflowing Pacific Water mainly remains in the upper layers of the Arctic owing to its lower density (Morrison *et al.*, 2012). As much of the ecological dynamics occur in these upper layers, the Pacific waters play more of a role in shaping these dynamics. In the Atlantic Sector, a large portion of the flow sinks below the surface waters of the Arctic as its density is higher than the surface layer waters (Polyakov *et al.*, 2017). Under these conditions, the primary influence of the Atlantic waters is in the deep Arctic. However, in recent years, the density of the inflowing water in the Atlantic Sector has been reduced such that the depth at which it flows into the Arctic through Fram Strait and into the Nansen Basin is shallower than in previous years (Randelhoff *et al.*, 2016). This has led to a higher upward heat flux that has contributed to further ice melt in the region. Another consequence of this has been reduced stratification with increased vertical mixing through winter convection resulting in higher nutrient levels in the surface waters (Randelhoff *et al.*, 2016). This contrasts with the Pacific Sector where the vertical stratification has increased in recent years (Zhuang *et al.*, 2021). A further difference in the two gateways is the strong outflow from the Arctic to the Atlantic through Fram Strait, but little outflow into the Pacific through Bering Strait. This results in greater two-way exchange between the sub-Arctic and Arctic ecosystems and their constituents in the Fram Strait region and a greater influence of the Arctic on the Subarctic in the Atlantic Sector. While the sea ice north of both straits has declined, the reduction in the Chukchi and Beaufort seas has been greater than in Fram Strait (Figure 3e and f). Sea-ice reduction in the Barents Sea has mirrored that in the Arctic Basin, while the sea-ice variability in the Bering Sea has not always, e.g. there was expansion of sea ice in some years in the Bering Sea when the ice was disappearing in the Arctic Basin and in the Barents Sea. (Overland *et al.*, 2014).

Projections under future climate change in both the Atlantic and Pacific gateways to the Arctic, however, indicate many likely similarities. Ocean and air temperatures will continue to rise (Figure 3k and l; and c and d, respectively) while there will be further reductions in sea ice including no ice in summer and additional decreases in areal coverage and thickness in winter (Figure 3i and j). Surface salinity will decrease due to melting ice, increased precipitation, and higher river runoff. With the loss of sea ice, light levels in summer will increase until sea ice totally disappears. Also, there will be more open areas with no sea ice allowing the Arctic waters to absorb more CO_2, thereby becoming more acidic (Figure 3m and n).

However, it must be remembered that the future projected changes are principally model-dependent. Such models vary in their ability to hindcast observations and there is sometimes a large spread in future conditions from different models (Figure 3). Therefore, one must be cautious in accepting the results from models, especially any single model. Consistent results between several models suggest that the results are likely robust although this is only true for models that are independent and this is not always the case since many models use similar formulations. However, examples of robust modelled variables include air and sea temperatures, precipitation, sea ice, and pH but even with these, rates of change are difficult to model well. Thus, for example, the observed rate of loss of sea ice in recent decades has been under-estimated by most models (Notz and SIMIP Community, 2020). Some variables such as wind and cloud coverage exhibit only relatively small changes and we therefore do not consider these projections robust at this stage. Another uncertainty is in the selection of CO_2 emissions and hence potential mitigation strategies.

Based on the literature as presented in our paper, comparing changes in the gateways to the central Arctic, future projections suggest the gateways will experience lower increases in air temperatures but higher precipitation rates. Snowfall will decline more in the gateways than in the central Arctic. Winds in the Central Arctic are expected to increase while those in the Barents and Bering seas, if they do increase, it will only be by a minor amount. Sea ice will disappear faster in the gateways than in the Central Arctic. Ocean temperatures will increase more in the gateways. In future, vertical stratification will become stronger in the Central Arctic compared to the gateways. The thickness of the upper mixed layers will decrease in the Central Arctic but will depend on the strength of the wind mixing. Upwelling will be mainly limited to the continental shelf regions in the Arctic, and it has been suggested will be stronger on the Pacific side. Owing to the faster rate of sea-ice loss and hence increased ice-free areas in the gateways, these areas are expected to experience lower aragonite saturation levels than the Central Arctic.

The major climatic changes that have occurred to date in the Arctic led Overland (2020) to hypothesize that the Arctic is becoming climatically less resilient, mostly related to the loss of sea ice and subsequently changes in the albedo feedback system. He suggested that in the future major climatic thresholds could be reached or even passed. If this happens, the Arctic will likely experience large and unexpected physical and chemical changes in the future. This could result in a large transformation in the Arctic ecosystems (Mueter *et al.*, this issue) and for their human inhabitants (Huntington *et al.*, 2020).

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Data availability

Data are available on request.

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