

REVIEW

Still Arctic?—The changing Barents Sea

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The Barents Sea is one of the Polar regions where current climate and ecosystem change is most pronounced. Here we review the current state of knowledge of the physical, chemical and biological systems in the Barents Sea. Physical conditions in this area are characterized by large seasonal contrasts between partial sea-ice cover in winter and spring versus predominantly open water in summer and autumn. Observations over recent decades show that surface air and ocean temperatures have increased, sea-ice extent has decreased, ocean stratification has weakened, and water chemistry and ecosystem components have changed, the latter in a direction often described as “Atlantification” or “borealisation,” with a less “Arctic” appearance. Temporal and spatial changes in the Barents Sea have a wider relevance, both in the context of large-scale climatic (air, water mass and sea-ice) transport processes and in comparison to other Arctic regions. These observed changes also have socioeconomic consequences, including for fisheries and other human activities. While several of the ongoing changes are monitored and quantified, observation and knowledge gaps remain, especially for winter months when field observations and sample collections are still sparse. Knowledge of the interplay of physical and biogeochemical drivers and ecosystem responses, including complex feedback processes, needs further development.

Keywords: Arctic, Ecosystem, Barents Sea, Sea ice, Climate change, Atlantification

1. Structure and scope of this review in the context of climate change

This interdisciplinary synthesis of status and changes in the Barents Sea system is based predominantly on

scientific literature published after 2010, although in some cases new unpublished data and results are presented. We address trends observed over the last four decades, when comparable and reliable observations exist,

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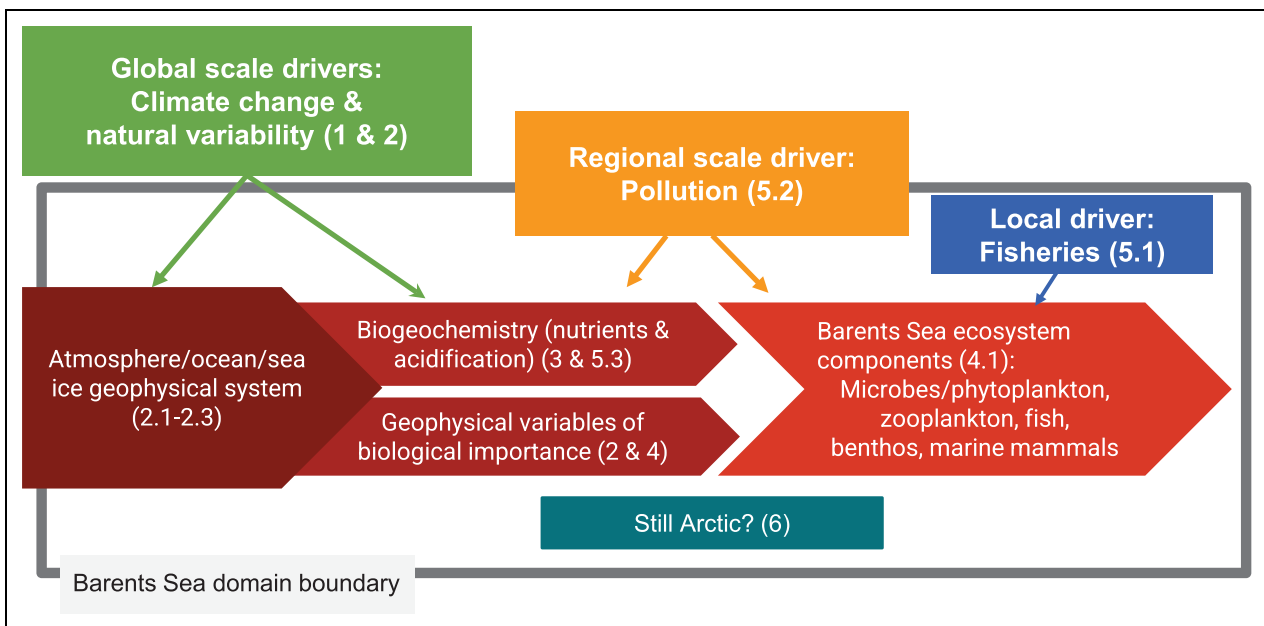


Figure 1. Schematic of the Barents Sea as an integrated physical-biological system. The figure includes the main drivers of change, placed outside, on the edge or inside the Barents Sea domain. The numbers in brackets refer to the respective chapters or subchapters in the text.

and also look ahead over the same time period. This time frame is most relevant for environmental management questions. The work is part of the ongoing project “The Nansen Legacy” (www.nansenlegacy.org), which aims to improve and integrate our understanding of the climate system, drivers and responses in environment and ecosystem in this very rapidly changing northern ocean domain.

On top of changes driven by external drivers, there are large short-term and long-term fluctuations in the Barents Sea atmosphere-ice-ocean system (**Figure 1**) due to internal variability. These fluctuations arise from instabilities in one component of the climate system or interactions between different components (Sutton et al., 2015). A good example of internal variability resulting in changes in the Barents Sea region is the well documented contrast between the warm and fisheries-rich years in the 1930s–1940s and the cold and relatively poor years in the 1960s (Drinkwater, 2006; Nakken, 2008; Drinkwater et al., 2014; Drinkwater and Kristiansen, 2018).

Human-introduced greenhouse gas increases are very likely the main driver of tropospheric warming since 1979 (Eyring et al., 2021). Global CO₂ emissions result in changes in Earth’s energy, freshwater and carbon budgets, thereby forcing changes in the transport of moisture, heat and mass towards the Arctic. These changes, in turn, affect the energy balance within the Arctic, including in the Barents Sea geophysical system (**Figure 1**). Moreover, changes in the Arctic at large may impact lower latitudes, for example, through outflows of sea ice (e.g., Spreen et al., 2020) and freshwater (e.g., de Steur et al., 2018) and via atmospheric couplings (e.g., Siew et al., 2020). Warming in the Arctic is occurring more rapidly than in other regions on the planet, and processes related to Arctic amplification (Serreze and Barry, 2011; Arctic Monitoring and Assessment Programme [AMAP], 2021)

are subjects of recent scientific work (e.g., Pithan and Mauritsen, 2014; Pefanis et al., 2020; Rantanen et al., 2022). On a year-to-year basis, the varying external forcing and the internal variability together determine Barents Sea water temperature, light conditions, stratification, ocean currents and other variables of importance to the ecosystem. Global climate change also directly affects the biogeochemistry on longer time scales (**Figure 1**) through warming, freshening, and ocean acidification. The World’s oceans take up roughly 25% of man-made CO₂ emissions (e.g., Watson et al., 2020), mitigating climate change on the one hand, but with ocean acidification effects on the other hand (e.g., AMAP, 2018; Rastrick et al., 2018). Moreover, the freshening occurring in some parts of the Arctic Ocean leads to a decrease in nutrients, alkalinity and carbonate ion concentrations in the surface water, where the latter two further contribute to ocean acidification (e.g., Chierici and Fransson, 2009; Fransson et al., 2015b; Fransson et al., 2016; Chierici and Fransson, 2018). Ocean currents and nutrients influence the productivity and life cycles of organisms in ecosystems (Hays et al., 2017; **Figure 1**). The large-scale changes are occurring alongside regional and local impacts of pollution, fisheries and other activities, which contribute significantly to variability of the Barents Sea ecosystem.

This synthesis summarizes the current knowledge regarding the coupled physical, biological and biogeochemical systems in the Barents Sea, including the boundary towards the Nansen Basin, along with a discussion of future perspectives. The review is organized in chapters and subchapters consistent with the compartments shown in **Figure 1**. Scientific findings were available in a larger number of studies for the western part of the Barents Sea than other subregions. We summarize the results of scientific process studies, mapping, and regular long-term

monitoring programs in the Barents Sea, including physical and human impacts of observed changes. Future knowledge needs and perspectives are addressed in the end.

1.1. The Barents Sea region and earlier reviews

The Barents Sea is one of several shelf seas of the Arctic Ocean, surrounded by archipelagos in the north (Svalbard in the northwest, Franz Josef Land in the northeast), Novaya Zemlya in the east, and northern Norway and northwestern Russia in the south (**Figure 2**). The Barents Sea is connected to other seas; in the west through the Barents Sea Opening (BSO) to the Norwegian Sea, in the north to the Nansen Basin, and in the east (openings north and south of Novaya Zemlya) to the Kara Sea. It has

a diverse bathymetry with shallow banks and deep trenches, but its depth is limited to <300 m in most areas.

There is a large inflow of Atlantic Water (AW; temperature, $T > 3.0^{\circ}\text{C}$, and salinity, $S > 35.0$; see Loeng, 1991) through the southern Barents Sea, entering the BSO and exiting north of Novaya Zemlya after substantial modification (**Figure 2**). Large heat losses occur where the AW is in direct contact with the atmosphere (i.e., in the southern and eastern Barents Sea), estimated at 76 TW (long-term average from different data sources; Smedsrud et al., 2013). There are large sea-ice inflows to the Barents Sea from the north and east, primarily in winter through the passages between Franz Josef Land and Novaya Zemlya, and between Svalbard and Franz Josef Land (Ellingsen et al., 2009; Kwok, 2009). Inflow variability is driven

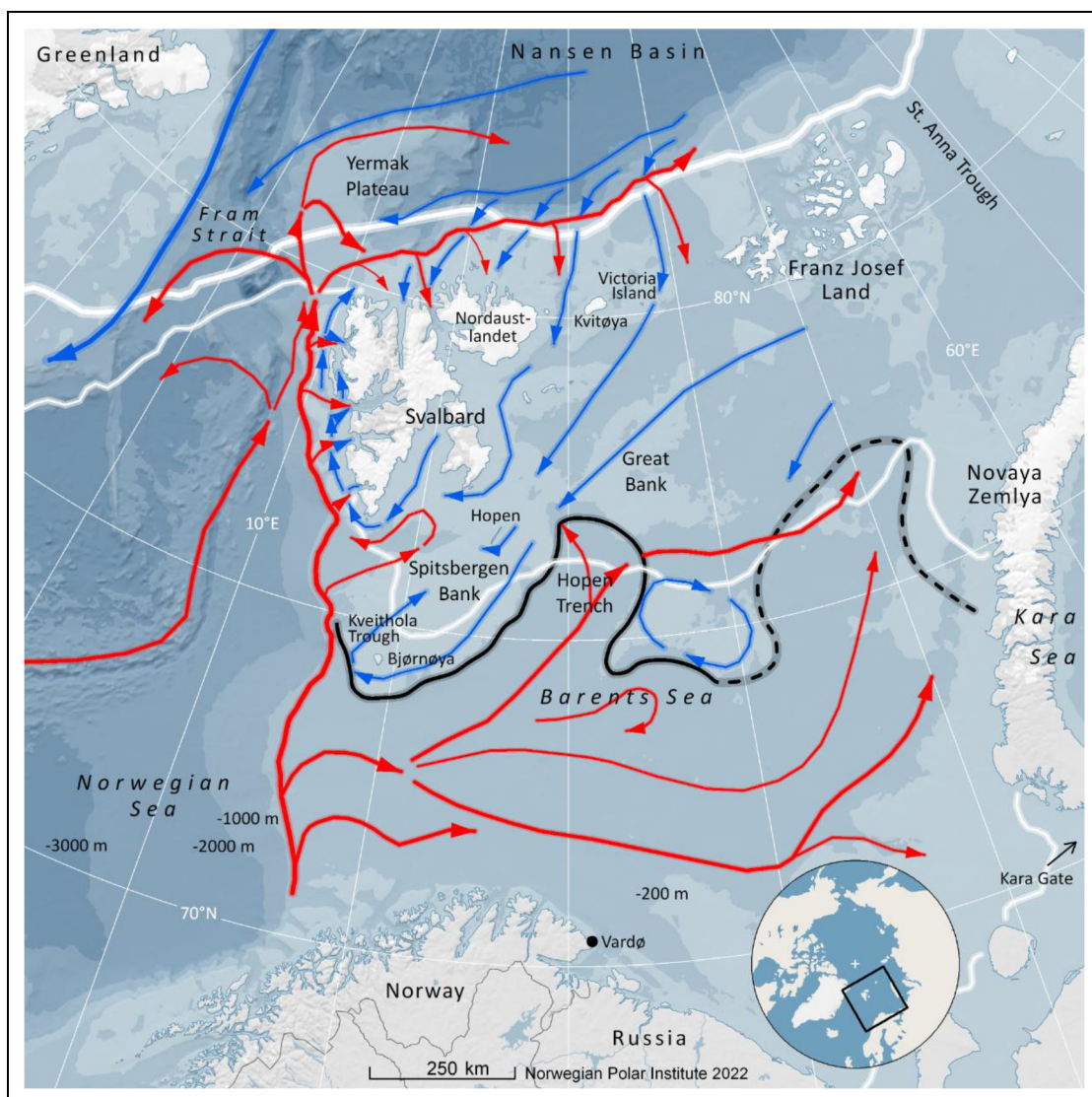


Figure 2. Map of Barents Sea and adjacent ocean areas with main ocean and sea-ice characteristics. The Barents Sea with adjacent ocean areas, and its setting in the Arctic (inset map). Currents are indicated with warm (red) and cold (blue) water masses. The Polar Front (black line) is supported by more observations in the west (solid line) than farther east (dashed line). Mean April and September sea-ice extent borders (2011–2020) from passive microwave satellite data are indicated by thin and thick white lines, respectively, and are based on NSIDC monthly means (Cavalieri et al., 1996). Depth contours/shadings distinguish between areas with depths less than 200 m, 200–1000 m, 1000–2000 m, and deeper in 1000-m steps.

primarily by atmospheric circulation, and the sea-ice inflow affects the Barents Sea ice-cover variability (Herbaut et al., 2015). When melting in summer the sea ice provides freshwater, which maintains the ocean stratification of the northern Barents Sea (Lind et al., 2018).

Climatically the Barents Sea can be divided into two domains: a warm, well-mixed and sea-ice-free Atlantic domain in the south; and a cold, stratified and seasonally ice-covered Arctic domain in the north (Loeng, 1991). In recent years our understanding of the Barents Sea and the processes influencing its ecosystem have increased significantly (e.g., Smedsrud et al. 2013; Csapo et al., 2021). At the same time, substantial changes are happening across the ecosystem, complicating interpretation of mechanistic studies against a baseline that may no longer be relevant. To investigate this inflow shelf (Carmack and Wassmann, 2006) in the midst of fundamental changes is exciting, but also challenging. Some key processes are still not fully understood, and several aspects of the system are not yet monitored.

The Barents Sea is currently experiencing rapid climate change, manifested in the loss of sea ice (Onarheim and Årthun, 2017; Asbjørnsen et al., 2020), a warmer and warming ocean (Barton et al., 2018; Skagseth et al., 2020), weakening ocean stratification in its northern parts (Lind et al., 2018) and a strengthening of stratification in the southern parts (Hordoir et al., 2022), changes in ocean chemistry (Skogen et al., 2014; Chierici and Fransson, 2018), a more variable and rapidly warming lower atmosphere (Screen and Simmonds, 2010; Isaksen et al., 2016; Isaksen et al., 2022), and changes in the ecosystem such as shifts in net primary production (Dalpadado et al., 2020), food-web characteristics (Kortsch et al., 2015) and spatial distribution of ecologically and commercially important fish stocks (Fosshem et al., 2015). The change is most apparent in the northern and eastern Barents Sea (Lind et al., 2018; Skagseth et al., 2020). While the northern Barents Sea loses sea ice, and in the future may transition climatically from a cold, stratified and sea-ice-covered Arctic sea to a warm, well-mixed and ice-free Atlantic sea (Lind et al., 2018), the eastern Barents Sea already has lost most of its sea ice (Onarheim et al., 2015) and warmed even more (Skagseth et al., 2020). These changes are part of a larger “Atlantification” or “borealization” process that also takes place further east in the Arctic Ocean (Polyakov et al., 2017; Polyakov et al., 2020; Ingvaldsen et al., 2021) and is expected to continue in the coming decades (Årthun et al., 2019; Dörr et al., 2021).

Earlier reviews about the Barents Sea have been published, including a book on the Barents Sea ecosystem (Sakshaug et al., 2009) related to the “Norwegian Research Programme for Marine Arctic Research” (ProMare, 1984–1989). Oceanographic conditions were summarized by Loeng (1991) and the pelagic ecosystem, by Loeng (1989) and Sakshaug et al. (1994). Oceanographic and biological long-term trends have been addressed by Matishov et al. (2012) and Eriksen et al. (2017). The variability and change in air-ice-ocean processes have been described by Smedsrud et al. (2013), who summarized the Barents Sea contribution to the Arctic climate system.

Work that took place in the marginal ice zone of the Barents Sea as a part of Norwegian (Research Council of Norway) projects focused on multidisciplinary process studies (ICE-BAR and MARINØK; Falk-Petersen et al., 2000; Falk-Petersen et al., 2004) and biological forcing of the carbon pump (CABANERA; Wassmann et al., 2006; Wassmann et al., 2008; Reigstad et al., 2011). Other studies with a more pan-Arctic perspective included future prospects for the Arctic Ocean seasonal ice zones with implications for the pelagic-benthic coupling (Wassmann and Reigstad, 2011; Ingvaldsen et al., 2021). Studying the ongoing changes in the northern Barents Sea and the role of the key drivers leading to these changes is important for understanding the mechanisms behind ecosystem processes, and for improving predictions of a future Arctic. We therefore find it timely to synthesize the current knowledge regarding the coupled physical, chemical, and biological systems in the Barents Sea, including the northern border towards the Nansen Basin in the central Arctic Ocean.

1.2. Paleorecords and historical changes

Paleorecords indicate that during the last ice age a grounded ice sheet covered the Barents Sea (e.g., Svendsen et al., 2004; Dowdeswell et al., 2010). When this ice sheet retreated between 11,000 and 7,000 years ago, AW began to enter, accompanied by surface warming in summer and sea-ice formation in winter (e.g., Aagaard-Sørensen et al., 2010; Risebrobakken et al., 2010; Berben et al., 2017).

The Arctic Front has been close to its present position since about 7,400 years ago (Risebrobakken and Berben, 2018). AW has been present in the northern and southwestern Barents Sea, albeit with a reduced influence, since around 7000 years ago (Lubinski et al., 2001; Smedsrud et al., 2013). From about 8,000–5,000 years ago, Arctic Water (ArW) took over, dominating in the NW Barents Sea (Polyak and Solheim, 1994). Onwards from around 5,000 years ago, the NW Barents Sea again experienced increased inflow of AW until today (Berben et al., 2017). An increased inflow of AW is similarly indicated through the northern boundaries around 3,500 years ago (Chauhan et al., 2016).

Historical sea-ice conditions have been reconstructed back to 1750 and merged with modern era satellite-based results by Divine and Dick (2006). Their analysis showed that interannual variability of sea ice in the Nordic seas remained almost constant throughout this period, whereas pronounced decadal to multidecadal variations identified in the Barents Sea ice extent had periods of 20 to 30 years. This variability was superimposed on a continuous negative trend in sea-ice extent, associated with a combined effect of anthropogenically induced warming and climate recovery to a mean state after the termination of the multicentennial cold period known as “Little Ice Age”. These findings support conclusions from Vinje (2001), who found evidence of persistent ice retreat since the second half of the 19th century. Lamb (1977, 1979, 1984, 1995) and Mörner et al. (2020) reconstructed ice-edge positions in the Barents Sea back to the late 16th

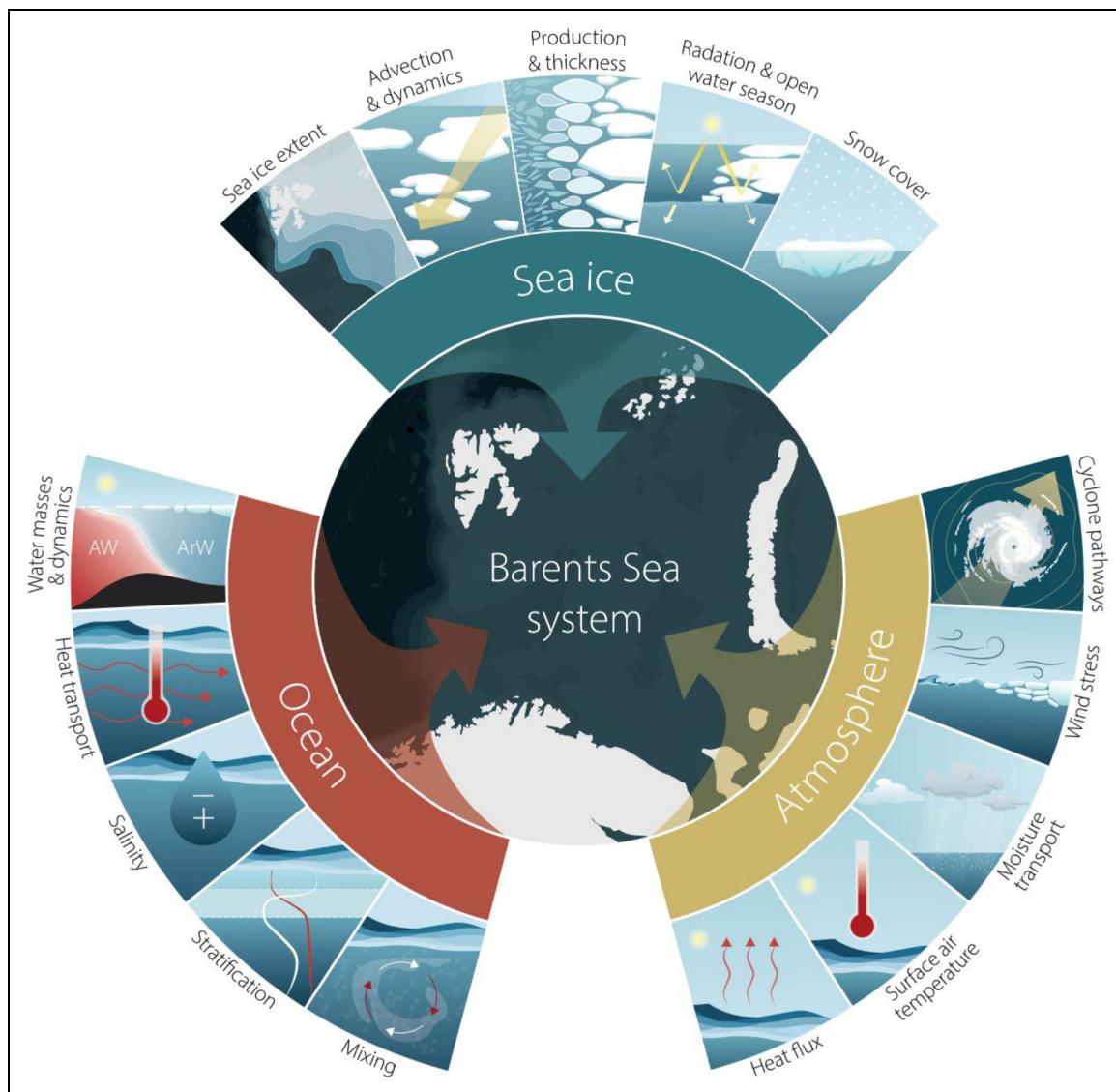


Figure 3. Schematic overview of physical processes and drivers affecting the Barents Sea system. Shown are important physical processes and drivers related to ocean, sea ice and atmosphere, all affecting the Barents Sea system. Figure developed by Frida Crossen (UiT The Arctic University of Norway/The Nansen Legacy).

century. In that record, the Barents Sea ice edge has been moving northward since about 1800, with intermediate, less strong shifts to the south over a few decades between 1860 and 1910 and again between the 1930s and 1950s. New studies using marine sediment proxies of sea ice and temperature in the northernmost Barents Sea reveal continuous persistence of both seasonal sea ice and AW inflow 10,000 to 6,000 years ago (Holocene Thermal Maximum), and also during warmer-than-present conditions (Pieńkowski et al., 2021). Current anthropogenic drivers of sea ice and inflow, however, differ from those in the past.

2. Status and changes of the atmosphere, ocean, and sea-ice systems

Prominent changes have occurred in the northern Barents Sea physical system over the last decades in the form of oceanic and atmospheric warming, the reduction in winter sea-ice cover, and corresponding increases in winter heat loss. The plethora of relevant variables, parameters

and processes in the atmosphere, ocean and sea ice are illustrated in **Figure 3**, and will be discussed in the thematic sub-chapters below. Here we demonstrate these changes using data for a subregion (**Figure 4**).

2.1. A complex interplay of drivers change the Barents Sea

The loss of sea ice follows an increased transport of ocean heat by AW into the southwestern Barents Sea through the BSO (Årthun et al., 2012; Stroeve et al., 2014), increased import of atmospheric heat (Woods and Caballero, 2016), and reduced volume of sea-ice inflow (Lind et al., 2018). Specifically, the annual variability in Barents Sea winter sea-ice cover is mainly driven by AW inflow with a 1-year to 2-year lag (Årthun et al., 2012). The multi-annual/decadal sea-ice variability is characterized by large additional warming and ice loss trends since the early 1980s (Onarheim et al., 2018). These trends are further explained by rising air temperature and radiative

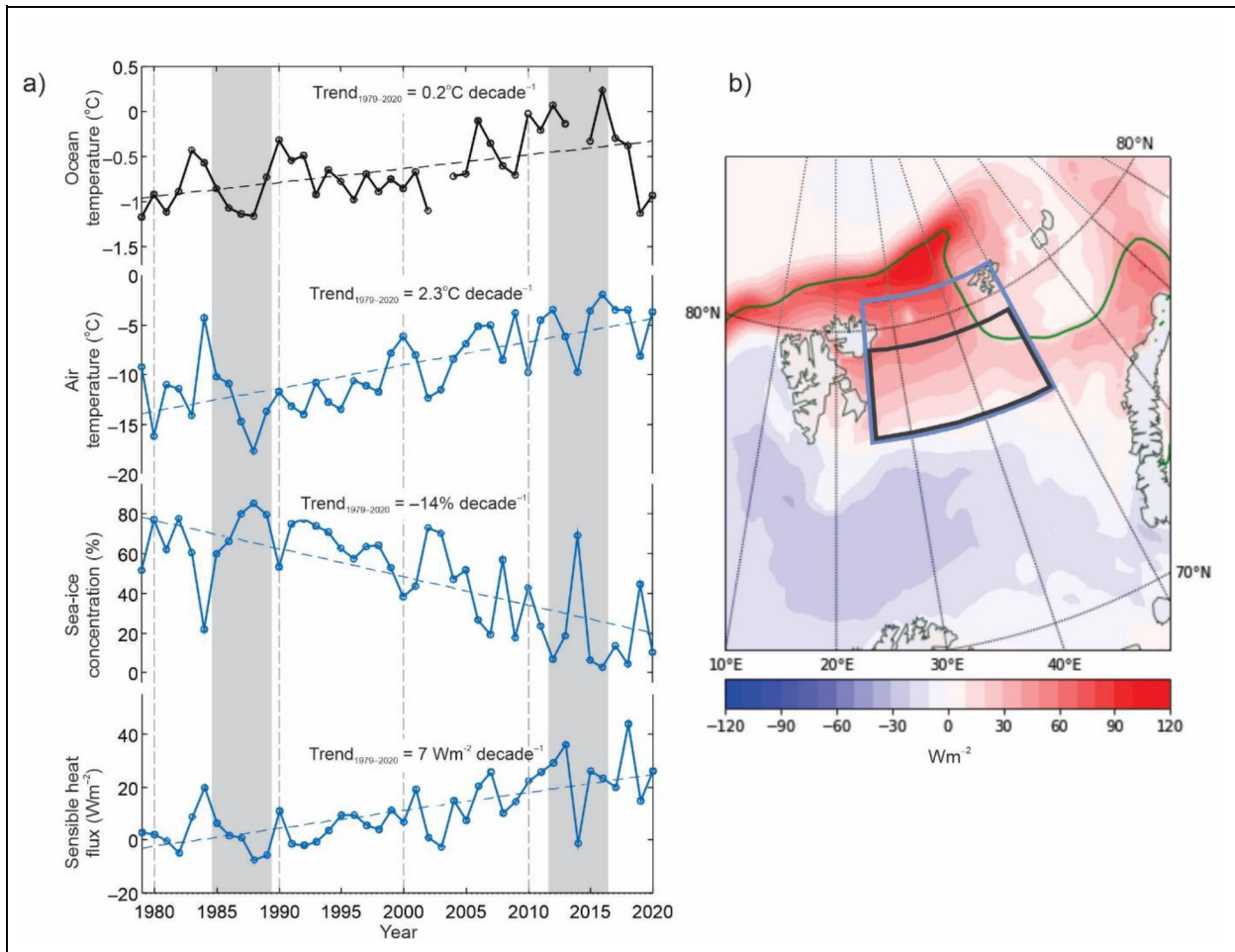


Figure 4. Northern Barents Sea time series: ocean and air temperatures, sea-ice concentration and sensible heat flux. (a) Time series of mean late summer–early autumn (August, September, October) subsurface (50–200 m) ocean temperature and mean winter (December, January, February) 2-m air temperature, sea-ice concentration and sensible heat flux from ocean to air in the Northern Barents Sea (region shown in panel b). Dashed lines indicate statistically significant linear trends ($p \leq 0.05$). The cold (1985–1989) and warm (2012–2016) periods, as referred to in **Figures 5** and **6**, are shown with grey shadings. (b) Mean sensible heat flux anomaly in winter (December, January, February) 2018 relative to 1979–2020. Mean sea-ice edge in winter (taken as 15% concentration) is shown with the green line. The boxes show integration areas for the atmospheric (black) and oceanic (blue) parameters shown in panel a). Atmospheric and sea-ice parameters are based on the ERA5 atmospheric reanalysis. Ocean temperatures are based on CTD observations from regional late summer surveys, as long-term winter observations in the region are not available. Mean ocean temperature was calculated only when at least 80% of the ocean integration box was covered by observations (thus not in the heavy sea-ice years of 2003 and 2014).

feedbacks due to larger open-water areas (Lee et al., 2017). The combined effects from frequent winter storms and enhanced heat content of AW are also crucial for explaining sea-ice melting processes realistically (Duarte et al., 2020). In addition, observations of sea-ice concentration combined with estimates of ice thickness change show large reductions in the volume of sea-ice import to the Barents Sea after 2005 (Lind et al., 2018). These reductions imply that recent atmospheric forcing has had a larger effect than oceanic forcing on sea-ice volume changes (Ingvaldsen et al., 2021). However, this result disagrees with analysis from Earth System Model Ensembles where the ocean heat transport still dominates (Dörr et al., 2021). These opposing results illustrate the needs for both observations and modelling experiments focusing on large-

scale changes and specific processes in the air, ice and ocean systems, as well as harmonization of observations and model outputs.

The atmospheric response to sea-ice changes in the Barents Sea has been the focus of several recent studies. Feedbacks between changes in ice cover and the atmosphere during winter months (Strong et al., 2009; Wu and Zhang, 2010) may operate via a delayed stratospheric pathway (King et al., 2016). From modelling studies, the atmospheric response to sea-ice loss appears to be rather weak (Screen et al., 2013; Mori et al., 2014) and sensitive to the mean state and the exact patterns of ice loss (Sun et al., 2015; Osborne et al., 2017). Therefore, while the sea ice may promote certain circulation patterns that can produce, for example, cold winters in Eurasia, most studies

indicate that this effect is small relative to the large inter-annual variability of the atmosphere (McCusker et al., 2016; Shepherd, 2016). However, the impacts might still be significant on a regional level, as demonstrated by events of extreme precipitation on the west coast of Svalbard in recent years explained by less sea ice east of Greenland facilitating income of southerly moist air (Müller et al., 2022).

Because the water under sea ice is undersaturated in CO₂ fugacity ($f\text{CO}_2$) relative to the atmospheric $f\text{CO}_2$ level, more open-water areas can lead to increased ocean uptake of atmospheric CO₂, particularly in combination with the effect of strong winds increasing the ocean CO₂ uptake (Fransson et al., 2017; see Section 3). A weaker stratification in the northern Barents Sea (Lind et al., 2018; further discussed in Section 2.2.2.) allows increased heat exchange between ocean and atmosphere (Fer, 2009), which can have substantial impact when this stratification change is viewed in combination with reduced sea-ice cover.

Extensive air-sea-ice interactions also occur in parts of the southern and eastern Barents Sea. AW is transformed into water masses of different density (e.g., Schauer et al., 2002; Lien and Trofimov, 2013; Barton et al., 2018; Schlichtholz, 2019) and leaves the Barents Sea in the east toward the St. Anna Trough (Dmitrenko et al., 2015). When exiting the Barents Sea, the AW has lost much of its heat and acquired a greater density (Årthun et al., 2011; Lien and Trofimov, 2013; Skagseth et al., 2020), but is still warm enough to melt ice (Gammelsrød et al., 2009).

The most prominent physical changes within the Barents Sea have occurred in these eastern and northeastern regions due to northward retreat of sea ice, warming, and changes in heat loss along the pathway of AW flow (Årthun et al., 2012; Smedsrud et al., 2013; Barton et al., 2018; Skagseth et al., 2020; Moore et al., 2022). A simple chain of cause and effect for the Barents Sea was postulated by Smedsrud et al. (2013). 1) A larger AW heat transport leads to local ocean warming. 2) The warming leads to an expansion of the area that does not freeze over, and hence a reduced ice cover. 3) The larger open-water area leads to an overall larger ocean-to-atmosphere heat loss of the throughflowing AW, thereby buffering the temperature variability in the water exported from the Barents Sea. Other studies have revealed substantial warming in the northeastern Barents Sea after 2000 (Lien and Trofimov, 2013; Barton et al., 2018) related to weaker heat loss in the eastern Barents Sea. The warming implies that the buffering effect has weakened, and that the region now exports warmer water to the deep Arctic basins (Barton et al., 2018; Skagseth et al., 2020). However, the present warming in the northeastern Barents Sea may also reflect a poleward shift of the buffering (cooling) area (Barton et al., 2018; Moore et al., 2022), indicating that most of the heat from the Barents Sea throughflow water is still lost before entering the Arctic Ocean (Shu et al., 2021).

Over the last century, the observed changes in sea-ice cover, ocean warming, heat loss, and CO₂ uptake have been faster in the northern Barents Sea than in the rest of the Arctic Ocean (Smedsrud et al., 2022). Some of these

ongoing changes are demonstrated using data for a subregion of the Barents Sea seasonal ice zone (**Figure 4**). Ocean temperature has increased by 0.2°C per decade over the period 1979–2020, while at the same time air temperature increased by 2.3°C per decade (upper panels in **Figure 4a**). Sea-ice concentration decreased by 14% per decade, and sensible heat flux increased by 7% per decade (lower panels in **Figure 4a**). The northern Barents Sea is therefore a hotspot of climate change that at the same time still retains “true Arctic” conditions. In the following sections we explore this concept in more detail.

2.2. Atmospheric state, variability and recent changes

2.2.1. The Barents Sea in a larger atmospheric system

The Barents Sea is located at the northeastern end of the low-pressure area (trough) extending northeastwards from the Icelandic low. Climatological winds are easterly in the northern Barents Sea, with southwesterly components dominating in the south. Mainly due to the warm AW and small sea-ice area for its latitude, the Barents Sea experiences high average surface air temperatures (SAT). The highest SAT are found in the southwest where the warm AW enters, whereas the lowest occur in the north, following the mean sea-ice extent. The northern Barents Sea is where that the greatest increases in winter SAT for the entire Arctic have been observed (Screen and Simmonds, 2010; **Figure 4a**).

Climate variability in the Barents region is linked with large-scale atmospheric processes, e.g., circulation patterns and cyclone pathways (Smedsrud et al., 2013). Hereby, the regional position and variability of the atmospheric polar front that outlines the border between preferentially northerly and westerly (or southwesterly) winds are of importance. Several studies have described specific linkages in detail (e.g., Sorteberg and Kvingedal, 2006; Koenigk et al., 2009; Kwok et al., 2009; Herbaut et al., 2015), but have also acknowledged that the interactive processes are not yet fully understood. The North Atlantic Oscillation (NAO), the leading mode of atmospheric variability in the region, previously has been correlated with AW inflow into the Barents Sea (Dickson et al., 2000) and the sea-ice cover (Deser and Teng, 2008). The NAO relationship with the Barents Sea appears non-stationary over longer time scales both for the NAO forcing on the AW inflow and sea ice (Smedsrud et al., 2013) and for the sea-ice forcing on the NAO (Kolstad and Screen, 2019). Since 2005, the NAO has been predominantly positive, with one exception in 2010 (Kolstad and Screen, 2019). The Barents Oscillation (BO), which has a centre of action over the Barents Sea, was argued by Skeie (2000) to be a better descriptor of Barents Sea variability. He found a strong correlation ($r = 0.76$) between the BO and the sensible heat loss of the Nordic Seas. However, as pointed out by, e.g., Tremblay (2001), the BO mode may not be robust.

2.2.2. Changes in surface air temperatures and cyclone activities, with impacts on sea ice and water masses

SAT over the Barents Sea have been above normal since about 2005 (**Figure 4a**). The largest positive anomalies

were found in the northern Barents Sea and are consistently positive for winter months. For example, recent observed winter temperature anomalies are typically 4°C on the west coast of Spitsbergen, and a re-analysis indicates comparable values over the Barents Sea (mean temperature anomaly 3°C–3.5°C during 2001–2015 versus 1971–2000; Isaksen et al., 2016). Changes in SAT over Svalbard show similar characteristics and correlate positively with northern hemispheric sea-ice extent, and partly with NAO (Osuch and Wawrzyniak, 2017). Osuch and Wawrzyniak (2017) also reported that the largest temperature changes occurred during the polar night, from the end of October until the end of February, in line with Screen and Simmonds (2010) and Isaksen et al. (2016). Significant correlation between SAT and sea-ice presence east and north of Spitsbergen suggests that much of the recent atmospheric warming in Spitsbergen is related to and driven by heat exchange from the larger contemporary open-water areas in the Barents Sea and north of Svalbard (Isaksen et al., 2016). When investigating SAT changes during the period 2001–2020 from different locations on Svalbard and Franz Josef Land, Isaksen et al. (2022) found a record-high annual warming of 2.7°C per decade, with a maximum in autumn of up to 4.0°C per decade.

Cyclone activity in the Atlantic sector of the Arctic has been changing, but with regional variations. Winter extreme cyclone activity between 60 and 90°N over the Greenland, Norwegian, and Barents seas and the entire Arctic decreased slightly from 1979 to 2014 (Koyama et al., 2017). Koyama et al. (2017) further showed that the Arctic Oscillation index and the wintertime extreme cyclone activity in these seas and the entire Arctic were positively correlated ($r =$ approximately 0.5), although possibly sensitive to the study period. Focusing on the Arctic North Atlantic, Rinke et al. (2017) found an increase in extreme cyclone events, equal to 6 events per decade over 1979–2015, according to data from Ny-Ålesund, Svalbard. Moreover, Wickström et al. (2020) found for winter months (December–February), in the period 1979–2016, a decrease in cyclone densities in southeastern Barents Sea and an increase in cyclone densities in the areas around Svalbard and in northwestern Barents Sea.

The atmospheric influence on sea-ice concentration in the Barents Sea is due to a combination of wind stress and thermodynamic fluxes from weekly (Fang and Wallace, 1994) to monthly time scales (Wu and Zhang, 2010; Sorokina et al., 2016). Atmospheric pressure patterns control the net ice advection between the Barents Sea, Kara Sea and Nansen Basin, contributing significantly to the winter sea-ice variability in the Barents Sea (Herbaut et al., 2015). An increase in poleward moisture transport by the atmosphere (Woods and Caballero, 2016) has been estimated to contribute 30% to the observed trend (1979–2011) in winter sea-ice loss in the Atlantic sector of the Arctic Ocean, as well as to the interannual variability (Park et al., 2015a). This increased atmospheric transport is consistent with a lower southern Barents Sea heat loss in recent years (Skagseth et al., 2020). In the northern Barents Sea, in contrast, the decline in winter sea-ice

concentration since 1979 is accompanied by higher ocean heat loss (Asbjørnsen et al., 2020; Skagseth et al., 2020; **Figure 4a**), with the highest January mean anomalies exceeding 120 Wm⁻² in 2018 (**Figure 4b**). This high heat loss is in line with findings by Screen and Simmonds (2010), who showed that the northern Barents and Kara Seas between 1989 and 2009 experienced the strongest increases in surface heat losses during October–December in the entire Arctic, alongside the greatest winter sea-ice loss. Sea-ice features on the kilometer scale are also affecting atmosphere properties and weather. Batrak and Müller (2018) have shown in a study from the eastern Barents Sea and west of Svalbard that sea ice can influence weather even several hundred kilometers from the ice edge.

The archipelagos of Svalbard and Novaya Zemlya represent obstacles to the local-to-mesoscale atmospheric flow in the Barents Sea region. For other Arctic regions, such as Greenland with surrounding waters, orographic flow phenomena like downslope windstorms and tip jets have been documented extensively and related to air-sea interactions important, e.g., for deep-water formation (Doyle and Shapiro, 1999; Pickart et al., 2003; Harden and Renfrew, 2012). Orographic flows may have an impact on the West Spitsbergen Current through elevated surface fluxes and wind-stress curl (Skeie and Grønås, 2000). Moore (2013) studied the impact that strong downslope wind, forming over the topography of Novaya Zemlya, has on air-sea interactions in the eastern Barents Sea. He found that the highest wind speeds occur along the western coastline of the archipelago—a region where dense-water formation is observed (e.g., Midttun 1985; Årthun et al., 2011)—and that ocean-surface heat loss doubles during these strong wind events. Moore (2013) further argued that these usually cold winds play an important role in the transformation of AW as it passes through the area on its way to the Nansen Basin.

2.3. Ocean hydrographical state, variability and recent changes

2.3.1. Main features of the Barents Sea circulation and hydrography

Of the two climatic domains in the Barents Sea (**Figure 5a and b**), the southern (Atlantic) domain is strongly influenced by the inflow of warm AW, the largest regional oceanic heat source. The northern (Arctic) domain is dominated by sea ice and Arctic waters maintaining a strong ocean stratification. Although the changes are more prominent in the northern domain (warming, sea-ice loss and reduced stratification), they are strongly influenced by changes in the AW inflow in the southern domain through feedbacks and regional processes (Ingvaldsen et al., 2021). The largest AW inflow enters through the BSO in the west (**Figure 2**; Ingvaldsen et al., 2002; Ingvaldsen et al., 2004a, 2004b; Lien et al., 2013). The annual variability of heat transport resembles the variations in volume transport, but on longer time scales the variation in upstream North Atlantic temperature becomes important (Skagseth et al., 2008; Årthun et al., 2012; Lien et al., 2017).

The northern domain of the Barents Sea is stratified, where sea-ice formation and melt influence the

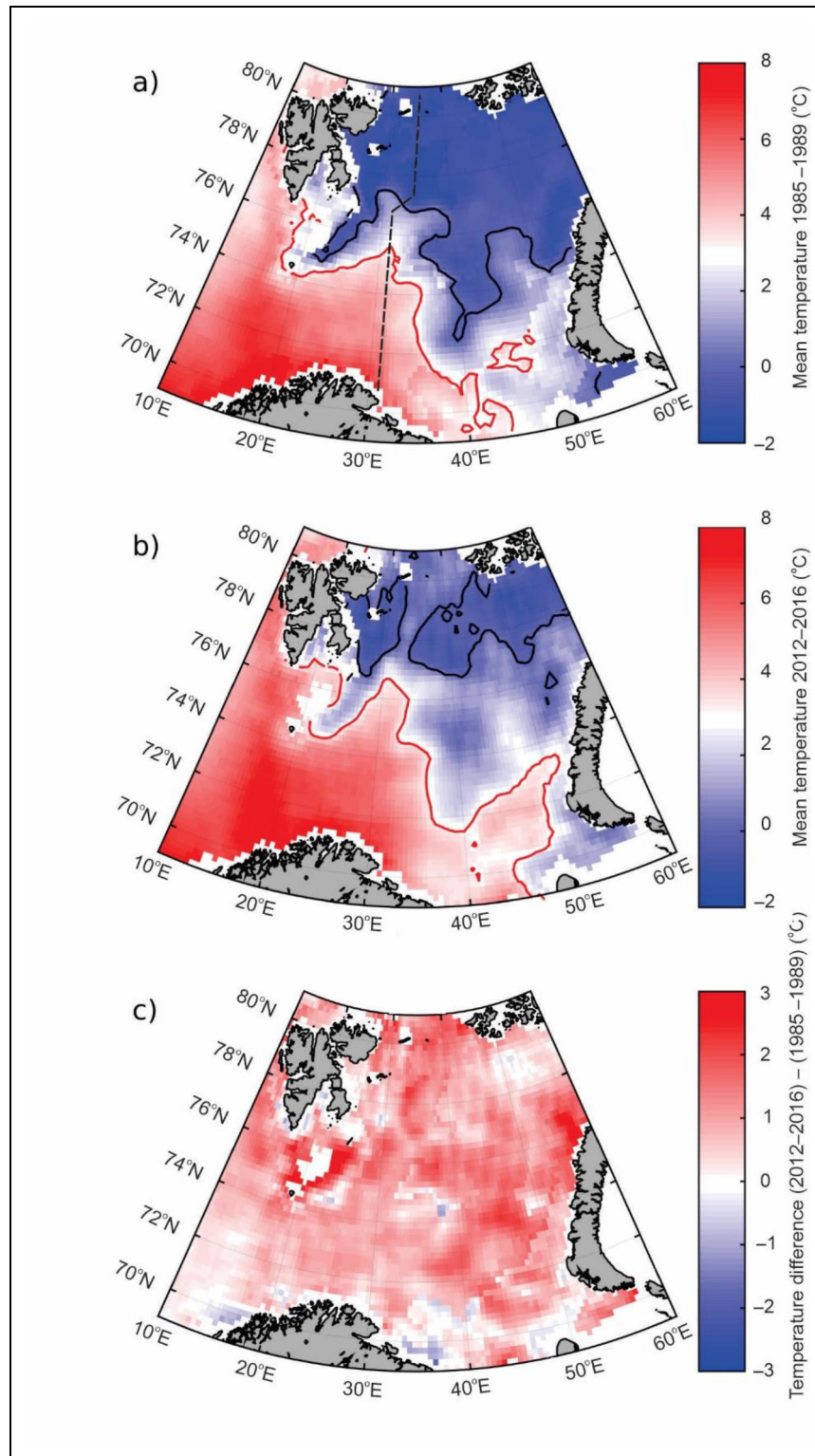


Figure 5. Ocean temperature maps for the cold (1985-1989) and warm (2012-2016) periods with the temperature differences. Mean temperatures between 50 m and 200 m depths in late summer (August, September, October) during the years (a) 1985–1989 and (b) 2012–2016 based on observations from regional surveys. Solid lines show the 0°C (black) and 3°C (red) isotherms. The dashed line in (a) marks the section from Vardo (Norway) in the south to the Nansen Basin in the north (see **Figure 6**). (c) Temperature difference between the two periods.

hydrography substantially. The upper layer consists of relatively fresh surface water, overlying an intermediate cold and relatively fresh Arctic layer, with warm AW and cold dense water towards the bottom (Falk-Petersen et al.,

2000; Lind and Ingvaldsen, 2012). The northern Barents Sea is exposed to intermittent inflow of modified but still warm AW from the north (water masses that reach the Barents Sea after moving clockwise around the NW part

of Svalbard), following the trenches cutting the northern continental slope (Lind and Ingvaldsen, 2012; Pérez-Hernández et al., 2017), in addition to possible AW influx from the south. The salinity of the Arctic layer determines the density difference between it and the deeper AW, which in turn largely controls the amount of vertical mixing between the two layers. This mixing impacts the AW temperature of the northern Barents Sea with a one-year lag (Lind et al., 2016). The stratification and presence of the Arctic layer depends on a freshwater content that is drained continuously by vertical mixing with the deeper AW. Thus, a freshwater input is needed to sustain the stratification. A strong co-variability between sea-ice inflows from the Arctic Ocean and the Arctic layer freshwater content reveals that melted, imported sea ice is a major freshwater source for this region (Lind et al., 2018). Inter-annual variability in sea-ice inflow from the north, and thus the volume of ice available for melting, depends more on regional atmospheric anomalies than on varying heat content available for melting ice in the AW boundary current following the northern continental slope (Lundesgaard et al., 2021). However, the freshwater input and stratification balance can also be partly maintained by varying advection of ArW into the region. The circulation of neither AW nor ArW in the northern Barents Sea is yet completely understood.

The northern part of the Barents Sea undergoes large seasonality in near-surface stratification. In winter, the water column becomes less stratified and more mixed due to cooling from heat loss to the atmosphere and brine release from ice formation. In summer, local ice melt, inflowing melt water, potentially meltwater from advected sea ice from outside the Barents Sea, and solar heating (later in the season) create a shallow (10–25 m thick) low-density surface layer (Sundfjord et al., 2007; Smedsrud et al., 2010). The strong seasonal stratification reduces the vertical extent of wind-driven mixing. However, over the shallower banks and around islands, strong tidal currents efficiently homogenize the water column even in summer (Sundfjord et al., 2008; Fer and Drinkwater, 2014). These shallow areas also facilitate convection driven by surface cooling and brine release in winter (Årthun et al., 2011). The spatial and seasonal variations of stratification may set up pressure gradients favoring lateral exchange, both within the northern Barents Sea and with the neighboring regions, which in turn could facilitate redistribution of water masses. However, this scenario is not yet adequately understood and merits further study.

The oceanic Polar Front separates the warm southern domain from the colder northern domain (**Figure 2**). This thermohaline “front” is rather a series of frontal structures extending from southwest of Svalbard towards Novaya Zemlya, but varying temporally and spatially in strength, width, and position. The Polar Front is controlled topographically, being largely stationary in the west, but less so in the east due to less steep bathymetric slopes (Oziel et al., 2016). In the west, the front is aligned along-flow and separates AW in the south from the colder and less saline (thus less dense) ArW in the north. However, smaller portions of AW flow “below” the front and into the

northern Barents Sea across the sill in the northern part of Hopenjupet (**Figure 2**). The salinity gradient and, more notably, temperature differences diminish eastward, contributing to a less well-defined front (e.g., Oziel et al., 2016). Therefore, in the east, the Polar Front also has an across-flow component as much of the AW is transformed to Barents Sea water (e.g., Lien and Trofimov, 2013; Barton et al., 2018). The reduced winter sea-ice cover in the central and eastern Barents Sea (Onarheim et al., 2015; Lien et al., 2017) eases access and makes winter observations more feasible today than in the past, but the lack of earlier winter observations hinders evaluation of changes in hydrography of the Polar Front during winter.

At the Barents Sea northern shelf break, AW and heat coming from Fram Strait are transported eastwards, further along the upper continental slope in the Atlantic Water Boundary Current (Renner et al., 2018). With the exception of wind-influenced near-surface waters and outflow of dense cold near-bottom water (Årthun et al., 2011), this boundary current limits exchange between the northern Barents Sea and the adjacent Nansen Basin. Furthermore, this current can feed heat into the northern Barents Sea through the channels between Nordaustlandet, Kvitøya, Victoria Island and Franz Josef Land (Matishov et al., 2009; Lind and Ingvaldsen, 2012). Few direct observations of this inflow exist (e.g., Aagaard et al., 1983). The few recent campaigns targeting the westernmost of these possible northern inflow pathways show large recirculation in the Kvitøya Trough leading into the Barents Sea (Pérez-Hernández et al., 2017), but also intensified inflow of the warmer and saltier AW water during autumn and early winter through both the Kvitøya Trough and a site impacted by the Franz Josef Trough (Lundesgaard et al., 2022); here, the relative density and positioning of this water may be critical for the northern Barents Sea ice conditions. This available information calls for better understanding of the inter-annual variability.

2.3.2. Recent oceanographic changes in the Barents Sea

The temperature in the Barents Sea is closely related to progression of AW temperature and volume anomalies, with AW inflow exhibiting strong variability on timescales ranging from years to decades (Furevik, 2001; Schlichtholz and Houssais, 2011; Yashayaev and Seidov, 2015; Årthun and Eldevik, 2016; Asbjørnsen et al., 2019). An increasing number of warm pulses, in combination with an overall warming trend, has gradually warmed the Barents Sea. Moreover, since 2000, reduced heat loss (Skagseth et al., 2020), possibly in combination with pulses of increased AW transport, has caused a poleward amplification of the AW warming (Ingvaldsen et al., 2021).

The measured volume flux of AW into the Barents Sea varies over periods of several years, but shows no significant trend over the period between 2004 and 2018 (Skagseth et al., 2020; see also Smedsrud et al., 2022). Over the longer time scale, simulations show large variability in AW heat transport of typically ± 10 TW over a few years, and a long-term increase in heat transport to the Barents Sea from around 40 TW to 60 TW over the last century

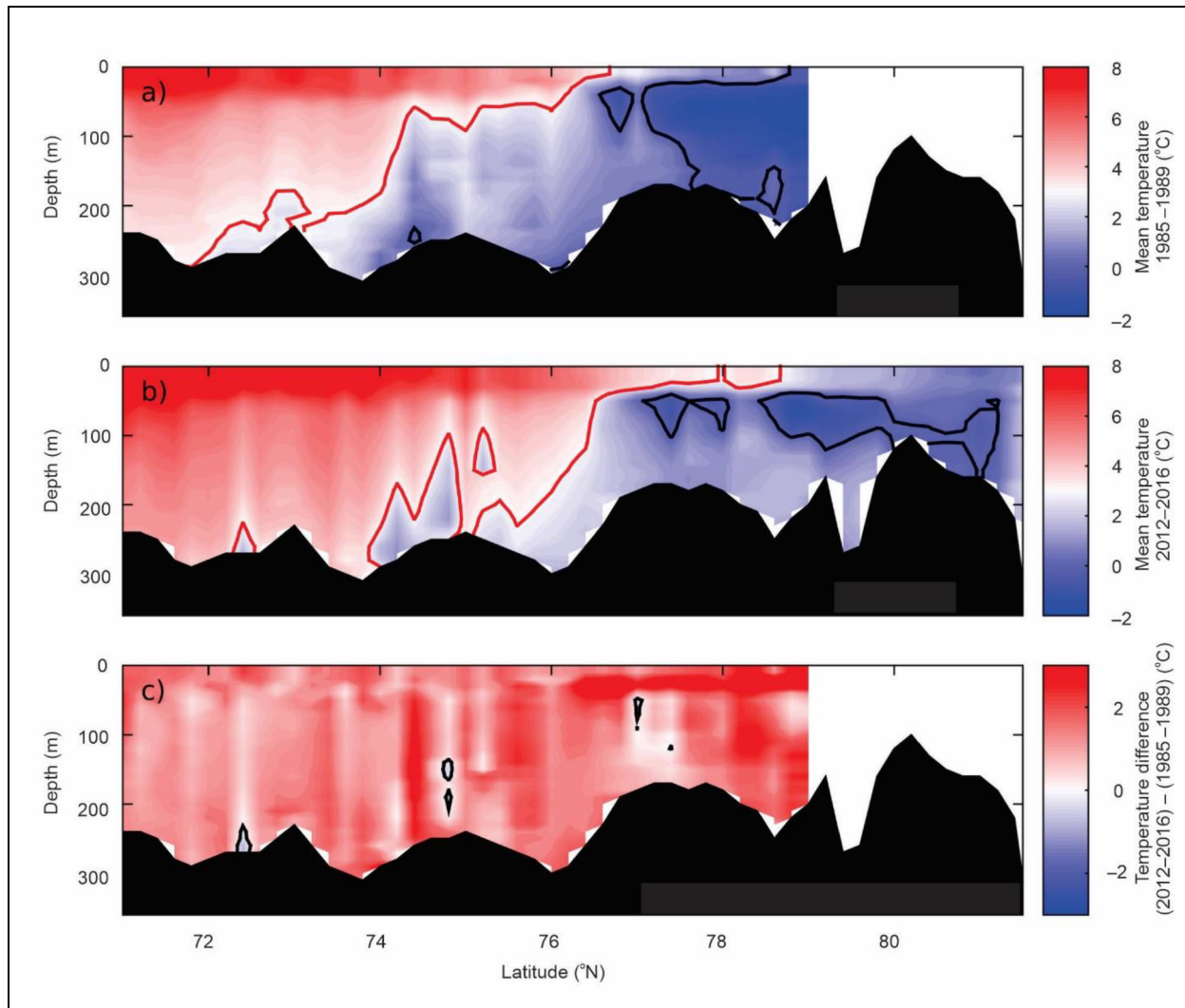


Figure 6. Barents Sea ocean temperature transect for 1985–1989 and 2012–2016 with the temperature differences. Mean temperature along a latitudinal section between 30°E and 34°E (see **Figure 5a**) in late summer (August, September, October) during the years (a) 1985–1989 and (b) 2012–2016 based on observations from a repeated transect from Vardo (Norway) in the south to the Nansen Basin in the north. Solid lines show the 0°C (black) and 3°C (red) isotherms. (c) Temperature difference between the two periods.

(Muilwijk et al., 2018). A significant increase of poleward heat transport of 21 TW in the form of warmer water being transported since 2001 has also been reported (Tsubouchi et al., 2020).

The Barents Sea warming (**Figures 5 and 6**) has generally created a northward shift of isotherms of a given temperature over time. This northward shift varies along the Polar Front, but is for example about 1°N or 100 km over the last 30 years in the surface layer along the 30°E transect (**Figure 6**). A larger northward shift (or amplified warming) is apparent for the deeper layers, with about twice the magnitude at 150–200 m (**Figure 6**). In the eastern Barents Sea, the surface 0°C isotherm has moved from 74°N to 78°N, while the 3°C isotherm has been displaced downstream along the AW flow along southern Novaya Zemlya (**Figure 5**). Earlier studies have shown that east of 32°E the Polar Front splits into two branches: a northern front associated with strong salinity gradients and a southern front with temperature gradients (Oziel

et al., 2016). Since the 1990s, the southern front in the eastern Barents Sea has shifted northwards (Oziel et al., 2016), while the northern front has remained relatively stable and is now the southern limit of the winter sea ice extent (Barton et al., 2018). Previously, when some sea ice drifted across the Polar Front and melted directly on top of AW on the Atlantic side, the AW was cooled and freshened in this way, whereas now this cooling and freshening does not occur (Barton et al., 2018). Therefore, the AW can keep a higher salinity and temperature on its passage through the eastern Barents Sea. However, the rate of salinification or freshening in the eastern Barents Sea also varies with the AW inflow (Årthun et al., 2011; Lien et al., 2013; Barton et al., 2018; Skagseth et al., 2020), the freshwater input from the Norwegian Coastal Current (Rudels et al., 2015; Shu et al., 2018), and mixing in the region (Lien et al., 2013; Schauer et al., 2002). Although the exported water has increased in salinity, but not in density due to the concomitant reduction in cooling after

2000, the export waters within a few years may freshen substantially due to an observed freshening of the upstream AW (Skagseth et al., 2020).

Significant salinity changes have occurred during summer for the surface and Arctic layers in the northern Barents Sea. There has been a 40% freshwater loss in the upper 100 m of this region between the periods 1970–1999 and 2010–2016 (Lind et al., 2018). The decreasing freshwater content and the associated weakened stratification enhance the heat and salt flux from the AW layer below, causing a positive feedback and further increasing the warming and the reduction in stratification (Lind et al., 2016). Such a process would resemble the recent observations of decreasing stratification and a shallowing of the AW occurring in the eastern Nansen Basin (Polyakov et al., 2017). We note, however, that the northern Barents Sea ice cover has returned to more normal conditions in the very recent time (Aaboe et al., 2021), thus likely facilitating an increase in freshwater content relative to the record-low 2012–2016 period. Regional sources might also contribute to increased freshwater input, such as meltwater from Svalbard's Austfonna icecap (Morris et al., 2020) and mass loss from other Svalbard glaciers (Geyman et al., 2022). However, how this freshwater forcing compares to that from sea-ice inflow and subsequent melt is not known. How the observed summer changes translate into the winter situation is only poorly known. A recent modelling study confirmed strong changes in summer stratification in the northern Barents Sea after 2000, while the changes during winter were characterized by only modest changes in stratification but a significantly shallower mixed layer depth (Hordoir et al., 2022). Winter data from the northern Barents Sea are clearly needed to address these issues; progress towards this goal is developing (e.g., Lundesgaard et al., 2022).

The ArW has warmed since the 1980s by about 1°C, with the main change occurring after 2004 (Dalpadado et al., 2012; Johannesen et al., 2012; Lind et al., 2018). Similar changes have been observed in the AW temperatures in the northern Barents Sea (Lind and Ingvaldsen, 2012), reflecting the AW temperature trend further south. The warming appears to be fed both from the north and south, leaving only a small volume of cold Arctic Water in the northwestern part of the Barents Sea (**Figure 6**).

2.4. Status and changes in the Barents Sea ice cover

2.4.1. Long-term decline in sea-ice extent

Beyond seasonal variations in sea-ice extent, with maxima in April and minima in September months (**Figure 2**), the sea-ice extent in the Barents Sea has decreased over time: –9.8% and –17.7% per decade in April and September, respectively (1979–2021; Norwegian Polar Institute, 2022a, 2022b). Because the absolute sea-ice area in September is relatively small, the percentage change appear to be the highest; however, in absolute area the changes in April are the highest (see below). The recent (three decades, 1988–2017) loss of Arctic winter sea ice, with most rapid losses occurring in the northeastern Barents Sea, is unprecedented in the observational record (Onarheim and Årthun, 2017). The disproportionate contribution of sea-

ice loss in the Barents Sea to the overall northern hemisphere sea-ice loss is exemplified by the fact that the Barents Sea covers roughly 4% of the northern hemisphere ice-covered area, but contributes 24% of the observed winter sea-ice area loss (Onarheim and Årthun, 2017). Between 1979 and 2016, the Barents Sea lost ice throughout the year (Onarheim et al., 2018), but mostly during winter and spring (November–June). The loss has been smallest in September (typical month of minimum extent) and large in April (maximum extent, with a loss of 478,000 km²), but largest in May and June (Onarheim et al., 2018). The small absolute numbers for September sea-ice loss can be explained by the presence of very little ice in the region at that time of the year. The decline in winter (January–April) sea-ice area has been as large as 23% per decade from 1979 to 2015 (King et al., 2017). Notably, within the Arctic, the winter sea-ice loss in the Barents Sea between 1979 and 2019 is the strongest among all Arctic regions with sea ice (Fox-Kemper et al., 2021).

King et al. (2017) demonstrated that the reduction in atmospheric freezing-degree days in the Barents Sea alone is insufficient to explain all the recent sea-ice cover changes. The observed reduction in sea ice should therefore be considered in the context of other local and regional changes (forcing factors), such as increased heat inflow via the BSO (Section 2.3.) and/or sea-ice transport from adjacent regions in the north and east (Hop and Pavlova, 2008; Kwok, 2009). Lind et al. (2018) estimated from satellite data a 40% ± 20% decline (2010–2015 mean versus 1979–2009 mean) in the sea-ice area imported to the Barents Sea, with sea-ice inflow primarily through the Franz Josef Land-Novaya Zemlya passage in winter. However, newer data (Ingvaldsen et al., 2021) show a slight increase again of sea-ice import into the northern Barents Sea in most recent years to similar levels as earlier; they showed that the relative portion of imported sea ice increased since about year 2000, because the total sea-ice area decreased. A recent investigation of the variability in interannual sea-ice extent over the last 40 years found a dominant mode in the areal change of sea ice in the northeastern Barents Sea, resulting from a combined effect of AW meeting winter sea ice, northerly winds and related sea-ice import from the north (Efsthathiou et al., 2022). Winds and sea-ice import were further found to be the causes for spatial redistribution of the Barents Sea ice cover, i.e., change in distribution without change in total area, including a “dipole mode” with increase of sea-ice concentration south of Svalbard and decrease southwest of Novaya Zemlya (and vice versa).

2.4.2. Thinner sea ice and longer open-water seasons

Few observational data sets of sea-ice thickness exist for the recent years in the Barents Sea (King et al., 2017). Data from moored upward-looking sonar recordings between 1994 and 1996 indicate substantial interannual variability of ice thickness in the NW Barents Sea, with a range of up to 1 m (Abrahamsen et al., 2006). King et al. (2017) compared airborne measurements of sea-ice thickness in the NW Barents Sea from surveys in 2003 and 2014. In 2003, the dominant sea-ice class was older than 2 years, with

a modal thickness in the range 0.6 m to 1.4 m, while in 2014 the ice was formed locally as first-year ice with a modal thickness in the range 0.5 m to 0.8 m. Earlier long-term observations from coastal sea ice at Hopen, Svalbard, indicate a decrease in ice thickness (Gerland et al., 2008). Ice thickness is controlled by external forcing, the time of onset of freezing in the region, and possible sea-ice advection from the neighboring areas such as the Nansen Basin (e.g., King et al., 2017) and the Kara Sea. In regions bordering the Barents Sea, indications for a decrease of sea-ice thickness have also been observed: during the N-ICE2015 expedition (Granskog et al., 2016; Granskog et al., 2018) over the Nansen Basin and Yermak Plateau just north of the Barents Sea, Rösel et al. (2018) found modal total (ice + snow) thicknesses of 1.6 m (ground-based electromagnetics) and 1.7 m (airborne electromagnetics) from observations between April and June 2015, which is lower than historical observations (1.8 m to 2.7 m) in the same region and time of year.

Emerging techniques for ice-thickness detection through satellite-based remote sensing, such as the combinations of satellite-based altimeters (CryoSat-2 and SMOS satellite; Ricker et al., 2017), a combination of satellite-based altimeter and synthetic aperture radar (SAR) data (Karvonen et al., 2022), or thermal satellite imagery from MODIS (Rudjord et al., 2022), can be used to investigate recent changes in ice thickness, but the spatial resolution of such datasets is often coarse, and time series are too short to give an indication of recent trends. However, first results from remote sensing-based measurements are promising and timely. Ricker et al. (2017) showed an exceptionally low number of freezing-degree days in the Barents Sea for the winter 2015–2016 relative to the years 2011–2015 and compared with the rest of the Arctic. The relative sparseness of quantitative information about sea-ice thickness in the Barents Sea combined with indications of changes highlights the need for better ice thickness data in the Barents Sea region.

Corresponding with the diminishing sea-ice cover in the northern Barents Sea (**Figure 4a**, third panel), the length of the open-water season has increased dramatically in the Barents Sea, by >5 days year⁻¹ in the 1998–2012 period (Park et al., 2015a), which is at least twice as fast as the Arctic average (Arrigo and van Dijken, 2015). This increase is especially evident in the region where the ice edge has retreated (**Figure 7**). From the 1980s to 2016, a substantial ice loss occurred in June and July, along with later freeze-up and loss of ice in October (Onarheim et al., 2018). This loss has important consequences for albedo, and thus solar heat input (Perovich et al., 2007; Perovich et al., 2011; Stroeve et al., 2014; Stroeve et al., 2021), for the overall surface energy balance, as well as for availability of light and length of season for primary production (Arrigo and van Dijken, 2015). A potential biological feedback is the increased heat absorption by phytoplankton in the absence of sea ice and with increased primary production (Park et al., 2015b), as the Barents Sea has very low absorption by colored dissolved organic matter (DOM) compared to other Arctic marginal seas (Petit et al., 2022). However, phytoplankton likely only affect the

vertical distribution of solar heating, and do not increase the amount of solar heating. The most rapid increase in days of open water during the coming decades in the Arctic is expected to occur in the Barents Sea region (Barnhart et al., 2016).

Information on the snow cover on sea ice in the Barents Sea is also sparse, but Forsström et al. (2011) found a mean spring snow thickness for Barents Sea first-year sea ice (1999) combined with Svalbard's land-fast sea ice (2003–2008) to be 0.13 m, which is lower than snow thickness on sea ice further west, in Fram Strait, during the springs of 2005, 2007 and 2008. Snow thickness on sea ice north of Svalbard was 0.53 m from April to early June 2015, which is 73% above the average value of 0.30 m from historical and recent observations in this region (Rösel et al., 2018). Available regional snow-on-sea-ice data are not sufficient yet to derive trends or changes over time or to discern real change from interannual variability.

3. Ocean biogeochemistry

Physical characteristics such as stratification, mixing of water masses, and sea-ice production and melt influence the dynamics of nutrients and carbon in the Barents Sea (Chierici and Fransson, 2018). Stratification affects the availability of nutrients for primary production in the euphotic zone and the exchange of carbon from surface to the deep ocean. CO₂ dissolution and carbon sequestration in the Arctic Ocean are influenced by the ocean temperature (enhanced dissolution under cooling) and sea-ice related processes, such as brine formation and deep-water formation, e.g., in the Nansen Basin and the continental slope north of Svalbard and Storfjorden (Anderson et al., 2004; Chierici and Fransson, 2018). Moreover, the cooling of the warm AW subducts CO₂-rich surface water to depth and transports anthropogenic CO₂ into the deeper Barents Sea and the Arctic Basin (Fransson et al., 2001; Olsen et al., 2010; Smedsrud et al., 2013; Chierici and Fransson, 2018). This transport of CO₂ also affects the process of ocean acidification (Omar et al., 2007; Lauvset et al., 2013).

3.1. Nutrient variability and biological CO₂ uptake

The nutrient conditions along the shelf break and in the Nansen Basin are impacted by the horizontal advection of AW, which contains considerable amounts of both nutrients and plankton (Wassmann et al., 2015). Studies of the relative impact of turbulence-induced nutrient flux during the productive season versus the seasonal supply resulting from winter convection show that the latter is by far the more important process in providing nitrate in the region north of Spitsbergen (Randelhoff et al., 2016).

The seasonal nutrient conditions in the Barents Sea reflect the combined impacts of water-mass distribution and the seasonal primary production. Contrary to many Arctic shelf seas, the Barents Sea is well mixed during the winter season with uniform nutrient concentrations throughout the water column (Reigstad et al., 2002; Codispoti et al., 2013). For the ice-free BSO, the range of winter concentrations of nitrate in the AW surface waters

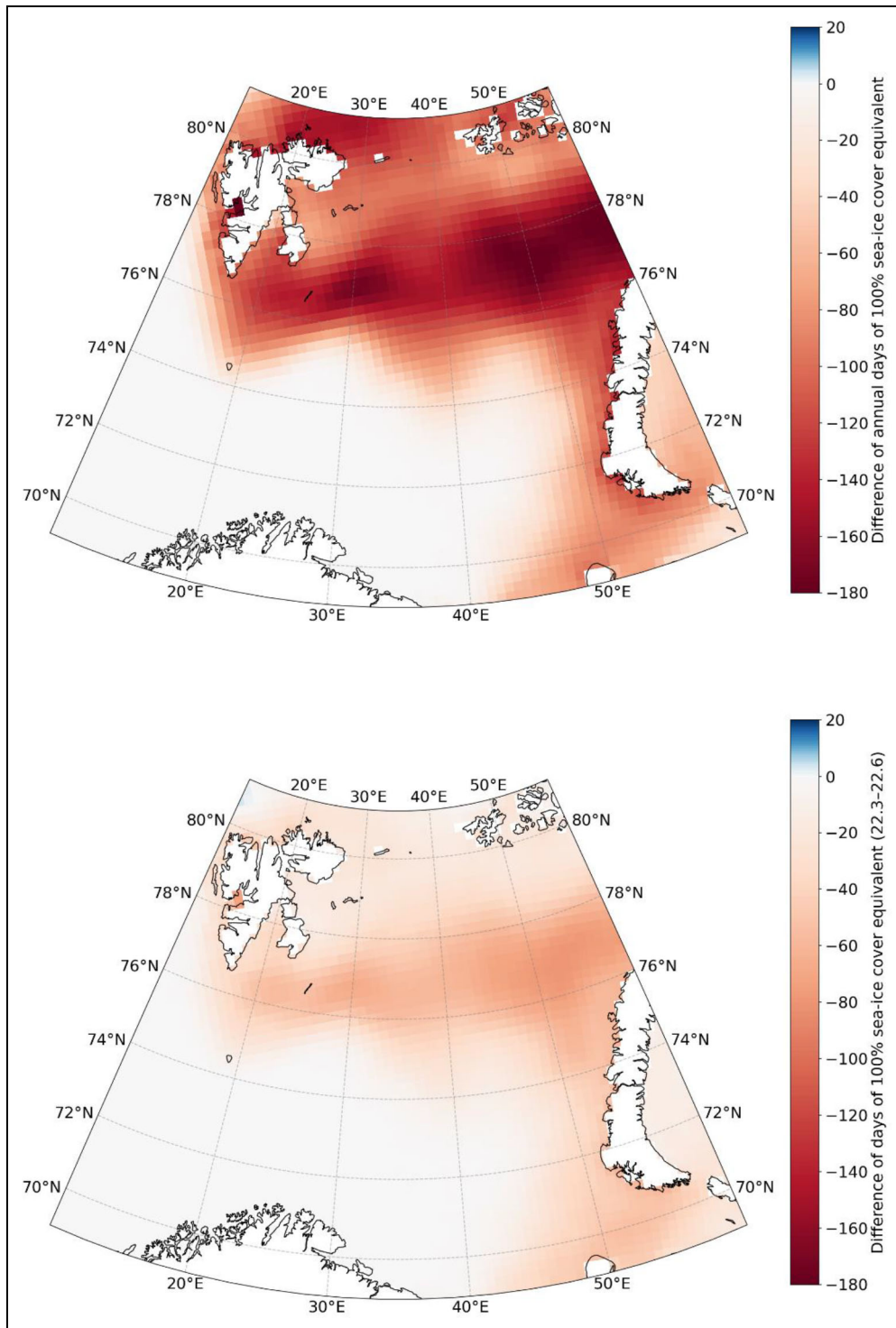


Figure 7. Annual and spring maps showing sea-ice cover changes in Barents Sea from 1985–1989 to 2011–2015. Change in number of days with 100% sea-ice cover equivalent between 1985–1989 and 2011–2015 for (a) full annual mean and (b) spring–summer season only (March 22 to June 22). The 100% equivalent represents the length of time in a given period when a given surface area was entirely ice-covered, calculated by converting sea-ice cover fraction to fraction of days with 100% cover. Based on the National Snow and Ice Data Center monthly means (Fetterer et al., 2017).

is 10–12 μM , with the onset of nitrate decrease from May–June at 73°N–74°N (Olsen et al., 2003; Ibrahim et al., 2014; Tuerena et al., 2021). A full-year cycle of the nitrate dynamics on the shelf break north of Svalbard (81.3°N) in 2012–2013 revealed a surface nitrate maximum of 10 μM

(at an approximate depth of 20 m) in March, with the largest decrease in June (Randelhoff et al., 2015). Nitrate maxima in March to late April were also observed on the northern Barents Sea shelf in 2017–2018, but with the strongest nitrate decrease reflecting production onset in

early May for an ice-free as well as an ice-covered mooring site (Henley et al., 2020). This synchronised onset of nitrate decreases differed between ice-covered and ice-free sites in the northern Barents Sea, with a slower nitrate decrease in open water (Henley et al., 2020). The timing of the nitrate decrease matches observations from the southern part of the marginal ice zone from the early 1990s (Kristiansen et al., 1994). The spatial pattern of nutrient decreases due to primary production (developed further in Section 4) does not necessarily follow a strict south–north progression, as it is related to light conditions regulated by stratification or vertical mixing in the south and by the ice dynamics in the north (Sakshaug and Skjoldal, 1989). Maximum nitrate decreases in May–June on the shelf north of Svalbard during the 6-month N-ICE2015 study (Granskog et al., 2016; Granskog et al., 2018) coincided with the largest concentrations of dissolved inorganic carbon (DIC) and decreases in CO₂ (Assmy et al., 2017; Fransson et al., 2017).

A study analysing a 30-year time series revealed a decreasing trend in integrated winter nitrate concentrations (0–200 m) of $-0.07 \mu\text{mol L}^{-1} \text{year}^{-1}$ in the BSO, resulting in a decrease from 12 μM to 10 μM in the period 1980–2010 (Oziel et al., 2017). This decreasing trend correlates with a 16% decrease in silicate concentration in the AW inflow into the Barents Sea between 1990 and 2010 (Rey, 2012), explained as a result of changes in the thermohaline circulation in the North Atlantic (see also Hátún et al., 2017). The decreasing trend in nutrients cannot be explained by increased stratification; on the contrary, the study by Oziel et al. (2017) identified a decreasing trend in stratification (difference between the surface density and the density at 100 m) of $-0.015 \text{ kg m}^{-3} \text{ year}^{-1}$ during the summer period and an increase in the mixed layer depth in August–September with 15 cm year^{-1} from 1980–2012 along the BSO.

The spatial pattern of the nutrient distribution going from the AW-influenced southern Barents Sea to the more Arctic-characterised northern Barents Sea shelf and into the AW-influenced shelf break shows high nutrient concentrations matching the high-salinity regions of AW origin (**Figure 8**). In summer, the surface nutrients, including nitrate, phosphate and silicate, are depleted down to a depth of approximately 50 m (**Figure 8**). The potential of mixing-induced nutrient supply was indicated around 74°N in 2012, where increased surface nutrient concentrations suggested recent mixing facilitated by the hydrographical conditions (**Figure 8**). Such episodic mixing in more weakly stratified AW has been suggested by Sakshaug and Slagstad (1991) to explain the high productivity in the southern Barents Sea and demonstrated in more recent studies (Fer and Drinkwater, 2014; Wiedmann et al., 2017). The depletion in nutrients was stronger farthest north (**Figure 8**).

The highest nutrient concentrations in the Barents Sea are found in the bottom water, with NO₃ concentrations >13 μM confined to deeper parts (**Figure 8c**) and likely reflecting high remineralisation rates of organic matter in the Barents Sea sediments (Freitas et al., 2020). Despite being a relatively deep Arctic shelf sea, the pelagic-benthic

coupling is relatively strong, but denitrification, prominent on other Arctic shelves, does not seem important in the Barents Sea (Tuerena et al., 2021). Using stable isotopes, Tuerena et al. (2021) found that the AW inflow provides the most important supply of nitrate in the south, reflected in a spatial gradient of proportional regeneration through seasonal nitrification of organic matter to NO₃ from less than 10% near the Polar Front to more than 80% in the Arctic waters in the northern Barents Sea.

3.2. Carbonate chemistry, air-sea CO₂ exchange and ocean acidification

3.2.1. Main carbonate chemistry features

The carbonate chemistry in the Barents Sea is influenced by air-sea CO₂ exchange and by physical, biological and chemical processes, as well as sea-ice processes (Fransson et al., 2001; Chierici and Fransson, 2018). The formation of sea ice and consequent release of CO₂-rich brine on the shallow shelves result in sinking of dense water recently in contact with the atmosphere. Some of this dense CO₂-rich water reaches the deeper basin, thus providing an efficient mechanism for carbon transport from the shelf break and northern Barents Sea to the deep waters in the Arctic Ocean (Chierici and Fransson, 2018; Rogge et al., 2022). CO₂ is also removed from surface waters by the release of ikaite crystals (CaCO₃) during ice melt (Nomura et al., 2013). When sea ice is formed, ikaite precipitates (Dieckmann et al., 2010), releasing CO₂ to the brine (Rysgaard et al., 2009; Rysgaard et al., 2012; Fransson et al., 2013; Fransson et al., 2017). At the time of sea-ice melt as well as during ice aging, some of the ikaite crystals escape from the ice to the underlying water where they dissolve, removing CO₂ in the process.

Biological processes play a major role in the Arctic carbon cycle and ocean CO₂ uptake (Chierici et al., 2011). High pH and low *p*CO₂ in surface water in summer are mainly due to CO₂ uptake by primary producers (Chierici and Fransson, 2018; Jones et al., 2021). About 70% of the oceanic CO₂ uptake in the Barents Sea is caused by biological CO₂ uptake (Fransson et al., 2001).

In the Barents Sea, variability in surface water (upper 50 m) DIC, pH and *p*CO₂ depends mainly on freshening and primary production (biological CO₂ consumption). The lowest surface DIC, total alkalinity (*A_T*) and *p*CO₂ values and the highest pH (9.3) values were observed north of 80°N (**Figure 8f–h**). The surface water *p*CO₂ is generally undersaturated (**Figure 8g**) relative to the atmospheric *p*CO₂ (about 400 μatm), as also found in other parts of the Barents Sea (Chierici and Fransson, 2018; Jones et al., 2018). This *p*CO₂ undersaturation indicates the potential for the Barents Sea to act as an oceanic CO₂ sink (e.g., Fransson et al., 2001; Omar et al., 2007; Lauvset et al., 2013). The annual mean uptake of atmospheric CO₂ in the region has been estimated to be 44 g C m⁻² by Fransson et al. (2001), 51 ± 8 g C m⁻² by Omar et al. (2007) and 48 ± 5 g C m⁻² by Lauvset et al. (2013). The highest DIC (>2200 $\mu\text{mol kg}^{-1}$), highest *p*CO₂, and lowest pH values (<7.97; **Figure 8g, h**) were found at the

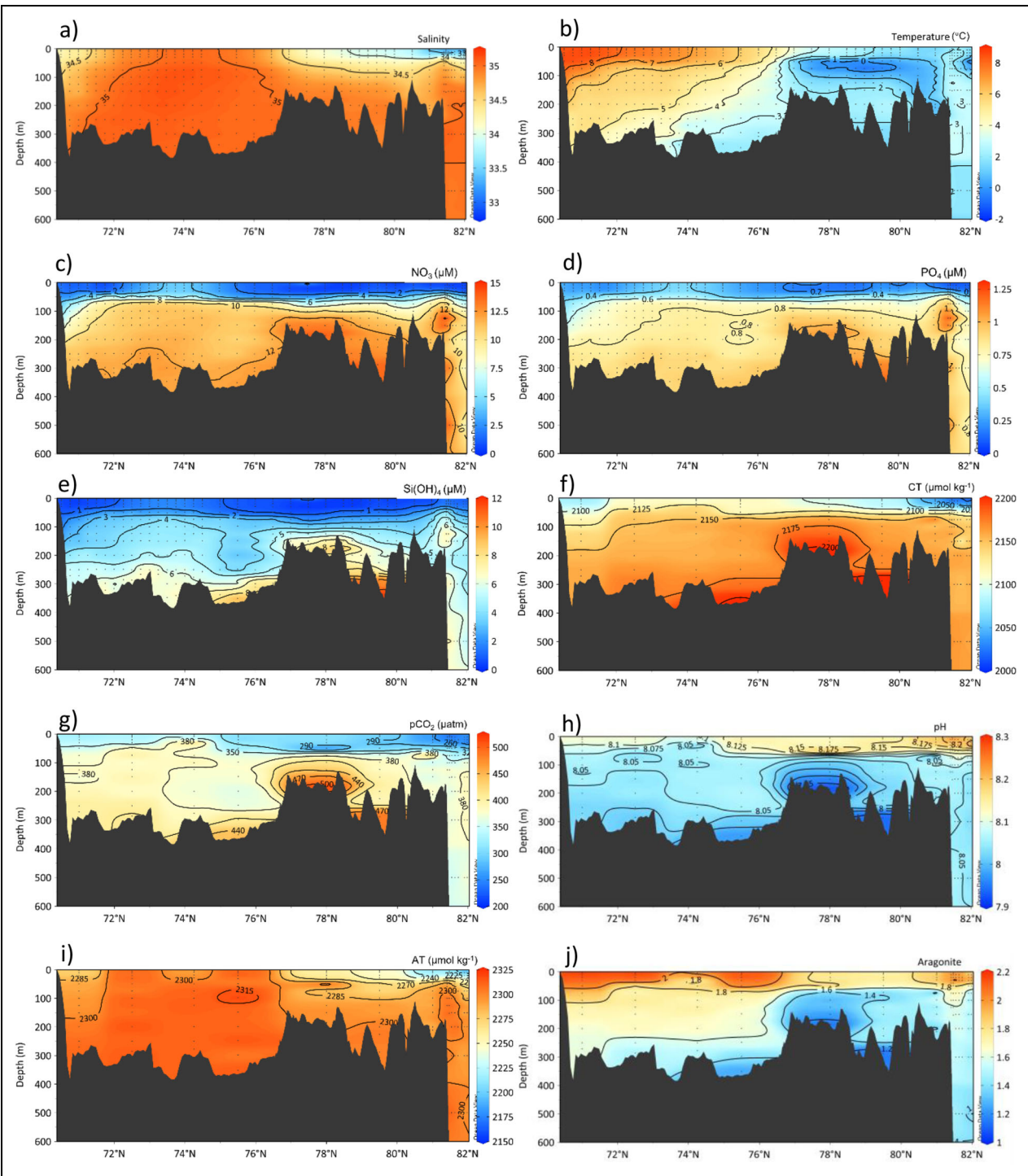


Figure 8. South-to-north distribution of physical and chemical water properties in the Barents Sea.

Distribution of (a) salinity, (b) temperature (°C), (c) nitrate (NO₃, μM), (d) phosphate (PO₄, μM), (e) silicate (Si(OH)₄, μM), (f) total dissolved inorganic carbon (CT, μmol kg⁻¹), (g) partial pressure of CO₂ (pCO₂, μatm), (h) pH, (i) total alkalinity (AT, μmol kg⁻¹), and (j) aragonite saturation, along the section from Vardø (Norway) in the south to the Nansen Basin in the north (see **Figure 5a**), from observations in September 2012. Locations where data were collected are indicated by dots in the diagrams.

bottom and in trenches in the seasonally ice-covered area (sea-ice edges in **Figure 2**). These findings are likely due to a combined effect of accumulation and remineralisation of organic matter producing CO₂ and the downward transported CO₂ by brine from sea-ice formation in winter (Fransson et al., 2013; Chierici and Fransson, 2018).

Calcium carbonate saturation of aragonite (Ω_A) is commonly used to define the ocean acidification state because it is a measure of the dissolution potential of aragonite shells and skeletons. The seasonally ice-covered waters in the northern Barents Sea have a large range of Ω values in the water column (Chierici and Fransson, 2018). The entire

water column is supersaturated regarding aragonite ($\Omega_A > 1$; **Figure 8e**). However, in the deep waters in the northern part with seasonal ice cover, low Ω_A values of about 1.2 are observed. A Ω_A value of 1.4 can be critical for some aragonite-forming organisms (e.g., the pteropod *Limacina helicina*) by negatively impacting their calcification of shell (e.g., Comeau et al., 2009; 2010; Bednarsek et al., 2012; Bednarsek et al., 2014; Manno et al., 2017).

Total alkalinity depends mainly on salinity changes related to water masses and mixing, but also on the dissolution and formation of calcium carbonate, such as formed from calcifying organisms and sea-ice ikaite (Chierici and Fransson, 2018; **Figure 8i**). At the shelf break, A_T (**Figure 8i**) increases similarly to nitrate (**Figure 8c**) and phosphate (**Figure 8d**), which may be caused by recent mixing transporting nutrients and A_T upwards in the water column to the surface.

On young sea ice, frost flowers may develop, due to upward-transported brine and in combination with cold and calm atmospheric conditions (Fransson et al., 2015a; Chierici and Fransson, 2018; Nomura et al., 2018). Frost flowers generally occur on top of newly formed sea ice in spring or in open cracks (e.g., leads) in winter (Fransson et al., 2013; Fransson et al., 2017; Nomura et al., 2018). The large surface area of the frost flowers enables efficient transfer of chemical substances, gases and particles, such as bacteria and sea-salts (e.g., Barber et al., 2014; Fransson et al., 2015a). Because the brine is rich in CO_2 , frost flowers facilitate loss of CO_2 from the ice to the atmosphere (Fransson et al., 2015a).

3.2.2. Carbonate chemistry trends and variability in the Barents Sea

The carbonate chemistry in the Barents Sea is seasonally variable (Lauvset et al., 2013), but shows a decreasing trend in pH and an increasing trend in $f\text{CO}_2$. These trends were confirmed by Ericson et al. (2023) who found that the surface water $f\text{CO}_2$ increase was up to 4 times faster than the atmospheric CO_2 increase rate in the areas with greatest sea ice loss in the northern Barents Sea. Becker et al. (2021) estimated an increased trend in the surface water pH of 0.001 year^{-1} for the period 1998–2016 in the southern Barents Sea. A larger pH decrease of -0.006 year^{-1} was estimated (1998–2016) specifically for Storfjorden (Becker et al., 2021), where the uptake and vertical transport of atmospheric CO_2 is facilitated by brine release and deep-water formation (Anderson et al., 2004). For the northern and eastern parts of the Barents Sea increased data coverage in pH and surface water $f\text{CO}_2$ has been obtained only recently. More observations, especially in autumn and winter, are required to identify and quantify anthropogenic CO_2 changes or other processes affecting ocean acidification (Jones et al., 2018; Ericson et al., 2023).

A seasonal study from January to June in the area north of Svalbard and the Nansen Basin showed the development of $p\text{CO}_2$ undersaturation in the surface water below the sea ice (Fransson et al., 2017). This condition was present mainly due to sea-ice processes such as brine rejection, ikaite dissolution from January to June, and biological CO_2 consumption in May–June. The observed

under-ice $p\text{CO}_2$ in that study ranged between $315 \mu\text{atm}$ in winter and $153 \mu\text{atm}$ in spring. Openings in the ice cover (i.e., leads) due to large storms promoted uptake of atmospheric CO_2 (Fransson et al., 2017). The CO_2 sink varied between $0.3 \text{ mmol C m}^{-2} \text{ d}^{-1}$ and $86 \text{ mmol C m}^{-2} \text{ d}^{-1}$, depending on the open-water fractions and storm events (Fransson et al., 2017). Moreover, Chierici et al. (2019) found that the entire region west and north of Svalbard was a CO_2 sink for atmospheric CO_2 , which was mainly driven by primary production and stratification due to meltwater in spring. A recent study using 27 Earth system models (Orr et al., 2022) highlights that the seasonal timing of $p\text{CO}_2$ might change in the Arctic Ocean in future, and by that change increase summer ocean acidification.

4. Status and changes of the ecosystem

The present climate and ecosystem of the productive southern Barents Sea are relatively well surveyed and understood (Sakshaug et al., 2009; Jakobsen and Ozhigin, 2011; Eriksen et al., 2018). This understanding has been further elaborated with regard to climate (Smedsrud et al., 2013), biomass and productivity (Dalpadado et al., 2014; Eriksen et al., 2017), ecosystem and carbon fluxes (Wassmann et al., 2006; Wassmann et al., 2015), and the impact of sea-ice change on biology and human activity (Meier et al., 2014). The situation is different for the winter ice-covered northern Barents Sea shelf and adjacent deep Nansen Basin, where ecosystems function fundamentally differently (Bluhm et al., 2015; Wassmann, 2015; **Figure 9**). The impacts of changing physical conditions on productivity, ecosystem function, and distribution of species in these northern regions have been explored only recently (Reigstad et al., 2011; Solan et al., 2020a; Solan et al., 2020b; Frainer et al., 2021).

The northern Barents Sea and adjacent slope to the Nansen Basin have become one of the most discussed areas of the Arctic Ocean because of observed and predicted rapid climatic change and linked biological consequences (Haug et al., 2017a). An approach to identify ecosystem responses to changes in ice cover and other environmental changes in this region could include a space-for-time strategy (Pickett, 1989). The approach assumes that investigations over a physical gradient mimic a temporal climatic gradient and provide insight into a future changing climate, in this case farther north or east. This approach is applied with a seasonal perspective in the Norwegian project “The Nansen Legacy” (www.nansenlegacy.org) by sampling along transects from the southern Barents Sea northwards into the Nansen Basin (**Figure 9**). In the Barents Sea, space-for-time reflects that going north may be equivalent to going back in time into Arctic conditions where seasonal sea ice still prevails, while going south reflects going forward in time towards warmer and ice-free conditions. A likely effect of global warming in the Barents Sea is a northward displacement of the Polar Front position (e.g., Oziel et al., 2016). However, confounding factors such as different radiative forcing and water masses with increasing latitude also need to be considered. Statistical analyses of satellite-derived chlorophyll data have shown that differences in bloom timing

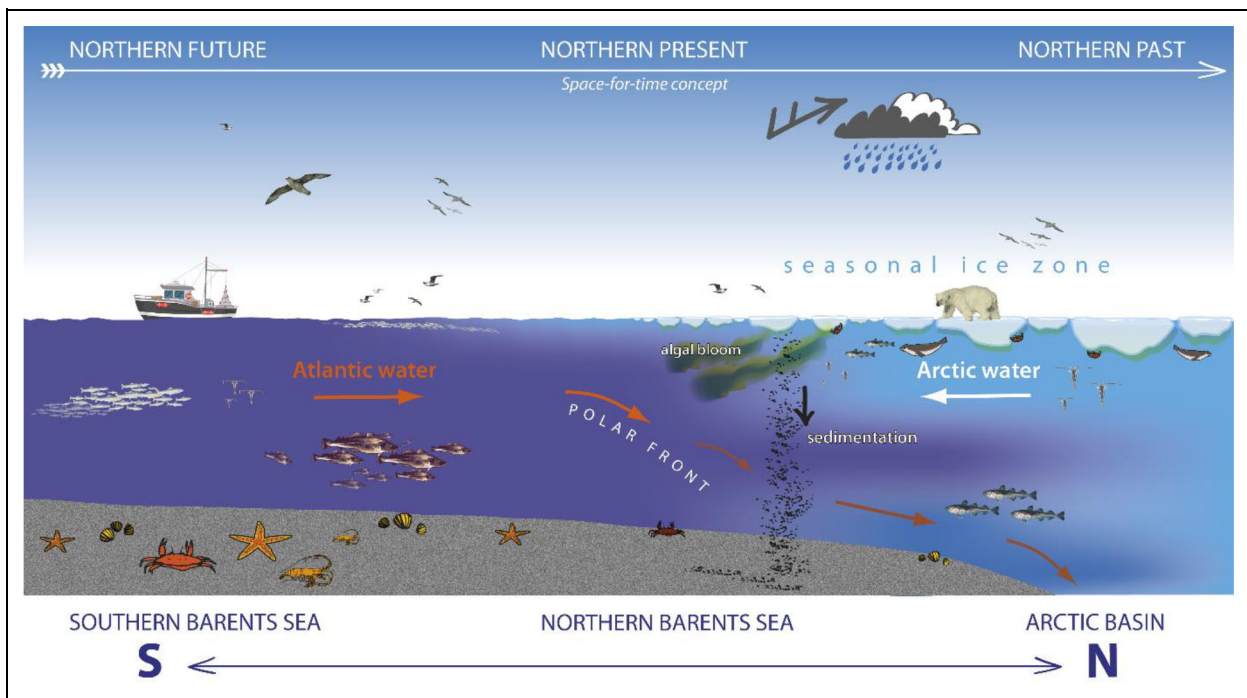


Figure 9. South-to-north schematic of the marine ecosystem in the Barents Sea. The marine ecosystem in the Barents Sea, from south to north, and the space-for-time concept: the possibility to study a temporal change by studying a spatial gradient; for the Barents Sea, by moving from south to north, back in time (see Section 4). Figure developed by Rudi Caeyers (UiT The Arctic University of Norway/The Nansen Legacy).

and magnitude along spatial climate gradients in the northern Barents Sea resemble differences between years with different climate conditions (Dong et al., 2020). This resemblance is probably linked to the strong connection between phytoplankton blooms and sea-ice retreat in the region (e.g., Dalpadado et al., 2020). Another space-for-time aspect is the timing of processes in the Barents Sea relative to those in Arctic shelf seas farther east. The Barents Sea inflow shelf might be a sentinel for those interior Arctic shelf seas, as they are exposed earlier to some of the changes and forcings, such as AW influence.

4.1. Main ecosystem components of the northern Barents Sea

The northern Barents Sea is a region with strong environmental gradients in water masses and sea ice. These gradients are largely responsible for regional differences observed in the distribution of boreal versus Arctic species, vital rates, food web transfers and pelagic-benthic coupling.

4.1.1. Microbes

The microbial food web of the euphotic zone serves as an interface between ocean chemistry (dissolved mineral nutrients and carbon) and the food web, directing energy in form of particulate organic material to harvestable resources or to the ocean interior via the biological carbon pump. Data on Arctic pelagic microbial community composition, diversity and food-web traits originate largely from studies in the Laptev Sea, the Canadian Arctic, the Beaufort Sea and the Chukchi Sea (Kellogg and Deming, 2009; Lovejoy et al., 2011; Li et al., 2013; Pedrós-Alió et al.,

2015; Dickinson et al., 2016). A few recent studies have reported on changes and seasonality in microbial community composition and dynamics in Arctic waters around Svalbard. The cyanobacterium *Synechococcus* has likely become a more important member of the picophytoplankton with increasing inflow of AW to the Arctic Ocean (Paulsen et al., 2016). Phytoplankton-associated Gammaproteobacteria and Flavobacteria dominate surface waters in summer, while Thaumarchaeota and Chloroflexi-types predominate under low light conditions, i.e., in winter and in deeper waters (Wilson et al., 2017). The most profound community changes occur in spring, with Gammaproteobacteria interactions dominating in the pre-bloom phase and Flavobacteria interactions during phytoplankton-bloom conditions (Müller et al., 2021). Experimental studies on Arctic microbial food webs suggest that altered trophic cascades from copepods through ciliates and flagellates affect bacterial growth rates, abundance and community composition via competition for mineral nutrients and predation (Tsagaraki et al., 2018). In a recent seasonal study about the region north of Svalbard, however, predation was found to affect bacterial community composition only in late summer, whereas substrate quality and quantity were otherwise more important than any other single factor (Müller et al., 2021). Substrate in this context is generally dissolved organic matter (DOM), which varies in quality depending on its source. For example, DOM from *Phaeocystis* blooms may be very abundant but of inferior quality for bacteria due to low nitrogen content (Olli et al., 2019). Thus, variability in top-down (predation) and bottom-up (availability and quality of DOM and inorganic nutrients) control leads to bacterial communities

with different competition and defense properties and may affect the overall carbon and nutrient flow in the system (Sandaa et al., 2017; Tsagaraki et al., 2018; Thingstad et al., 2020).

4.1.2. Phytoplankton and ice algae

Microscopic algae living in sea ice (ice algae) and the underlying water column (phytoplankton) constitute the primary producers in the Arctic marine ecosystem (Søreide et al., 2010; Leu et al., 2015). Dominant species in communities vary seasonally, and ice-algal communities also vary with sea-ice location (e.g., landfast versus pack ice; van Leeuwe et al., 2018) and between first-year and multi-year ice (CAFF, 2017; Hop et al., 2020). The northern Barents Sea is dominated by annual pack ice, and ice-algal production has been estimated to be $5 \text{ g C m}^{-2} \text{ year}^{-1}$, corresponding to 20% of the total annual primary production in the region (Hegseth, 1998). The main ice-algal growth period is mid-March to mid- or late June when melting becomes important (Hegseth and von Quillfeldt, 2022). Ice-algal blooms tend to be dominated by diatoms, though hundreds of taxa including flagellates, dinoflagellates, and ciliates contribute as well, and phenology varies through bloom stages (Leu et al., 2015; CAFF, 2017; Kauko et al., 2018). In the Barents Sea pack ice, ice algae form a loosely attached sub-ice algal layer, with *Nitzschia frigida* dominating medium thick ice, while other pennate diatoms *N. promare* and *Fossilaphycus arcticus* dominate thinner sea ice (Hegseth and von Quillfeldt, 2022).

No time series of phytoplankton communities exists for the Barents Sea region, but scattered studies provide information on seasonal patterns. Blooms in open water are generally dominated by centric diatoms (e.g., *Chaetoceros* spp. and *Thalassiosira* spp.) in the early part of the season, but flagellates and the prymnesiophyte *Phaeocystis pouchetii* also play important roles in the Barents Sea (Hegseth, 1998; Wassmann et al., 2005; Wassmann et al., 2006; Degerlund and Eilertsen, 2010; Vodopyanova et al., 2020). Pico- and nanoflagellates ($<20 \mu\text{m}$) dominate the phytoplankton community in March and late summer, with more heterotrophic flagellates and dinoflagellates in late summer (Ratkova and Wassmann, 2002).

Seasonal sea-ice melt along the ice edge enhances the primary production during spring through stratification of the water column (Babin et al., 2015; Renault et al., 2018), and remote sensing reveals earlier onset of spring blooms by nearly a month (from mid-June to mid-May) in the northern Barents Sea due to earlier melt of sea-ice cover (Dalpadado et al., 2020). The timing of ice-algal and phytoplankton blooms and their relative contribution to total Arctic primary production determine the amount of energy available to sympagic (sea-ice-associated) and pelagic ecosystems (Falk-Petersen et al., 1998; Leu et al., 2011; Leu et al., 2015; Brown et al., 2017; Kauko et al., 2018; Kauko et al., 2019; Ehrlich et al., 2021). As the ice algae melt out of the ice during spring, they contribute significantly to the vertical flux of organic matter and represent a seasonal source of high-quality carbon for the benthos (Tamelander et al., 2008; Tamelander et al., 2009; Carroll et al., 2014).

Openings in the form of leads in the pack ice, as well as ice and snow thickness, affect the onset and magnitude of the planktonic blooms, which may also occur below the ice if the light is sufficient early in the season; such blooms may involve diatoms or *Phaeocystis pouchetii* (Arrigo et al., 2012; Arrigo et al., 2017; Assmy et al., 2017). Under-ice phytoplankton blooms can be produced locally (Arrigo et al., 2012; Arrigo et al., 2017) or advected from open waters (Johnsen et al., 2018). The blooms will be sustained as long as sufficient nutrients are available and tend to follow the receding marginal ice zone northwards (Wassmann et al., 2006; Wassmann and Reigstad, 2011). For the shelf break region north of the Barents Sea, advection of phytoplankton exceeds the local production by up to 50 times and underlines the importance of advection for regional biomass values (Vernet et al., 2019). The average total primary production in the Barents Sea is around $90 \text{ g C m}^{-2} \text{ year}^{-1}$, but can vary between $20 \text{ g C m}^{-2} \text{ year}^{-1}$ and $200 \text{ g C m}^{-2} \text{ year}^{-1}$, with 30% higher values in years with little sea ice (Sakshaug, 2004). The annual gross primary production (simulated 1995–2007) is higher in the ice-free south ($106\text{--}134 \text{ g C m}^{-2} \text{ year}^{-1}$) compared to the seasonally ice-covered northern Barents Sea ($54\text{--}67 \text{ g C m}^{-2} \text{ year}^{-1}$; Reigstad et al., 2011).

Macroalgae are common primary producers along hard-bottom Arctic coasts, and the biomass of large brown algae has increased in shallow waters ($<5 \text{ m}$ depth) because of less sea ice (Kortsch et al., 2012; Krause-Jensen and Duarte, 2014; Bartsch et al., 2016; Al-Habahbeh et al., 2020; Krause-Jensen et al., 2020). Few regional estimates of primary production by macroalgae exist (Dunton et al., 1982; Borum et al., 2002), and none for the Barents Sea region.

4.1.3. Key zooplankton and sea-ice fauna

The Barents Sea holds a diverse zooplankton community with the most prominent differences across the area expressed in species abundances and biomass rather than in taxonomic composition (e.g., Daase et al., 2021); however, here we give a brief taxonomic overview. Small copepods ($<2.5 \text{ mm}$ total length as adults) are dominated by *Oithona* spp., which are typically most abundant in the upper part of the water column (Svensen et al., 2011; Hop et al., 2021b). Other abundant small copepods belong to the genera *Pseudocalanus* and *Microcalanus*. Microzooplankton biomass is lower north of the Polar Front than in AW south of the front, where mixotrophic ciliates may be important for energy transfer (Franze and Lavrentyev, 2017). Mesozooplankton biomass is dominated by *Calanus* copepods (Aarflot et al., 2017), but euphausiids, chaetognaths and pelagic, hyperiid amphipods are also important contributors (Søreide et al., 2003; van Engeland et al., 2023). Boreal species, such as *Calanus finmarchicus*, krill (*Thysanoessa inermis*, *T. longicaudata* and *Meganyctiphanes norvegica*), and the amphipod *Themisto abyssorum* are typically associated with AW (Skjoldal, 2021). Farther north in Arctic water masses, larger copepod species (*C. glacialis*, *C. hyperboreus*) constitute much of the biomass together with the amphipod *Themisto libellula* (Dalpadado and Skjoldal, 1996; Søreide et al., 2003; van

Engeland et al., 2023). Other characteristic zooplankton groups associated with Arctic water masses include pteropods (*Limacina helicina* and *Clione limacina*) and ctenophores (*Mertensia ovum* and *Beroë cucumis*; Søreide et al., 2003; Blachowiak-Samolyk et al., 2008a; Blachowiak-Samolyk et al., 2008b). Ctenophores are important predators on zooplankton, and in the Barents Sea *M. ovum* has been estimated to be able to consume daily up to 9% of the copepod biomass during times of high ctenophore abundance (Swanberg and Båmstedt, 1991). The larger *B. cucumis* preys on *M. ovum* as well as zooplankton (Falk-Petersen et al., 2002).

The mesozooplankton biomass in the Barents Sea has been variable, from $<3 \text{ g m}^{-2}$ to $>10 \text{ g m}^{-2}$ dry mass in the period 1990–2010, with 50% of the interannual variability explained by predation from pelagic fishes (Dalpadado et al., 2012; Stige et al., 2014), though it has been relatively stable since the mid-2000s (Dalpadado et al., 2020). Advection of large quantities (i.e., 4 times the locally produced biomass) of boreal zooplankton through the BSO (Edvardsen et al., 2003a; Edvardsen et al., 2003b; Dalpadado et al., 2012; Dalpadado et al., 2014) tends to stabilize zooplankton populations in the Atlantic part of the Barents Sea. Similarly, the area north of Svalbard is supplied by these boreal advective inputs (Basedow et al., 2018). Zooplankton biomass is controlled by both bottom-up and top-down processes (Søreide et al., 2013; Dalpadado et al., 2014; Stige et al., 2018; Stige et al., 2019; Dalpadado et al., 2020). Bottom-up processes are linked intrinsically to seasonal variations in primary production, temperature, ice cover and advection (Mueter et al., 2009; Reigstad et al., 2011; Dalpadado et al., 2014) through their influence on both habitat and food sources. Dietary trophic markers of some key zooplankton show a relatively weak relation to sea-ice algae during both summer and winter, likely reflecting the low abundance and quality of ice-associated carbon during summer and the inaccessibility or absence of algae inside the ice during winter (Kohlbach et al., 2021a; Kohlbach et al., 2021b). In spring, however, estimated ice-algal carbon production and consumption plays a substantially larger role (Søreide et al., 2013; Ehrlich et al., 2021). More data are needed from the ice-covered spring period to reveal the full importance of ice algae for the Barents Sea ecosystem. Top-down processes affecting zooplankton relate to predation by pelagic fish stocks such as capelin (Gjosæter et al., 2002; Dalpadado and Bogstad, 2004; Stige et al., 2014; Stige et al., 2019; Dalpadado et al., 2020) and seabirds (Hovinen et al., 2014a; Vihtakari et al., 2018), particularly in shallow waters (Aarflot et al., 2020).

Sea-ice fauna in the northern Barents Sea and north of Svalbard is dominated by ciliates in the small size fraction and by larger copepod nauplii and harpacticoid copepods (Ehrlich et al., 2020; Timchenko et al., 2021). Taxa such as nematodes that are common elsewhere in sea ice are rare in the present decade, with a potential decline hypothesized to be linked to changes in ice transport from Siberia via the Transpolar Drift (Ehrlich et al., 2020). Under-ice fauna includes pelagic taxa immediately under the ice, as well as sympagic amphipods (Lønne and Gulliksen

1991); of the latter, the gammarid *Gammarus wilkitzkii* has declined in the Atlantic Arctic sector due to the loss of multi-year ice (Hop et al., 2021a).

4.1.4. Fish, marine mammals and seabirds

Capelin (*Mallotus villosus*) is the main forage fish species in the boreal community of the Barents Sea, whereas the polar cod (*Boreogadus saida*; e.g., Aune et al., 2021) functions similarly in the Arctic community (Hop and Gjosæter, 2013). Both species respond to increasing ocean temperatures and decreasing sea ice, but while capelin responds by expanding its distribution northwards (Ingvaldsen and Gjosæter, 2013), polar cod responds with restricted distribution and poorer recruitment (Huserbråten et al., 2019; Gjosæter et al., 2020). Moreover, the individual growth of both species increases with temperature at age 1, although the influence of abiotic factors weakens with increasing age (Solvang et al., 2017; Dupont et al., 2021). The pelagic compartment in the Barents Sea also has large contributions from juvenile fishes (Eriksen et al., 2011). The total pelagic biomass in the Barents Sea is on average about 17 million tonnes, of which about 10 million tonnes are in the southern part (Figure 10). However, this biomass includes both fish larvae/juveniles and macroplankton (Eriksen et al., 2016; Eriksen et al., 2017).

The most abundant demersal fish species in the Barents Sea are the Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), beaked redfish (*Sebastes mentella*), Greenland halibut (*Reinhardtius hippoglossoides*) and long rough dab (*Hippoglossoides platessoides*) (Johannesen et al., 2012). Of these, Atlantic cod is the most abundant, and Atlantic cod and Greenland halibut are the species with the most northern and northeastern limits of their distributions. These boreal species are also found along the west coast of Spitsbergen up to 81°N and along the western part of the northern coast of Spitsbergen. In addition, the Arctic fish community consists of many less abundant and often much smaller demersal species, such as sculpins, eelpouts and snailfishes (Fossheim et al., 2015; Mecklenburg et al., 2018).

Some key endemic marine mammals, including ringed seals (*Pusa hispida*), white whales (*Delphinapterus leucas*), narwhals (*Monodon monoceros*) and bowhead whales (*Balaena mysticetus*), have adapted to life at high latitudes and spend their whole life within the region (Vacquie-Garcia et al., 2017; Lone et al., 2019). Other species, such as harp seals (*Pagophilus groenlandicus*) and the whales in the rorqual family (Balaenopteridae) migrate into the northern waters to forage in the productive waters, but spend the rest of the year in their largely temperate distributional ranges (Haug et al., 2017a). Harp seals and minke whales (*Balaenoptera acutorostrata*) are the most abundant marine mammal species. In the North Atlantic Arctic and adjacent shelf seas, they often forage on zooplankton and pelagic fishes at ocean fronts and other areas where upwelling stimulates high productivity (Kovacs and Lydersen, 2008). While distributional overlap is seasonally large, trophic partitioning among dominant marine mammals has been documented (MacKenzie et al., 2022). The role of ice-derived carbon in marine mammal

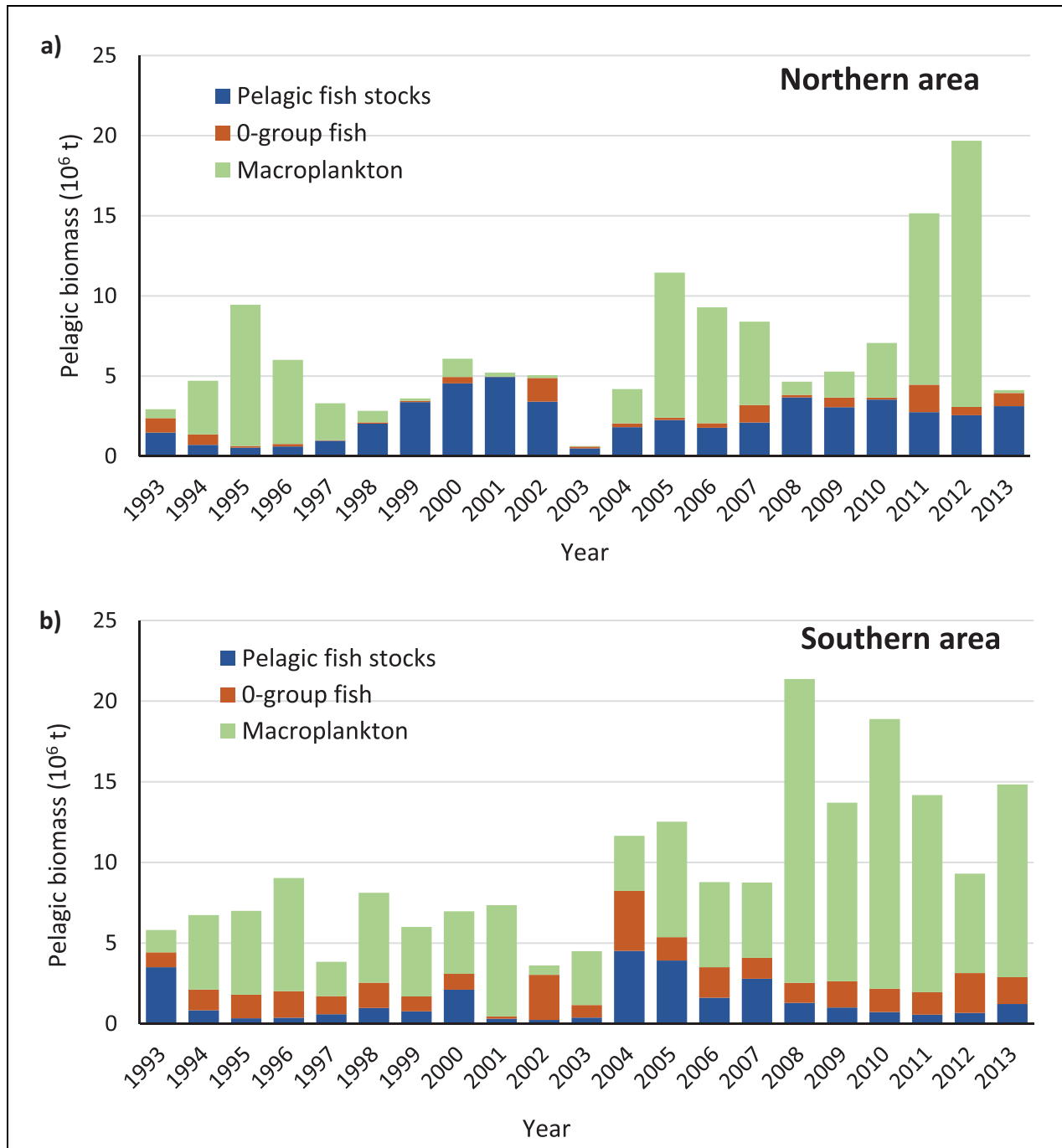


Figure 10. Diagrams of estimated fish and macroplankton biomasses in southern and northern Barents Sea 1993–2013. Estimated pelagic biomasses of pelagic fish stocks, 0-group fishes and macroplankton (mainly krill) in the (a) northern and (b) southern Barents Sea for the period 1993–2013. For further description of the data series see Eriksen et al. (2017).

nutrition is poorly constrained, but first estimates suggest substantial contributions to seasonally ice-associated species (Kunisch et al., 2021).

Polar bears (*Ursus maritimus*) utilize the marginal ice zone in the Barents Sea and den on the islands in the western Barents Sea (Lone et al., 2018b; Merkel et al., 2020). The number of bears has been estimated to be about 1,000, of which 700 resided in the pack ice of the marginal ice zone (Aars et al., 2017, 2018). Their main prey are ice-associated seals, such as ringed seals, but they can

also prey on harp seals when they haul out and rest on the pack ice (Smith and Stirling, 2019). Reductions in sea ice are a major threat to the species and may force them to spend more of their time and energy in water while travelling on the ice (Lone et al., 2018a).

Large numbers of seabirds (3.5 million breeding pairs) nest on the islands around Barents Sea (i.e., Svalbard, Franz Josef Land, and Novaya Zemlya). The most important seabirds with regard to abundance are little auk (*Alle alle*), Brünnich's guillemot (*Uria lomvia*), Northern

fulmar (*Fulmarus glacialis*), black-legged kittiwake (*Rissa tridactyla*) and common guillemot (*Uria aalge*) (Anker-Nilssen et al., 2000). They feed on different pelagic components of the Barents Sea ecosystem, including both zooplankton and fishes. Because seabirds depend on rather specific prey in the marine system, they function as environmental indicators for changes in the Barents Sea ecosystem.

4.1.5. Benthos

Benthos plays a major role in the overall energy flow on Arctic shelves. In fact, benthic invertebrates provide one of the four main energy flow pathways through this ecosystem (Pedersen et al., 2021). Regionally, different benthic assemblages are responsible for these energy flows. The Barents Sea can be divided into four main megafaunal regions related to depth, temperature, salinity, and number of ice-days (Jørgensen et al., 2015a). In the southwest, the megabenthos is dominated by filter-feeders (sponges) in the inflow area of warm AW, while the deeper trenches had primarily a detritivorous fauna (echinoderms). In the southeastern and western areas, predators (sea stars, anemones and the snow crab *Chionoectes opilio*) prevailed together with filtrating species (sea cucumber and bivalves) within a mosaic of banks and slopes (Zakharov et al., 2021). Suspension-feeding brittle stars were common in the northwestern and northeastern regions, where snow crab is also increasing. The Polar Front, which separates hydrographic and ice regimes, also separates boreal and Arctic benthic macrofauna and the relative rates of their bioturbation activity (Cochrane et al., 2009; Solan et al., 2020a). The meroplanktonic (benthic larval) assemblages also vary on either side of the Polar Front (Descôteaux et al., 2021). These regional patterns in faunal composition are mirrored in dissimilar food web characteristics, such as more predator-prey links and higher levels of both omnivory and connectance in the boreal parts of the Barents Sea seafloor (Kortsch et al., 2015; Kortsch et al., 2019). Notably, benthic secondary production of the communities in the seasonally ice-covered northeastern region is higher than in the permanently ice-free southwestern and central area (Degen et al., 2016). Along the continental slope, densities drop dramatically and community structure shifts towards deep-sea communities with high north-Atlantic affinities (Włodarska-Kowalczyk et al., 2004; Bluhm et al., 2020). Overall, carbon storage in the form of seafloor biota is thought to be high in the Barents Sea (Souster et al., 2020), leading to the suggestion that this and other Arctic shelf seafloor systems should be included in global blue carbon estimates (Solan et al., 2020b).

Arctic benthic ecosystems are often assumed to be highly vulnerable to ongoing climate change and are expected to undergo wholesale shifts in structure and function. Shifts in seafloor biota are documented in coastal assemblage and functional structure (Al-Hababeh et al., 2020) as well as food web properties (Kortsch et al., 2015; Kortsch et al., 2019), yet species-distribution modeling has projected only small overall benthic habitat changes among Arctic, boreal, or Arcto-

boreal groups, or between calcifying and non-calcifying groups. Some taxa, however, including several that are characteristic and/or habitat-forming fauna on some Arctic shelves, have shown dramatic changes, suggesting a potential for significant ecosystem impacts (Renaud et al., 2019). Clearly, other pressures such as bottom trawling also change benthic communities in the Barents Sea, for example through depressing species richness (Kędra et al., 2017).

In the last decade, the role of previously unstudied habitats and sub-regions in the (northern) Barents Sea has begun to emerge. Cold seeps, where methane and other reduced compounds emerge at the seabed, are now recognized as commonly occurring in the Barents Sea where they form chemosynthetic habitats supporting unique but highly-variable seafloor communities. Such seep communities support high densities of chemosymbiotic worms (Siboglinidae and Frenulata polychaetes) and bivalves (*Mendicula cf. pygmaea*; Sen et al., 2018; Åström et al., 2019; Karaseva et al., 2021). Aggregations of heterotrophic macrofauna and megafauna were associated with characteristic seep features such as microbial mats, carbonate outcrops and chemosymbiotic worm-tufts (Åström et al., 2019; Åström et al., 2020). In addition, communities of opportunistic polychaete species and bivalves, known to inhabit oxygen-depleted environments and organic-enriched sediments, are found in sediments of the Kveithola Trough, also thought to be related to methane seepage in the neighboring Storfjorden Trough (Caridi et al., 2019). First evidence suggests that chemosynthesis-derived carbon from these seeps enters the Barents Sea food web, at least locally (Åström et al., 2019).

4.1.6. Vertical linkages in ice-covered and ice-free regions

Latitudinal gradients in hydrography and sea-ice cover, and related changes in productivity regime and community composition, result in variations in the sympagic-pelagic-benthic coupling in different parts of the Barents Sea (Olli et al., 2002; Tamelander et al., 2006; Wassmann et al., 2006; Reigstad et al., 2008; Reigstad et al., 2011; Ehrlich et al., 2021). Seasonal sea-ice melt in the marginal ice zone produces a stratified euphotic zone, where ice-algal blooms sink out partially ungrazed, resulting in tight sympagic-pelagic-benthic coupling (Olli et al., 2002; Tamelander et al., 2006; Søreide et al., 2006, 2007; Reigstad et al., 2008; Søreide et al., 2013, **Figure 9**). The entire sympagic community is released when the sea ice melts (with the exception of occasional multi-year ice floes), including microbes, meiofauna, and macrofauna (Hop and Pavlova, 2008; Bluhm et al., 2018), and may then sink to the bottom or enter the pelagic food web. Ice amphipods and polar cod can use the pelagic area as habitat for part of their life cycles (Berge et al., 2012; Hop and Gjosæter, 2013; Kunisch et al., 2020) and may serve as vectors for sympagic production to top predators. In contrast to ice-associated production, the majority of the production from the open-water phytoplankton blooms will enter the pelagic food web if zooplankton grazers are present, although a temporal mismatch with grazers results in

a seasonally high vertical flux to the seafloor. When pelagic grazers are abundant, their faecal pellets also contribute carbon to the benthos (Wexels Riser et al., 2007; Renaud et al., 2008). Variation in the vertical flux patterns in the region, partially related to sea-ice extent in a given year (e.g., Wassmann and Reigstad, 2011), leads to spatial variability in ecological patterns at the seafloor, including benthic community structure, carbon cycling and partitioning of food resources among seafloor faunal components (Piepenburg et al., 1995; Carroll et al., 2008; Renaud et al., 2008; Solan et al., 2020b). Standing stocks of zoobenthos were investigated recently and yielded the highest carbon levels in the northern Barents Sea (Souster et al., 2020).

Even though annual primary production is comparably low in the northern Barents Sea, significantly higher megabenthic secondary production occurs at the seafloor in the northeastern, seasonally ice-covered regions of the Barents Sea (Degen et al., 2016). Large predatory or filter-feeding benthic invertebrates populating the seafloor suggest tight sympagic-pelagic-benthic coupling, often in combination with high abundance of zooplankton in the near-bottom layer and low predation pressure from large fishes (Søreide et al., 2013; Jørgensen et al., 2015a).

4.2. Long-term changes in the Barents Sea ecosystem

Some of the most rapid and substantial climate-driven changes in marine ecosystems are expected at high latitudes. In regions within or bordering the Arctic, rates of warming (surface air temperature increase) are 2–4 times higher than the global average (Overland et al., 2016; Rantanen et al., 2022) and, for the northern Barents Sea, 5–7 times higher (Isaksen et al., 2022). The Barents Sea has experienced significant warming and sea-ice retreat over the last few decades, which in turn has affected the distribution and biomass of marine species (Figure 11), reorganizing ecological communities and influencing

ecosystem functions (Dalpadado et al., 2012; Johannesen et al., 2012; Wiedmann et al., 2014; Kortsch et al., 2015; Kortsch et al., 2019; Eriksen et al., 2017; Frainer et al., 2017).

Substantial changes in production have occurred at the base of the food web in marginal Arctic seas. The productive season has been prolonged (Arrigo and van Dijken, 2015), and both early pelagic under-ice blooms (Assmy et al., 2017; Ardyna et al., 2020) and advected blooms under sea ice (Johnsen et al., 2018) have been observed. The occurrence of autumn blooms has increased substantially in Arctic marginal seas during the last decade (Ardyna et al., 2014). The steepest increase in chlorophyll-*a* concentrations over the years 2003–2016 for the entire Arctic has occurred during May in areas of the ice-free western Barents Sea, with an overall positive trend averaging $0.79 \text{ mg m}^{-3} \text{ year}^{-1}$ (Frey et al., 2021). Oziel et al. (2022), using ocean color satellite remote sensing data, found a chlorophyll-*a* increase of 85% between 1979 and 2016 for the Barents Sea. The annual net primary production for the Barents Sea, as estimated from remote sensing data, has increased substantially, with estimates varying between 110% over the 1998–2017 period (Dalpadado et al., 2020) and 88% over the 1998–2018 period (Lewis et al., 2020). In addition, recent poleward intrusions of the coccolithophore *Emiliana huxleyi*, a tracer for temperate ecosystems, have been observed (Hovland et al., 2013; Oziel et al., 2020), and *Phaeocystis* bloom frequency has likely increased over the past two decades (Orkney et al., 2020).

The ongoing warming and sea-ice reductions have expanded the favourable thermal habitat for boreal zooplankton, such as *Calanus finmarchicus*, krill, and the jellyfish *Periphylla periphylla* (Geoffroy et al., 2018), whereas Arctic zooplankton (e.g., *Themisto libellula*) have retreated farther north (Zhukova et al., 2009; Orlova et al., 2015; Eriksen et al., 2017). In the western Barents Sea, indications of ongoing borealization of the zooplankton

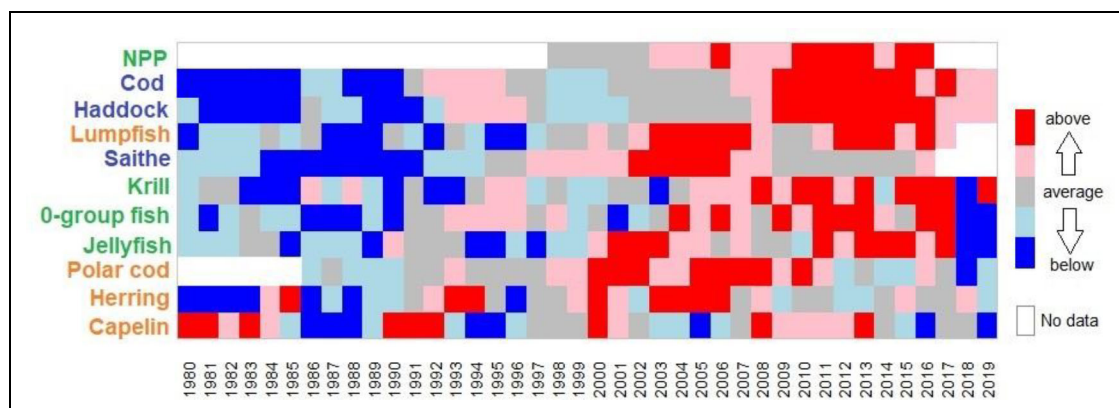


Figure 11. Diagram covering Barents Sea phytoplankton, zooplankton, and fish development from 1980 to 2019. Barents Sea ecosystem time series from late summer to early autumn 1980–2019. The data cover the biomass of phytoplankton and zooplankton (green font) and of pelagic fishes (orange font) and demersal fishes (blue font). The variables were sorted by trend. Cells with values of the average (1980–2019) are shown in grey, cells with values above the average in pink to red, and cells with values below the average in aqua to blue. White cells indicate no data available. Time series were standardized to zero mean and unit variance. For further description of data series see Eriksen et al. (2017) and doi.org/10.21335/NMDC-1069717541.

community have been evident, with decreasing proportions of the Arctic *C. glacialis* over the past 20 years occurring simultaneously as *C. finmarchicus* has increased (Aarflot et al., 2017). The warming has also been associated with redistribution of species and increasing biomass of 0-group fishes, krill and jellyfish (Eriksen et al., 2020). During the last 3 decades, the total biomass of the pelagic compartment increased from 6 million tons to 30 million tons and doubled from the 1990s to the 2000s (**Figure 10**). Seabirds feed on different pelagic components of the Barents Sea ecosystem, including both zooplankton and fishes. Seabird monitoring has shown that some species, such as the Brünnich's guillemot, have declined since the early 1990s, whereas the common guillemot has increased in some locations, such as Bjørnøya (Anker-Nilssen et al., 2017).

The recent warming has also caused northern expansion of boreal pelagic species such as mackerel (*Scomber scombrus*) and capelin (Berge et al., 2015b; Haug et al., 2017a). On the other hand, Arctic fishes such as the polar cod declined in distribution and biomass from about 1.5 million tonnes to <0.5 million tonnes in 2017–2019 (Hop and Gjosæter, 2013; Eriksen et al., 2015); this despite that growth conditions, reflected in length-at-age, improve with reduced sea ice (Dupont et al., 2020). After 2019, recruitment has improved and the stock increased to 1.7 million tonnes in 2020 (ICES, 2021b), possibly in combination with the slight cooling observed during recent years. Variability and change in sea-ice cover negatively affect the population dynamics of this keystone species of the ice-associated food web (Huserbråten et al., 2019; Gjosæter et al., 2020). Ongoing decreases in other unexploited Arctic species are also reported (Frainer et al., 2021).

Boreal demersal commercial fish species like Atlantic cod, haddock, and redfish (*Sebastes* spp.) have shown positive trends in biomass with expanded distributions in the 2010s (Haug et al., 2017a). The total stock biomass of Atlantic cod reached an unprecedented high (4.4 million tons) in 2013, a level not seen since the 1940s, and the expansion of the stock can be related to increasing seawater temperatures with less sea ice in the Barents Sea, as well as effective stock management (Kjesbu et al., 2014). Warm climate and high cod-stock size are associated with high capelin-cod overlap in the northern Barents Sea, with consequences for predator-prey dynamics and harvesting (Howell and Filin, 2014; Fall et al., 2018). The cod biomass has decreased since the peak in 2013 but is still widely distributed and above the long-term mean (ICES, 2021a, 2021b).

Expansion of boreal demersal species into the northern area has resulted in reductions in the Arctic demersal fish community, community-wide distributional shifts and functional changes in the food web (Kortsch et al., 2015; Frainer et al., 2017; Kortsch et al., 2019). Moreover, the northern regions have experienced both an increase in benthic warm-water species (Jørgensen et al., 2019) and the invasion of snow crab (Araya-Schmidt et al., 2019). The northward expansion of commercial fish species and westward expansion of snow crab increase the exposure of benthic species to capture by fishery activity and of small

prey species to crab predation (Jørgensen et al., 2019). Snow crab is also a prey item for cod, increasing in proportion over time (Holt et al., 2021). The presence of non-indigenous species has also been confirmed in both the adult and meroplankton communities, though the sources remain unclear (Descôteaux et al., 2021; van den Heuvel-Greve et al., 2021).

Disentangling the effect of climate variability and change from fisheries activity is indeed challenging. Recent progress based on “Chance and Necessity” modeling principles (Planque and Mullon, 2019) revealed that trophic control in the Barents Sea tends to fluctuate between bottom-up and top-down control over time rather than being persistent over long periods (Sivel et al., 2021). Thus, the cumulative impacts of climate and fisheries on ecosystem properties, such as ecosystem stability, trophic control, productivity and harvest potential, are not yet fully resolved. A recent study from the Barents Sea revealed that knowledge of a species' distribution and the number and nature of environmental factors defining its habitat could determine the predictability of that species persisting under environmental change (Husson et al., 2020).

4.3. Winter and polar night conditions

Especially in the marine environment, winter and polar night are not synonymous. While the former is most often defined based on temperature, the latter is defined based on astronomical conditions affecting solar angle and, thus, availability of sunlight (Berge et al., 2020b). The coldest months in the marine environment are often late in the winter and close to the spring equinox (Cottier and Porter, 2020). In contrast, due to the combination of low sun angles or polar night and the attenuation of light from ice and snow cover, light levels in the water column already begin in October or November to be very low, and remain low for most of the (thermally defined) winter at high latitudes (Johnsen et al., 2020).

In the Barents Sea and at high latitudes in general, the primary production regime is highly seasonal. Life-history traits, such as accumulation of lipids and extensive seasonal vertical migrations of herbivorous zooplankton, have evolved in response to the short productive seasons (Conover and Huntley, 1991; Falk-Petersen et al., 2009; Wassmann et al., 2011; Dalpadado et al., 2014). During winter, the irradiance at sea surface in the visible part of the light spectrum, i.e., photosynthetically active radiation (400–700 nm), is extremely low, typically in the range of 5×10^{-9} to 1.5×10^{-5} $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ (Båtnes et al., 2015; Cohen et al., 2015; Ludvigsen et al., 2018), resulting in primary production rates close to zero (Leu et al., 2011; Johnsen et al., 2020). Low irradiance also reduces feeding by some predators, including zooplankton, fishes, and seabirds (Kaartvedt, 2008; Varpe, 2012; Ludvigsen et al., 2018), whereas tactile predators, such as jellyfish, can maintain their feeding (Geoffroy et al., 2018). Low winter food supply in a presumably bottom-up driven system (Hessen and Kaartvedt, 2014) may cause inactivity during the polar night (Smetacek and Nicol, 2005). However, recent ecological studies during the polar night have

indicated that activity levels and biological interactions across most trophic levels and phyla remain elevated during winter, which is important for system functioning throughout the year (Berge et al., 2015a). Berge et al. (2020a) have also demonstrated that light pollution during the darkest part of the polar night may strongly affect natural processes and ecosystem function.

Continuous monitoring of downwelling irradiance at 79°N (Ny-Ålesund, Svalbard) has been established (ArcLight observatory) in 2017, providing hourly data in the PAR range (Johnsen et al., 2021), and absorbed quanta for diatoms in the red, green, and blue parts of the spectrum (Grant et al., 2023). Finally, a light model for the Barents Sea, based on radiative transfer theory, was validated to provide similar results as the ArcLight irradiance data (Connan-McGinty et al., 2022).

5. Human impacts

Anthropogenic climate change transforms Arctic ecosystems, but may also amplify other human impacts on the ecosystems. With a warmer climate, large parts of the Arctic previously covered by sea ice year-round are becoming increasingly accessible to humans. Together with technological developments, this increased accessibility opens the region to fisheries, petroleum activities, deep-sea mining, shipping, and tourism. The Arctic is also exposed to other human influences, including ocean acidification caused by anthropogenic CO₂ emissions, and local as well as long-distance transported pollutants, the effects of which may interact with the effects of climate change. Here we review the main human impacts on the ecosystem in the northern Barents Sea and adjacent slope areas of the Arctic Ocean.

5.1. Fisheries

5.1.1. Trends in fish abundance and fisheries

Arctic peoples depend on the ocean for the provision of food, and commercial fisheries constitute important parts of the (sub-)Arctic economy (Mikkelsen and Hoel, 2011). The term “fisheries” refers in this context to harvesting of living marine resources, both fish and crustaceans, such as shrimp and crabs, and marine mammals (seals and whales). The development of catches in the Barents Sea and along the Norwegian coast north of 62°N is relevant in this context, as the commercial species found in our focal area of the Barents Sea migrate over larger areas. Noteworthy is that commercial finfish fisheries, unlike crustacean fisheries, are essentially of boreal fishes (that partly expand into the Arctic) and not true Arctic-origin fishes. Catches in this area have shown considerable decadal-scale fluctuations during the last 50 years driven by a combination of climate and fishing (**Figure 12**). Harvest rates have decreased in the 2000s following the introduction of harvest-control rules for Atlantic cod, haddock and capelin (for cod, see, e.g., Kjesbu et al., 2014). The latest fishery to develop is that for the invasive snow crab, which started at a low level in 2013 but is currently between 15,000 and 20,000 tonnes annually. The snow crab is a benthic predator (Manushin et al., 2016) that can impact benthic prey (Jørgensen et al., 2015b), threaten

biodiversity (Hansen, 2016), and compete with other bottom-feeding species. Shrimp catches have also increased considerably from 2017 to 2019, but are still well below the recommended quota level in the 2010s. Polar cod has been fished commercially, mainly by Russia, with catches >100,000 tons in some years in the 1970s (Aune et al., 2021), although catches in the last decade have been very low.

Fish stocks in the Barents Sea have moved northwards and eastwards in recent years (e.g., Landa et al., 2014; Fosheim et al., 2015), causing increasing catches in the Svalbard fisheries protection zone (Misund et al., 2016), although the trend seems to have been halted and even slightly reversed recently (ICES, 2021a). Spawning areas of the commercial stocks have varied (e.g., Carscadden et al., 2013; Opdal and Jørgensen, 2015; Sundby, 2015; Langanen et al., 2018), but no new major spawning areas have been observed. The fisheries follow the fish to some extent, and increasing parts of the summer and autumn fisheries have taken place in northern and eastern parts of the Barents Sea in recent years. However, a large proportion of the catches of commercially important species such as cod and capelin are taken close to the spawning areas on the Norwegian coast in winter–early spring. The exclusive economic zones also affect the geographical distribution of the fisheries, as Russian fishers have allocated quotas in the Norwegian zone, where there are more large cod than in the Russian zone. Young fish that are below the minimum landing size are generally found farther east, which has probably limited eastwards movement of the fisheries.

5.1.2. Species interactions affecting fisheries

The Barents Sea is one of relatively few areas where ecosystem processes are included in tactical fisheries management (Skern-Mauritzen et al., 2015). Two of the dominant species in the fisheries are capelin and cod, with capelin being a major prey of cod. When the annual fishing quota for capelin is set by the Joint Norwegian–Russian Fisheries Commission, capelin consumption by cod is considered in order to reduce the risk of capelin-stock decline and adverse feeding conditions for cod. However, the capelin stock fluctuates and has collapsed 4 times during the last 4 decades. The first three collapses were likely driven by recruitment failure mainly caused by predation from young herring (*Clupea harengus*) on capelin larvae (Gjøsaeter et al., 2016). During each of these collapses, the fishery was closed for a period of 4–5 years. The reason for the fourth, minor collapse, which caused the fishery to be closed in 2016–2017, is uncertain, but is possibly linked to high predation from cod. The capelin fishery was reopened in 2018 and closed again in 2019–2021, but was opened again in 2022 (ICES, 2020b). To sustainably manage the fisheries on the tightly interlinked fish populations in the Barents Sea, a better understanding is needed on how fishing, in combination with climate, affects the target species as well as their predators, competitors and prey. Other harvesting strategies including species at lower trophic levels that are not commercially exploited today may increase the total yield substantially, with limited impacts on fish stocks (Nilsen et al., 2020).

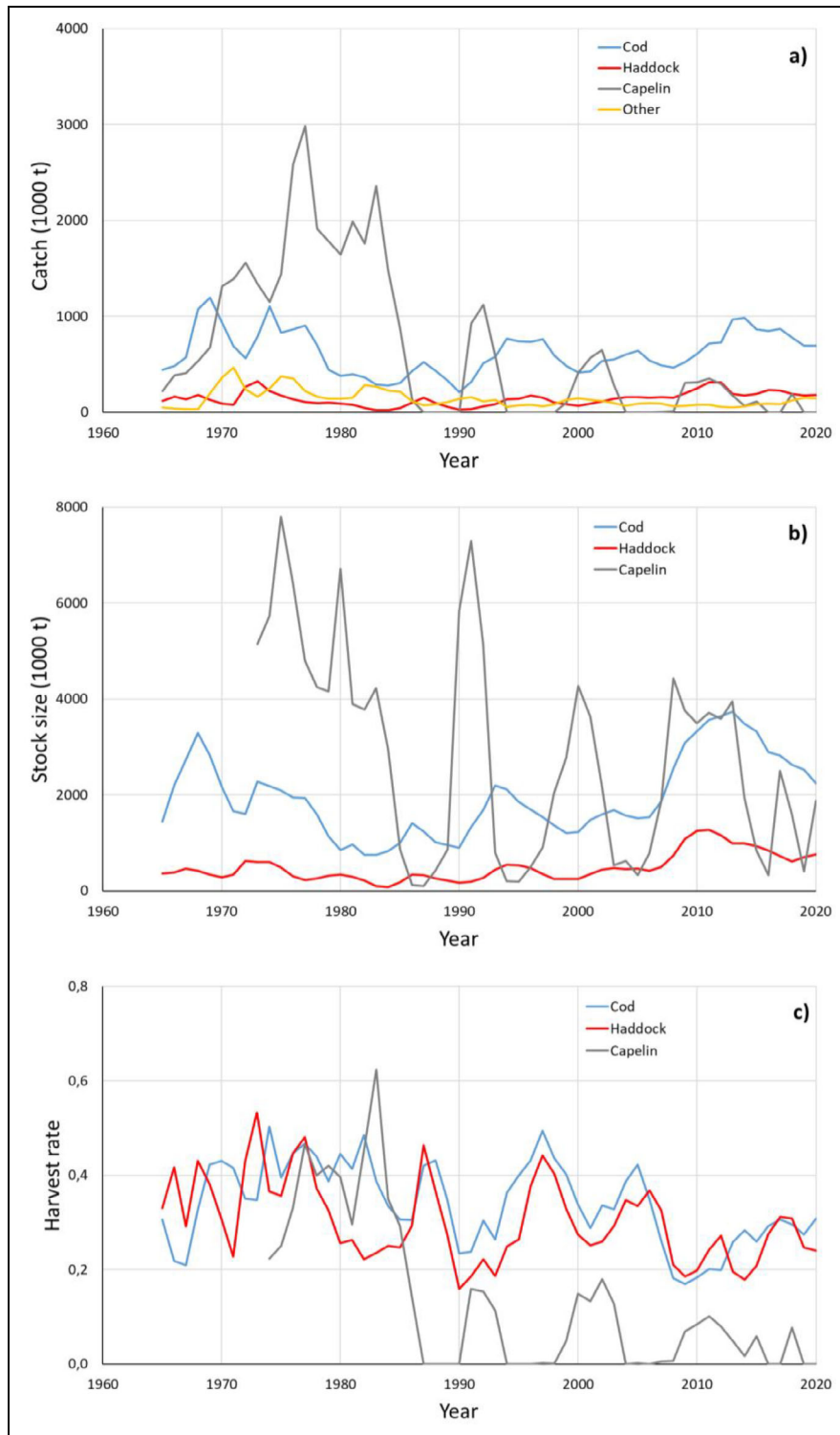


Figure 12. Time series of catch, stock size, and harvest rate for main Barents Sea fish stocks. Time series of (a) catch, (b) stock size, and (c) and harvest rate (catch divided by stock) for the three main fish stocks in the Barents Sea, cod, capelin and haddock, for the period 1965–2020. Catches of four other important stocks combined (redfish, Greenland halibut, polar cod and shrimp) are also shown. In total, these seven stocks account for more than 95% of the catches in the Barents Sea.

5.1.3. Effects of trawling on Barents Sea benthic habitats

Declines in biomass have been recorded for benthic megafauna from untrawled to trawled areas, suggesting that trawling affects the biomass of most respective species negatively (Jørgensen et al., 2015a). Detrimental

effects of trawling were inferred from negative relationships of bottom trawling intensity with densities of most common epibenthic species in the Barents Sea (Buhl-Mortensen et al., 2016) and epibenthic species richness and from altered epibenthic community composition (Kędra et al., 2017).

Bottom habitats in Norwegian waters are protected against trawling through a host of measures, e.g., a ban on trawling at depths >1000 m, and 12 nautical mile reserves around most of the Svalbard archipelago (Jørgensen et al., 2020). Pelagic trawling for cod was banned in the 1970s, as such catches often comprised large numbers of undersized fish or damaged fish. The most recent preliminary closures to trawl fisheries in the Northern Barents Sea, covering an area of 442,022 km², entered into force in 2019 and are based on detailed seafloor surveys over a decade (Jørgensen et al., 2020). However, new technological developments with better size selectivity of the trawls may make it feasible to re-introduce pelagic trawling for cod.

5.2. Pollution

5.2.1. Why pollution in the Arctic?

Despite the long distance from the primary sources of anthropogenic contaminants, pollutants have been present in the Arctic for decades, with the initial discovery of organic hazardous substances in seabirds and mammals in the early 1970s (AMAP, 1998). In addition to long-range transport, sources of current and increasing local pollution within the Arctic have been identified (AMAP, 2017b) due to increased human activity (AMAP, 2017a). Despite global bans and the phasing out of many compounds, legacy pollutants such as polychlorinated biphenyls (PCBs) still dominate in Arctic wildlife (Dietz et al., 2015). Another recent challenge is marine litter, mainly plastics, which are observed in both surface and deeper waters of the Barents Sea (Cózar, et al., 2017; Grøsvik et al., 2018; von Friesen et al., 2020). Although the focus on global occurrence of microplastics is increasing (e.g., Barnes et al., 2009), there is still sparse information on the presence of microplastics in the Arctic and its biota (e.g., Lusher et al., 2015; Grøsvik et al., 2018; Hallanger and Gabrielsen, 2018; Yakushev et al., 2021; Bergmann et al., 2022), and even less on potential biological effects of microplastics.

5.2.2. Accumulation and effects of pollution

High latitude ecosystems are adapted to a high dependency on lipids as an energy source in periods of low food availability (Conover and Huntley, 1991; Falk-Petersen et al., 2007). Lipids are important with respect to contaminants, as many of the contaminants in question are highly organic and lipophilic. Lipids are thus important as a biological “sink” of contaminants in organisms, and also as a source, as mobilization of lipids results in a remobilization of contaminants to the blood stream making them available to reach target organs susceptible to their effects (Bustnes et al., 2010). Lipids are also important in the generational transfer of energy (and contaminants) from mother to offspring (Borgå et al., 2004). Lipid-associated contaminants, such as PCBs, are more efficiently transferred maternally than protein-associated substances like per- and polyfluoroalkyl substances (PFAS) and heavy metals such as mercury (Hitchcock et al., 2017). Seasonality of bioaccumulation and food-web magnification of contaminants in the Arctic pelagic marine ecosystem have been observed in coastal fjord systems (Hargrave et al., 2000;

Hallanger et al., 2011), but information from the shelf seas is still sparse. For the southern Barents Sea, the seasonal bioaccumulation has been modelled (De Laender et al., 2010) and to some extent validated, showing lower bioaccumulation factors for cod, capelin and herring in summer compared with other seasons. The coverage of contaminants in the seawater reported through the European Union Water framework directive and the Marine Strategy Framework Directive is poor for the Barents Sea, whereas the data status is moderate to good for selected biota (European Environment Agency, 2018). There, samples of selected fish species and benthos were collected tri-annually for monitoring of pollutant levels in biota (e.g., McBride et al., 2016; van der Meeren and Prozorkevich, 2019). In addition, polar bears (*Ursus maritimus*) and selected other species are studied either annually or more sporadically (e.g., Lucia et al., 2017; Routti et al., 2018; Tartu et al., 2018; Lippold et al., 2019; Blévin et al., 2020), whereas comprehensive studies of pollutant movement through the Barents Sea food web, from zooplankton through fish to seabirds and marine mammals, have been scarce during the past two decades (e.g., Borgå et al., 2001; Borgå et al., 2004; Haukås et al., 2007).

5.2.3. Responses to oil components exposed via food and water

The development of early life stages of Arctic calanoid copepods is affected by oil components such as polycyclic aromatic hydrocarbons (PAH), whereas adults showed no physiological effects (Toxværd et al., 2018a). Other studies of different copepod endpoints, however, show reduced feeding and reduced winter survival and lipid mobilization (e.g., Norregaard et al., 2014; Toxværd et al., 2018b, 2019). The polar cod have been exposed experimentally to oil contaminants in both food and water and have shown enzymatic effects and genotoxicity even at low PAH concentrations (<15 µg L⁻¹; Nahrgang et al., 2010a). Nahrgang et al. (2019) also found a negative impact of crude oil exposure on growth performance of adult polar cod with low condition in the early spring. Oil-contaminated food reduces growth rates and energy reserves, whereas oil in water can depress their metabolism (Christiansen and George, 1995; Christiansen et al., 2010; Nahrgang et al., 2010a; Nahrgang et al., 2010b; Nahrgang et al., 2019). However, the most severe effects on growth and survival of polar cod are on their larval stages (Bender, 2020; Bender et al., 2021).

5.2.4. Multiple drivers and stressors—The interaction

A major challenge in describing current change or projecting future ecosystem state is that multiple drivers interact with each other (Carlsson et al., 2016; Tartu et al., 2017), as well as with the diverse array of contaminants present in the system. Organisms are exposed simultaneously to a wide variety of varying drivers, which singly or in combination can be stressors. Multiple stressors can interact in a variety of manners: they can cancel each other out (antagonistic), show a combined effect (additive) or reinforce each other (synergistic). In calanoid copepods, the combined effects of increased temperature and pyrene

concentration were species-dependent (Hjort and Nielsen, 2011), illustrating the complexity of stressor interactions. In combination with other stressors and drivers, the potential population effect of contaminants is predicted to be more severe than exposure to each stressor separately (Bustnes et al., 2015; Bårdsen et al., 2018). Climate change is expected to cause alterations in bioaccumulation of organic contaminants in Arctic marine food webs (Borgå et al., 2010). Growth rates of phytoplankton can be affected by multiple drivers, as experiments studying interaction of $p\text{CO}_2$ with temperature, light and nutrients have shown (Seifert et al., 2020).

5.3. Effects of ocean acidification

As mentioned above, increased sea ice and glacial meltwater cause freshening of surface and coastal waters, leading to increased ocean acidification (Chierici and Fransson, 2009; see also Section 3). The Arctic Ocean is already undersaturated with regard to aragonite in shelf regions influenced by freshwater (Chierici and Fransson, 2009).

Ocean acidification has negative effects on egg production, growth, ingestion, metabolic expenses, and larval development of numerous invertebrate species, including the Arctic copepod *Calanus glacialis* (e.g., Thor et al., 2018) and the cold-water pteropod *Limacina helicina* (Lischka et al., 2011; Manno et al., 2017). Some studies have suggested that populations or certain life stages of, e.g., copepods and cold-water corals are sensitive to ocean acidification (e.g., Weydmann et al., 2012; Lewis et al., 2013). However, there are also some indications that Arctic copepods may be robust against ocean acidification (Bailey et al., 2017) and that organisms that are adapted to variable environmental conditions will be able to counter future changes (Reusch, 2014), as exemplified by Arctic phytoplankton and ice algae (Torstensson et al., 2021). Even though teleost fishes are generally resilient against ocean acidification (Pörtner, 2008; Melzner et al., 2009a; Melzner et al., 2009b), eggs and early life stages tend to be more sensitive to changes in environmental CO_2 levels (Frommel et al., 2012; Stiasny et al., 2016). Fish populations within the Arctic ecosystem may also be affected by ocean acidification through indirect effects via their invertebrate prey. Experiments on ocean acidification and warming on Atlantic cod and polar cod have shown that changes in temperature have an overriding effect, and thus, the combined effect of future changes in these factors in the Barents Sea may be positive for boreal species and negative for Arctic species (Kunz et al., 2016).

5.4. Other human impacts

Since 2010, petroleum activities, shipping, and aquaculture have increased with potential effects on the wildlife (ICES, 2017, 2020a). Transported oil and gas volumes are also expected to increase along with traffic along the Northern Sea Route (Skjoldal et al., 2013; Henderson and Loe, 2014).

Environmental risks have been evaluated to manage the potential for harmful effects of maritime activities (Hauge et al., 2014; Bambulyak et al., 2015). Increased seismic investigations and sound from ship engines and

thrusters are expected to increase the under-water noise level (e.g., Stanley et al., 2017).

Tourism to the Arctic has increased during the recent decade (Stephen, 2018; Runge et al., 2020), and the accessibility and scenery of the Barents Sea marginal ice zone represent a potential for increasing tourism activity. However, overcrowding (Bystrowska, 2019) and climate change that alters the expected tourist experiences (Kaján, 2014; Nicholls and Amelung, 2015; Bystrowska, 2019) may become negative for tourism over time.

Noise levels in the sea may have negative impacts on the communication between conspecifics, as well as navigation for fish and marine mammal stocks (e.g., Stanley et al., 2017). While several ice-associated whale species are increasing (Vacquié-Garcia et al., 2017), many seabird populations are in decline (Anker-Nilssen et al., 2017). Although food limitation and predators are natural stressors for seabirds (Fredriksen et al., 2013), they are also vulnerable to oil spills (Haney et al., 2017). However, attribution of population declines to specific stressors is not straightforward.

6. Discussion: Is the Barents Sea becoming less "Arctic"?

Although marine ecosystems throughout the world are structured and function based on similar physical, biogeochemical, and ecological principles, there are, arguably, characteristics of a system that make it "Arctic". Extreme seasonality in solar radiation, low air and sea temperatures, seasonal or persistent sea-ice cover, and water column stratification determined largely by salinity differences are examples of characteristics that alone and in combination describe Arctic marine systems. These physical factors strongly influence ecosystem processes ranging from atmospheric fallout of contaminants and CO_2 flux between the atmosphere and ocean to timing and intensity of primary production, the biological carbon pump, and composition of seasonal and resident biological communities.

Ecological factors that are enhanced in Arctic systems include relatively few species compared with temperate and tropical regions, the elevated importance of lipid-driven food webs, and generally low levels of human impact (disturbance, contamination, species introductions). Biomes unique to polar ecosystems, such as sea-ice communities, and the extensive seasonal feeding and breeding migrations of fish, birds, and marine mammals to the region also can define marine systems as Arctic.

Clearly this list is not exhaustive, but the combined impacts of these physical, biogeochemical, and ecological characteristics produce much of what makes a marine ecosystem Arctic. We use this list to evaluate whether the Barents Sea is still of Arctic nature after the recent and rapid climate change we have observed over the past 3–4 decades, and to what extent the Arctic status of the region may change in the next decades.

6.1. Still Arctic?

Despite its location well above the Arctic Circle, guaranteeing high-Arctic seasonality in solar radiation, the

southern Barents Sea can be described as more of a boreal ecosystem. Lack of sea ice and a strong influence of Atlantic Water lead to thermally regulated stratification. Primary productivity is generally high, and wind-driven mixing can produce secondary blooms in autumn (Ardyna et al., 2014). Further, most of the fish (Fossheim et al., 2015) and benthic (Cochrane et al., 2009; Jørgensen et al., 2015a) communities have boreal affinities, and zooplankton communities are increasingly dominated (in biomass) by boreal copepods (*Calanus finmarchicus*), krill (*Thysanoessa inermis* and *Meganyctyphanes norvegica*), and jellies (*Cyanea capillata*; Orlova et al., 2015; Eriksen, 2016; Aarflot et al., 2017). Atlantification of the southern Barents Sea in terms of physical, biogeochemical, and ecological parameters is in an advanced state (Ingvaldsen et al., 2021). In addition, this southern region of the Barents Sea is the most impacted by human activities such as trawling, shipping and petroleum production, although there have been few documented pollution events. Thus, the southern Barents Sea lacks many of the characteristics by which we define marine ecosystems as Arctic.

We argue, however, that despite some trends associated with climatic change, the northern Barents Sea ecosystem should still be classified as “Arctic”. Sections 2–4 provide considerable detail on the individual components and their current status, but here we highlight evidence from integrated impacts on ecosystem structure and function.

The northern Barents Sea is warming and exhibiting loss of winter sea ice (e.g., Årthun et al., 2012). Less ice throughout the Arctic has led to greater ice mobility such that ice imported to the northern Barents Sea from the Laptev Sea is the largest driver of interannual variability in sea ice (Ingvaldsen et al., 2021). So, whereas sea ice is now thinner, more mobile, and present for a shorter period of the year, it is still sufficient to support sea-ice biota, including ice-algal production. Ice melt dominates water column stratification, and the mixed-layer depth has increased (Oziel et al., 2017). Primary productivity exhibits high interannual variability both in quantity and timing due to the variability in ice cover and timing of melt (Kohlbach et al., 2023). Thus, despite trends in some physical drivers, processes behind bloom initiation remain “Arctic”.

The pelagic food web of the northern Barents Sea remains dominated in biomass by the high lipid-content copepod *Calanus glacialis*, which continues to have seasonal vertical migrations to surface waters during phytoplankton bloom periods. Copepods concentrate energy produced by microalgae and make it available to lipid-rich fish such as capelin and polar cod, thus playing a key role in nutrition of resident and seasonally migrating fish, seabirds, and marine mammals. In some years, boreal fish appear to displace Arctic species in the northeastern Barents Sea (Fossheim et al., 2015), but there is considerable annual variation in this potential trend (Frainer et al., 2017). Food-web structure has been resilient to both heavy fishing pressure and climatic change, and the role of krill in energy transfer has increased since the early 2000s (Pedersen et al., 2021). Although poorly constrained, there is no evidence for significant changes in the biological carbon pump or vertical flux patterns of the

northern Barents Sea (Dybwad et al., 2022). These processes are tightly linked to potential changes in CO₂ uptake and carbon subsidies to benthic communities in the region.

Thus, despite the Barents Sea undergoing significant changes in sea-ice cover and both atmospheric and water temperatures, it appears to remain Arctic in structure and functioning. Indeed, a recent analysis indicated weak evidence for change in the northern Barents Sea relative to baseline levels in a variety of parameters ranging from temperature to distribution of biomass across trophic levels (Siwertsson et al., 2023). Current trajectories and recent model results, however, suggest that this region may soon function differently than it currently does: its Arctic status may be changing.

6.2. Beyond 2030: A New Arctic

The Barents Sea is warming and will continue to do so in the future (Årthun et al., 2019; Drinkwater et al., 2021; Shu et al., 2021). The volume of the AW inflow is predicted to become somewhat reduced, but with increased overall heat transport (Årthun et al., 2019). This future increase in Atlantic heat transport is reflected in a northward penetration of warm water into the Arctic Ocean (Dörr et al., 2021). Although pronounced internal climate variability (Årthun et al., 2019; Olonscheck et al., 2019; Dörr et al., 2021; Madonna and Sandø, 2021; Rieke et al., 2023) leads to large uncertainty in future projections of temperature and sea-ice cover (Bonan et al., 2021), some modelling studies show absence of winter sea-ice cover in the Barents region by 2050 (Onarheim and Årthun, 2017; Rieke et al., 2023). Regarding biogeochemistry, models indicate that aragonite will reach undersaturation during parts of the year in the bottom waters on the continental shelf in the northern Barents Sea already by 2030 (Popova et al., 2014; Wallhead et al., 2017), and future scenarios suggest a drop of up to 0.35 units in the surface pH by 2065 (Skogen et al., 2014). In the worst case all waters will be undersaturated with respect to aragonite (Fransner et al., 2022). This process is ongoing, and despite inherent inertia in the ecological system, an expectation that the northern Barents Sea will become less Arctic as its main physical and biogeochemical drivers change is reasonable.

Recent studies show that the northern Barents Sea acts as a net sink for atmospheric CO₂ and that the main seasonal drivers are meltwater inputs and biological CO₂ uptake during photosynthesis (Jones et al., 2023). Long-term *f*CO₂ trend estimates showed a rapid rise of *f*CO₂ in the surface waters in the Barents Sea and north and east of Svalbard of 4.2–5.5 $\mu\text{atm year}^{-1}$ over the winter to summer seasons (Ericson et al., 2023). This rise is twice as fast as the atmospheric CO₂-increase rate in the period 1997 to 2020 and coincided with the area of largest sea-ice loss (more open areas; Ericson et al., 2023). Fransson et al. (2017) also found substantial ocean-CO₂ uptake in leads and openings during winter. Consequently, with expanding open areas and continued sea-ice loss, the Barents Sea will likely become an even stronger CO₂ sink in the future, where the largest change will likely be during winter and in the seasonally ice-covered area. A stronger CO₂ sink will

speed up ocean acidification in this area. As this area still has large data gaps especially in winter and spring, the $f\text{CO}_2$ measurements in this period are crucial to make estimates of the ongoing trend and future effect of increasing $f\text{CO}_2$ in the water column.

Thinner ice cover and earlier sea-ice retreat in the Barents Sea will lead to a shift in the timing of the ice-algal bloom, or its disappearance altogether, and likely result in an earlier phytoplankton bloom (Wassmann and Reigstad, 2011; Ji et al., 2013; Ardyna and Arrigo, 2020). In recent years, the highest increase in primary production has occurred in the northern Barents Sea in today's marginal ice zone (Wassmann and Reigstad, 2011; Renaud et al., 2018; Dalpadado et al., 2020). There is considerable uncertainty in modelling studies as to whether primary production will increase, decrease, or remain the same in the next 30–80 years (Slagstad et al., 2011; Skaret et al., 2014; Sandø et al., 2021). This uncertainty in future primary production is important to resolve as, together with bloom timing, it can have consequences for secondary production and vertical flux (Wexels Riser et al., 2007; Søreide et al., 2010; Varpe, 2012) in the region. One predicted result of global climate change is an increase in pelagic bacterial abundance (Sarmiento et al., 2010). Changes in bacterial communities can be expected to alter both viral abundance and diversity, with effects on the overall carbon and nutrient flow in the system (Sandaa et al., 2017; Tsagaraki et al., 2018). Thus, the manifold changes in the pelagic ecosystem caused by warming and ice loss can reduce the efficiency of the biological carbon pump, thought to be quite strong in the northern Barents Sea now (e.g., Reigstad et al., 2011; Buesseler et al., 2020).

Future warming may cause the Arctic copepod *Calanus glacialis* to be displaced from the northern Barents Sea shelf to the continental slopes and basins of the Arctic Ocean (Slagstad et al., 2011; Ershova et al., 2021), while the boreal *C. finmarchicus* will expand into the northern Barents Sea (Slagstad et al., 2011) and into the Arctic Ocean (Wassmann et al., 2015; Tarling et al., 2022). Replacement of Arctic with boreal zooplankton species on the Barents Sea shelf may cause structural and functional changes in the marine food web (Gluchowska et al., 2017), partly because the boreal species are generally smaller and less lipid-rich than the Arctic congeners (Falk-Petersen et al., 2009). This difference impacts plankton-eating fishes and seabirds that selectively consume the larger zooplankton to build seasonal lipid reserves (Wold et al., 2011). Because lipids are rapidly transferred up the food web, changes in the energy flow can have negative consequences for marine mammals and seabirds that rely on lipid stores for insulation, maintenance energy, and reproduction (Falk-Petersen et al., 2007; Wold et al., 2011; Hovinen et al., 2014b; Haug et al., 2017b). However, these consequences may be compensated by more efficient transfer of energy from primary producers to higher predators because of shorter generation time and higher population turnover rate for zooplankton in a warmer Arctic (Renaud et al., 2018).

Reorganization of regional biodiversity is expected throughout the food web. Warming bottom waters and

potentially altered food supplies increasingly may allow more boreal benthic invertebrate taxa to become established in both the southern and northern Barents Sea (Renaud et al., 2015). Similarly, the rapid addition of boreal species will increase the biodiversity of fishes in the northern Barents Sea initially, but this phase is likely transitory and may be followed by a decline driven by Arctic species loss (Pecuchet et al., 2020; Frainer et al., 2021). Fish stocks predicted to do poorly include polar cod, along with a number of non-commercial Arctic fish stocks already challenged by predation and competition from expanding boreal species (Fossheim et al., 2015; Kjesbu et al., 2021). Predictability of rate and direction of change is indeed challenged by the pulsed character of warming, including heat waves, triggering sudden bursts of ecological responses (Husson et al., 2022).

Future fisheries are expected to approximately average harvesting levels in the last decade, as most commercial species are harvested close to sustainable levels. Climate warming will determine the future spread of the snow crab in the Barents Sea (Pavlov and Sokolov, 2003; Bakanev, 2015), and the snow crab fishery is expected to expand into the areas around Svalbard (Hansen, 2016). Increased warming may increase the spreading of the Kamchatka red king crab (*Paralithodes camtschaticus*) northwards in the Barents Sea from its current distribution near the Norwegian-Russian mainland coasts (Christiansen et al., 2015). Some commercial species such as cod and haddock are unlikely to expand in distribution beyond the continental shelf break (Ingvaldsen et al., 2017), while others, such as capelin, redfish and Greenland halibut may be less restricted (Hollowed et al., 2013a; Hollowed et al., 2013b). Continued northward expansion of mackerel into the southern Barents Sea in summer (Nottestad et al., 2016; Haug et al., 2017a) could lead to development of a regional fishery for this species as recently observed in Icelandic and Greenlandic waters, but the consequence of large mackerel stocks on food-web interactions is unexplored.

Current northward range expansions by boreal marine mammals will likely lead to increased competition with endemic Arctic species, as well as putting these Arctic species at greater risk of predation, disease, and parasite infections (Moore and Huntington, 2008; Kovacs et al., 2011; Skern-Mauritzen et al., 2011; Laidre et al., 2015; Haug et al., 2017a; Vacquié-Garcia et al., 2017; Hamilton et al., 2019; Moore et al., 2019). Competition for food with the currently large Atlantic cod stock may also affect body conditions of marine mammals (Øigård et al., 2013; Bogstad et al., 2015; Solvang et al., 2021). Loss of sea ice is already affecting species such as white whales and ringed seals (Kovacs et al., 2011; Stenson et al., 2020), and ice retraction from the shallow (100–350 m) shelf to the deep polar basin reduces access to bottom-associated prey species for harp seals (Haug et al., 2021) and walrus. In the longer term, foraging success, fertility rates, mortality rates and pup survival can be expected to be impacted for several populations of endemic Arctic marine mammals (Laidre et al., 2008; Kovacs et al., 2011; Hamilton et al., 2015).

Continuing warming and sea-ice loss in the northern Barents Sea will likely result in weaker pelagic-benthic coupling and higher retention in a more complex pelagic food web (Wassmann et al., 2006). Thus, the food supply to the benthos is expected to be reduced, particularly during late spring and early summer when ice algae usually constitute a high-quality food source (Tamelander et al., 2006). A relative increase in importance of advected sources of carbon has been suggested (Hunt et al., 2016; Vernet et al., 2019). Current climatic trends also suggest a distinct decline of benthic secondary production in the northeastern Barents Sea in the future (Degen et al., 2016), and possibly reduced carbon sequestration at the seafloor, which is currently thought to be higher in the sea-ice-covered region (Faust et al., 2020). However, findings of *increased* pelagic-benthic coupling during a period of sea-ice decline in Baffin Bay (Olivier et al., 2020) suggest that even the direction in which pelagic-benthic coupling may develop is unclear. Resolving these uncertainties is important, as the role of the Barents Sea seafloor for both nutrient cycling and carbon sequestration is thought to have been underestimated (März et al., 2022), and this role has bearing on whether the region will be a net source or sink of atmospheric CO₂.

Fundamental changes in seasonality, biogeochemical cycling, metabolic rates and partitioning of productivity are expected to occur in the northern part of the Barents Sea as warming continues (Reigstad et al., 2011; Holding et al., 2015; Tremblay et al., 2015; Mesa et al., 2017). These changes, combined with altered species distributions, will likely alter ecosystem vulnerability as indicated by studies of functional diversity, redundancy and food-web modularity (Wiedmann et al., 2014; Kortsch et al., 2015; Pécuchet et al., 2020). Taken together, current understanding suggests that the northern Barents Sea in a few decades will no longer be fully “Arctic”. Instead, a “New Arctic” ecosystem, one with Arctic light and stratification regimes, but mixed boreal and Arctic species pools, lack of sea-ice algae, and (potentially) strongly altered biological carbon pump, will characterize the region.

7. Conclusions: Management, knowledge gaps, and outlook

An ecosystem in transition presents many challenges for management of harvestable resources, as well as the ecosystem as a whole. Continued ocean warming will most likely lead to fisheries expanding further northwards and to increases in the length of the fishing season due to broader stock distributions and increased access (Stocker et al., 2020). Changes in the location of spawning areas may require longer feeding migrations for some species like capelin (Huse and Ellingsen, 2008). Shifts in spawning locations from one jurisdiction to another, e.g., like a shift in cod spawning site locations from the Lofoten Islands and into the Barents Sea as far east as Murmansk by the 2070s (Sandø et al., 2020), present fisheries-management challenges as well as regional and international governance issues.

A framework for managing the marine ecosystem and all human activities (oil and gas industry, fishing and

shipping) in the Norwegian sector of the Barents Sea has been formalized in the form of an integrated management plan, issued by the Norwegian government in 2006 and updated several times since then (Olsen et al., 2007; KLD, 2020). Following new CMIP6 projections and regardless of emission scenario, the summer sea ice will be lost in all the Arctic shelf seas within several decades. However, the Barents Sea is the only Arctic shelf sea for which ice-free conditions in winter are projected before the end of this century (Årthun et al., 2021). Changes discussed in this review, hence, have substantial implications for human activity. One consequence is that new management measures for commercial fisheries have now been developed (Jørgensen et al., 2020), paying attention specifically to changes related to global warming. Human activity, in turn, will continue to affect the biological and physical systems of the Barents Sea. Longer ice-free seasons and easier accessibility increase the importance of research, monitoring, observing systems and environmental management to secure sustainable resource use. Furthermore, addressing ecological surprises, i.e., low-probability but high-impact events, when addressing future changes can increase readiness, such that managers can respond to limit the impact of potential disruptions (Mueter et al., 2021).

Whereas management systems are already in place and well developed, we lack the knowledge needed to reduce uncertainty in projections for the future state of the Barents Sea. Many specific knowledge gaps have been detailed in the text above, but generally these gaps include themes like: (i) understanding of the coupling between atmosphere, sea ice and ocean to identify drivers impacting the sea-ice zone; (ii) improved understanding of the coupling processes between the physical and biological systems; and (iii) improved models of the Polar Front zone and the seasonal ice zone of the Barents Sea (Faglig forum for norske havområder, 2019). Regional monitoring and research have become and will need increasingly to become integral parts of pan-Arctic observation and forecast systems (e.g., Lee et al., 2019), and climate and ecosystem models that integrate new data in near-real time need to be improved.

One area that offers hope for rapidly filling knowledge gaps is the recent development of new instrument-carrying platforms (remotely operated vehicles, autonomous underwater vehicles, unmanned surface vehicles, drones, buoys and satellites) and improved physical and biological sensors (temperature/salinity, acoustic, optical, and turbulence; e.g., Engelsen et al., 2002, 2004; Fossum et al., 2018; Johnsen et al., 2018; Ludvigsen et al., 2018; Kolås et al., 2022). Such instrument-carrying robots can provide high-resolution data in time and space, filling observational gaps and adding to ongoing long-term monitoring (e.g., Arneberg et al., 2020). New satellite-based sensors can help to fill in information on sea-ice thickness and volume changes where no in situ observations exist, e.g., the coming Copernicus Polar Ice and Snow Topography Altimeter CRISTAL (Kern et al., 2020). Ice-tethered platforms allow in situ long-term observations from within the ice-covered habitat, providing much needed

data that help close seasonal and spatial gaps where there is still hesitation to deploy mobile advanced technology under sea ice (Berge et al., 2016). These new tools can complement existing instrumentation to improve sampling on finer scales, at times and in places where human-based sampling is challenging (under ice, polar night), and contextualize data by combining sensors and sampling scales.

This review of recent scientific results from the Barents Sea shows that the physical, biogeochemical, and ecological systems have changed over the past two decades. Scientists are challenged not only to quantify the changes, but also to identify new processes and scenarios that have not been observed in this region earlier. Our review shows that substantial advances in understanding status, trends, processes, and inherent system linkages have been achieved in the past decades as a result of large and small-scale research efforts from multiple nations, individually and collaboratively. However, some challenges and gaps in knowledge and observations remain. Among those gaps are few in situ data from winter (e.g., Berge et al., 2020) and early spring, as is also the case on a pan-Arctic scale (Gerland et al., 2019). A second gap is the lack of high-resolution spatial information from both observations and model outputs, in both lateral and vertical dimensions. Finally, the Barents Sea cannot be viewed in isolation from the rest of the Arctic (e.g., Carmack and Wassmann, 2006; Burgass et al., 2019). Attempts to view the region in a larger conceptual context have begun (Wassmann et al., 2020), and comparative studies, both in terms of physical processes (atmosphere-ice-ocean interaction; Graham et al., 2017) and ecosystem properties (e.g., Hunt et al., 2013; CAFF, 2017; Ardyna and Arrigo, 2020; Nöthig et al., 2020), have yielded significant insights into different modes of ecosystem functioning. Results of recent observational and experimental studies in the northern Barents Sea (The Nansen Legacy) and the wider Arctic (Distributed Biological Observatory, e.g., Grebmeier et al., 2019; Multidisciplinary drifting Observatory for the Study of Arctic Climate: MOSAiC, e.g., Nicolaus et al., 2022) have come far to connect findings from different regions of the Arctic. If we can further integrate knowledge from across the pan-Arctic and fill the knowledge and technological gaps presented here, we will be in a good position to face the challenges for understanding and managing the marine ecosystem of the New Arctic.

Data accessibility statement

All data plotted in this manuscript are publicly available from online repositories, such as through the Norwegian Marine Data Centre (NMDC; nmhc.no) or the Norwegian Polar Data Centre (data.npolar.no of the Norwegian Polar Institute). Ocean temperatures shown in **Figures 4** and **5** are based on CTD observations from annual joint Institute of Marine Research (IMR)–Polar branch of the FSBSI “VNIRO” (PINRO) surveys covering the entire Barents Sea in August–October (data available at <https://doi.org/10.21335/NMDC-290836407>). Barents Sea ecosystem time series shown in **Figures 10** and **11** are based on observations from the same surveys (data available at <https://doi.org/10.21335/NMDC-2002594157> and <https://doi.org/10.21335/NMDC-1069717541>).

Ocean temperatures shown in **Figure 6** originate from CTD observations from the Vardø-N section sampled annually by IMR in September (data available at <https://doi.org/10.21335/NMDC-290836407>). The atmospheric data in **Figure 4** are based on the ERA5 analysis (data are available from the Copernicus Climate Change Service (C3 S) Climate Data Store (<https://cds.climate.copernicus.eu/>)). Monthly means of sea-ice concentration data used in **Figures 2** and **7** were retrieved from the National Snow and Ice Data Center in Boulder, CO, USA. Data on nitrate, phosphate, silicic acid, and total dissolved inorganic carbon, and total alkalinity (**Figure 8**), originate from the Fram Centre Arctic Ocean flagship project “A-TWAIN” (<https://www.npolar.no/prosjekter/a-twain/>) expeditions in September 2012, and from the IMR repeated hydrography section Vardø-N in September 2012. Time series of catch, stock size and harvest rate shown in **Figure 12** were taken from the ICES Arctic Fisheries Working Group (data available at <https://doi.org/10.21335/NMDC-416643420>).

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Competing interest

All authors declare that they have no competing interests.

Author contributions

Contributed to conception and design: SG, BJB, MC, HH, RBI, MR, LHS, LCS, AS, TE.

Contributed to acquisition of data: n/a (review article).

Contributed to analysis and interpretation of data: All authors.

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