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REVIEW

Polar oceans and sea ice in a changing climate

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Polar oceans and sea ice cover 15% of the Earth's ocean surface, and the environment is changing rapidly at both poles. Improving knowledge on the interactions between the atmospheric and oceanic realms in the polar regions, a Surface Ocean–Lower Atmosphere Study (SOLAS) project key focus, is essential to understanding the Earth system in the context of climate change. However, our ability to monitor the pace and magnitude of changes in the polar regions and evaluate their impacts for the rest of the globe is limited by both remoteness and sea-ice coverage. Sea ice not only supports biological activity and mediates gas and aerosol exchange but can also hinder some in-situ and remote sensing observations. While satellite remote sensing provides the baseline climate record for sea-ice properties and extent, these techniques cannot provide key variables within and below sea ice. Recent robotics, modeling, and in-situ measurement advances have opened new possibilities for understanding the ocean–sea ice–atmosphere system, but critical knowledge gaps remain. Seasonal and long-term observations are clearly lacking across all variables and phases. Observational and modeling efforts across the sea-ice, ocean, and atmospheric domains must be better linked to achieve a system-level understanding of polar ocean and sea-ice environments. As polar oceans are warming and sea ice is becoming thinner and more ephemeral than before, dramatic changes over a suite of physicochemical and biogeochemical processes are expected, if not already underway. These changes in sea-ice and ocean conditions will affect atmospheric processes by modifying the production of aerosols, aerosol precursors, reactive halogens and oxidants, and the exchange of greenhouse gases. Quantifying which processes will be enhanced or reduced by climate change calls for tailored monitoring programs for high-latitude ocean environments. Open questions in this coupled system will be best resolved by leveraging ongoing international and multidisciplinary programs, such as efforts led by SOLAS, to link research across the ocean–sea ice–atmosphere interface.

Keywords: Arctic Ocean, Southern Ocean, Atmosphere, Sea ice, Ocean

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1. Introduction

Both polar regions in the north and south share the features of remoteness and sea-ice coverage; however, their atmospheric and hydrographic features differ in key ways. Firstly, the Antarctic is a continent surrounded by an ocean and the Arctic is an ocean surrounded by land. Shelf seas comprise one-third of the Arctic Ocean, with a maximum depth of 5,500 m, whereas the Antarctic continental shelf is relatively narrow and the Southern Ocean reaches up to 7,200 m depth. As a result, Arctic sea ice is more closely linked to the benthic environment than in the Antarctic (e.g., Thomas, 2017). Secondly, differences in seasonality and formation processes lead to key contrasts between Arctic and Antarctic sea-ice age, thickness, surface, and internal properties. Finally, the Antarctic Circumpolar Current isolates Antarctic waters from mid-latitudes, while the atmosphere is isolated from anthropogenic pollution sources and thus represents the closest analog to preindustrial conditions (Hamilton et al., 2014). In contrast, ocean currents and synoptic weather patterns penetrate far north into the Arctic, resulting in seasonal and episodic impacts of both anthropogenic pollution and natural emissions from lower latitudes (Willis et al., 2018; Schmale et al., 2021; Boyer et al., 2023). These differences lead to a divergent range of ocean, atmosphere, and sea-ice processes at each pole, with implications for the response of polar regions to global climate change.

Polar regions are geographically the furthest from industrial activities, yet both poles are clearly impacted by anthropogenic climate change. However, key differences arise between the poles in current and projected outcomes for polar amplification of atmospheric warming, carbon dioxide (CO_2) and heat uptake by polar oceans, and response of the icescape to atmospheric and ocean warming. The Arctic near-surface atmosphere has warmed nearly 4 times faster than the rest of the globe (1979–2021; Rantanen et al., 2022), with uneven amplification regionally (Meredith et al., 2019). This polar amplification of warming is not yet observed in Antarctica as a whole, though West Antarctic regions have warmed most significantly (Meredith et al., 2019). Our current understanding makes predicting the timing for emergence of Antarctic warming amplification difficult, leading to an urgent need to understand this system while Antarctica remains relatively pristine (Mallet et al., 2023). Both polar oceans continue to take up more CO_2 (Landschützer et al., 2015; DeVries et al., 2017) and heat (Liu and Curry, 2010; Huguenin et al., 2022) in response to anthropogenic greenhouse gas emissions (Meredith et al., 2019). The Southern Ocean dominates global ocean heat uptake (35%–43% of the increase in global ocean heat content in the upper 2,000 m during 1970–2017; Frölicher et al., 2015; Shi et al., 2018) despite comprising just one-quarter of the global ocean. Though the Arctic Ocean contributes a smaller proportion of global ocean heat uptake, sea-ice loss has driven an Arctic upper ocean warming trend of 0.5°C per decade (1987–2017; Timmermans et al., 2018). Arctic sea ice is becoming thinner, younger, and more ephemeral (Stroeve and Notz, 2018; Schweiger et al., 2019), with the strongest decreases in extent observed in summer (–12.8% ± 2.3% per decade in September) compared to winter (–2.7% ± 0.5% per decade in March; Onarheim et al., 2018). CMIP6 climate models predict that most of the Arctic Ocean will be ice-free in summer before 2050 (Notz and SIMIP Community, 2020). In contrast, overall Antarctic sea-ice extent shows no significant trend between 1979 and 2018 (Ludescher et al., 2019); however, a decrease is predicted over the next 50–100 years (Roach et al., 2020), and the last 7 austral summers have produced 3 unprecedented extreme low Antarctic sea-ice events (2017, 2022, and 2023). Large uncertainties remain in projections of sea-ice response to climate change owing to the complexity of interactions in the ocean–sea ice–atmosphere system (Meredith et al., 2019) and lack of sufficient observational data, which has motivated recent major observational campaigns (e.g., Granskog et al., 2018; Schmale et al., 2019; Nicolaus et al., 2022; Rabe et al., 2022; Shupe et al., 2022).

Despite major and expensive international efforts, the polar seas remain understudied. Individual disciplines have separately led efforts to synthesize progress and gaps in methods, key variables and processes in sea ice, the ocean, and the atmosphere. We aim to bring together different research approaches with complementary perspectives that represent the breadth and diversity of the Surface Ocean–Lower Atmosphere Study (SOLAS) science community. We connect disciplinary silos to provide an integrated perspective on air–sea interactions in polar regions, and how these regions contribute to and respond to climate change. We summarize recent (past 5–10 years) advances (Sections 2–4) in our understanding of the coupled ocean–sea ice–atmosphere system and future directions (Section 6). We focus on how progress is driven by both emerging observational strategies (Section 5) and cross-disciplinary scientific efforts (Section 7), and on how this research links to social and global issues of polar governance, and climate mitigation and adaptation (Section 8). This work is motivated by the rapid advances and wealth of data collected from satellite and autonomous ocean platforms, setting the pace for a new era of observations in polar regions. Effective use of existing and emerging technological advances to observe and understand these complex systems requires a multidisciplinary approach which is facilitated by SOLAS and related cross-disciplinary efforts, such as Scientific Committee on Oceanic Research (SCOR) working groups emerging from the SOLAS science community (Section 7).

2. Recent advances in sea-ice biogeochemistry

Understanding the drivers of marine productivity is paramount to quantify the effects of changes in the physical environment on the ocean uptake and emission of bioactive gases and aerosols (**Figure 1**).

2.1. Light and nutrients in polar seas

2.1.1. Polar open ocean

Strong seasonality and the complexity of sea-ice features create a polar light environment with extreme variability. Areas closer to the poles and with higher sea-ice coverage experience low light availability, especially during the

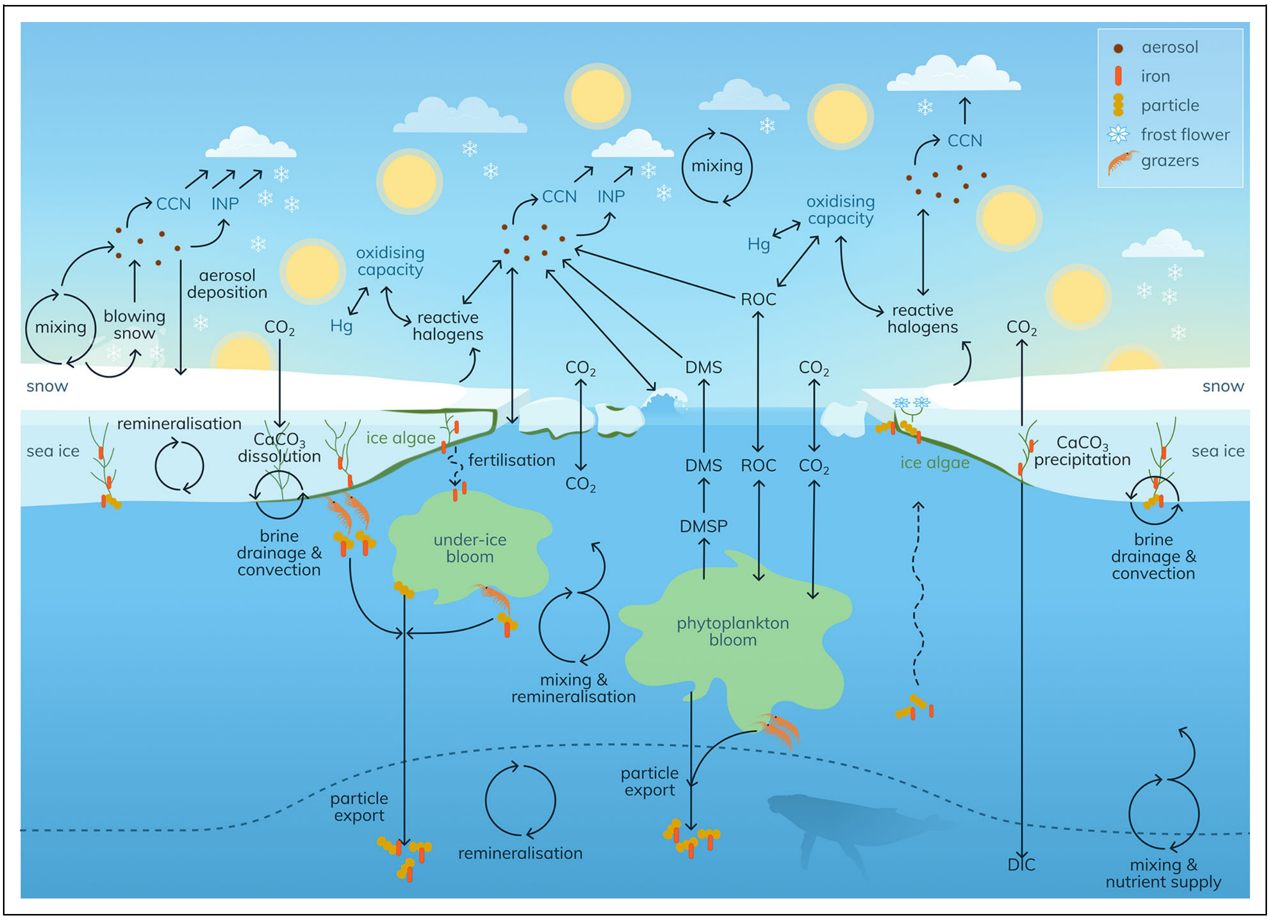

Figure 1. Schematic representation of coupled processes in the ocean–sea ice–atmosphere system. Similar to other regions of the global ocean, spring blooms in polar regions are initiated when the water column stabilizes and enough light becomes available to drive increases in photosynthesis (Section 2.1 and 2.2). The end of the algal bloom is marked by nutrient exhaustion, consumption by marine grazers, and in the case of ice algae, melting of their sea-ice habitat. Light availability within and under the ice is controlled by snow and sea-ice thicknesses (Section 2.1). Nutrient concentrations are controlled in the upper ocean by the degree of stratification, and in sea ice by brine transport and exchange with the underlying seawater (Section 2.1). The polar seas and sea ice are overall a sink for CO_2. Primary production in sea ice (ice algae) and seawater (phytoplankton) followed by particle export to depth contributes to this CO_2 sink. Air–sea exchange in the presence of sea ice occurs through direct exchange between ocean and atmosphere (i.e., in leads, polynyas, marginal ice zones; Section 3.2), transport within sea ice, and exchange across the atmosphere–ice interface (Section 3.1). Sea ice, frost flowers, and saline snow are potential sources of reactive halogen species (Section 4.1), which can control mercury (Hg) depletion and atmospheric oxidizing capacity (i.e., the sum of HO_x radicals, hydrogen peroxide (H_2O_2), ozone (O_3), and XO radicals where X is Cl, Br or I). Polar oceans and sea ice regulate the uptake and emission of both aerosol, such as sea spray particles (Section 4.2) and associated biological material, and climate-active gases (Section 4.2–4.3), such as dimethyl sulfide (DMS) and reactive organic carbon (ROC) gases. These interactions can lead to emission and formation of aerosols that act as cloud nuclei (i.e., both cloud condensation nuclei [CCN] and ice nucleating particles [INP]).

polar winter, whereas areas at lower latitudes are less light-limited. Within the water column, organic matter and ocean dynamics such as vertical mixing and stratification dictate light availability for phytoplankton, especially during the summer. Intense vertical mixing in the Southern Ocean replenishes surface waters with nutrients but can also cause light limitation when phytoplankton are mixed below the euphotic depth. Sea-ice melt, however, can strengthen the stratification and allow enhanced photosynthetic activity of phytoplankton within the euphotic zone until nutrients become exhausted. Satellite ocean color observations and in-situ measurements are useful to assess the timing and magnitude of polar spring blooms (Perrette et al., 2011; Sallée et al., 2015; Behrenfeld et al., 2017; Renaut et al., 2018; Kauko et al., 2021) and associated ecological and biogeochemical (BGC) processes.

In addition to light, primary production in the Arctic Ocean is limited by low nitrate concentrations (Mills et al., 2018; Ko et al., 2020). Over the last 30 years, surface water nitrate concentrations in the western Arctic Ocean decreased by 79% (Zhuang et al., 2021). Lowered nutrient concentrations may be driven by sea-ice melt through a combination of freshwater driven stratification, which

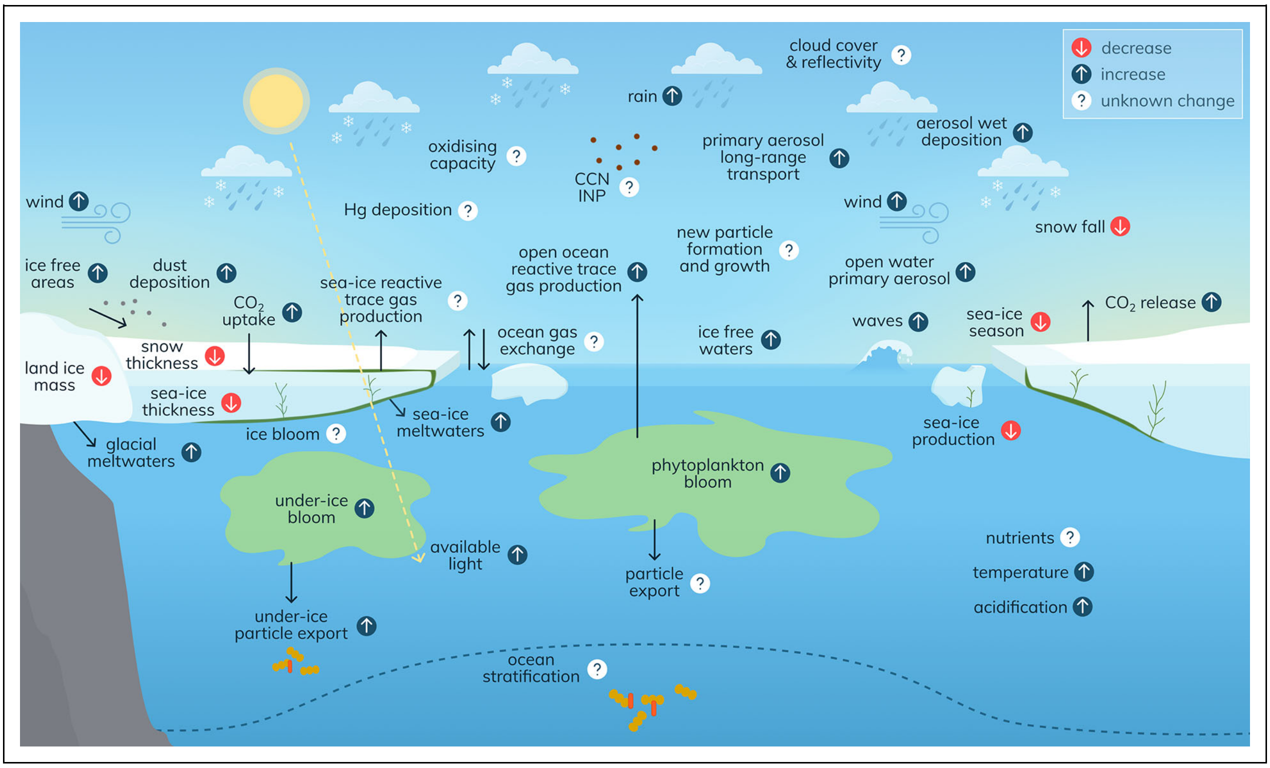

Figure 2. Climate change impacts on key environmental conditions and processes in polar oceans and sea ice. The Arctic and Southern Oceans are changing in profound ways. The polar regions are losing land ice, exposing more ice-free land, and releasing more glacial meltwaters into the surrounding oceans. The oceans are absorbing more heat and becoming more acidic. Rain will become more frequent, at the expense of snow deposition. These warmer conditions will likely lead to shorter sea-ice seasons at both poles, and thinner snow and sea-ice cover. Increases in light availability as a result of a decreasing sea-ice cover is likely to increase primary production, although the future reservoir of nutrients in surface waters is unknown and will depend on the balance between enhanced terrestrial inputs and unknown changes in surface ocean stratification. Increases in primary production are likely to drive an increase in the biological uptake and production of climate-active and aerosol-forming gases. Waves are likely to increase as winds and open water areas increase, with impacts on the exchange of particles and gases. Seasonal outcomes for the atmospheric aerosol population, cloud nuclei (both CCN and INP), oxidizing capacity, and Hg deposition remain uncertain as changing processes within diminishing sea-ice regions are poorly quantified. Ultimate outcomes for cloud cover and reflectivity across seasons are uncertain and will affect the atmospheric energy balance, and both sea-ice melt and freezing.

limits resupply of nutrients from subsurface waters, and more favorable light conditions, which enhance short-term biological nutrient uptake (Zhuang et al., 2021). New inputs of nitrogen may arise from wildfire aerosol deposition (Ardyna et al., 2022), coastal erosion, and riverine inputs (Terhaar et al., 2021). This terrigenous nitrogen input can sustain up to 50% of the Arctic Ocean net primary production (NPP) and will likely increase over the 21st century (Frey et al., 2007; Fritz et al., 2017), which could increase Arctic Ocean NPP (Terhaar et al., 2019). Large uncertainties about the future trophic status (eutrophic vs. oligotrophic) of Arctic Ocean regions (**Figure 2**) remain, as changes in ocean stratification may be offset by both turbulent mixing and upwelling (Tremblay et al., 2015; Lannuzel et al., 2020), and higher terrigenous nitrogen input (Fritz et al., 2017).

The polar Southern Ocean is remote from iron-rich land masses (Martin, 1990) such that changes in the iron supply, together with light availability, are the main drivers of marine productivity in surface waters. Iron inputs arise from multiple atmospheric, oceanic, and cryospheric sources. While dust deposition is not a dominant iron source (Wagener et al., 2008), ocean fertilization from Antarctic dust could increase (de Jong et al., 2013; Bhattachan et al., 2015; Nowak et al., 2018; Duprat et al., 2019) as ice-free land areas expand in the future (Lee et al., 2017). Similarly, glacial–interglacial contrasts in iron deposition from the Dome C ice core paleoclimate record suggest possible future changes in Patagonian dust inputs (Wolff et al., 2006). Deposition of volcanic dust (Perron et al., 2021) and biomass burning aerosol can also lead to significant iron inputs. For example, extensive aerosol deposition from Australian wildfires was associated with a widespread phytoplankton bloom in the Pacific Southern Ocean (Weis et al., 2022). Melting icebergs and ice shelves may act as continuous iron sources (St-Laurent et al., 2017; Hopwood et al., 2019), while sea-ice melt waters can drive polynya productivity (Moreau et al., 2019). Iron and nutrient-rich shelf waters fertilize downstream phytoplankton blooms around sub-Antarctic islands (Landwehr et al., 2021; Kerguelen and Crozet Islands, and South Georgia; Robinson et al., 2016). In addition, snow meltwaters (van Der Merwe et al., 2015) and hydrothermalism (Holmes et al., 2017) from islands contribute to local blooms. Observations of iron, and other trace metals (e.g., manganese, cobalt), in the ice and ocean remain scarce, which limits our ability to quantify their concentrations, chemical speciation, and bioavailability (Smith et al., 2022).

2.1.2. Sea ice

Characterization of light in sea ice is hindered by structural complexity of the sea-ice matrix and sampling challenges (Katlein et al., 2021). Light transmittance is controlled by snow cover, with snow attenuation coefficients about an order of magnitude greater than those of sea ice. Drifting snow and melt pond formation creates spatially and temporally dynamic light fields that select for unique algal species, acclimation states, and levels of oxygen production or consumption (Campbell et al., 2022). Studying algal blooms within and beneath sea ice among variable light conditions requires bio-optical methods and under-ice remote sensing platforms. Recording light conditions experienced by ice algae is key, as even a small amount of light may induce short-term physiological responses in primary producers (Morgan-Kiss et al., 2006). As a result, models that describe photoacclimation of ice algae produce more realistic phenology (Tedesco et al., 2012).

Recent reviews have advanced our understanding of nutrient cycling in Antarctic sea ice (Fripiat et al., 2017), and similar data compilation efforts are crucially needed in the Arctic. Clear seasonal trends appear in pack ice, with high macronutrient concentrations in autumn and winter due to a supply from underlying seawater, and depletion in spring and summer due to uptake by ice algal communities. Remineralization of organic matter and nutrient recycling, potentially mediated by biofilms (Roukaerts et al., 2021), can drive nutrient concentrations far in excess of surface waters. The discovery (Loscher et al., 1997) that Antarctic sea ice is rich in iron has led to some limited focus on trace metals in late winter and springtime sea ice, with observations limited to the East Antarctic sector (Lannuzel et al., 2016). The mechanisms of iron incorporation during sea-ice formation remain uncertain (Janssens et al., 2016). While short-lived iron fertilization is suspected to arise from melting sea ice, enhanced seawater iron concentrations in response to melt have not been observed.

2.2. Algal blooms

2.2.1. Polar open ocean algal blooms

Arctic Ocean primary production may have increased due to sea-ice loss and longer growth seasons (**Figure 2**; Arrigo and van Dijken, 2015; Ardyna and Arrigo, 2020). Nutrient inputs from upwelling (Lewis et al., 2020) and land (rivers and coastal erosion; Terhaar et al., 2021) also contribute to enhanced primary productivity (Section 2.1). Phytoplankton dynamics in the Arctic are ultimately driven by the balance between atmospheric forcing, and salinity and temperature driven stratification (Randelhoff and Guthrie, 2016; Ardyna and Arrigo, 2020). Later freeze-up, particularly in the eastern Arctic, may drive more frequent fall blooms (Ardyna et al., 2014). Poleward advection of Atlantic and Pacific currents (Woodgate, 2018; Oziel et al., 2020) suggests that the Arctic domain is shrinking, with temperate phytoplankton like *Emiliania huxleyi* now expanding into polar seas (Oziel et al., 2020). Evaluating the impacts of phytoplankton community shifts (e.g., on the marine food web and BGC cycles) remains difficult because marine BGC models only describe these processes to a limited extent (Beaugrand et al., 2019).

All regions of the Southern Ocean are likely to experience changes in phytoplankton productivity and community composition with climate change, although the nature of those changes is uncertain and spatially variable (Montes-Hugo et al., 2009; Henson et al., 2016; Deppeler and Davidson, 2017). Twenty years of ocean color observations suggest that the Southern Ocean is getting "greener" (Del Castillo et al., 2019), particularly in Western Antarctic Peninsula waters where sea-ice cover has decreased (Moreau et al., 2015). However, primary production at the base of the mixed-layer has decreased over the same period, and the overall direction of change in NPP is not clear (Pinkerton et al., 2021). Marginal Ice Zone (MIZ) blooms may account for up to 15% of annual Southern Ocean NPP. Approximately two-thirds of this production can occur in early phases of MIZ blooms, which likely occur under partial ice cover and are thus invisible to ocean color remote sensing (Taylor et al., 2013). BGC-Argo floats show that phytoplankton growth actually initiates 4–5 weeks before the sea-ice retreat (Hague and Vichi, 2021).

2.2.2. Under-ice algal blooms

The pelagic spring algal bloom begins under the ice, before melt is complete. Both ice algae and polar phytoplankton are adapted to extremely low light conditions, which suggests that they can survive through winter to seed the spring bloom (Randelhoff et al., 2020; van Leeuwe et al., 2020). The seeding potential of sea ice is species-specific, and only the first algal biomass increase appears linked to the release of sympagic ice algae into the water column, whereas summer pelagic algal blooms are likely controlled by hydrographic conditions (van Leeuwe et al., 2020).

Under-ice blooms (UIBs) have been observed in the Arctic since the late 1950s (Ardyna et al., 2020). The timing of a UIB depends on light penetration within the upper mixed layer, which itself depends on snow depth, ice thickness, the presence or absence of melt ponds, and the absorption of light by ice algae, other biota and material (e.g., sediments) incorporated in sea ice. UIBs have so far been mainly observed in the MIZ, but as sea-ice cover becomes more dynamic UIBs may expand further into the ice pack (Barber et al., 2015). Unlike the Arctic Ocean, Antarctic UIBs have only recently been identified by deployments of under-ice BGC-Argo floats (Arteaga et al., 2020; Bisson and Cael, 2021; Hague and Vichi, 2021; Horvat et al., 2022). Under-ice phytoplankton growth is likely to start earlier as sea ice retreats earlier at both poles, and becomes increasingly thin and dynamic (**Figure 2**). This change in bloom phenology may impact the seasonal air–sea carbon flux and the biological carbon pump (Hague and Vichi, 2021). While existing studies confirm that under-ice algal blooms are productive, direct comparison of geographic estimates from models with float data may be problematic because of uneven spatial coverage (Horvat et al., 2022).

2.2.3. Sea-ice algal blooms

Loss of Arctic multiyear sea ice (MYI) and thinning of first year sea ice (FYI) and snow cover combine to create increasing light availability within and below sea ice (Veyssière et al., 2022), which stimulates larger sea-ice algal blooms (Tedesco et al., 2019; Lim et al., 2022). Thinning of snow cover and shifting ice seasons toward more favorable photoperiods together drive earlier algal blooms and an increase in sea-ice algal growth. However, the narrowing time window during which sea ice is present sets an upper limit for ice algal accumulation (Tedesco et al., 2019). Changes in Southern Ocean sea-ice and snow thickness remain highly uncertain (Webster et al., 2018; Shen et al., 2022), making assessments of future states difficult. Ice algal primary production will ultimately be dictated by a trade-off between light gain and habitat loss in both the polar oceans, with a maximum total annual production in sea ice set by nutrient availability (Section 2.1). Transient states of high production may arise in the coming decades, for example, through sea-ice warming that will create a more porous ice structure, facilitating nutrient exchange, and providing habitat for algal growth (Tison et al., 2017).

2.3. Effects of UV radiation at high latitudes

Solar ultraviolet (UV) radiation can decrease phytoplankton (Moreau et al., 2010), ice-algal (Ryan et al., 2012), and net community production (Garcia-Corral et al., 2014; Moreau et al., 2014), as well as DMS emissions (Toole et al., 2004) by damaging cellular DNA. The UV impacts on biological processes are generally stronger in the Southern than in the Arctic Ocean due to the persistent stratospheric O_3 hole over Antarctica, in contrast to the more subtle and intermittent stratospheric O_3 losses over the Arctic (Wilka et al., 2021). While stratospheric O_3 depletion is expected to recover during this century, the rate of O_3 recovery differs between the poles (Dhomse et al., 2019) and may be slowed by more frequent and intense wildfires (Solomon et al., 2023). These complexities add to the challenges of predicting the BGC responses to projected UV light changes.

2.4. Sea-ice biogeochemical models

Large-scale modeling of sea-ice biogeochemistry has advanced rapidly in many aspects since it was last reviewed (Vancoppenolle and Tedesco, 2016). First, pan-Arctic simulations of sea-ice algae have improved by incorporating physical processes that were identified as important in 1D studies, but were missing in large-scale models. These processes include brine rejection, which improves CO_2 fluxes (Moreau et al., 2015; Mortenson et al., 2018) and vertical exchange of nutrients at the ice–ocean interface (Jin et al., 2018); light transmission through sea ice and snow, which impacts algal growth (Hayashida et al., 2019); and incorporation of additional BGC exchange processes such as DMS emissions (Hayashida et al., 2019; Hayashida et al., 2020). Model intercomparisons indicate a phenological shift in Arctic sea-ice algal spring blooms, but no clear trend in the total production despite a continuous decline of Arctic sea ice (Watanabe et al., 2019). Advances are now being made to incorporate sea-ice biogeochemistry into Earth System models (Moreau et al., 2016; Jeffery et al., 2020).

3. Recent advances in gas exchange studies in sea-ice regions

All climate active gases studied in lower-latitude oceans (CO_2, CH_4, N_2O, and DMS) are likely important in polar oceans, but the presence of sea ice complicates pathways for air–sea gas transfer. Unfortunately, not all relevant gases have been equally studied in polar oceans, though key transfer processes (i.e., diffusion, turbulent transport) are relevant for all gases. Diffusion rates show that direct air–sea gas transfer *through* the sea-ice volume is likely insignificant for most gases (Loose et al., 2011), but flux measurements of greenhouse gases (particularly CO_2) have shown significant exchange between the atmosphere and both the ice surface and the surface ocean in the presence of sea ice.

3.1. Gas exchange at the atmosphere—ice interface

During initial ice growth, a small fraction of the brine expelled by freezing seawater is transported upward and can form a brine skin that wets the overlying snow cover (Massom et al., 2001), contributes to frost flower formation (Style and Worster, 2009), and affects the salinity and brine volume fraction of the ice–snow interface (**Figure 1**). During melt, the formation of wet snow and eventually melt ponds creates a surface with potentially extensive liquid water content. Whenever liquid water exists at the surface of sea ice that surface can exchange gases with the atmosphere.

3.1.1. Air—ice exchanges of CO_2

Historically, a large disagreement existed in the magnitude of CO_2 fluxes from enclosure and eddy covariance methods (Miller et al., 2015). Butterworth and Else (2018) showed that this was likely due to instrument biases inherent in eddy covariance. These biases can be eliminated by removing water vapor from the sampling stream, or by using cavity-enhanced gas analysers that do not experience significant contamination of the CO_2 signal in the presence of water vapor fluctuations (Prytherch et al., 2017). Results obtained from enclosures and eddy covariance are now more consistent (Butterworth and Else, 2018). Together these flux observations show that the magnitude and direction of CO_2 exchange depends on the difference in the gas concentration between the sea-ice surface and air, the brine volume fraction at the sea-ice surface, and the ice surface conditions, including snow cover (e.g., Nomura et al., 2013). CO_2 fluxes are on the order of ± 5 mmol m^{-2} d^{-1}; significantly lower than fluxes observed over open water, but important over the global sea-ice extent. Melting ice acts as a sink of atmospheric CO_2 (in the range of 0 to -5 mmol m^{-2} d^{-1}), while newly forming sea ice releases CO_2 to the atmosphere (in the range of 0 to $+5$ mmol m^{-2} d^{-1}). Regional variations in these fluxes have not been adequately assessed, nor is the duration of uptake or outgassing well constrained. Both of these issues are being investigated through a global compilation of sea ice CO_2 fluxes, conducted as part of the SCOR Working Group 152–Measuring Essential Climate Variables in Sea Ice (ECV-Ice).

In the Arctic, the decrease in summer sea-ice extent has outpaced the decrease in winter sea-ice extent, leading to substantially more first-year sea ice, and thereby a larger area experiencing annual melt and freeze-up (Stroeve and Notz, 2018). Since these are the periods when gas exchange with the ice surface is active, air–ice gas exchange processes may become a more significant fraction of CO_2 exchange budgets in the Arctic. In the Antarctic, higher snow cover significantly affects the air–ice CO_2 fluxes, with snow reducing the magnitude of CO_2 exchange.

3.1.2. Air—ice exchange of other gases

Surface flux observations over sea ice for gases other than CO_2 are very limited. Recently, a new chamber system was used for methane (CH_4) (Nomura et al., 2022), showing release of CH_4 by the ice surface. Other types of chambers, coupled to analysers that measure discrete air samples, may be useful for examining fluxes for gases such as DMS, $CHBr_3$, CO_2, and N_2O (Nomura et al., 2012). In addition, stable isotopic measurements from discrete air samples would provide information about the formation process of the target gases. Eddy covariance measurements of CH_4 flux (Thornton et al., 2020) and O_3 flux (Muller et al., 2012) have been reported. Other gas fluxes may be measured using eddy covariance, but the need for high-frequency (typically 10 Hz) gas concentration measurements imposes practical limits related to sensor design and deployability. During the MOSAiC expedition, DMS, CO_2, CH_4, and O_3 fluxes were measured over a number of different ice surfaces by both chamber and eddy covariance techniques (e.g., Shupe et al., 2022; Barten et al., 2023). These new observations will provide insight into gas fluxes across heterogeneous icescapes.

3.2. Air—sea gas exchange in the presence of ice

3.2.1. Gas transfer velocity

The first studies to evaluate the role of air–sea gas exchange in the presence of mixed ice cover, naturally began by considering how air–sea exchange is estimated under open ocean conditions, and assumed that fluxes could be scaled by the open water fraction (Sweeney, 2003; Takahashi et al., 2009). Since that time, some studies using eddy covariance from shipboard measurements support the application of a linear scaling relationship (Butterworth and Miller, 2016; Prytherch et al., 2017), while lab studies indicate that turbulence-influencing processes in the sea-ice zone, other than wind, can either increase or decrease gas transfer velocity (Loose et al., 2017). These processes include shear in the ice-water boundary layer (McPhee, 2008), buoyant convection or stratification (Loose et al., 2017; Prytherch and Yelland, 2021), and modifications to the capillary-gravity wave field by fetch reduction and the dampening action of sea ice (Loose et al., 2014). Eddy covariance CO_2 flux measurements from an ice-affixed tower adjacent to a large lead (a linear, typically transient, open water feature) determined a 30% reduction in air–sea gas exchange rates due to sea ice (Prytherch and Yelland, 2021). Gas transfer rates from radon-deficit profiles have supported both suppression and enhancement (Rutgers van der Loeff et al., 2014; Loose et al., 2017) due to the presence of sea ice, whereas laboratory studies have generally indicated enhancement (e.g., Loose et al., 2009). Comparison between results is often confounded by different approaches to determine sea-ice concentration and analysis of the surface flux footprint (Watts et al., 2022). Bigdeli et al. (2018) used a wave-age based model (Sutherland and Melville, 2015) in addition to convection/stratification and ice-water shear to show how gas transfer can be enhanced in some circumstances beyond the linear scaling with open water. However, the more common scenario appears to be a repression in gas transfer velocity by wave field dampening, which is consistent with the findings of Prytherch and Yelland (2021). Recently, measurements of total kinetic energy dissipation using SWIFT buoys revealed the potential for multiple appropriate transfer functions, driven by the nature of ice cover (Smith and Thomson, 2019). Satellite remote sensing techniques, such as microwave altimetry, can provide observations that are more closely related to the turbulence processes that drive gas exchange than wind speed (Shutler et al., 2020), and may be useful in resolving ambiguity surrounding enhanced or suppressed gas exchange in the presence of sea ice.

3.2.2. Stratification

The frequently highly stratified surface ocean is an important factor regulating air–sea gas exchange in polar environments (**Figure 1**). Extreme surface stratification can frustrate efforts to accurately assess the air–sea concentration gradient, which has implications both for studies attempting to measure gas transfer velocity, and those that attempt to apply the gas transfer velocity to estimate flux. This is a particularly pernicious problem in the Arctic, where both sea-ice melt and river waters often form thin meltwater layers with very different composition from what is observed by either underway systems or even "surface" rosette bottles (Murata et al., 2008; Miller et al., 2019; Ahmed et al., 2020; Dong et al., 2021). Correction of underway data to surface conditions may be possible in some cases (Ahmed et al., 2020). However, such corrections are very limited in spatial and temporal applicability, because of variability in the causes of the surface stratification (i.e., sea-ice melt, river waters, or a mixture of the two), the different geochemistries of sea-ice melt and river waters draining different watersheds (e.g., sea-ice melt is undersaturated in CO_2, whereas river waters are often supersaturated), and changeable meteorological conditions. Optical remote sensing can be used to track freshwater plumes (e.g., Juhls et al., 2022), and may have some utility in identifying regions where stratification effects need to be carefully considered before computing gas exchange rates.

3.2.3. Air—sea exchange of gases beyond CO_2

While dissolved CO_2 is often undersaturated with respect to atmospheric concentrations in polar surface waters, driving a relatively large exchange, fluxes of other climate-relevant gases are often below eddy covariance detection limits. However, potential CH_4 emissions in shallow shelf regions can be large due to release from sediments, melting hydrates, and riverine and glacial inputs (Thornton et al., 2020; Manning et al., 2022). In deeper waters, near-surface concentration measurements suggest smaller sea-air CH_4 fluxes (Fenwick et al., 2017; Manning et al., 2022) though much larger fluxes have been derived from aircraft observations over wintertime leads (Kort et al., 2012). Glacier melt may play a significant role in the CH_4 budget of the Arctic Ocean (Christiansen and Jørgensen, 2018; Lamarche-Gagnon et al., 2019; Manning et al., 2022). Near surface concentration measurements of N_2O also suggest small sea-air fluxes (Heo et al., 2021), though measurements are scarce.

3.2.4. Impacts of changing ice cover

The lack of consensus on sea ice effects on gas transfer complicates assessment of the impacts of changing sea ice on gas fluxes. This issue is most important wherever open water and sea ice exist together; in MIZs, polynyas, and flaw leads (leads that form at the interface between landfast and pack ice). Rolph et al. (2020) found no trend in Arctic MIZ extent over 40 years, even as the extent of summer sea ice has moved further North. Similarly, there is no wide-spread evidence of greater lead fraction (Wang et al., 2016) or polynya formation in the Arctic, although trends certainly could emerge as the ice cover continues to become younger and thinner and once winter sea-ice concentrations start to decrease. Therefore, the Arctic Ocean surface area where gas exchange occurs in the presence of sea ice has likely remained constant; however, our inability to agree on whether or not gas exchange is enhanced or suppressed under sea-ice conditions is a major knowledge gap (Section 6). In the Antarctic, long periods with significant open water areas will enhance direct ocean–atmosphere interactions and may allow CO_2 outgassing from the ocean during winter (Shadwick et al., 2021).

3.3. The sea-ice carbon pump

Because sea-ice brines are enriched in dissolved inorganic carbon (DIC), as well as salts, brine rejection during sea-ice formation should sequester carbon in deep waters if it eventually contributes to deep convection. Rysgaard et al. (2012) hypothesized that calcium carbonate formation in sea ice could further enhance carbon drawdown by fractionating alkalinity and DIC, with excess DIC exported with the brines and excess alkalinity released to surface waters, enhancing summer CO_2 absorption from the atmosphere. Although $CaCO_3$ precipitation in sea ice has been observed in both Antarctic (Dieckmann et al., 2008) and Arctic (Dieckmann et al., 2010) sea ice, DIC-alkalinity fractionation has been more difficult to document (Else et al., 2022). Experiments using global ocean circulation models have indicated that inorganic carbon export with sea-ice brines can have significant influence on regional carbon distributions and ocean acidification, but may be a relatively minor component of global carbon sequestration (Grimm et al., 2016; Moreau et al., 2016). In addition, brine rejection depth, which can vary with ice formation rate (e.g., König et al., 2018), can have a large impact on the resulting carbon sequestration as well as the seasonal calcium carbonate saturation state (Mortenson et al., 2020). A key open question is the importance of the sea-ice carbon pump (without alkalinity fractionation) to the global carbon cycle.

4. Recent advances on atmospheric chemistry and aerosol in sea-ice regions

The interconnections between polar oceans, sea ice, snow on sea ice and the overlying atmosphere have direct implications for reactive, short-lived atmospheric trace gases, aerosol, and cloud nuclei (both CCN and INP; **Figure 1**). Improved mechanistic understanding of processes that influence the exchange and abundance of oxidants, reactive trace gases and aerosol is required to predict climate-driven changes in polar atmospheric chemistry, aerosol, and cloud properties (**Figure 2**).

4.1. Atmospheric oxidizing capacity over polar oceans and sea ice

4.1.1. Lower troposphere oxidation processes

Lower troposphere oxidative capacity, that determines the lifetime of climate-active gases such as CH_4, is driven by the abundance of hydroxyl radical (OH) and of other oxidants including O_3, H_2O_2, nitrate radicals (NO_3), nitrogen oxides (NO_x), peroxy radicals (HO_2, RO_2), and reactive halogens (Alexander and Mickley, 2015). Oxidant abundance is coupled through nonlinear cycling reactions, and is strongly affected by air–snow interactions (Barbero et al., 2021; Ahmed et al., 2022; Barten et al., 2023). Active halogen chemistry occurs during spring and drives depletion of O_3 and mercury (Hg) (e.g., Steffen et al., 2008; Simpson et al., 2015; Ahmed et al., 2023). In addition to affecting the oxidative capacity (e.g., Marelle et al., 2021), these O_3 depletion events lead to enhanced deposition of toxic Hg that bioaccumulates in food webs (Dastoor et al., 2022). Year-round bromine depletion, with respect to sea water, in Antarctic aerosol demonstrates significant reactive bromine release from sea-ice regions (Legrand et al., 2017; Hara et al., 2018; Frey et al., 2020). While bromine has received most attention, iodine chemistry also contributes to springtime tropospheric O_3 depletion (Raso et al., 2017; Benavent et al., 2022). Ice-core observations of iodine concentrations show an O_3-iodine feedback and suggest that projected increases in iodine emissions could have a strong effect on the abundance of tropospheric O_3 (Cuevas et al., 2018). Chlorine chemistry plays only a minor role in O_3 depletion but is involved in consumption of

ROC gases (Ramacher et al., 1999), thereby indirectly affecting the oxidative capacity.

The response of polar atmospheric oxidizing capacity to climate and environmental change is uncertain. Increasing anthropogenic activities (e.g., shipping, fossil fuel extraction) may drive increased emissions of key oxidants (e.g., NO_x), with uncertain consequences on the partitioning and cycling of reactive radicals, such as halogens and HO_x (e.g., Custard et al., 2015; McNamara et al., 2019). In addition, ice core stable isotopic proxies for oxidant abundance show that tropospheric oxidants are sensitive to climate change with the O_3/HO_x ratio increasing in colder climates (Geng et al., 2017).

4.1.2. The role of snow on sea ice

Many emissions that influence the oxidative capacity come from snow on sea ice, wind-blown snow particles or sea-salt aerosols under sunlight conditions (Abbatt et al., 2012; Pratt et al., 2013; Toyota et al., 2014; Bartels-Rausch et al., 2014; Marelle et al., 2021). Although much work has already been done on this topic (e.g., McNeill et al., 2012; Peterson et al., 2019; Edebeli et al., 2020; McNamara et al., 2020; Gao et al., 2022; Jeong et al., 2022), our understanding of multiphase sea salt aerosol and snowpack chemistry remains limited, motivating experiments under in-situ or controlled conditions. New method development is required to detect and quantify critical species (**Table 1**; Pratt, 2019). Short- to medium-lived reactive halocarbons (e.g., CH_2Br_2, CH_2BrCl) are potential longer-range carriers of reactive halogens to the remote atmosphere, while very short-lived gases (e.g., $CHBr_3$, CH_3I) are potential contributors of halogen radicals in the polar marine boundary layer via photolysis and oxidation reactions (Tinel et al., 2023). Significant bromocarbon production has been observed from Antarctic sea ice during wintertime (Abrahamsson et al., 2018), which shows that bromine loss processes were active in the sea ice in the absence of sunlight, and thus wintertime processes relevant for atmospheric oxidation capacity require more investigation. A complete picture of halogen emissions and impacts on tropospheric chemistry requires measuring a wide range of volatile, short-lived reactive halocarbons of biogenic and abiotic origin (Abbatt et al., 2012; Simpson et al., 2015; Abrahamsson et al., 2018).

4.2. Reactive trace gases from polar oceans and sea ice

Sinks for atmospheric oxidants, and sources of secondary aerosol precursors (Section 4.3.2), include DMS and an array of ROC gases. For example, higher dissolved concentrations of ROC and organosulfur gases can occur in the MIZ compared to open water (Wohl et al., 2022), and polar marine regions can be a source of benzenoid compounds (Wohl et al., 2023). Dissolved organic matter photochemistry or multiphase oxidation at the polar ocean surface can drive emission of oxygenated ROC gases (Mungall et al., 2017). Further, polar dissolved methanethiol (CH_3SH) concentrations appear non-negligible (Gros et al., 2023), with potentially significant implications for the atmospheric SO_2 budget (Chen et al., 2021; Novak et al., 2022). However, the majority of current knowledge is focused on DMS and observations of other ROC gases are limited.

4.2.1. DMS in polar open oceans

Arctic and Antarctic observations have expanded in the last decade, illustrating the need to recalibrate climatological DMS records against under sampled regions. Recent observations (Stefels et al., 2018; Abbatt et al., 2019; Kim et al., 2021) highlight strong gradients and variability in DMS tied to hydrographic features (localized sea-ice melt, stratification), phytoplankton speciation and biomass (Jarníková and Tortell, 2016; Jarníková et al., 2018; Uhlig et al., 2019; Lizotte et al., 2020); the relevance of polynyas (Tortell et al., 2011; Tortell et al., 2012); and large discrepancies with existing climatologies (Stefels et al., 2018; Kim et al., 2021; Hulswar et al., 2022). Presence of strong DMS and dimethyl sulfoniopropionate (DMSP) producers, especially the haptophyte *Phaeocystis*, drive high DMS concentrations in the Southern Ocean (Kim et al., 2017; Stefels et al., 2018) and Canadian sectors of the Arctic (Galí et al., 2021). Circulation changes (Mueter et al., 2021) and increased poleward progression of spring blooms (Renaut et al., 2018; Polyakov et al., 2020) may impact the phenology of microbial communities that produce DMS, including the diversity of genes for DMS(P) cycling in polar oceans (Teng et al., 2021).

4.2.2. DMS in the marginal ice zone

In contrast to the global oceans (Sellegri et al., 2023), high dissolved DMS concentrations are associated with transitional areas between ice-covered and ice-free waters (Lizotte et al., 2020; Wohl et al., 2022). In the MIZ, DMS concentrations and fluxes can be enhanced by phytoplankton blooms boosted by high light exposure and stable, nutrient-rich environments (Perrette et al., 2011; Taylor et al., 2013; Arrigo et al., 2015; Lu et al., 2020); dominance of strong DMS(P) producers and accumulation from ice algal release (Levasseur, 2013; Galindo et al., 2014; Hayashida et al., 2017; Galí et al., 2021); weaker biological DMS removal (de Valle et al., 2009); and stronger production via stress or food-web interactions (Galindo et al., 2015; Galí et al., 2021). Ice melt seasonality drives photosynthetic activity and DMS(P) exudation through both salinity and light intensity (Galindo et al., 2015; Kameyama et al., 2020), and vertical segregation of auto- and heterotrophic sulfur-cycling (Galí et al., 2021).

Most models treat sea ice as a cap for DMS emissions from the ocean (Section 3), but DMS is known to vent through cracks and leads, at ice edges, and during melt (Hayashida et al., 2017; Lizotte et al., 2020; Wohl et al., 2022). Such short-lived, intense emission events may become more important to regional DMS fluxes (Webb et al., 2019) as lead openings occur more frequently in the future (Comiso et al., 2017; Kwok, 2018; Stroeve and Notz, 2018). While polar ice-free waters may dominate increasing regional emissions (Lana et al., 2011; Galí et al., 2018; Hayashida et al., 2020), future changes in the icescape (e.g., ice age and melting stage) may alter the dynamics of both sympagic and pelagic communities and

Table 1. New and emerging observing tools

Observing Tools	Key Variables	Selected References
Ocean and Sea-Ice Biogeochemistry		
Genomic-, transcriptomic-, and proteomic-based approaches	Biogeography, phylogeny, and evolutionary history	Demina et al. (2022); Luhtanen et al. (2018); Mock et al. (2016); Royo-Llonch et al. (2021)
	Metabolic potential and diversity	
	Adaptation mechanisms	
Noninvasive methods: multimodal endoscopy, in-ice microscopy, and melt probes	Sea-ice optical properties	Babin et al. (2019); Mundy et al. (2007); Perron et al. (2021)
	In-ice structure of the light field	
	Photosynthetically Active Radiation (PAR)	
	Nutrients, including trace metals	
	Dissolved gases	
	Chlorophyll *a*	
Remotely operated vehicles (ROV; including under-ice remote sensing using hyperspectral radiometers and imagers)	Temperature	Campbell et al. (2022); Cimoli et al. (2020); Meiners et al. (2017)
	Conductivity and salinity	
	Chlorophyll *a*	
	PAR	
	Backscatter	
Unmanned aerial vehicle (UAV)	High resolution imaging	Carlson et al. (2019); de Boer et al. (2022); Reineman et al. (2016)
	Air–sea turbulent fluxes	
	Radiative fluxes	
	Surface albedo	
	Sea surface temperature variability	
	Ocean surface waves and biogeochemistry	
Autonomous underwater vehicles (AUV; including gliders)	Sea surface temperature variability	Dowdeswell et al. (2008); Hoppmann et al. (2022); Spears et al. (2015); Williams et al. (2015)
	Dissolved oxygen and other gases	
	PAR, turbidity and diffuse attenuation coefficient (Kd)	
	Seawater pH	
	Chlorophyll *a*	
	Water leaving radiance (nLw)	
	Surface reflectance	
	Particulate organic carbon (POC) and particle size distribution	
	Colored dissolved organic material (CDOM)	
	Nitrate	
	Discrete samples for e.g., trace metals	
Animal Borne Sensors	Sea surface temperature	McMahon et al. (2021)
	Conductivity and salinity	
	Dissolved oxygen	
	Chlorophyll *a*	
	PAR	
BGC-ARGO	Sea surface temperature	Boss et al. (2008); Hague and Vichi (2021); Johnson et al. (2016); Johnson et al. (2015); Johnson et al. (2013); Körtzinger et al. (2004);
	Conductivity and salinity	
	Dissolved oxygen	

(continued)

Table 1. *(continued)*

Observing Tools	Key Variables	Selected References
	PAR Seawater pH Nitrate Chlorophyll *a* Optical backscattering coefficient	Moreau et al. (2020); Newman et al. (2019); Riser et al. (2018); Xing et al. (2011)
Ice tethered profilers, ice and autonomous drifting buoys	Surface temperature Conductivity and salinity Currents Dissolved oxygen and other gases Chlorophyll *a* PAR (downwelling and upwelling)	Hill et al. (2022); Timmermans et al. (2010)
Satellite ocean color	Chlorophyll *a* Cyanobacterial pigments Total suspended matter Turbidity, attenuation coefficient of diffuse light CDOM	Groom et al. (2019)
Gas extraction coupled with mass spectrometry	Isotopic fractionation within bulk ice	Jacques et al. (2021)
Air–sea fluxes		
Fast gas sensors for eddy covariance	Air–sea flux In the last decade: CO_2 Emerging EC systems (established for other environments, but new to sea ice): CH_4, DMS, O_3	Barten et al. (2023); Blomquist et al. (2010); Butterworth and Else (2018); Osterwalder et al. (2021); Prytherch et al. (2017); Prytherch and Yelland (2021)
Self-logging seawater gas concentration analysers	CO_2 beneath sea ice	Duke et al. (2021)
Remote-sensing tools (satellite-based and others)	Dissolved gas concentrations Turbulence parameters in surface seawater Freshwater layers Sea surface microlayer	Galí et al. (2019); Neukermans et al. (2018); Shutler et al. (2020)
Unmanned Aerial Vehicles (UAV)	Sea ice concentration and surface properties Snow depth Seawater samples in difficult or dangerous conditions (e.g., polynyas, leads, melt ponds)	Carlson et al. (2019); Cassano et al. (2010)
Head-space techniques (e.g., with mass spectrometry detection)	Dissolved oxygen and other gases (e.g., CO_2, DMS, isoprene, methanethiol, acetone, and other ROC gases)	Gros et al. (2023); Wohl et al. (2022)
Wave gliders, saildrones, and buoys	Air–sea fluxes of momentum and heat Air–sea fluxes of CO_2	Monteiro et al. (2015); Swart et al. (2019); Thomson and Girton (2017)
Atmospheric trace gases and aerosol		
Miniaturized, light-weight, and fast particle counting and sizing instruments (deployable on airborne platforms; e.g., tethered balloons, heli-kite)	Vertically resolved aerosol number and size Cloud nuclei concentrations Size-resolved aerosol deposition fluxes	Farmer et al. (2021); Held et al. (2011); Pilz et al. (2022)

(continued)

Table 1. *(continued)*

Observing Tools	Key Variables	Selected References
Chemical ionization mass spectrometry (thermal-desorption, low pressure and atmospheric pressure techniques)	Reactive organic carbon, sulfur, and nitrogen gases Reactive halogen compounds Atmospheric radicals Sulfur dioxide Trace gas fluxes Low volatility aerosol precursor gases Molecular cluster composition	Baccarini et al. (2021); Baccarini et al. (2020); Beck et al. (2021); Blomquist et al. (2010); Brean et al. (2021); Jokinen et al. (2018); Lawler et al. (2021); Pernov et al. (2021); Raso et al. (2017)
Active and passive remote sensing (e.g., differential optical absorption spectroscopy, DOAS)	Reactive halogen compounds	Benavent et al. (2022); Carlson et al. (2010); Simpson et al. (2018)
Isotope ratio mass spectrometry	Stable, multi-isotopic composition in aerosol	Burger et al. (2022); Ishino et al. (2021)

thus have far-reaching consequences for the sources, strength, and seasonality of DMS emissions (Kim et al., 2017; Uhlig et al., 2019; Lizotte et al., 2020). Extrapolation of current trends in dissolved DMS to ice-free summer conditions remains uncertain (**Figure 2**) due to possible shifts in climate-plankton feedbacks that are complicated by the response of DMS-producing communities to ocean acidification and warming (Six et al., 2013; Hussherr et al., 2017; Schwinger et al., 2017; Hopkins et al., 2020a; Hopkins et al., 2020b; Bock et al., 2021).

4.2.3. DMS in sea ice

Sea ice shapes DMS production through its influence on pelagic and sympagic microbial communities and related trophodynamics (Section 2). Ice-associated communities periodically produce DMS concentrations several orders of magnitude higher than global oceanic averages (Tison et al., 2010; Levasseur, 2013; Carnat et al., 2018; Webb et al., 2019). DMS is present at the bottom of sea ice (Nomura et al., 2011; Galindo et al., 2015), with platelet crystals integrated into the ice interior (Carnat et al., 2014), in brine inclusions (Asher et al., 2011; Carnat et al., 2016; Damm et al., 2016), and in brackish melt ponds (Gourdal et al., 2018; Park et al., 2019). Together the seasonal progression of solar radiation, and ice and brine dynamics, control sympagic microbial biomass, taxonomy and distribution (Damm et al., 2016; Carnat et al., 2018), invasion of brine channels by predatory zooplankton (Stefels et al., 2018), flushing of brines to underlying seawater (Carnat et al., 2014; Galindo et al., 2014), and light availability for DMS-producing microbial communities under the ice (Levasseur, 2013; Galindo et al., 2015; Leu et al., 2015).

4.3. Atmospheric aerosol and cloud nucleating particles

Efforts to understand aerosol and clouds in sea-ice environments are motivated by a need to understand the changing natural aerosol baseline in the Arctic in response to warming and Arctic amplification (Schmale et al., 2021); and characterize the Antarctic aerosol baseline (Hamilton et al., 2014) while this region remains relatively pristine and not yet impacted by significant polar warming amplification (Meredith et al., 2019; Schmale et al., 2019; Mallet et al., 2023). Observations in pristine regions are invaluable for reducing model uncertainty in aerosol–cloud interactions (Regayre et al., 2020). In pristine or polluted conditions, polar clouds mediate the atmospheric energy balance, surface temperature, and ice-melt (Pithan et al., 2018; Willis et al., 2018; Huang et al., 2019; Schmale et al., 2021); however, models struggle to represent cloud properties and aerosol processes that drive available CCN and INP. Model biases in high-latitude Southern Ocean sea-surface temperature are linked to cloud coverage, phase (unrealistically high INP) and reflectivity, while polar CCN concentrations are often underpredicted (Croft et al., 2019; Schmale et al., 2019; Landwehr et al., 2021; McCoy et al., 2021). However, observations show the importance of both realistic INP concentrations (Vergara-Temprado et al., 2018; Murray et al., 2021) and sub-100 nm CCN (i.e., typically too small to act as CCN over lower-latitude oceans; Abbatt et al., 2019; Baccarini et al., 2020; Karlsson et al., 2021; Tatzelt et al., 2022). Understanding the processes that control CCN and INP, and their distributions over polar oceans and sea-ice environments, is therefore critical to building a predictive understanding of polar change (**Figure 2**).

4.3.1. Primary aerosol: Aerosol particles emitted directly to the atmosphere

Primary aerosol from polar open ocean and marginal ice zones.
The high-latitude Southern Ocean is one of the largest sources of sea spray aerosol (SSA) on Earth (Landwehr et al., 2021; Moallemi et al., 2021), and this source may increase in the future with intensification of westerly winds (Sen Gupta and England, 2006). CMIP6 models have a large uncertainty in present-day polar SSA abundance (Lapere et al., 2023). SSA drives the CCN budget in winter,

whereas in summer SSA comprises a smaller fraction (∼30%) of CCN (Schmale et al., 2019; Tatzelt et al., 2022). However, the poorly quantified sub-100 nm fraction of SSA may mean this contribution is larger than previously thought (Lawler et al., 2021; Xu et al., 2022). Changing transport patterns impact Arctic SSA by favoring transport from the North Atlantic (Pithan et al., 2018; Heslin-Rees et al., 2020). SSA is also produced in open leads and polynyas (May et al., 2016; Kirpes et al., 2019), though fluxes appear locally relatively small (Held et al., 2011). These emissions can contribute to saline snow on sea ice and to blowing snow aerosol production (Chen et al., 2022).

The relative contribution of local production and long-range transport of primary INP is a key open question for both poles (Murray et al., 2021). SSA contains organic material (e.g., Kirpes et al., 2019), including marine nano/microgels and primary biological aerosol particles that are efficient INP (Després et al., 2012; Moallemi et al., 2021; Tatzelt et al., 2022). Few measurements of INP in the Antarctic exist compared to the Arctic, where concentrations are generally higher (Welti et al., 2020; Creamean et al., 2022; Porter et al., 2022; Tatzelt et al., 2022). In the Arctic, local biological INP are more abundant in summer, and INP-active material can be transported through the ocean, upwell in sea-ice regions and be emitted to the atmosphere (Creamean et al., 2019). Some evidence exists for a wintertime biological INP source from polynyas and leads (Hartmann et al., 2020); however, Arctic winter INP are more likely long-range transported (Creamean et al., 2019; Porter et al., 2022). Terrestrial material transported by river waters or coastal erosion can also contribute to the INP load in Arctic Ocean surface waters (Irish et al., 2019; Barry et al., 2023).

Primary aerosol from sea ice.
Sublimation of blowing snow is an important source of aerosol in the Antarctic in winter and spring (Levine et al., 2014; Giordano et al., 2018; Frey et al., 2020) and possibly in the Arctic (Chen et al., 2022; Confer et al., 2023), although the contributions of the snow-covered ice surfaces and open water (leads, polynas, see above) can be challenging to disentangle. Arctic sea salt-containing aerosol is more prominent in winter (Leaitch et al., 2018; Schmale et al., 2022) despite a larger sea-ice extent, suggesting that primary aerosol sources other than SSA may be important. Antarctic aerosol at coastal and inland sites is persistently depleted in sulphate relative to seawater, and so must be emitted from a fractionated sea-ice source (e.g., Legrand et al., 2017). Frost flowers contribute to snow and ice chemical signatures (e.g., sulphate depletion), but are themselves too rigid to produce aerosols (Roscoe et al., 2011; Willis et al., 2018; Chen et al., 2022). Aerosol composition in blowing snow events mirrors that of ambient Antarctic aerosol (Frey et al., 2020), suggesting an aerosol source from saline blowing snow in which evaporating snow crystals leave behind particles (e.g., Yang et al., 2008; Huang and Jaeglé, 2017). While model parameterizations estimate aerosol emission from blowing snow, they do not take into account non-sea-salt components (e.g., McNeill et al., 2012) and may underestimate particle size and number. Still, these parameterizations can reproduce seasonality in sea salt aerosol in both polar regions (Huang and Jaeglé, 2017; Yang et al., 2019). The contribution of blowing snow to CCN and INP is unconstrained, owing to the challenge of blowing snow event prediction from wind-speed and temperature alone, and uncertainty in the size and composition of suspended snow particles (e.g., Chen et al., 2022).

4.3.2. Secondary aerosol: Aerosol particles produced in the atmosphere from precursor gases

Secondary aerosol from polar open ocean and marginal ice zones.
Arctic and Antarctic new particle formation (NPF) and growth occurs primarily between late spring and early fall (e.g., Croft et al., 2016; Freud et al., 2017; Lachlan-Cope et al., 2020), and can be driven by emission from productive near-ice waters (Willis et al., 2018; Abbatt et al., 2019; Lachlan-Cope et al., 2020; Brean et al., 2021; Quéléver et al., 2022). Despite iodine (HIO_3, I_xO_y, IO) concentrations being orders of magnitude higher than in the Arctic (Raso et al., 2017), the major driver of Antarctic NPF appears to be sulfuric acid (Jokinen et al., 2018; Baccarini et al., 2021). NPF and growth is driven by diverse chemical contributions, from sulfuric acid, methanesulfonic acid (MSA, sourced from DMS oxidation), ammonia, amines and semi-to-low volatility organic vapors (Burkart et al., 2017a; Willis et al., 2017; Willis et al., 2018; Croft et al., 2019; Baccarini et al., 2020; Beck et al., 2021; Chang et al., 2022). These processes can facilitate particle growth to sizes greater than approximately 20 nm, and contribute to polar CCN concentrations (Leaitch et al., 2016).

Predominant particle precursors and key outcomes (e.g., frequency, vertical location, growth to CCN-sizes) differ between the poles. Over the high-latitude Southern Ocean, NPF likely occurs primarily in the free troposphere (McCoy et al., 2021). Over the Antarctic continent and coastal sea ice, topography is such that NPF and subsequent growth occurs in both the near-surface layer and free troposphere (Schmale et al., 2019; Lachlan-Cope et al., 2020). Newly formed particles from aloft mix down toward the surface where they may further grow (Baccarini et al., 2021; Landwehr et al., 2021). Common to the few direct observations of Antarctic NPF is limited particle growth, which may indicate a lack of condensable gases. Summertime NPF in Arctic regions often occurs in the near-surface layer, where low preexisting aerosol surface area can be maintained by efficient scavenging of accumulation mode aerosol (e.g., Burkart et al., 2017b; Lee et al., 2020; Schmale and Baccarini, 2021). Depending on the region, increasing NPF prevalence in Arctic summer is linked to not only changing atmospheric transport patterns (Pernov et al., 2022) but also increasing open water area (Dall'Osto et al., 2017; Dall'Osto et al., 2018). The drivers are unclear; open ocean productivity has increased at the same time that the UIBs have likely become more prevalent (Section 2). Whether this trend will continue in an ice-free summer is unclear (**Figure 2**).

Secondary aerosol from sea ice.
NPF and growth over consolidated pack ice can be driven by transport of precursors or emissions from melt ponds,

leads, and polynyas. Transport of marine aerosol precursors can lead to NPF over coastal and inland Antarctic regions (Weller et al., 2018; Lachlan-Cope et al., 2020). In addition, sea ice sources of low volatility iodine-containing gases, including iodic acid (HIO_3) and iodine oxides (IxOy) are important drivers of NPF and growth (Sipilä et al., 2016; Baccarini et al., 2020; Beck et al., 2021). Emission of iodine-containing gases (Section 4.1) may be driven by autumn sea-ice formation and O_3 deposition at snow and ice surfaces (Carpenter et al., 2013; Baccarini et al., 2020). In the absence of sufficient sulfuric acid, particle growth by HIO_3 condensation can be sufficient to nucleate and grow CCN-sized aerosols (Baccarini et al., 2020).

5. Tools and platforms for new observations and synthesizing existing data

5.1. New and emerging observing tools

New possibilities for understanding the ocean–sea ice–atmosphere system are being opened by recent advances in observing tools and technologies, and novel application of existing tools in polar environments (**Table 1**). Recent developments in satellite remote sensing have facilitated enhanced observations of polar seas, sea ice, and the overlying atmosphere (Pope et al., 2017; Bange et al., 2023; Gabarró et al., 2023). New satellite missions, such as Sentinel-3, provide high spatial resolution observations of oceanographic features, icebergs, and sea-ice extent and properties. Synthetic Aperture Radar imaging technology can operate through clouds, as well as day and night, and is widely used for monitoring sea-ice dynamics. Multispectral and hyperspectral imaging technology have also vastly improved observations of the optical properties of the ocean, including algal blooms. Recent advances in robotics and sensor miniaturization have increased deployments of automated and remotely operated vehicles in polar regions, enabling observations with vertical resolution under ice and within the lower atmosphere. In the ocean, laboratory-based experiments (e.g., cultures of phytoplankton, sea-ice tanks), analysis of archived samples, and new analytical instrumentation (e.g., omics-based approaches) offer additional avenues for progress. In the atmosphere and surface ocean, high time-resolution measurement techniques are enabling direct observation of chemical and physical fluxes, and high time- and spatial-resolution observations of trace gas and particle concentrations. Compromises between time-resolution, chemical specificity, and detection limits remain an ongoing challenge for observations of reactive compounds at low concentrations in the atmosphere and surface ocean.

5.2. Tools and community platforms for connecting and synthesizing existing data sets

In addition to development and deployment of new observing tools, more effort is needed to synthesize already existing knowledge across environmental compartments of the ocean–sea ice–atmosphere system. While many excellent efforts in this area exist (e.g., groups like the Southern Ocean Observing System [SOOS], Antarctic Sea-ice Processes and Climate [ASPeCt], International Arctic Systems for Observing the Atmosphere [IASOA], Svalbard Integrated Observing System [SIOS] and others), some communities studying polar ocean environments have been much more effective in this area than others. Overall, efforts toward a broad, systems-level integration of existing knowledge and data are hampered by disciplinary siloing and lack of common language across communities studying the ocean–sea ice–atmosphere interface (Sections 2–4). As databases of existing observations have become more available in some fields, their inherent value for providing new insights and synthesizing knowledge and for model development has only become clearer (Newman et al., 2019; Swart et al., 2019; Arteaga et al., 2020). Currently available systems often have different goals, such as gathering, curating and linking existing data through a central webpage (e.g., IASOA, SOOSmap, OceanOPS, and SOCCOM), or integrating research efforts across disciplines (e.g., SOOS, and SIOS). Increased use of standard data formats and platforms across the disciplines studying polar ocean and sea ice environments will enable the research community to more easily access data, such as through an online interface that draws data remotely from existing archives. This approach makes data more accessible, while still being maintained by relevant expert communities, and removes the large hurdle of collating multidisciplinary data into a single platform. These goals are consistent with FAIR (Findable, Accessible, Interoperable, Reusable) data principles to increase data reuse and are represented within the aims of the Observing Air–Sea Interactions Strategy (OASIS) initiative (SCOR Working Group 162; Cronin et al., 2023).

6. Knowledge gaps and future directions

6.1. Ocean and sea-ice biogeochemistry

A key question is how changes in the ocean, atmosphere, and cryosphere will impact polar coastal and open ocean biogeochemistry through changes in light fields, nutrient deposition and availability, and productivity in the seasonal ice zone (**Table 2**). Warming and changes in the icescape are impacting ice algae and phytoplankton phenology both within and under the sea ice (Section 2); however, the underlying drivers of shifts in light and nutrient availability remain poorly understood. Quantification of the light field, and its dependence on snow thickness and ice dynamics, will be improved by BGC-Argo floats equipped with PAR sensors (Bisson and Cael, 2021). Sources and sinks of nutrients in sea-ice ecosystems require better quantification, with a focus on nutrient-rich aerosol fluxes (Hamilton et al., 2023), incorporation of seawater components into growing sea ice (e.g., iron, organic and inorganic carbon, salts, brine flushing and release, CO_2 dynamics), and glacier and ice sheet meltwater inputs. Temporal records of polar ocean response to the meltwater input will be facilitated by moorings and ice buoys equipped with BGC sensors, and water samplers located near ice shelves. New observations must focus on under sampled regions and seasons; wintertime observations are still lacking, especially on shallow continental shelves where Argo floats are not yet fully operational. Inaccessible coastal regions can be

Table 2. Summary of knowledge gaps

Knowledge Gap	Observation Gap	Model Gap
Sea Ice Biogeochemistry		
Impact of snow deposition and sea-ice dynamics on light fields	Under and within ice light measurements Baseline record of snow thickness	Light fields within sea ice Multiscale, spatiotemporal variability in light fields
Mechanisms for nutrient and organic matter retention in sea ice	Temporal observations in autumn and winter Improved vertical sample resolution spanning varying ice structures, salinity, and biomass Ice tank experiments targeting nutrient incorporation in sea ice, with and without organic matter Role of exopolysaccharides in this processes	Iron dynamics (e.g., solubility, complexation, precipitation) in sea ice across varying gradients of temperature, salinity, and pH Characterization of turbulent-driven nutrient supply Microbial biofilms and their role in nutrients retention in sea ice
Response of surface ocean nutrient inventory to changes in the cryosphere	Long-term variations and trends in surface ocean nutrient inventory Nutrient content and melt rate of glaciers, ice shelves, and ice sheets Aerosol wet and dry deposition fluxes Trends in nutrient drawdown driven by increasing primary production	Nutrient supply from upwelling, wind mixing, rivers, aerosol deposition, and glacial ice melt Projected future changes in these nutrient inputs
Nutrient uptake by sea-ice algae and polar phytoplankton	Controlled experimentation on polar phytoplankton and sea-ice algae and their responses to environmental change Mapping of elemental ratios in algal cells	Sea-ice specific nutrient uptake, remineralization rates, and elemental ratios
Contribution of the seasonal ice zone to polar ocean productivity	Productivity and PAR in the seasonal ice zone, combined in, over and under sea ice Large scale detection of under ice blooms Export of particles under sea ice Quantification of loss terms: grazing pressure, viral and fungal infection, and microbial loop processes in ice covered waters and sea-ice environments Observations in low production seasons (fall and winter) Algal respiration in sea ice	Model parameterizations for collective ice, under-ice and ice-edge phytoplankton blooms Accurate multiseason assessments
Response of ocean productivity to warming and changes in the icescape	Nutrient (including iron and other bioactive metals) flux from melting cryosphere Response of microbial activity to changing light, nutrient, salinity, and pH conditions Impacts on O_2, CO_2, and other climate active dissolved gases Shifts in phytoplankton and sea-ice algal assemblages and diversity	Functional group and/or species-level variability in acclimation potential and production Characterization of microhabitat-specific changes (e.g., pond vs. bottom-ice communities)

(continued)

Table 2. *(continued)*

Knowledge Gap	Observation Gap	Model Gap
Air–sea Fluxes		
Enhancement or suppression of gas transfer velocity in the presence of sea ice	Direct flux measurements of key species (e.g., CO_2 and CH_4) in a range of sea-ice environments and seasons, co-located with strong ancillary data (ice concentration, dissolved gas concentration, ice motion, currents, and wind)	Parameterizations of air–sea exchange in sea ice regions
Characterization of thin surface water layers in the presence of ice melt	Development of robust sensors that can sample close to the ice/water and water/air interfaces autonomously Development of sampling platforms (UAVs/AUVs, moorings, and ice buoys) that can collect water samples in extreme stratification	The role of stratification in large-scale estimates of gas exchange Vertical resolution of ocean models sufficient to capture thin meltwater layers (typically < 1 m depth)
Quantification of small magnitude air–sea fluxes from intermittently occurring water surfaces on varying spatial scales	Sensitive flux measurement techniques, such as floating chambers or eddy accumulation Further development and application of techniques for improving EC measurement sensitivity, such as flux averaging or intermittent flux measurements, such as wavelet analysis	Parameterization of gas exchange from small-scale open water features
Role of subglacial melt water as a source of climatically active gases (e.g., CH_4 and N_2O)	Sampling subglacial meltwater under ice sheets and in the water column	Parameterization of these sources in coastal regions
Status of current and future polar oceans as a source or sink of CH_4, N_2O, and other climate-active gases	Extensive campaigns to measure dissolved CH_4 and N_2O, coupled with improved parameterizations of transfer velocity	Inclusion of air–sea exchange of CH_4 and N_2O in models of polar ocean regions
Atmospheric Chemistry, Aerosol, and Clouds		
Primary aerosol flux response to warming and changes in the icescape, and implications for ice core reconstruction of past sea ice	Particle fluxes from leads, polynas and MIZ, including temperature dependence and INP activity Aerosol composition and fluxes from blowing snow on sea ice Disentangling sea ice, snow and open water aerosol sources using chemical signatures Aerosol deposition to snow and sea ice surfaces Quantify changes in SSA transport to polar regions	Polar specific primary aerosol flux parameterizations rooted in observations, with temperature dependencies and reliable representation of atmospheric inversion layers Sub-100 nm sea-spray source function Aerosol deposition to ocean, snow, and ice surfaces
Secondary aerosol response to warming and changes in the icescape	Direct measurements of low volatility aerosol precursors (e.g., sulfur & iodine gases) Chemical speciation of reactive carbon, sulfur, nitrogen, and iodine-containing gases Sufficient measurements of aerosol precursor gases to build climatologies Air–sea(ice) fluxes of aerosol precursor gases	Chemical and biological processes underlying emission of aerosol precursor gases Polar-appropriate parameterizations for aerosol formation and growth Coupled sea-ice biogeochemistry and atmospheric chemistry DMS climatologies representative of polar regions

(continued)

Table 2. *(continued)*

Knowledge Gap	Observation Gap	Model Gap
	Dissolved and gas phase trace gas concentrations in under sampled regions, covering spatial heterogeneity, and seasonality	Climatologies of non-DMS trace gases, and parametrization of emissions from ice and ocean
	Direct links to biogeochemistry in sea ice and ocean (e.g., response of key trace gas producers to ice and environmental change)	
Reactive halogen, Hg and oxidant response to changes in sea-ice and snow abundance and chemistry	Chemical and biological mechanisms of reactive halogen release from sea ice, snow, and aerosols	Coupled halogen and Hg cycling
	Physical and chemical transformations in snow and sea ice that control halogen emissions and recycling	Boundary layer and surface stability
	Hg fluxes across sea-ice environments and seasons	Descriptions of halogen and oxidation capacity controls on trace gas oxidation, NPF, and particle growth
	Reactive trace gas abundance, fluxes, and controls on oxidation capacity	Explicit links between sea-ice physical and chemical transformations, halogen emissions and influence on Hg deposition and reemission
	Hg and halogen processes in under sampled regions of the central Arctic and Southern Oceans	Explicit parameterization of snow/ice Hg chemistry and influence of halides on reemission potential
Response of cloud properties to warming and changes in the icescape	CCN & INP abundance, size, chemistry, and sources in under sampled regions and seasons	Feedbacks between ocean, sea ice, and atmosphere
	Aerosol removal in clouds, by precipitation scavenging and dry deposition to ocean, snow, and ice surfaces	Cloud supersaturation and representation of mixed-phase clouds
	Cloud residual composition	Aerosol processes and removal in clouds
	Vertical distribution of CCN & INP	Aerosol deposition to ocean, snow, and ice surfaces
	Cloud supersaturation	Aerosol size distributions, and activation as CCN
		Polar INP parameterizations

accessed using animal-borne sensors, such as those measuring light availability and bio-optical parameters (Labrousse et al., 2018). In-situ observations are complemented by laboratory studies, such as sea-ice tanks and microbial culturing experiments, that can isolate key processes. Important variables and processes include diversity and primary production of algal functional types in sea ice, ice algal growth rates, release from sea ice, heterotrophic remineralization, and transfer and emission of gases.

Numerical models are a key tool to understand the role of BGC processes in polar systems and how this role may be altered in a changing climate. Key directions for future model development include improvements in the vertical distribution of algal biomass in Antarctic sea ice and the sea surface nitrate distribution in the Arctic Ocean (Jeffery et al., 2020), both of which are expected to improve global model estimates for sea-ice algal production. Additional advances in the representation of sea-ice, such as floe size distributions and land-fast sea ice (Hunke et al., 2022), will expand the capability of large-scale models into areas known for highly productive sea-ice habitats and active air–sea exchange.

6.2. Air—sea fluxes

A major challenge is determining gas transfer velocity parameterizations for the open water portion of the icescape (cracks, flaw leads, polynyas, etc.). Presently, we are not confident in whether gas transfer velocity is enhanced or suppressed by the presence of sea ice, though both may occur under different conditions. The continuously moving and deforming sea-ice environment necessitates eddy covariance measurements onboard ships. However, these measurements are challenging because of the (usually) very small flux signals and the mixture of sea-ice and water surfaces in the measurement footprint (on the order of $\sim 1\ km^2$) that can confound the theoretical requirement for homogeneity. Challenges of heterogeneity can be avoided through smaller footprint measurements on lower ice-fixed masts adjacent to open water, but such observations depend on accessibility and bring a high risk of instrumentation loss (Prytherch and Yelland, 2021).

To derive accurate air–sea fluxes in the polar oceans using bulk exchange formulations, we need to develop better ways to determine gas concentrations in surface waters, particularly in thin surface meltwater lenses. An obvious, although extremely challenging, solution is development of robust surface floats and buoys, capable of surviving and staying at the surface through both sea-ice formation and melt, instrumented with geochemical sensors also able to survive the winter season. Remote sensing observations will help identify how surface water chemistry and ice concentration evolves in different regions and across seasons. Time-resolved information from multiple sensors can provide insights into ice and river plume dynamics (optical remote sensing), surface salinity (passive microwave), and wind speeds (scatterometer or altimeter). Machine learning and neural network-based methods are showing potential to provide new tools to develop integrated understanding from sparse observations (e.g., Chen et al., 2019; Gloege et al., 2022). Nonetheless, in order for either remote sensing or machine learning to be effective, they need to be fed and evaluated with more in-situ data. Therefore, we encourage field scientists working in the polar oceans to collect more "bucket" surface water samples on their expeditions, or to deploy instruments capable of measuring near-surface gas concentrations. Such data need to be archived along with their rosette and underway data sets, so that they can be used to develop better algorithms for true surface conditions.

6.3. Atmospheric chemistry, aerosol, and cloud nuclei

A central question is how warming and changes in the icescape are impacting atmospheric oxidation capacity, Hg deposition, and aerosol and cloud nuclei (i.e., both CCN and INP) concentrations. The magnitude and direction of future changes are uncertain (**Figure 2**, **Table 2**), in part because of poorly understood connections with biological, chemical, and physical processes in the ocean and sea ice. Major knowledge gaps remain across aerosol emission, formation and loss processes; the identity, emission fluxes, and fate of reactive trace gases; and interactions between the atmosphere, sea ice, and snow on sea ice (**Table 2**). Flux observations of both reactive trace gases and particles are lacking, including emission and deposition to ocean, snow and ice surfaces; such measurements may motivate polar-specific flux parameterizations (Section 3). Molecular-level understanding of particle formation and growth will be improved by direct measurements of sub-100 nm particle composition and aerosol precursor gases (e.g., Schmale and Baccarini, 2021). Future observations should target a range of ROC, sulfur, nitrogen, and halogen-containing trace gases in both the atmosphere, surface ocean, and sea ice. The chemistry of snow on sea ice exerts a key, and poorly understood, control on oxidation capacity, Hg cycling, and primary aerosol production (e.g., McNeill et al., 2012; Simpson et al., 2015; Frey et al., 2020). Past observations focused on air–snow–ice chemical interactions, in the context of ice core interpretation, can now be used to better understand aerosol emission and deposition in sea-ice regions (e.g., Levine et al., 2014; Rhodes et al., 2017). However, even with new observations across these areas, a persistent challenge is that atmospheric observations and modeling are frequently disconnected from relevant ocean and sea ice processes (Section 2 and 3).

New observations are needed across heterogeneous sea-ice types, seasons, and polar ocean regions. Long-term observations (Section 7.1) are needed to address year-to-year variability, trends and seasonality of aerosol, cloud nuclei (CCN and INP), reactive trace gases and oxidants (e.g., Peterson et al., 2016; Lachlan-Cope et al., 2020; Lubin et al., 2020; Creamean et al., 2022; Boyer et al., 2023). Seasonal observations of trace gases will inform on whether ice-melt driven production processes are relevant during the autumnal ice-formation period (e.g., Baccarini et al., 2020), and the role of halogen production and oxidation processes in the dark wintertime (e.g., Abrahamsson et al., 2018). Vertically resolved observations are needed to better understand aerosol–cloud interactions, local and remote aerosol sources, and particle production mechanisms. In addition, many regions of both polar oceans remain under-sampled, including the Central Arctic basin and much of the Antarctic and high-latitude Southern Ocean. New observations should focus on expanding regional coverage across the heterogeneous polar oceans.

7. Cross-disciplinary linkages required to deliver this research

7.1. Long-term observations

Sustained, long-term observations of essential variables must be expanded to achieve a system-level understanding of changing polar ocean and sea-ice environments. At the same time, existing observations and archived samples must be leveraged using new technologies and approaches (e.g., Moschos et al., 2022). A particular challenge for long-term observatories in the polar oceans is development of surface platforms that can not only survive both freeze-up and melt while staying at the surface but also host sensors to monitor BGC and physical variables in both the oceanic and atmospheric boundary layers. Substantial progress has been made in designing and building robust sea-ice buoys (e.g., Knepp et al., 2010; Berge et al., 2016; Hill et al., 2022), but the problem remains that the vast majority of the sensors we would like to deploy on such buoys are not sufficiently robust, and a step-change is required in how we design and build chemical sensors for deployment in the polar regions. Surface platforms in the polar oceans can only be drifters, not moorings, and therefore shore-based stations are currently the only practical in-situ platforms available for collecting long-term time series of air–sea interactions in the polar regions. Thus, our communities must also better leverage satellite-based remote sensing observations to expand seasonal and long-term coverage of variables relevant to air–sea exchange (e.g., Pope et al., 2017; Shutler et al., 2020; Gabarró et al., 2023). Examples of successful and impactful, and emerging, cross-disciplinary efforts exist (Lee et al., 2019; Newman et al., 2019; Smith et al., 2019; Swart et al., 2019); however, our system-level understanding is hampered when these efforts do not link and cover essential variables across the ocean–sea ice–atmosphere interface (e.g., Thomas et al., 2019) and incorporate a wide range of expertise in modeling, in-situ and remote sensing observations (e.g., Green et al., 2021). Even as observational coverage in polar ocean regions has improved significantly in the past decades and satellite remote sensing has provided better access to polar regions, major gaps exist outside the summer seasons, in the ice-impacted ocean, at the ocean–sea ice–atmosphere interface, and for both biological and chemical variables across the interface (e.g., Newman et al., 2019). Our communities must collectively develop an approach to bridge the inherently disparate timescales of ocean and atmospheric measurements, for example, through distributed sensor/buoy networks in the ice and ocean, coupled with time-series measurements of ocean, ice and atmosphere essential variables. Coordinated efforts across nations and disciplines have an important role to play in bringing together our communities to improve our long-term observing capability (e.g., Steiner and Stefels, 2017; Thomas et al., 2019; Cronin et al., 2023; Mallet et al., 2023).

7.2. Concerted modeling efforts

While sea-ice and ocean biogeochemistry, and atmospheric chemistry are tightly coupled, very few models representing ocean–ice–atmosphere exchanges include sea-ice biogeochemistry, let alone the links with the atmosphere. This is in part due to a still limited understanding of these processes and uncertainties in their representations across models at different scales, from one-dimensional models, to regional and Earth System models. Model uncertainty is driven by our limited understanding of relevant processes, limited spatial and temporal coverage of observations, and consequent limited ability to build adequate model parameterizations. Concerted model intercomparisons, such as the Ice Algae Model Intercomparison Project (Watanabe et al., 2019; Hayashida et al., 2021) and intercomparisons for ocean primary production (Vancoppenolle et al., 2013) and ocean acidification (Steiner et al., 2014) are an important tool to identify where limited process understanding and parameterization development leads to differences between models. A key focus going forward should be on improved representation of coupled ocean–ice–atmosphere processes in models across different temporal and spatial scales, which will help us to better interpret observations and understand links to climate change impacts.

7.3. Coordinated multidisciplinary observations

The different temporal and spatial scales of atmospheric and oceanographic measurements pose a particular challenge in designing integrated field studies in the polar oceans, where sea-ice dynamics and variability impose further constraints on our ability to measure key variables with adequate spatial and temporal coverage. Even when atmospheric scientists and oceanographers gather explicitly to design a joint field program, the group can easily devolve into separate atmosphere and ocean camps that require fundamentally different ship operations to reach their goals. The only way to resolve this dynamic is to focus concerted efforts toward building a common language and to identify ways to study the keystone processes that link our realms across the ocean–sea ice–atmosphere interface. International efforts are ongoing and emerging to provide community guidance for designing process-based interdisciplinary studies that can integrate atmospheric, ocean, and sea-ice observations and for establishment of essential variables (e.g., SOOS, BEPSII [https://sites.google.com/site/bepsiiwg140/home], CATCH [https://www.catchscience.org/home], PICCAASO [https://www.piccaaso.org/], and SCOR Working Groups, including working groups 152 ECV-Ice, 163 CIce2Clouds, and 166 DMS-PRO). Such groups are coming together to produce actionable recommendations that will be critical for future coordinated multidisciplinary observations.

7.4. Integrated model-observation efforts

A key and ongoing need is for close, two-way collaboration between observationalists and modelers to improve our system-level understanding, advance collective parameterization development, and improve understanding of observations (Steiner et al., 2016). Our communities must prioritize training of early career scientists in this cross-disciplinary context, to give them the tools to approach their science questions from an integrated observational and modeling perspective. Field observations and laboratory/mesocosm studies must be designed to facilitate model development (Newman et al., 2019). Observations in remote and pristine regions are key for constraining model uncertainty (Regayre et al., 2020). However, a challenge is the dichotomy between the type of measurements needed to target process-level understanding and the broad temporal and spatial scale of observations needed to constrain large-scale models. Observational efforts should be designed to fulfill both priorities. Further, modeler-observer collaboration should target conceptual models, to motivate development of process-level numerical models and inclusion of relevant processes in regional and Earth system models. Such efforts are needed to resolve persistent issues, such as model representation of CCN numbers over the high-latitude Southern Ocean (Schmale et al., 2019; McCoy et al., 2020; Landwehr et al., 2021), and are ongoing in international efforts under the purview of the SOLAS Polar Oceans and Sea Ice Theme, such as SCOR Working Group 163 – CIce2Clouds.

8. Social and global relevance

8.1. Polar governance

The Arctic Council supports extensive monitoring and assessment, and derives policy recommendations based on those assessments (for a summary on the proceedings over time in the context of ocean acidification and climate change see Steiner and VanderZwaag, 2021). However, beyond those assessments, efforts to address mitigation and adaptation to ocean acidification by the Arctic Council have been very limited. While much of the economic interest is on fisheries, the reference to science, monitoring and environmental protection includes SOLAS-relevant topics, most prominently the exchange of climate-active gases and ocean acidification. Ecosystem functions related to regulating ecosystem services includes functional diversity, which is likely to respond positively to protection.

Human activities in the Southern Ocean (including science, tourism and fishing) are managed in accordance with objectives and provisions of the Antarctic Treaty System (ATS), which comprises the 1959 Antarctic Treaty and its related international agreements. Scott (2021) discusses the ATS in the context of ocean acidification and emphasizes that despite strong environmental principles, none of the ATS instruments creates obligations to mitigate or prevent ocean acidification or climate change. This reflects that the ATS instruments provide for the governance and management of human activities in the Antarctic region, including response and adaptation to external threats, but they do not have the scope to directly address the sources of global pressures. Accordingly, simultaneous action through the ATS and through relevant global frameworks, such as the United Nations Framework Convention on Climate Change, is necessary to achieve the general ATS obligation to comprehensively protect the Antarctic environment, and dependent and associated ecosystems.

8.2. Climate mitigation, adaptation, and intervention in polar ocean and sea-ice environments

As concern about climate change has finally taken root throughout the general population, many proposals for intervention have emerged, and the polar regions are not exempted. Ideas to increase oceanic primary production through ocean fertilization and enhance the planetary albedo have not only been proposed but in many cases are actively being developed. Among the more dramatic proposals are those to restore Arctic sea ice, in order to increase albedo and slow ocean warming. Two methods have been suggested to accomplish this, including pumping seawater to the surface of the ice during winter, when it will rapidly freeze and thicken the ice (Desch et al., 2017), and spreading highly reflective glass microbeads over the ice to reduce its melt rate (Field et al., 2018). Whereas physical climate models indicate that either of these methods could increase the planetary albedo, if deployed on a large enough scale, both could have wide ranging impacts on polar ecosystems and air–sea exchange, which would likely extend to temperate oceans and other Earth system compartments (Miller et al., 2020).

The scope for restoring degraded coastal ecosystems may not be as great in the polar oceans (where ecosystem degradation has been slower) as at lower latitudes. However, as sea-ice retreats and the oceans warm, kelp and seagrass species may be migrating northward and increasing their biomass in the Arctic (Krause-Jensen et al., 2020; Filbee-Dexter et al., 2022). Conversely, the potential for changing coastal ecosystems to increase carbon drawdown and sequestration in the polar oceans may be limited by confounding factors, such as increased turbidity from rivers and wind-mixing (Bonsell and Dunton, 2018). Regardless of whether the approach to climate intervention is technological, based on enhancing natural processes, or a combination of the two, there will be side effects, unintended consequences, and fringe benefits. SOLAS science, with our unique perspective on how the atmospheric and oceanic realms interact to control climate, has an important role to play in evaluating the efficacy of proposed interventions and predicting their consequences.

9. Conclusions

This article brings a SOLAS perspective to the impacts and consequences of climate change on polar environments. The sea-ice ecosystem supports all ecosystem service categories (Steiner et al., 2021); most relevant for SOLAS are climate regulating services, including sea-ice associated BGC processes which produce aerosol and aerosol precursors and modify atmospheric oxidation capacity and the exchange of greenhouse gases.

Progress on open questions at high latitudes is hampered by the logistical constraints associated with sea ice observations, with deployment of traditional platforms and interpretation of satellite observations presenting particular challenges and complications. Many state-of-the-science measurement techniques for air–sea gas fluxes and aerosol composition have only been very recently deployed in polar regions and require dedicated deployment of nonautonomous instrumentation aboard research vessels. Advances in remotely operated platforms and sensor miniaturization are enabling new observations in the polar ocean–sea ice–atmosphere system, including under sea ice and vertically through the lower troposphere.

Key knowledge gaps that prevent meaningful prediction of climate-driven changes in sea-ice environments (**Figure 2**, **Table 2**) highlight interconnections between sea-ice biogeochemistry, air–sea fluxes, and atmospheric composition and chemistry. Recent advances made in these areas demonstrate the need not only for improved observational coverage across seasons and heterogeneous sea-ice environments but also for better connection of observations with models across scales. Only with a broader understanding of the system across seasons and icescapes will we be able to predict the impacts of warming and changes in the icescape on sea-ice biogeochemistry, air–sea fluxes of greenhouse gases, particles and aerosol precursors, and resulting implications for the atmosphere. Observations and modeling in polar regions remain largely uncoupled, which has impeded progress in our understanding of major interconnected processes across the ocean–sea ice–atmosphere system. Better knowledge of these interactions is required to predict sea-ice impacts on aerosol, trace gases, and cloud cover over polar oceans, which in turn affect sea-ice melt and freezing and BGC activity through nutrient and light availability.

Changes in the polar regions will strongly impact the sea-ice and polar ocean system, along with its role in regulating the polar atmosphere, clouds, and climate. The interactions of sea ice and polar seas with fringing ice shelves adds another level of complexity and uncertainties in the ocean–sea ice–atmosphere system. The ongoing loss of continental ice, and associated increase in glacial erosion and riverine inputs, are likely to further alter the uptake and emission of bioactive gases at both poles.

The only viable mitigation measure to preserve the unique polar ocean–sea ice–atmosphere system, and the ecosystem services it provides, is a rapid and sustained reduction in carbon emissions. Our communities studying polar oceans and sea ice are beginning to mitigate the environmental impacts of our own research activities through the new tools and technologies we discuss in this article, including satellite remote sensing approaches, remotely operated observation platforms, floats, and buoys. However, there remains a strong need for in-situ observations, which motivates the use and development of research vessels powered by low-carbon, alternative fuels. Alongside the promotion of more sustainable fieldwork practices, this highlights the pressing need for initiatives like RISE (Responsible Science Initiative, under the umbrella of the MOSAiC expedition), which actively influence and contribute to more environmentally responsible practices in polar research.

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