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COMMENTARY

Untangling the influence of Antarctic and Southern Ocean life on clouds

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Polar environments are among the fastest changing regions on the planet. It is a crucial time to make significant improvements in our understanding of how ocean and ice biogeochemical processes are linked with the atmosphere. This is especially true over Antarctica and the Southern Ocean where observations are severely limited and the environment is far from anthropogenic influences. In this commentary, we outline major gaps in our knowledge, emerging research priorities, and upcoming opportunities and needs. We then give an overview of the large-scale measurement campaigns planned across Antarctica and the Southern Ocean in the next 5 years that will address the key issues. Until we do this, climate models will likely continue to exhibit biases in the simulated energy balance over this delicate region. Addressing these issues will require an international and interdisciplinary approach which we hope to foster and facilitate with ongoing community activities and collaborations.

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Introduction

The Southern Ocean and Antarctica are distant from human sources of atmospheric pollutants, instead being dominated by natural aerosol and vapors (Hamilton et al., 2014). These natural aerosol and vapors are mostly formed through an intricate process of emission by biological organisms modulated by biogeochemical processes, as well as sea spray production. Aerosol particles seed clouds that can produce rain and snowfall, and reflect energy back to space or trap it in the lower atmosphere (**Figure 1**).

Recent targeted field campaigns (e.g., Fossum et al., 2018; Schmale et al., 2019; Webb et al., 2019; McFarquhar et al., 2021; Sellegri et al., 2023) have measured aerosol, reactive gases, and cloud properties to describe these processes more quantitatively. New datasets from these campaigns have been instrumental in tailoring our models of the Earth's systems to more realistically represent the Southern Ocean. For example, these datasets have been used to build new global climatologies of important marine biological compounds (Hulswar et al., 2022), to constrain uncertainties in Earth's radiation budget (Regayre et al., 2020), and to develop new parameterizations of aerosol emissions (Hartery et al., 2020; Sellegri et al., 2021) and growth (Revell et al., 2019). We have also learned a lot from these measurements about the delicate balance between liquid and ice clouds at subfreezing temperatures (Zaremba et al., 2020; Alexander et al., 2021; D'Alessandro et al., 2021; Mace et al., 2021a; Zaremba et al., 2021), the potential role of biological particles in cloud-ice formation (McCluskey et al., 2018; Uetake et al., 2020), ice multiplication processes (Järvinen et al., 2022), and dynamical processes (Wang et al., 2020; Schima et al., 2022) in this balance. This knowledge has guided improvements in how these clouds are simulated in various Earth System Models (McCluskey et al., 2019; Atlas et al., 2020; Gettelman et al., 2020; Vignon et al., 2021).

Findings from these campaigns have highlighted that biological organisms in Southern Ocean surface waters and Antarctic sea-ice have a potentially large influence on our atmosphere (Landwehr et al., 2021; Mace et al., 2021b; Rocco et al., 2021; Twohy et al., 2021; Dall'Osto et al., 2022). But these campaigns have also revealed major gaps in our understanding of complex processes influenced by these organisms. Despite the recent progress, our climate models still require improvements in their representation of aerosol and cloud processes operating in the Southern Ocean and Antarctica (e.g., Gettelman et al., 2020). New multidisciplinary observations are needed to build upon, evaluate, and challenge what we have already learned.

The latest generation of climate models, prepared for the recent Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6), still show significant biases in the amount of sunlight reaching the surface of the Southern Ocean (**Figure 2**) compared to satellite observations. This is a clear indication that we

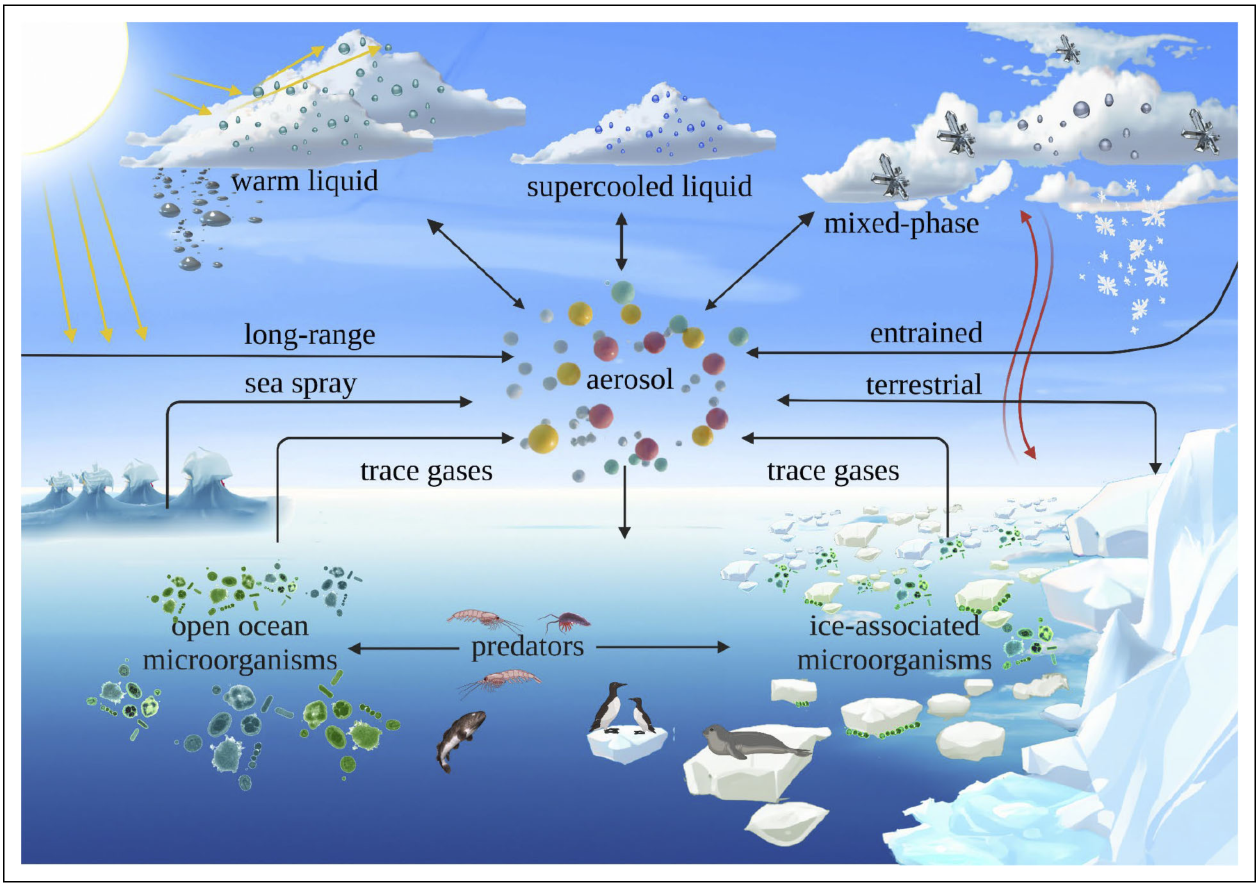

Figure 1. Interactions between microbiota, gases, aerosol, clouds, radiation, and precipitation in the Southern Ocean and Antarctic.

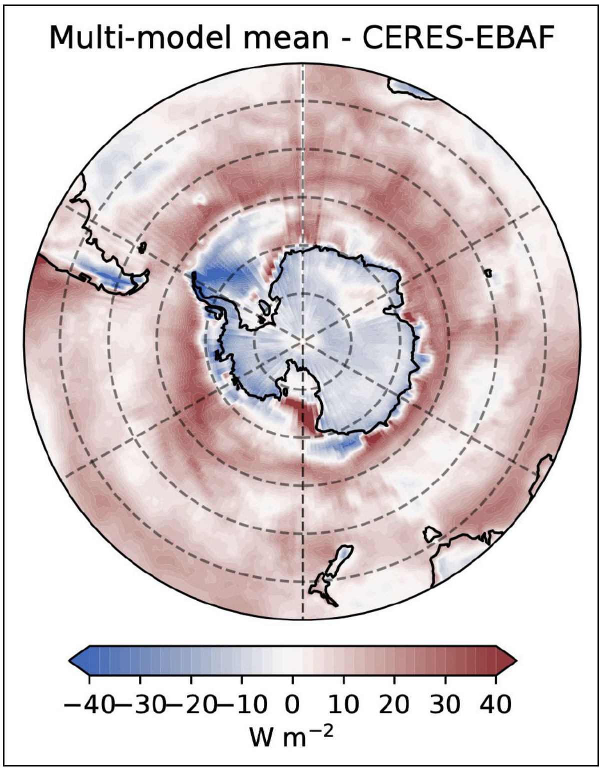

Figure 2. The mean austral summer time bias in the amount of sunlight reaching the surface (incoming shortwave radiation) in 22 of the Coupled Model Intercomparison Project phase 6 (CMIP6) models which fall into the "likely" range of equilibrium climate sensitivity with respect to the CERES-EBAF satellite product (W m^{-2}). See the Supplementary Material for more details for the CMIP6 models.

still have a long way to go in understanding how clouds form and evolve in this region, and in implementing this knowledge into our climate models. While meteorological processes play an important role in the energy balance of Earth's surface, we also need to describe and quantify how biological organisms influence the chemistry and physics of the atmosphere. Until we do this, it is unlikely that we will be able to accurately predict precipitation and the energy balance, with acceptable precision, in a region sensitive to both.

The consequences of these gaps in our knowledge extend beyond Antarctica and the Southern Ocean region. Aerosol emitted by human activities have offset roughly a third of the warming from anthropogenic greenhouse gases at the global scale (Forster et al., 2021). For any future pathway of greenhouse gas emissions, the biggest source of uncertainty is how interactions between aerosol, clouds, precipitation, and radiation will change. This uncertainty stems from a lack of understanding of both the sources of natural aerosol (Carslaw et al., 2013) and how they interact with clouds and sunlight (Forster et al., 2021). Over most of the planet, aerosol particles in the present day are markedly different from the preindustrial era on a global scale (Hamilton et al., 2014). The overall influence that aerosol particles have on present-day climate is therefore different from the preindustrial era. Ice cores have been vital in extending the short instrumental records of aerosol composition from decades to millennia. While deep ice cores are valuable archives of natural aerosol and atmospheric composition (e.g., Goto-Azuma et al., 2019), they do not provide direct information about aerosol and cloud processes in the distant past.

Our best path forward is to explore the regions furthest away from human populations, like Antarctica and the Southern Ocean with state-of-the-art measurements, experiments, and models. This natural, pristine region, relative to other regions of the Earth (Hamilton et al., 2014), is the closest environment we have to a preindustrial baseline that we can use to assess human impacts on our atmosphere. Despite its remoteness, the Antarctic and Southern Ocean environment has experienced changes since the industrial revolution. Well-mixed greenhouse gases are far reaching, stratospheric ozone depletion has caused changes in dynamics (Bhatti et al., 2022), and with tourism around Antarctica on the rise, the threat of local pollution from fossil fuel combustion will also increase (Cordero et al., 2022), on top of increases in contaminants such as persistent organic pollutants, heavy metals, and microplastics (McConnell et al., 2014; Krasnobaev et al., 2020; Aves et al., 2022). Antarctica has also not yet seen the same scale of abrupt changes as the Arctic in response to recent warming (Gulev et al., 2021). We need to understand aerosol-cloud processes and their climate impacts in the Antarctic and Southern Ocean region before they are further impacted by ongoing anthropogenic changes. To do this, new and integrated observations and modeling efforts over larger spatial and temporal scales are needed.

More attention needs to be given to the interactions between biology, aerosol, and clouds in the Southern Ocean and Antarctic region. Field data are logistically challenging to obtain, and interactions hard to measure. Field measurements should be augmented by laboratory studies targeting fundamental processes, which can then be used to inform models at all scales. Modelers need a breadth of expertise covering each of these fields. It is also essential to have modelers involved in field and laboratory experimental design in coherent research programs. Leveraging the expertise of modelers will help ensure that the most appropriate experiments are conducted such that the knowledge can be translated to model improvements. This will deliver us the best opportunity at reducing climate model uncertainties (Regayre et al., 2020) and give more confidence in our future projections.

At the moment there is limited integration between the scientific disciplines of ocean and sea-ice biogeochemistry and atmospheric chemistry and physics. While this is natural given that there are still fundamentals within each discipline that we are still trying to understand, now is the time to harmonize and work on understanding coupled processes together. We need a coordinated, collaborative, and internationally integrated approach. We require expertise from scientists making observations of the physics, chemistry, and biology of the ocean, cryosphere, and atmosphere (Thomas et al., 2019; Paton-Walsh et al., 2022), as well as sophisticated methods to bring these data together (e.g., Landwehr et al., 2021).

The Antarctic and Southern Ocean region is a complex and diverse system. Local physical processes and ecosystem structures and functions vary drastically longitudinally and along strong latitudinal gradients (Dall'Osto et al., 2017; Landwehr et al., 2021; Dall'Osto et al., 2022). These include phytoplankton community structure and phenology as well as interactions in microbial and higher-trophic level food webs and the presence or absence of light and micronutrients like iron. These interactions, along with physicochemical drivers such as temperature, wind speed, and acidity determine the amount and diversity of emissions into the atmosphere. The presence of different types and stages of growth and melt of sea-ice, which fluctuates by millions of square kilometers every season, modulates these interactions. Even in the open ocean, processes differ at higher and lower latitudes. We don't know how sensitive atmospheric chemistry and clouds are to spatial as well as temporal variability in sea-ice dynamics and ecosystem processes.

If we do not understand these interactions now, we cannot predict how sensitive they are to future climate change. We must address these complexities while Antarctica and the Southern Ocean are still mostly close to their pristine preindustrial states. In this commentary, we define the most urgent research priorities. We determined these priorities by identifying gaps in our understanding of the coupled biogeochemical and atmospheric processes around Antarctica and the Southern Ocean, incorporating insights from recent measurement and modeling efforts. We then outline near-term field projects planned to address these priorities. Many of these field projects were conceptualized independently but share common objectives. This highlights the urgency and international recognition of our need to investigate the links between ocean and ice biology with the atmosphere in this remote region. By unifying our efforts, we aim to provide the most comprehensive understanding of how Antarctic life influences climate.

Research priorities

1. The biogeochemistry of the Southern Ocean and Antarctic sea-ice environments

Marine microbes, including bacteria, phytoplankton, and ice algae, can produce a range of compounds which can be emitted to the atmosphere (Carpenter et al., 2012; Carlson and Hansell, 2015; O'Dowd et al., 2015; Wohl et al., 2023). Different algal species throughout their life cycle produce varying quantities and types of carbon-, sulfur-, nitrogen-, and halogen-containing (organic) molecules. However, the production, transport, and exchange processes of these compounds at the ocean- and sea-ice-atmosphere interfaces are difficult to quantify. This leads to large uncertainties in the inventories used to describe these emissions in Earth System Models.

The abundance and diversity of microalgae, and what they emit, is driven by a range of complex factors. These include oxidative and heat stresses, the availability of nutrients and light, and the dynamics of the ecosystem that include the organisms that interact with them, including phytoplankton, zooplankton, bacteria and viruses, and their predators (Simó, 2001). Comprehensive and simultaneous measurements of microbial food webs and the sulfur and organic compounds they produce, in the water and in and under sea-ice, are rare. Satellite measurements of chlorophyll a, the main photosynthetic pigment, are often used as a proxy for phytoplankton abundance and their byproducts. While useful to infer qualitative biological links between the ocean, sea-ice and atmosphere (e.g., Dasarathy et al., 2021), chlorophyll a does not indicate when, where, how much, and what material plankton emits into the atmosphere (Burrows et al., 2014; O'Dowd et al., 2015; Mahajan et al., 2019; Hulswar et al., 2021; Rocco et al., 2021). Satellites are not able to detect chlorophyll through clouds and sea-ice, which is problematic given the high cloud fractions (typically >80%, [Mace et al., 2009; Kay et al., 2016]) and sea-ice coverages over the Southern Ocean. Furthermore, ocean-ice-ecosystem models usually determine chlorophyll a based on simulated phytoplankton concentrations and assumed ratios of chlorophyll a with carbon or nitrogen. This is not necessarily consistent among models and can cause inconsistencies in how these models are evaluated (Steiner et al., 2016b). We therefore need more spatial and temporal in situ observations that are linked to ecosystem dynamics and their physical environment to identify key processes and key species relevant for atmospheric emissions. Representation of these ecosystems in Earth System Models is also still in its infancy but rapidly developing (Bonan and Doney, 2018; Tedesco et al., 2019; Bock et al., 2021; Hayashida et al., 2021). The challenge will be guiding this development in a way that represents reality while still being computationally feasible to run in an Earth System Model.

2. The composition of the lower atmosphere

Organic and inorganic materials that are transferred from the ocean and ice play a key role in aerosol production and cloud formation. While quantifying the production of organic material from biological processes in the ocean and sea-ice is a significant challenge, this is further compounded with a poor understanding of how material is actually transferred into the atmosphere (Hartery et al., 2020; Wohl et al., 2020; Landwehr et al., 2021). Sea spray from breaking waves and bubble bursting is an important mechanism for emitting these organic and inorganic compounds from the top layers of seawater as primary aerosol, while reactive gases are also released as a complex function of wind speed and temperature (Tesdal et al., 2016; Bell et al., 2017). Blowing snow is also an important but poorly constrained source of sea salt aerosol over the Antarctic continent and coast, with consequences for cloud formation and halogen chemistry (Yang et al., 2008; Huang and Jaeglé, 2017). The uncertainty of the flux of particles and gases at the interface of the sea and ice surfaces and atmosphere must be tackled. Both controlled laboratory experiments (e.g., Rocco et al., 2021) are needed to understand the physical and chemical processes as well as field experiments to put them into a broader context. Knowledge from these measurements can be used in conjunction with models to understand the sensitivity and consequences of the fluxes of compounds into the atmosphere (Steiner et al., 2016a).

Once emitted, aerosol particles and reactive gases undergo complex chemical transformations in the atmosphere. These newly formed products can transition between the gas and condensed liquid or solid phase, although many chemical processes remain to be discovered before we are able to realistically represent them in numerical models (e.g., Baccarini et al., 2021). Sea spray aerosol particles can act as a surface that organic, sulfur, and to a lesser extent, nitrogen vapors can condense onto, facilitating growth and other chemical reactions. Under the right conditions, those vapors have the opportunity to nucleate new aerosol particles. We know that sea spray together with new particle formation processes in the free troposphere above the planetary boundary layer are responsible for forming the vast majority of cloud-relevant aerosol over the Southern Ocean (McCoy et al., 2015; Fossum et al., 2020; McCoy et al., 2021; Moallemi et al., 2021; Dall'Osto et al., 2022). Further complicating this is the potential role that precipitation has in scavenging aerosol populations (Kang et al., 2022). Where, when, and how these processes work is not yet fully addressed.

Most efforts so far have focused on wind-driven sea spray aerosol, and the emission and fate of sulfur species, such as dimethyl sulfide released through algal and bacterial activity (Stefels et al., 2007) produced by algae and mainly bacteria. Although there are large uncertainties in the emission (Hulswar et al., 2022) and chemistry (Veres et al., 2020) of well-studied compounds like dimethyl sulfide, we might also be critically underestimating the importance of other reactive trace gases and biological particles. A role for nitrogen gases (ammonia and methylamines) in facilitating nucleation of sulfuric and methanesulfonic acids over Antarctic waters has only recently been realized (Jokinen et al., 2018; Brean et al., 2021), and a new particle formation role for iodine has also been suggested in coastal areas (Sipilä et al., 2016). The role that terrestrial aerosol particles play, such as those emitted on the coast and in dry valleys of Antarctica, is still not known. We need detailed measurements of the abundance, size, and composition of the aerosol particles in different regions around Antarctica, above open ocean and sea-ice, in different seasons and at different altitudes above the surface. These measurements must be linked with the physics, biology, and biogeochemistry of the water and sea-ice, preferably with coincident in situ observations but also with controlled tank experiments in the laboratory and in mesocosms.

3. Biogeochemical links to clouds and precipitation

Every cloud droplet is formed on the surface of an aerosol particle. If aerosol particles are large enough and have an affinity for water, they will act as cloud condensation nuclei. The number, size, and composition of aerosol, whether from sea spray or the condensation of biogenic gases, is crucial for determining the number of droplets in clouds. Adding to this complexity is the prevalence of supercooled liquid water clouds, which contain liquid droplets below 0°C. These supercooled liquid water clouds occur more frequently over the Southern Ocean than anywhere else in the world given comparable temperatures and supersaturations (McFarquhar et al., 2021), a feature of the atmosphere that climate models fail to capture. A leading hypothesis for the high occurrence of supercooled liquid clouds is that this is due to a low abundance of ice nucleating particles over the Southern Ocean, which would allow droplets to freeze at subzero temperatures down to approximately −38°C (McCluskey et al., 2018; Vergara-Temprado et al., 2018; Vignon et al., 2021). Unlike dusty and polluted regions elsewhere, ice nucleating particles over the Southern Ocean might mostly originate from organic or primary biological material mixed up in sea spray aerosol (Moallemi et al., 2021), but we still lack sufficient data to prove this (Burrows et al., 2022). The delicate balance of liquid cloud droplets and ice crystals, influenced by aerosol as well as surface, radiative, microphysical and thermodynamic processes, moderates when and where clouds rain or snow, and determine the vertical profiles of radiative and latent heating and cooling.

While measurements of cloud, precipitation, and aerosol properties have been collected in several recent voyages, the data remain geographically sparse and focused mostly on the East Antarctic summer. Additional measurements that broaden this data set to include different geographic regions and meteorological and seasonal conditions need to be collected simultaneously with measurements of relevant ocean biology, chemistry, and fluxes of trace gases and primary aerosols.

4. Separating biogeochemical and physical influences

The links between ocean and sea-ice biology, aerosol, and clouds are underpinned by various physical processes. In the atmosphere, the structure of the lowest layer of the troposphere is governed by oceanographic and surface properties, including the presence of sea-ice, as well as by meteorological forcing including the thermodynamic structure of the lower atmosphere (Landwehr et al., 2021). Extratropical cyclones and frontal systems play an important role in day-to-day variability. On a larger scale, the division between the Polar and Ferrel atmospheric circulation cells acts as a barrier, with the strong surface westerlies in the Ferrel cell to the north and easterlies in the Polar cell to the south. Climate modes of variability such as the Southern Annular Mode, the El Nino-Southern Oscillation, and the Indian Ocean dipole introduce variability into these systems on timescales that can last months or years. These physical processes drive the transport of moisture and aerosol vertically and horizontally in the atmosphere, facilitating cloud formation and precipitation. Further, the relative importance of secondary cloud ice formation processes (e.g., rime splintering, fragmentation of freezing drops, ice-ice collisions, and sublimation fragmentation [Zhao and Liu, 2022]) over the Southern Ocean also needs to be further explored (Atlas et al., 2022; Hoose, 2022).

As sea-ice forms, melts, and then refreezes, this can create key differences in the structure of the sea-ice. These processes impact the growth of sea-ice biology (Steiner et al., 2016a). For example, new ice forming below existing solid sea-ice layers can facilitate the vertical movement and growth of algal material within the ice. Alternatively, heavy snow can push down floating ice allowing algal material from the ocean to infiltrate into the complex layers of ice and snow. This can allow favorable growth conditions resulting in extremely high biomass in these so-called gap layers (Kattner et al., 2004). Outside of sea-ice, ocean dynamics also play an important role in the vertical and horizontal transport of heat, salt, and biological material. These processes govern not only the production of ocean and sea-ice biology but also the timing and location of when this material is exposed to and emitted into the atmosphere.

It will be important to understand, observationally and with model output, the links from biological sources to clouds in the context of these complex sea-ice, weather, and climate phenomena. While physical processes including ocean circulation and sea-ice dynamics influence atmospheric processes that drive cloud and precipitation formation, they also underpin the properties and evolution of biological ecosystems themselves. How all these processes will evolve with climate change isn't clear (Twohy et al., 2021). The interplay and feedback between these Antarctic and Southern Ocean biological, chemical, and physical processes on short and long-time scales further highlights the need for an interdisciplinary approach.

5. Interactions with other chemical, biological, and physical systems

Establishing the links between biogeochemistry, aerosol, clouds and other chemical, biological, and physical systems within the Southern Ocean and Antarctic environment is an important research priority. For example, the presence of aerosol has important implications for the lifetimes and concentrations of other inorganic chemicals in the atmosphere including mercury, ozone, nitrogen oxides, and halogen species. Salty snow (including on sea-ice) and sea salt aerosol are the main sources of reactive bromine and reactive chlorine to the lower atmosphere. For iodine, which is a more potent ozone destruction agent, the sources are far less understood. These chemicals have implications for the oxidative capacity of the atmosphere (Saiz-Lopez et al., 2007; Abbatt et al., 2012; Simpson et al., 2015).

Aerosol particles are key species that sustain chemical cycles by providing surfaces for multiphase chemistry and facilitating removal from the atmosphere to ocean and ice environments via wet and dry deposition. Wet and dry deposition is also the main way that atmospheric trace species arrive at the ocean, ice, and snow surfaces. Species including iron (Mahowald et al., 2005), phosphorus (Mahowald et al., 2008), and nitrogen (Duce et al., 2008; Altieri et al., 2021) are important for facilitating ocean biological activity, while mercury (Cossa et al., 2011) is a major biological contaminant. Understanding deposition processes of marine and biogenic aerosol to surface snow, along with knowledge of the present-day sources and other atmospheric processes, are essential for interpreting longer ice core records of aerosol chemistry and for validating novel ice core proxies of past sea-ice (e.g., Vallelonga et al., 2021) and primary production. All of this is coupled to the radiative budget and the physical Southern Ocean system through the state of sea-ice, heat and momentum exchanges, and meteorological systems over the Southern Ocean and the Antarctic continent.

6. Two-way learning between models and observations

The gaps in knowledge highlighted above are further reflected in our models. Many of the described processes are not included in models, particularly not in Earth System Models. When these processes are included, they are often grossly simplified, with many interactions neglected. This is a huge challenge facing the community. Key areas of model development include novel ocean and sea-ice models with more sophisticated functional-group-level biogeochemistry, two-way coupling of biogeochemistry to aerosol-chemistry, improved chemical-aerosol pathways, and better resolved aerosol-cloud microphysics. Developing more accurate emission inventories will be essential in these efforts. To advance these models, early and ongoing communication between modelers and observationalists is crucial (Steiner et al., 2016a).

Experimental process studies linking ocean biogeochemistry and atmospheric composition should be guided by the processes identified as missing or highly sensitive in the models. An emphasis should be placed on variables that are either present in the models or can be reasonably implemented in the near future so that observations can be meaningfully used to constrain or evaluate model parameterizations. Examples of this include experiments on board research vessels that use sea spray generation (Sellegri et al., 2021) or air-sea tanks (Rocco et al., 2021), where we can measure or manipulate the biogeochemistry in the water (e.g., by adding nutrients) and quantify how different biological species and their life cycles influence the flux of gases and aerosol into the air. Separately, air chamber studies that can finely control environmental conditions should be used to better quantify the complex chemical reactions that these gases undergo in the unique conditions of the Antarctic and Southern Ocean (e.g., Wollesen de Jonge et al., 2021; Shen et al., 2022).

Because Southern Ocean observations are scarce, with high-quality ambient measurements sometimes lasting only weeks and over limited domains, it can be difficult to identify whether or not these measurements are representative. It should therefore be a priority to make repeated measurements collected at the same location but across different years and seasons, and to do this over different geographic regions and environments. These measurements should include a thorough description of environmental ancillary data (Steiner et al., 2016a).

On shorter timescales of hours to days, measurements that target the evolution of plankton and sea ice blooms and their products, aerosol particles and reactive gases, and clouds can offer unique case studies for high-resolution modeling. The challenge here is to link observations of atmospheric processes to measured ocean and sea ice emissions that occurred across a variable area upwind. Studies that include Lagrangian atmospheric observations downwind of ocean emissions (e.g., large but delimited phytoplankton blooms) would be extremely informative, although are challenging to undertake.

Early integration of modeling can also be used to inform field measurements. With simulations run before and during field campaigns, and identifying the most significant uncertainties, we have the best chance of targeting the correct time, place, and processes to advance our knowledge. Modelers need the resources to be able to adopt important new discoveries made in the field and lab, which take into account computational limitations. It is therefore crucial that a continuing open dialogue between modeling groups and observational teams starts well in advance of any field work, and continues until well after its conclusion.

The role machine learning and artificial intelligence modeling approaches might have in improving the way we understand and predict links between biogeochemistry, the cryosphere, and the atmosphere is still not clear. This is a rapidly developing area of science but there is still a disconnect between scientists that have expertise in these domains and those that have expertise in machine learning tools (Fleming et al., 2021). Some possible avenues are in using observations to train data-driven parameterizations (Mallet et al., 2023; McNabb and Tortell, 2023), for better understanding the links between different systems (Fuchs et al., 2018; Dadashazar et al., 2021; Landwehr et al., 2021), and for identifying important events in observational data (Guyot et al., 2022; Su et al., 2022). If we have more observations to draw from, these tools could be applied to both existing and new biogeochemical, ecological, ocean, sea ice, and atmospheric datasets to offer novel insights into how these systems are linked (Karpatne et al., 2017; Dueben et al., 2022).

Upcoming opportunities and needs

Long-term observational programs are the best means of understanding seasonal and long-term trends. For a region where seasons dictate access, these long-term stations provide some of the only observations in winter. There are currently 15 land-based stations (**Figure 3**) with continuous atmospheric measurements. They operate either on the Antarctic continent, sub-Antarctic islands, or countries bordering the Southern Ocean. Many of these stations, however, include only basic or limited measurements of aerosol and reactive gases. Because the basic infrastructure is already established, there are opportunities to reinforce and extend the atmospheric monitoring capabilities of these stations. This would provide valuable knowledge of the transport and evolution of reactive gases and aerosol, as well as their interactions with clouds.

Continuous measurements aboard mobile platforms provide crucial information about the interactions between land, ocean, ice, and the atmosphere in both space and time. There are only 2 such platforms that measure the atmosphere continuously in the Southern Ocean. Australia's RV Investigator makes atmospheric observations roughly 300 days a year at sea. Since 2015, it has spent 65% of its time south of Australia. The French RV Marion Dufresne II started year-round atmospheric measurements in the Indian Ocean in 2021. Every summer it will likely cover the same route between the French Islands in the Southern Ocean. A crewed floating platform, "Polar POD," will also be deployed in late 2023 that will have oceanographic and atmospheric measurement capabilities and will drift along the Antarctic circumpolar current. Antarctic resupply icebreaking vessels should expand their monitoring capabilities in a similar way so that we also continuously monitor the sea-ice interface with the atmosphere. Measurements on mobile platforms can help fill in the gaps from land-based stations that are distant from regions of productivity in the ocean and sea-ice. Remotely operated platforms such as gliders, floats, and moorings across the Southern Ocean also provide detailed complimentary data.

Targeted campaigns are also a critical complement to long-term monitoring efforts. They allow focused process-level observations of the environment. Over the coming 4 years, we are aware of 22 fully funded or proposed campaigns (**Figure 3**) exploring the links between marine and terrestrial biogeochemistry and the atmosphere. This will include both in-situ and remote sensing observations on a range of platforms including land stations, ships, and aircraft. The campaigns will be complimented by remotely operated platforms such as gliders, floats, and moorings. We expect variability in biogeochemistry and atmospheric properties and their interactions in the different sectors around Antarctica. These 22 projects will help us to describe these variabilities.

Combining the strengths of long-term monitoring with targeted measurement campaigns gives the best of both worlds. State-of-the-art measurements of everything from microorganism abundance and diversity to aerosol formation and cloud phase will be invaluable for climate model development. We need these measurements to challenge and improve our climate models, evaluate process-level models, as well as to develop new retrieval products of biological and atmospheric data from satellite measurements. There will also be opportunities to support the validation and development of upcoming satellite products. For example, the PACE (Plankton, Aerosol, Cloud and ocean Ecosystem) satellite mission is due to start in January 2024 (Werdell et al., 2019). Early planning will ensure that both the satellite missions and surface-based campaigns we describe here benefit from each other.

While planning is well underway for the upcoming campaigns we have listed here, there is still scope to enhance interdisciplinarity and coordination to ensure we make the most of this unprecedented opportunity to understand the Southern Ocean and Antarctic region. It is likely that other research projects are currently being planned and so we encourage collaboration as much as possible. Furthermore, there is scope to augment the measurement campaigns already planned to maximize the scientific knowledge we can gain.

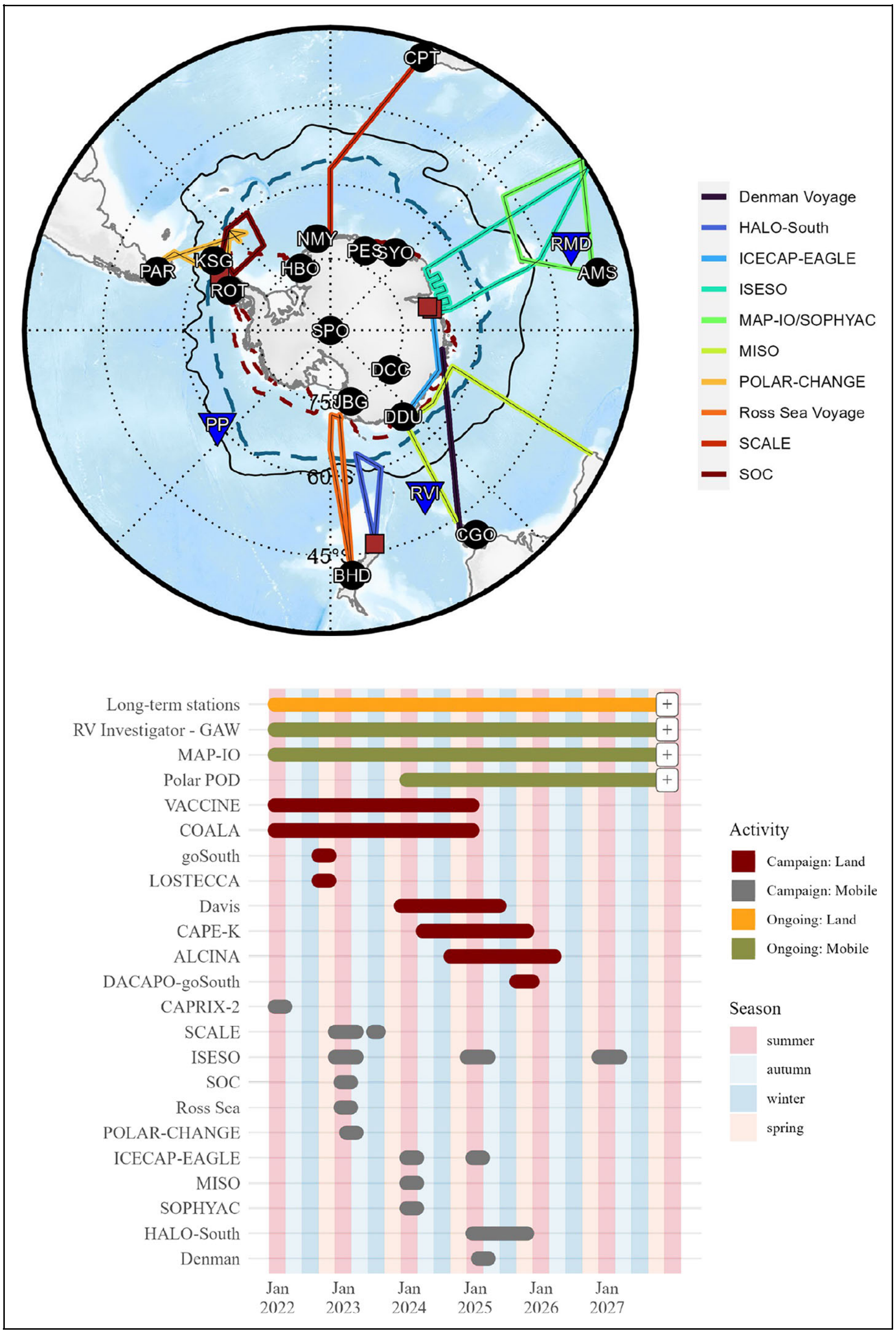

Figure 3. Upcoming measurement programs in the region targeting biogeochemistry-atmosphere measurements. Please note that this list might not be exhaustive and there could be changes to dates and positions prior to measurements. Top: map showing the locations of long-term measurement programs and planned campaigns at stationary sites and on mobile platforms. Long-term stations are identified by their World Meteorological Organization-Global Atmosphere Watch (WMO-GAW) ID and include South Pole Observatory (SPO), Neumayer (NMY), Rothera (ROT), King Sejong Station (KSG), Halley (HBO), Concordia (DCC), Jang Bogo Station (JBG), Princess Elisabeth Antarctica (PES), Syowa (SYO), Dumont d'Urville (DDU), Punta Arenas (PAR), Baring Head (BHD), Kennaook-Cape Grim (CGO), Amsterdam Island (AMS), Cape Point (CPT), and indicated with black dots. Other land-based stations that are not part of WHO-GAW but will support atmospheric observations (i.e., Davis, Palmer and Bharati Antarctic stations, and the Southern New Zealand Invercargill Area) are indicated with dark red squares. The general positions of the RV Investigator (RVI) and RV Marion Dufresne II (RMD) during their voyages as well as the Polar POD (PP) as it transits the Antarctic circumpolar current in the Southern Ocean are indicated as blue triangles. Mobile platform tracks are indicative only. The black solid line indicates the location of the oceanic polar front, while the blue and red dashed lines indicate the climatological sea-ice extent for September and February, respectively. Bottom: A timeline of upcoming measurement programs. Note that the RVI—GAW and MAP-IO programs will sample outside of the Southern Ocean as well. Campaign details can be found at www.piccaaso.org.

In line with the research priorities outlined, we suggest that future observational campaigns should focus on resampling the same air masses containing cloud and aerosol, so we can better learn how they evolve on short timescales. Ideally, some of these field campaigns on mobile platforms would follow air masses to observe the evolution of aerosol and cloud. This could also possibly be achieved with land-based stations that have similar and cross-calibrated instruments. Efforts should also include additional controlled tank and chamber experiments, allowing us to better isolate and understand specific individual processes, such as how different microorganism species produce and emit compounds into the atmosphere.

There is also a requirement for more aerosol and cloud observations further south (e.g., south of the Polar Front) and especially over different sea ice conditions. Observing the spring and autumn transition seasons where there is greater variability in the ice algae and phytoplankton blooms in order to determine their impact on cloud properties will be vital. Any observations in winter are also extremely valuable, with biological and photochemical activity at a minimum. Vertical profiling measurements of aerosol and cloud properties are rare but also crucial for linking surface source measurements to clouds aloft. Any opportunities to include these measurements on crewed or uncrewed aerial vehicles or balloon platforms should be taken. Crucially, modeling at a range of spatial scales and complexities is integral to these efforts.

Our strategy

We invite researchers and institutions in this space to join PICCAASO (Partnerships for Investigations of Clouds and the biogeoChemistry of the Atmosphere in Antarctica and the Southern Ocean), a recently launched initiative to improve coordination and collaboration of upcoming campaigns. The goal of PICCAASO is to augment and amplify the scientific discoveries from each independent project. International and multidisciplinary collaborations will be essential. These projects should coordinate with, rather than duplicate, each other. Critical to this is sharing resources: labor, expertise, training, ideas, infrastructure, and models. Data will be shared in accordance with FAIR (Findable, Accessible, Interoperable, and Reusable) data principles (Wilkinson et al., 2016) and efforts should be made so that consistent metadata formats are adhered to where possible.

In **Table 1** we propose a list of key variables that should be measured where possible to provide guidance in model improvement. Measurements of a number of these variables across disciplines in a specific season or location during a single field campaign will be extremely valuable for understanding processes. While this might be logistically challenging for any one field campaign, bringing together measurements of the same variables across regions and seasons from various field campaigns will still provide an unprecedented ability to robustly evaluate and improve our Earth System Models over the Southern Ocean and Antarctica.

What will success look like? A starting point would be a significant reduction in the radiation bias that is present in the current generation of global climate models over the Southern Ocean. But this could conceivably be achieved by tuning models to simulate the correct radiation, even in unphysical ways. Correctly simulating the Southern Ocean energy budget for the right reasons will require improvements across a number of systems. We need to understand which biological species are responsible for producing compounds that modulate aerosol production, including organic compounds that we are yet to characterize. Once we know this, we need a way to feasibly parameterize this in our biogeochemical-ocean-ice models. These biogeochemical models need to be coupled to atmosphere models that have sophisticated aerosol-chemistry schemes that can account for various species that are emitted into the atmosphere, as well as their chemical and physical transformations and condensation into cloud droplets. The cloud microphysics schemes in our models also need to be able to deal with the high occurrence of supercooled liquid clouds over the Southern Ocean. This will require a better understanding of how ice crystals form in the presence of ice nucleating particles, a better understanding of secondary ice production processes, and potentially a new way to parameterize the biological origin of these particles. Simulating precipitation correctly will have similar challenges to simulating cloud microphysical properties. If our climate models can realistically simulate precipitation over the Southern Ocean, this will be a good indication of success. Once we have the ability to accurately simulate these biological, chemical, and physical processes for the present-day, then we can have confidence in our ability to make accurate projections into the century.

There is already momentum in international and interdisciplinary collaboration. Communities like CATCH (Cryosphere and Atmospheric Chemistry), BEPSII (Biogeochemical Exchange Processes at the Sea-Ice Interfaces), SOLAS (Surface Ocean - Lower Atmosphere Study), IGAC (International Global Atmospheric Chemistry), SCOR WG #163: CIce2Clouds (Coupling of ocean-ice-atmosphere processes: from sea-Ice biogeochemistry to aerosols and Cloud), and SOOS (Southern Ocean Observing System) have started to tackle the problems highlighted in this commentary. We want to continue this community approach to enable a step-change in our knowledge of how Antarctic and Southern Ocean biogeochemistry influences our climate. Incorporating modelers early into projects is integral to success. The projects discussed here provide a good start. But the complexity of the system, and the sheer size of the Antarctic and Southern Ocean region, mean that no one country or institution can solve all the problems alone.

Time is running out. A changing climate and increasing human activity risk quickly changing and contaminating the region. We have a unique opportunity to understand the world's last pristine environment. But we have to act now. This critical science is essential to guide our future relationships with our planet.

Table 1. The most urgent key variables or properties that need to be measured around the Southern Ocean and Antarctica

Variables	Measurement Requirements
Phytoplankton species, abundance and lifecycle Bacterial, viral, and zooplankton abundance Nutrient concentrations Environmental properties (oxygen, pH, temperature, salinity)	These measurements are typically made near the surface of the ocean with a high time resolution using automatic samples devices and sensors. Vertically resolved measurements in the water depth can be done with bottle casts during dedicated water sonde profiles and net hauls. Sea ice measurements are extremely valuable but more difficult to collect as these require manual measurements in the sea ice.
Reactive gas concentration and flux	Measurements of atmospheric reactive gas concentrations are typically made from sampling inlets on ships or monitoring stations. Gas concentrations in ice or dissolved in seawater can be made. If both are done simultaneously, flux estimates can be calculated. Additionally, vertically resolved concentrations of key reactive gases in the boundary layer and free troposphere on aircraft platforms are very valuable.
Aerosol concentration and size distribution	Total and size-resolved aerosol number, cloud condensation nuclei, and ice nucleating particle concentrations are typically measured from ship or land-station sampling lines. Vertical profile measurements in the troposphere require an aircraft, uncrewed aerial vehicle, or tethered balloon but are very valuable.
Aerosol composition	Aerosol mass spectrometry can be done for high time-resolution composition analyses from ship or land stations. Filter measurements can also be undertaken and provide more detailed composition information at the cost of sampling time and potential sampling artefacts. Size-resolved aerosol composition and vertically resolved composition into the troposphere are very valuable.
Cloud properties	Cloud fraction and layer heights can be measured or retrieved from surface-based lidar and radar instruments and sky cameras. Cloud phase and some cloud microphysical properties can also be retrieved from lidars and radars. Cloud dynamics and turbulence can be measured by wind profilers and Doppler cloud radars from ground and aircraft platforms. Uncrewed aerial vehicles or aircraft measurements allow for valuable in situ measurements of cloud droplet and ice crystal concentrations and size distributions.
Precipitation properties	Precipitation rates can be measured at the surface with various techniques. Optical disdrometers are valuable on ship and land platforms to calculate precipitation rates, phase, and size distribution. Surface-based radars can be used to retrieve vertically resolved precipitation rates.
Meteorology and radiation	Temperature, humidity, pressure, wind speed, and direction measurements are typically made on ships and at land stations. Downward and upward shortwave and longwave radiation measurements can be made on these platforms. Radiosonde balloons provide basic meteorological information vertically throughout the troposphere.

Supplemental files

The supplemental files for this article can be found as follows:

CMIP6 model methods and evaluation. Pdf

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Competing interests

The authors declare no competing interests exist.

Author contributions

Wrote the manuscript and designed the figures: MDM, RSH, SLF.

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