

REVIEW

Status of ocean observations in the Indian Sector of the Southern Ocean

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One of the largest sectors of the Southern Ocean is the Indian Sector, which plays an important role in regulating the Earth's climate and supports a diverse ecosystem. To understand how climate change impacts the environment in this sector, ocean observations are collected via various platforms, including conventional ship-based technologies, autonomous instruments (e.g., animal-borne sensors, autonomous underwater vehicles, and profiling floats), satellites, and other remote sensing methods. However, the harsh environment, remoteness, and natural obstacles such as sea ice and clouds limit year-round ocean observations by vessel and satellite, respectively. This incomplete data coverage makes predicting future scenarios a challenge. Here, led by the Regional Working Group for the Indian Sector of the Southern Ocean in the Southern Ocean Observing System, we examined the status of multidisciplinary ocean

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observations in the Indian Sector. Our review covers oceanography, sea ice, biogeochemistry, air–sea flux, pelagic and benthic biology, and direct anthropogenic pressures. We also address seasonal and spatial gaps, along with platform biases. Furthermore, we explore the synergies between modelling and observations, highlighting how models can test hypotheses, address observational gaps, and, in turn, benefit from improved observational data. Finally, we provide recommendations for enhancing the observing system in the Indian Sector of the Southern Ocean to better understand its current state and anticipated future changes.

Keywords: Antarctica, Ocean observations, Multidisciplinary, Climate change, SOOS

1. Introduction

The Southern Ocean Indian Sector (SOIS) spans all waters south of 32°S, from 20°E south of Cape Agulhas, South Africa, to 170°E east of Australia, as defined by the Southern Ocean Observing System (SOOS, **Figure 1A**). It is an important region for Antarctic Bottom Water formation (Rintoul and Garabato, 2013) and hosts economically significant fisheries, such as Antarctic toothfish (*Dissostichus mawsoni*) and Patagonian toothfish (*Dissostichus eleginoides*; Kock et al., 2007; Caccavo et al., 2021). While large parts of the SOIS are so-called high-nutrient, low-chlorophyll regions due to a limitation in micronutrients (Trull et al., 2001; Shadwick et al., 2015), other areas are characterised by high primary productivity in the water column, for example, around the Kerguelen and Crozet Islands or at the sea-ice edge along the continent (Lasbleiz et al., 2014). Similar to other sectors of the Southern Ocean, the SOIS is highly susceptible to climate impacts, including glacier thinning (Pritchard et al., 2012; Khazendar et al., 2013), reduced sea ice (Josey et al., 2024), and warming along the northern boundary of the Antarctic Circumpolar Current (Armour et al., 2016). These physical changes are expected to drive ecosystem shifts, such as the southern migration of Antarctic krill as seen in the Atlantic Sector of the Southern Ocean (Kawaguchi et al., 2023), a potential transition towards pelagic ecosystems dominated by gelatinous zooplankton (Kelly et al., 2020b), and changes in suitable foraging areas for marine predators breeding in the sub-Antarctic, resulting in increased commuting distances (Hindell et al., 2016; Hindell et al., 2020). Additionally, human activities, including the re-establishment of the commercial krill fishery (Kawaguchi and Nicol, 2020), growing tourism (Liggett et al., 2011), and intensified research activities near scientific bases on the continent and sub-Antarctic islands (Brooks et al., 2019), may further exacerbate ecosystem changes.

To improve our understanding of direct and indirect human impacts on the SOIS, a system of sustained, multidisciplinary ocean observations is essential. Sustained observations are repeated measurements of physical, biogeochemical, and biological parameters, ideally encompassing multiple seasons and years, using consistent and comparable methodologies. Long-term observation strategies are necessary to study trends due to climate change. For example, Schlunegger et al. (2019) estimated time lags of 9–18 years for the impact of rising atmospheric CO₂ on ocean acidification and the carbonate pump, and 27–85

years for its effects on the biological carbon pump. Hence, short-term field campaigns and one-off measurements are insufficient to capture long-term processes influenced by climate change.

This review was developed by the SOOS community and led by the SOOS Regional Working Group for the Indian Sector to describe the current state of ocean observations in the SOIS across multiple disciplines, as well as their spatial and temporal gaps. Co-authors were either members of the leadership team of the working group or responded to an open call via the SOOS mailing list and associated international networks. This approach encouraged the collaboration of many researchers from different disciplines, career stages, and countries. While we aimed to provide a comprehensive overview of the status of ocean observations, the review is by no means a complete summary of all initiatives or ocean observing methods employed in the SOIS. The cited studies are provided as examples of successful initiatives and reflect the present state of ocean observations to the best of our knowledge. For the purpose of this review, we adopted a northern boundary of approximately 32°S, consistent with the SOOS definition (Constable et al., 2018). This study builds on the 2017 SOOS workshop synthesised by Constable et al. (2018) and provides an update on the current directions of the ocean observing system in the SOIS.

The review is structured as follows: Section 2 outlines the key drivers of physical, chemical, and biological processes in the SOIS, including anthropogenic pressures such as fisheries and pollution. Section 3 examines the current state of ocean observations across disciplines, covering oceanography, sea ice, biogeochemistry, lower, middle, and higher trophic levels, the benthic ecosystem, and anthropogenic impacts. Section 4 highlights current modelling efforts to enhance ocean observation coverage and deepen our understanding of Southern Ocean processes. Finally, Section 5 offers recommendations for future research priorities and collaborative efforts, aligning with international initiatives such as SOOS and the United Nations Decade of Ocean Science for Sustainable Development (Ocean Decade, 2021–2030).

2. Key drivers of physical, chemical, and biological processes in the Indian Sector

The Southern Ocean is key for the global ocean circulation as it connects to water masses from other ocean basins, as

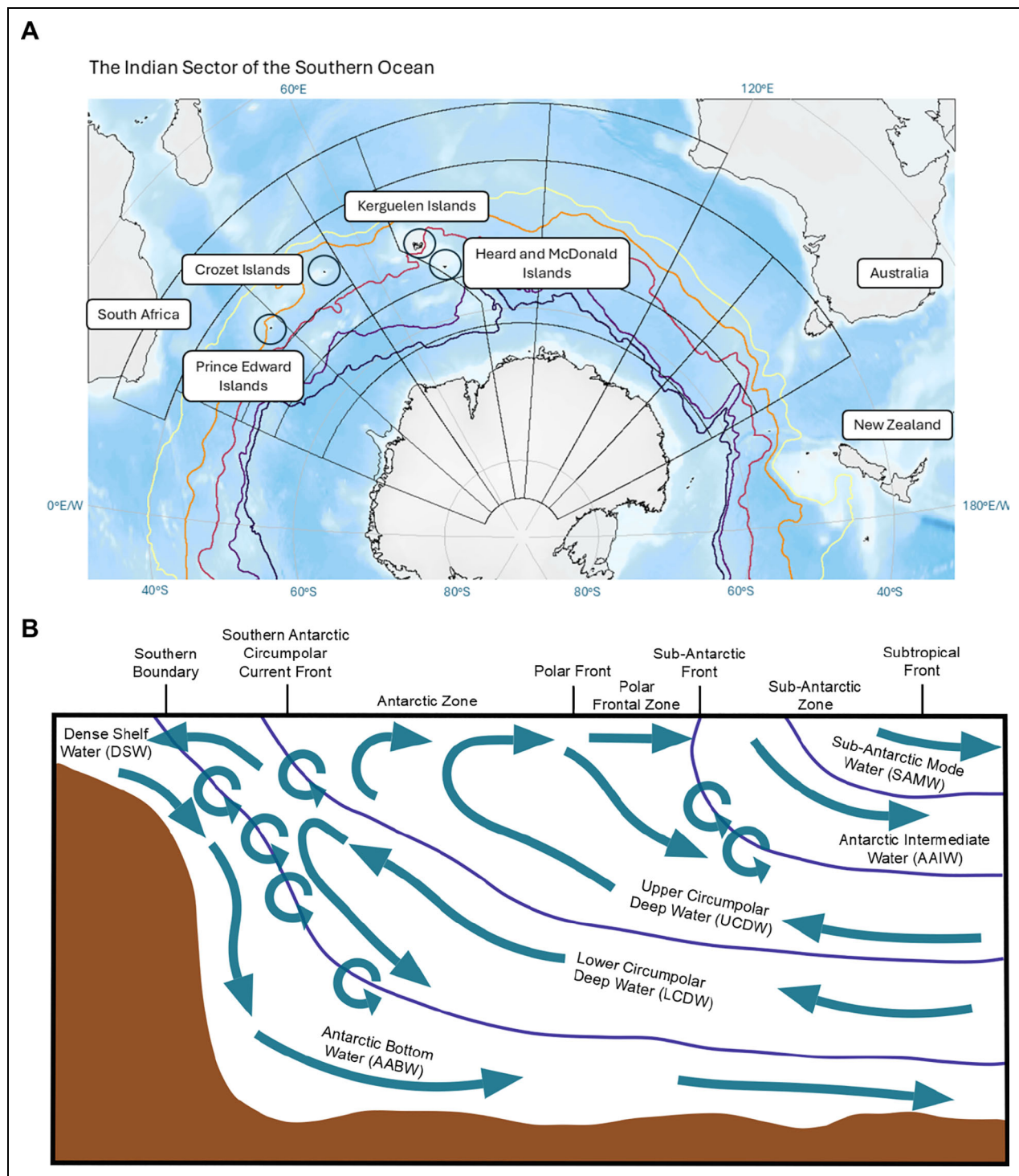


Figure 1. Overview of the Indian Sector of the Southern Ocean and main water masses and currents. (A) The Indian Sector of the Southern Ocean (black boxes) encompasses sub-Antarctic islands, such as Prince Edward Islands (South Africa), Crozet Islands (France), Kerguelen Islands (France), and Heard and McDonald Islands (Australia). Ocean currents are described by Park and Durand (2019) and defined by fronts, from north to south: Northern Boundary (yellow), sub-Antarctic Front (orange), Polar Front (red), Southern Antarctic Circumpolar Current Front (purple), and Southern Boundary (blue). (B) Simplified overview of major water masses, fronts, and currents in the Southern Ocean, modified after Speer et al. (2000).

well as the surface with the deep ocean (Speer et al., 2000; Rintoul and Garabato, 2013; **Figure 1B**). North of the Antarctic Circumpolar Current (ACC), in the Sub-Antarctic Zone, Sub-Antarctic Mode Water (SAMW) forms over winter, resulting in one of the deepest mixed layers in

the global ocean (Sallée et al., 2006). SAMW, together with Antarctic Intermediate Water (AAIW), subducts into the ocean interior, transporting oxygen, nutrients, and particles towards the tropics (Fernández Castro et al., 2022). South of the ACC, warm Circumpolar Deep Water (CDW)

upwells towards the surface, exchanging heat and gases with the atmosphere (Narayanan et al., 2023). Close to the Antarctic continent, Dense Shelf Water (DSW) is formed during sea-ice formation. In some locations known as latent heat polynyas, wind and currents transport sea ice away from the coast and maintain areas of open water in winter; these areas allow very high levels of localised sea-ice production, with the associated brine rejection forming a cold, very salty water mass (DSW). Once DSW overflows, it mixes with CDW and forms Antarctic Bottom Water (AABW). AABW is the densest water mass in the global ocean and transports heat, freshwater, oxygen, and carbon to the deep ocean (Bailey et al., 2023; Schmidt et al., 2023).

The northernmost region of the Southern Ocean, the Subtropical Zone, is characterised by warm, salty surface waters (Orsi et al., 1995), where nutrient availability limits phytoplankton growth and biological carbon uptake (Arteaga et al., 2014). Temperature-driven changes in solubility compete with biological uptake and lead to the Subtropical Zone being a sink for carbon dioxide through all seasons. Moving south, the Sub-Antarctic Zone is characterised by high macro-nutrient but low-chlorophyll concentrations and deep, winter mixing (Rintoul and Trull, 2001). Phosphate and nitrate are abundant year-round, while silica is depleted by the height of summer (Trull et al., 2001); insufficient iron concentration is thought to be the main factor limiting primary production (Bowie et al., 2009; Lannuzel et al., 2011; Tripathy and Jena, 2019). Despite this limitation, carbon export is close to the global median, mediated at least in part by heavy grazing of a phytoplankton bloom that is better described as a 'slow burn', rather than the typical spring bloom of the Northern Hemisphere (Shadwick et al., 2015; Trull et al., 2015; Eriksen et al., 2018; Trull et al., 2018; Wynn-Edwards et al., 2020). Further south, the Polar Frontal Zone and Antarctic Southern Zone are characterised by cold and fresh surface waters with elevated nutrient concentrations; these regions have recently been identified as important sources of carbon dioxide to the atmosphere during the autumn and winter seasons, likely due to the supply of carbon-rich deep water from below (Gray et al., 2018; Williams et al., 2018; Bushinsky et al., 2019). In the seasonal ice zone, seasonality is influenced by the formation and melting of sea ice in the East Antarctic region, with phytoplankton blooms starting under the ice with the relief of light and/or iron limitation and extending into the open water summer season without fully depleting macronutrients (e.g., Sambrotto et al., 2003; Shadwick et al., 2014).

Large changes in plankton community composition are associated with changes in temperature, nutrient concentrations, light availability, and other physical and biogeochemical factors across oceanic fronts in the Southern Ocean described above (Jacques, 1994; Deppeler and Davidson, 2017; Naik et al., 2020). For example, the dino-flagellate to diatom ratio changes from north to south (Smayda and Reynolds, 2003). Changes such as these indicate responses to nutrient availability and speak to the multiple strategies by phytoplankton for maximising

available resources (e.g., employing diversity in feeding modes, i.e., auto, mixo- and heterotrophy). High phytoplankton growth rates under optimal conditions can lead to rapid depletion of available nutrients, as one or more species bloom, with flow-on effects for higher trophic levels, and biogeochemistry (Bi et al., 2021). Changes in the abundance and species diversity are also evident when comparing open ocean to shelf waters and the ice zone around Antarctica (Jacques, 1994; Petrou et al., 2016), where diatoms dominate and often a single genus (e.g., *Fragilariopsis* spp.) accounts for most biomass. Sea-ice algae are uniquely adapted to a seasonally ephemeral environment, with distinct algal communities occupying brine channels and pack ice. Productivity is elevated in spring, with the highest biomass often at the ice-water interface (Ugalde et al., 2016).

As grazers of phytoplankton, the distribution, abundance, and community composition of zooplankton are highly dependent on the phytoplankton abundance and community composition, as well as the position of fronts and other oceanographic features (Chapman et al., 2020). Zooplankton in the SOIS can reach very high biomass during summer, for example, on the Kerguelen Plateau (mesozooplankton) or in the Crozet area (salps), even surpassing the biomass of phytoplankton locally (Yang et al., 2022), with consequences for both active and passive carbon export (Halfter et al., 2020; Halfter et al., 2022; Boyd et al., 2024). Unlike in the Atlantic Sector of the Southern Ocean, Antarctic krill (*Euphausia superba*) does not reach similarly high abundances, though swarms have been reported locally (Cox et al., 2022). Similar to zooplankton and krill, changes in fish communities are driven by a range of environmental parameters. For example, for mesopelagic fish, efforts to develop bioregionalisation models include environmental drivers, such as sea surface temperature, water depth, nutrients, sea-ice concentration and extent, sea surface height, and chlorophyll-a (Chl-a; Koubbi et al., 2010; Caccavo et al., 2021). Fish communities differ between coastal Antarctica and beyond the shelf break, across oceanic fronts, under sea ice versus open water, and around the sub-Antarctic islands (Chapman et al., 2020; Caccavo et al., 2021).

Environmental variability is a key determinant of bird and marine mammal populations in the SOIS (Arthur et al., 2015; Carpenter-Kling et al., 2020; Orgeret et al., 2022; Reisinger et al., 2022). Common factors are sea-ice extent, concentration, and duration (Jenouvrier et al., 2005a; Bailleul et al., 2007), water temperature (Bailleul et al., 2007; Orgeret et al., 2022), the oceanic circulation and the location of frontal systems (Arthur et al., 2016; Chapman et al., 2020), eddies (Bailleul et al., 2010; Dragon et al., 2010), bathymetry (Arthur et al., 2017), wind (Weimerskirch et al., 2012; Arthur et al., 2017), and broad-scale indices of the Southern Annular Mode and the Southern Oscillation Index (Jenouvrier et al., 2005b; Trathan et al., 2007). Biogeochemical and biological determinants such as nutrients, primary productivity, and Chl-a concentration are also important drivers (Jaud et al., 2012; Arthur et al., 2017). In turn, the biogeochemical and biological properties are strongly modulated by physical drivers (Prend

et al., 2019; Henley et al., 2020; Sarmiento et al., 2023). As the distribution and abundance of marine prey are intrinsically coupled with physical and biological oceanographic properties, these factors also shape the availability of prey to predators, likewise influencing their distribution, foraging success, and abundance (Bailleul et al., 2007; Jaud et al., 2012). Birds and marine mammals must also cope with inter- or intraspecific competition, such as competition for prey resources (Camprasse et al., 2017; Dehnhard et al., 2020; Hindell et al., 2021), predation (Reisinger et al., 2016), and breeding space (Dehnhard et al., 2020). In the SOIS, relationships between the environment and predator productivity show a high level of periodicity, typically of 3–4 years (Trathan et al., 2007).

Benthic fauna, both those living on and in the substrate, are influenced by a range of environmental factors. The abundance and diversity of benthic fauna commonly decrease with increasing depth of the seafloor (e.g., Gutt and Starman, 1998; Barry et al., 2003; Koubbi et al., 2010; Post et al., 2011; Bhaumik et al., 2023), though these relationships are not universal (Cummings et al., 2010). Distinct benthic communities can inhabit comparable depths (Dayton and Oliver, 1977; Barry and Dayton, 1988; Baishnab et al., 2023), as, for example, differences in food availability also influence the abundance and richness of seafloor fauna (Jansen et al., 2017; Jansen et al., 2018a; Jansen et al., 2018b; Jansen et al., 2020). Further, major bathymetric features such as canyons influence ocean currents and can concentrate food supply, creating environments in which diverse ecosystems can persist even at depths of 1000 m (Post et al., 2011). Many other environmental variables have been identified as influencing benthic fauna, often variable depending on the type of fauna considered. Water current speeds (e.g., Gambi and Bussotti, 1999; Cummings et al., 2010) and sediment composition (e.g., Rehm et al., 2006; Choudhury and Brandt, 2007; Kröger and Rowden, 2008) influence the type of habitat available, ranging from low-current muddy/sandy environments commonly found in the basins to high-current rocky environments at the edges of the shallow banks and along the shelf break. While water temperatures are relatively stable year-round on the Antarctic continental shelf (Post et al., 2014), many Antarctic benthic species are thought to be uniquely adapted to the cold Antarctic shelf waters (e.g., Peck et al., 2004; Griffiths et al., 2017). In the shallower part of the Antarctic continental shelf, the frequency of iceberg scours can impact benthic fauna strongly (Gutt, 2001; Robinson et al., 2021), creating a patchy seascape of disturbed and undisturbed habitat. Similarly, within the sub-Antarctic, long-term variation in the position of the sub-Antarctic Front can influence the benthos through altered food supply (Von Der Meden et al., 2017). Lastly, the importance of some environmental drivers of benthic fauna varies between the Antarctic and the sub-Antarctic, as the extreme seasonality on the Antarctic shelf, sea-ice covered for many months each year, gives way to milder conditions in the sub-Antarctic.

Currently, the major anthropogenic pressures in the SOIS are fishery operations, tourism, plastic and other pollutants (particularly along coastlines and near

sub-Antarctic and Antarctic research bases), marine traffic as a vector for invasive species, as well as large-scale climate and environmental changes (Liggett et al., 2011; Kawaguchi and Nicol, 2020; Smith et al., 2020; Suaria et al., 2020; Thomalla et al., 2023). These anthropogenic pressures are commonly concentrated in areas where human activities are highest, with the exception of global drivers such as climate change. For example, with the opening of the Wilkins ice runway in the Australian Antarctic Territory in 2008, transport-based pollutants and plastic pollution increased (Suaria et al., 2020; Pattiaratchi et al., 2022). The Wilkins runway has made the Indian Sector more accessible, including for short-term non-operational and non-research visits, and has increased the human presence in the near-coastal SOIS, particularly over summer. Likewise, fishery operations in the SOIS region have increased more recently, based on the Chinese krill fishery expanding into the area since 2016–2017 (Kawaguchi and Nicol, 2020). This increase in fishing effort in the SOIS has also been a major driver of the increased bycatch in this region (Barbraud et al., 2012; CCAMLR, 2021).

Larger-scale environmental shifts driven largely by anthropogenic climate change, such as ocean warming, acidification, deoxygenation, and sea level rise, are all detected within the SOIS but are not regionally specific (Clem et al., 2024). For example, the Southern Ocean circulation is currently undergoing a major reorganisation that potentially affects (and is affected by) ice shelf-ocean processes (Herraiz-Borreguero and Naveira Garabato, 2022). At the Antarctic margins, the warming ocean drives ice shelf thinning and sea level rise from ice sheet mass losses (Pritchard et al., 2012; Smith et al., 2020). The effects of climate change can be seen varying in intensity across the SOIS, but the drivers behind these effects, causing them to become more localised in certain areas, are still mostly unknown. New proxy-based estimates of regional iron limitation that exploit ship-based and autonomous platforms suggest a progressive trend of increased iron stress over the last two decades (Ryan-Keogh et al., 2023). Increasing when, where, and how ocean observations are collected will improve our understanding of these climatic changes in the SOIS and connections with lower latitude changes (Hwang et al., 2017). The effects of these environmental changes on the ecosystem in the SOIS region are only starting to be understood. Many of these global environmental changes are drivers for large-scale ecosystem shifts (Deppeler and Davidson, 2017; Hancock et al., 2018).

3. Status of ocean observations

3.1. Physical oceanography

The key physical hydrographic variables that define the seawater state are temperature and salinity. Additionally, though strictly a chemical variable, the oxygen concentration is an invaluable proxy for the age of a water mass, and therefore its likely source. In the Southern Ocean, the primary sources of these data are ship-based conductivity, temperature, depth (CTD) profiles, autonomous profiling floats (primarily Argo floats), and instrumented animals

(especially Elephant seals, due to their long travel range, deep diving abilities and their preference for the presence of sea ice, especially during the austral winter; **Figure 2**). Gliders and uncrewed aerial vehicles have been invaluable platforms for field campaigns, but to date have not been deployed for sustained, that is, repeated, long-term observations in the SOIS. The contributions of the three most common oceanographic platforms since the International Geophysical Year (1957–1958) are summarised in **Figure 3**.

Ship-based CTDs remain the gold standard of hydrographic observations but are also the sparsest (top row of **Figure 3**). Observations are concentrated near repeat transects of the World Ocean Circulation Experiment, especially the SR3 section running directly south from Tasmania, Australia, as well as in circumpolar regions and near-coastal Antarctic stations. Winter data are especially sparse, even in sub-Antarctic waters unaffected by sea ice. Autonomous profiling floats are the most evenly

distributed data at any time of year (middle rows of **Figure 3**). However, most float profiles concentrate on the upper 2000 m, and the sea-ice zone is significantly under-observed. Under-ice capable floats are now a proven technology (Wong and Riser, 2011), but observations off and on the Antarctic continental slope require float deployments near the coast, far from routine ship tracks other than routine resupply of coastal Antarctic stations. Also, more efforts are needed to locate the position of these floats when profiling under sea ice. Locating the under-ice position is possible using sonar moorings (Klatt et al., 2007; Hancock and Boebel, 2024), but these moorings require ship time for maintenance and replacement. An alternative, less expensive strategy on the continental shelf is to minimise float movement by setting them to rest on the seabed between profiles (Wallace et al., 2020). The need to monitor the deep ocean has motivated the development of deep Argo floats (Foppert et al., 2021), proving to be an extraordinary resource for tracking

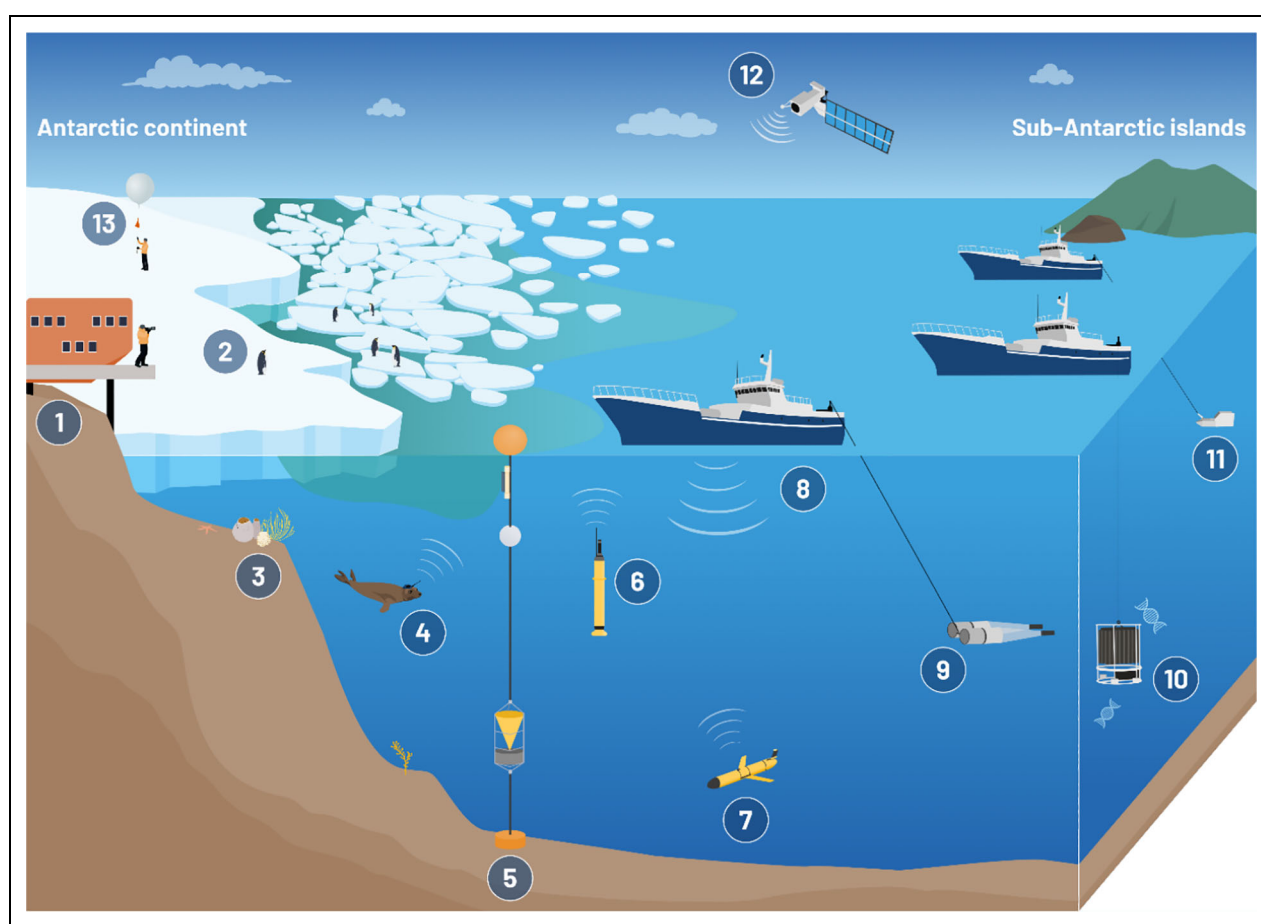


Figure 2. Examples of technologies for sustained ocean observations in the Indian Sector of the Southern Ocean. The numbers refer to the following methods and technologies: (1) research bases as regular monitoring sites; (2) land- and ice-based observations, for example, surveys of bird and mammal colonies or sea ice campaigns; (3) monitoring of benthic communities especially along the continental shelf; (4) instrumented mammals, for example, seals; (5) short- and long-term moorings; (6) profiling floats, both Argo and Biogeochemical-Argo floats; (7) gliders and other autonomous underwater vehicles; (8) ship-based continuous observations, for example, acoustic surveys or other sustained underway observations; (9) Net deployments to collect plankton and nekton; (10) conductivity, temperature, depth (CTD) profiles of the water column, as well as collection of water, for example, environmental DNA analysis; (11) continuous plankton recorder surveys; (12) remote sensing using satellites, for example, for ocean colour; and (13) atmospheric measurements, for example, using weather balloons.

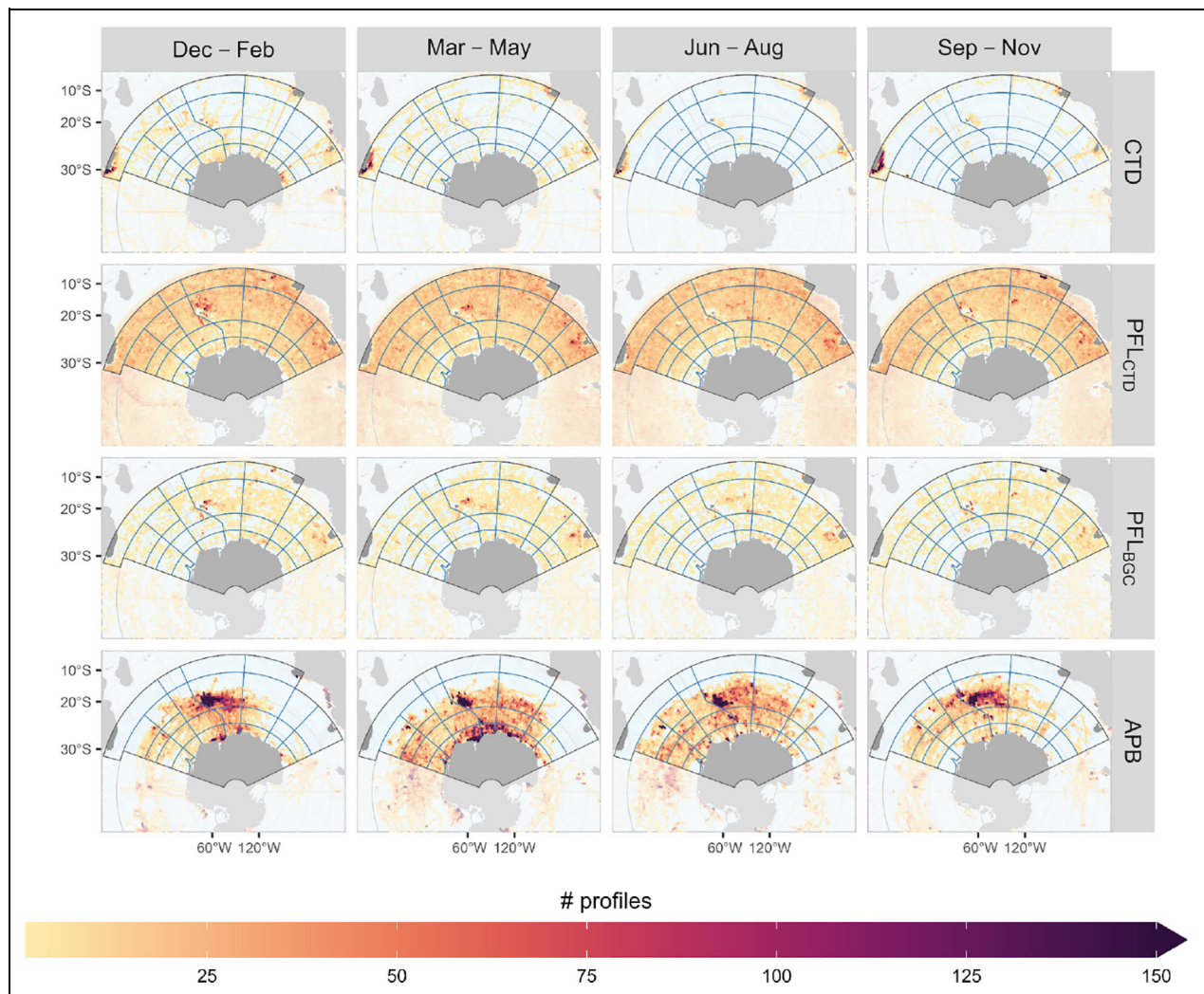


Figure 3. Examples of oceanographic and biogeochemical observations in the SOIS per season. Number of profiles collected per season and $1 \times 1^\circ$ grid cell by shipboard high-resolution casts for conductivity, temperature, depth (CTD; top row), Argo profiling floats (PFL; middle two rows) including from those that sample only ocean physics (PFL_{CTD}) and those that also sample biogeochemistry (PFL_{BGC}), and autonomous pinniped bathythermographs (APB; bottom row) for the SOIS region between 1958 and 2021. The data were obtained from the World Ocean Database (Mishonov et al., 2024). Platform abbreviations (CTD, PFL, and APB) presented here follow World Ocean Database terminology.

Antarctic Bottom Water (Gunn et al., 2023). Also noteworthy is that almost all the float observations are from the Argo era of the last 15 years. Instrumented seals have provided a rich source of year-round data (bottom row of **Figure 3**), totalling >400,000 profiles within the SOIS since tagging began in 2004. However, most profiles (79%) are from spring and summer and are concentrated near the sub-Antarctic islands (namely, the Kerguelen and Macquarie Islands), where tagging typically occurs. Seal-borne CTDs tend to have poor vertical resolution, and their accuracy is lower than Argo and ship-based CTDs, so further development and post-calibration of the profiles are needed (Roquet et al., 2014; Jonsen et al., 2024).

Overall, autonomous technologies have proven essential in providing year-round hydrographic observations in the remote SOIS, but critical data gaps are present at the Antarctic margins, especially in the eastern SOIS region that is rarely visited. For a sustained observing system to

be successful, different approaches are needed within the deep Southern Ocean, the seasonal ice zone, and the Antarctic continental margins. Realistically, ongoing year-round observations in those regions are only possible through the deployment of under-ice profiling floats and moorings in regions vulnerable to climate change and sea level rise. Success with sustained observing can only be achieved when we fill the observational gaps in those areas never or rarely visited before.

3.2. Sea ice

Direct and autonomous in situ observations of sea ice and its snow cover are elusive across much of the Southern Ocean, including the Indian Sector. While widely accepted that comprehensive sea-ice observations rely on satellite-based sensors, direct measurements of the sea ice from ice-strengthened vessels as well as tethered and autonomous instruments remain crucial to obtain a more

complete understanding of sea-ice processes and interactions, and hence their impacts on the local, regional, and global Earth system. The sea ice in the SOIS is limited to a relatively narrow belt (extending to about 300 km at annual maximum) across the continental shelf and the adjacent Southern Ocean. This belt is not only one of the narrowest in terms of latitudinal extent, but also the sector with sea ice at the lowest latitude. Many in situ sea-ice observations in the SOIS are either short deployments or, due to the oceanic circulation, soon expelled from the sea-ice zone, making capturing long-term trends and variability in sea-ice conditions difficult.

The Antarctic Sea ice Processes and Climate (ASPeCt) programme (Allison and Worby, 1994) ensures standardised ship-based observations of sea-ice concentration, thickness, topography, floe size, snow and melt pond characteristics, and traces of primary production. The Scientific Committee on Antarctic Research (SCAR) endorses ASPeCt observations to be acquired during all voyages into the southern sea-ice zone; however, few voyages are made every year in the SOIS (Worby et al., 2008). To reduce the commitment of observers, to enable near-continuous data acquisition and to remove observer bias, (semi-)autonomous observing systems are being commissioned on several icebreakers. These systems typically include: complementary multi-camera systems with optical, thermal, and multispectral cameras (Tersigni et al., 2023); permutations of wave-ice radar, electromagnetic, laser, sonic and snow radar sensors to derive sea-ice draft, total freeboard and snow thickness; radiometers and pyranometers to obtain incoming and outgoing radiation components, derive surface-specific albedo and measure sea/ice surface skin temperature; in addition to a suite of atmospheric, oceanic, and biogeochemical sensors (Newman et al., 2019; Heil et al., 2023). Employing artificial intelligence to streamline and harvest information from the various sensor packages enables near real-time analysis of the observations, including the generation of synthetic ASPeCt data as well as assessments of sea-ice conditions to aid navigation and support scientific or logistical activities (e.g., Li et al., 2024).

ASPeCt also provides agreed observing methods and standards for sampling on sea-ice stations, including for physical and biogeochemical properties (Worby et al., 1998; Meiners et al., 2018). Opportunities for in situ sampling during sea-ice stations require dedicated ship time and are often supplemented by autonomous sensor packages, including those deployed on, within or underneath the sea ice itself, on ocean-mounted moorings, or on remotely operated or autonomous underwater and aerial drones. Two crucial observational networks for Antarctic sea ice fill this niche: the International Programme for Antarctic Buoys and the Antarctic Fast-Ice Network. Between them, they deploy drifting sea-ice and snow buoy networks and maintain long-term measurement sites on the near-coastal fast ice. Under the international programme, buoys are largely deployed to address specific research questions and, contrary to their Arctic twin, are not sustained by operational funding. This funding situation, the low-frequented region, and the generally

divergent oceanic surface circulation make obtaining sufficient buoy cover difficult.

In addition to traditional observing infrastructure, Antarctic sea-ice observations are incomplete without satellite observations, as vast areas of the Southern Ocean sea-ice zone are inaccessible and inhospitable for ground-based observations. Satellites provide a unique vantage point to acquire data from which to derive sea-ice extent, freeboard, and other relevant variables covering large areas and providing repeat data to build long-term records. Satellite observations have been ongoing for several decades, providing valuable long-term records of sea-ice change. Numerous satellite-based sensors and missions are used to derive sea-ice variables. These datasets provide information required to identify long-term patterns and trends. Regardless, accurately deriving sea-ice thickness from space-borne observations remains a complex challenge. While satellite altimetry like CryoSat-2 and ICESat-2, and especially the Cryo2ICE initiative, have brought significant improvements, there are still uncertainties and limitations to routinely deriving sea-ice thickness, especially in regions with complex ice conditions and snow cover. To address this issue, refined satellite missions with high-resolution and frequent sampling are required, such as the European Space Agency's dual-frequency radar altimetry missions CRISTAL (to be launched in 2027) and the proposed NASA Explorer mission EDGE. The near real-time availability of many satellite-derived products makes them an indispensable tool to support ice-vested navigation and safety, both for shipping and aviation within the vastness of the Southern Ocean.

3.3. Biogeochemistry and air–sea fluxes

Due to its remoteness and the associated logistical challenges, the SOIS is one of the least sampled regions of the world's oceans. The general lack of long-term in situ biogeochemical observations (with the exception of the Southern Ocean Time Series site) contributes to large uncertainties around climatologies. Many biogeochemical processes show variabilities from diel (e.g., due to insolation), weekly (e.g., due to weather systems), seasonal (e.g., due to seasonal stratification), and interannual cycles (e.g., due to ocean-atmosphere oscillations). High-resolution observations from, for example, moored platforms (**Figure 2**) can help the detection of regular cycles versus long-term trends, although only for their region of representativeness. Autonomous platforms such as floats greatly expand regional and temporal coverage; however, even a 10-day sampling interval may miss synoptic events and/or mesoscale features (Monteiro et al., 2015; Djetchouang et al., 2022; Nicholson et al., 2022).

The Southern Ocean Time Series is the longest-running observatory in the Southern Ocean and currently the only moored open ocean observation platform in the Sub-Antarctic Zone (e.g., Shadwick et al., 2015; Trull et al., 2019; Wynn-Edwards et al., 2020). It is located southwest of Tasmania, Australia (at approximately 47°S, 142°E), and delivers meteorological observations as well as multi-trophic observations of inorganic carbon and nutrients, biological production and carbon export with two deep

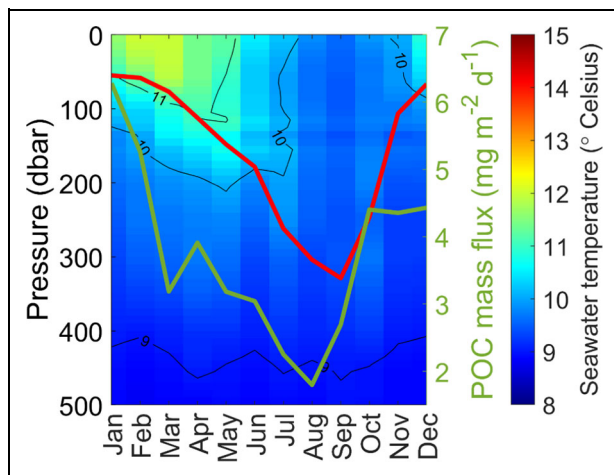


Figure 4. Examples of mooring data in the SOIS. A gridded temperature climatology obtained from the air–sea flux mooring as part of the Southern Ocean Time Series site, with the mixed layer depth in red on the left axis and the particulate organic carbon (POC) flux climatology from 1000 m in green on the right axis.

water moorings (**Figure 4**). Carbon export measurements with deep-moored sediment traps at 1000 m, 2000 m, and 3800 m started in 1997, with roughly fortnightly resolution. Data gaps in this record are due to instrument failure and/or logistical issues (Wynn-Edwards et al., 2020). Meteorological observations and water column property measurements (e.g., temperature, salinity, and oxygen) have been available since 2009, with resolutions ranging from minutes to hours and a depth down to approximately 500 m. Based on regional oceanography and remote sensing, the Southern Ocean Time Series site is considered to be representative of a broader region of the Sub-Antarctic Zone south of Australia (Trull et al., 2001), which was recently confirmed by a study comparing carbon export estimates from biogeochemical (BGC)-Argo float measurements in the broader region with sediment trap data (Yang et al., 2024).

There are two sections of the Global Ocean Ship-Based Hydrographic Investigation Program (GO-SHIP) in the SOIS, sections SR3 and I9S, which have been reoccupied several times over the last decades (e.g., Shadwick et al., 2015; Conde Pardo et al., 2017), with full-depth hydrographic (temperature, salinity, oxygen) and inorganic nutrient and carbon profiles collected between Australia and Antarctica. The data are available through the Global Ocean Data Analysis Project (Key et al., 2015; Olsen et al., 2016). On some occupations, dissolved and particulate trace metal samples have also been collected as part of the international GEOTRACES programme and made available as part of a series of intermediate data products (e.g., Sedwick et al., 2008; Cossa et al., 2011; Tagliabue et al., 2022). Several nations contribute to the international Ships of Opportunity Programme in this sector of the Southern Ocean, and underway surface observations of temperature, salinity, and CO₂ partial pressure are collected and contributed to large programmes like the Surface Ocean Carbon Atlas (Bakker et al., 2016) contributing

to quantifying the magnitude of the Southern Ocean Carbon sink (e.g., Bushinsky et al., 2019).

Over the last several years, the network of profiling floats carrying biogeochemical sensors, for example, BGC-Argo, has expanded considerably (middle rows of **Figure 3**), and seasonally resolved observations of oxygen, pH, nitrate, Chl-a, and particle backscatter are contributing to rapid advances in our understanding of the seasonality of biogeochemistry in the Southern Ocean (Bushinsky et al., 2017; Gray et al., 2018; Moreau et al., 2020; Ryan-Keogh et al., 2023; Yang et al., 2024).

Ocean biogeochemistry controls the sea–air fluxes of several climatically relevant chemical trace gases, including, but not limited to, sulphur compounds, halogen species, volatile organic compounds, and so on (Nightingale and Liss, 2003). These compounds affect the atmospheric composition and can also affect the formation of new particles and clouds, hence affecting the climate. In this regard, the SOIS is one of the least sampled oceans, with few campaign-based datasets available at the moment. Observations in other parts of the world over the last few decades have shown the importance of sustained observations of the surface ocean–lower atmosphere parameters. As the SOIS brings together diverse water and air masses, understanding sea–air interactions there and the changes that can occur in the future is important. Presently, only a few observations of climatically relevant trace gases such as dimethyl sulphide (Hulswar et al., 2022), carbonyl sulphide (Mihalopoulos et al., 1991), halocarbons (Saiz-Lopez and Von Glasow, 2012), iodide/iodate (Chance et al., 2019), isoprene, and monoterpenes (Rodríguez-Ros et al., 2020) have been made in the SOIS. These observations are supplemented by atmospheric observations of the same trace gases at ground stations such as Amsterdam Island, Antarctic stations and observations on ship-based campaigns such as the Indian Southern Ocean Expeditions (Sciare et al., 2000; Mahajan et al., 2019; Chance et al., 2020; Wagh et al., 2023; Mahajan et al., 2024). However, these observations are still too few to accurately quantify the impact of these emissions on regional and global scales and identify whether their emissions will increase/decrease with climate change. Also missing are observations of several other important trace gases, such as carbonyl sulphide, amines, and nitrogen compounds, which can affect not only the lower atmosphere but also the stratospheric ozone.

3.4. Lower and mid-trophic levels

Despite playing an important role in the marine food web by regulating fluxes of essential nutrients and providing energy for higher trophic levels, the seasonal α - and β -diversity patterns of bacteria, archaea, and eukaryotic microorganisms remain elusive in the Southern Ocean (Raes et al., 2024). Even in the recent global ocean surveys (e.g., Sunagawa et al., 2015; Larkin et al., 2021), only a handful of studies have investigated microbes in the SOIS (González et al., 2014; Sinha et al., 2019; Hörstmann et al., 2021; Sow et al., 2022; Chowdhury et al., 2024). To date, detailed analysis of microbial community

composition along with measurements of physiological rates lag behind physicochemical and plankton diversity and biomass measurements in the SOIS (Lo Monaco et al., 2010; Hörstmann et al., 2021; Metzl et al., 2022).

Characterising biodiversity in a holistic manner across the food web, from viruses to whales, using environmental DNA (eDNA) represents a shift in our capacity to monitor the ocean (Suarez-Bregua et al., 2022). Globally, genomic tools are increasingly being incorporated into national monitoring programmes, as seen in the United States (Goodwin et al., 2024) and Australia (De Brauwer et al., 2023). Transitioning from traditional observational methods to advanced approaches (such as eDNA) is challenging. Many consortia advocate for a pragmatic approach that combines various monitoring methods to survey marine biodiversity over spatial and temporal scales. The rich data produced with modern genomic approaches allow us to observe subtle movements in biodiversity that are important in identifying places of high ecological value to monitor the health of keystone species and vulnerable ecosystems (Chavez et al., 2021). Researchers in the Southern Ocean using eDNA have explored diverse topics, including krill bacterial microbiomes (Clarke et al., 2019), fish trophic ecology (Clarke et al., 2020; Vasiliadis et al., 2024), scat and diet ecology (Deagle et al., 2023), plankton biogeography (Suter et al., 2021), and large-scale biodiversity transects, including the detection of taxa of biosecurity concerns (Nester et al., 2024). Effective monitoring across large spatial and temporal scales is a significant challenge, but eDNA offers a cost-effective method to observe ocean biology at the same resolution as we observe the physicochemical world. Environmental DNA will become a standard tool to map biodiversity, distribution, and connectivity, especially as collection methods are integrated via auto-samplers on dedicated research vessels, ships of opportunity, drones, and gliders (Preston et al., 2024).

Knowledge of phytoplankton community composition is fundamental to understanding lower trophic level responses to environmental change at many scales (Behrenfeld et al., 2021). As different functional groups (e.g., coccolithophorids, diatoms, dinoflagellates, etc.) have differing micro- and macro-nutrient requirements, community composition intimately reflects prevailing oceanic conditions and biogeochemistry (Boyd et al., 2008). Species-level abundance data can be converted easily to biovolume/biomass and thus provide another insight into community size distribution and C/N biomass under local environmental conditions (Eriksen et al., 2019).

Chl-a concentration is an important indicator for phytoplankton biomass and primary production. Both Chl-a and various accessory pigment concentrations can be diagnostic in understanding the community composition. Ocean colour data can be tracked through satellites to examine the health, distribution, and density of phytoplankton blooms (Cetinić et al., 2024). In situ pigment concentration is measured with either a high-performance liquid chromatography, a fluorometer, or a spectrophotometer. In the case of satellite observations, an ocean colour sensor measures spectral upward radiance

(or reflectance) at the sea surface, and Chl-a is estimated using an in-water algorithm, which is an empirical relationship between in situ historical surface spectral upward radiance (or reflectance) and surface Chl-a. Therefore, satellite Chl-a measurements need to be ground-truthed against pigment analysis at that particular location (Chan et al., 2022). Phytoplankton carbon fixation efficiency, that is, primary productivity, depends significantly on the environmental conditions and therefore will be influenced by global climate change (Thomalla et al., 2023).

Satellite ocean colour remote sensing is a useful tool to close temporal and spatial gaps of in situ data of phytoplankton biomass, functional types, pigment composition, and primary productivity (Moore and Abbott, 2000; Jasmine et al., 2009; Hirawake et al., 2011; Takao et al., 2012; Kerker et al., 2020; Kerker et al., 2023; Tripathy et al., 2024). While several ocean colour sensors on the polar orbit satellites are currently operational and continue to observe the SOIS, missing data due to cloud, sea ice, and high solar zenith angle are unavoidable issues that reduce data availability (Groom et al., 2019). Therefore, in situ observations of bio-optical variability in the SOIS are sparse and mostly restricted to the summer season (Hirawake et al., 2000; Kerker et al., 2020; Kerker et al., 2021; Kerker et al., 2022). In addition to satellites, hyperspectral radiometry is an effective optical tool to understand underwater light attenuation (Lee et al., 2002) and generates useful inputs for ocean colour models (McClain, 2009). However, there are very few studies in SOIS that incorporate the measurements by hyperspectral radiometry (Kerker et al., 2022), because obtaining accurate estimates by this technique remains an enormous task with uncertainties associated with operations, seasonality, and optical complexity of oceanic waters (De Moraes Rudorff et al., 2014; O'Reilly and Werdell, 2019).

Phytoplankton species-level changes in abundance and diversity take place at varying spatial and temporal scales that can be difficult to sample using ship-based methods (Eriksen et al., 2018); thus, species-level information for the SOIS is relatively sparse compared to more accessible parts of the Indian Ocean. To understand phytoplankton biomass and size spectrum, a full suite of in situ techniques (e.g., microscopy, flow-cytometry, etc.) is required to cover cell sizes ranging from picoplankton ($<2\ \mu\text{m}$) to microplankton ($>20\ \mu\text{m}$) and mesoplankton ($>200\ \mu\text{m}$). While species-level microscopy-based observations can be time-consuming, they are critical and complementary to the full interpretation of satellite and pigment-based methods (Schlüter et al., 2011). Advances in molecular approaches for cataloguing diversity offer a tantalising look at previously unknown or undescribed diversity; however, attention must be paid to reconciling observations made using older techniques with newer datasets (McManus and Katz, 2009).

For in situ pigment analysis and understanding the distribution of biomarkers, high-performance liquid chromatography is commonly employed. In the SOIS, such data are available south of Australia (Clementson et al., 2001; Johnson et al., 2013; Takao et al., 2014), the western coastal region of the SOIS (30–80°E, south of 62°S; Wright

et al., 2010), northern sections at the border to the Indian Ocean, and further south off Lützow-Holm Bay (Hirawake et al., 2011; Takao et al., 2012; Kerkar et al., 2020), the sub-Antarctic and Polar Frontal zones from approximately 40°S to 60°S (Robinson et al., 2021), and the coastal waters around the Kerguelen Islands (Uitz et al., 2009; Lasbleiz et al., 2014; Jena, 2017). Because all these observations of in situ pigment concentrations were snapshots and not monitored routinely, using them to understand the phytoplankton community succession is difficult.

For measuring primary productivity, incubating water samples with carbon isotopes over a certain period (1–24 hours) is the most common method, widely adopted to quantify primary productivity (Westwood et al., 2011; Tripathy et al., 2014; Tripathy et al., 2015; Trull et al., 2015; Kerkar et al., 2020). Others have used incubations with $\delta^{15}\text{N}$ (Thomalla et al., 2011; Gandhi et al., 2012; Prakash et al., 2015; Tripathy et al., 2018). Compared to satellite observations, in situ estimation of pelagic primary productivity is labour-intensive and time-consuming; hence, the number of in situ observations is low, both in the SOIS and globally. Nevertheless, in situ measurements are important to validate satellite estimates and develop site-specific models (Hirawake et al., 2011; Kerkar et al., 2020). As for other ship-based observations, measurements of primary productivity are restricted mostly to the austral summer (December to February) due to ship availability. Estimates for other seasons (e.g., Del Castillo et al., 2019) are usually based on remotely sensed Chl-*a*. In addition, there are very few recent measurements of size-fractionated accounts of primary productivity (Ning et al., 1993; Fouilland et al., 2000).

Globally, zooplankton play a pivotal role in the marine ecosystem as the main grazers on phytoplankton, thereby transferring carbon to higher trophic levels, as well as contributing to carbon export and sequestration (Frederiksen et al., 2006; Steinberg and Landry, 2017). The effort dedicated to zooplankton sampling in the global ocean has increased markedly over the past decades, encompassing both short- and long-term experiments and collections, as well as the establishment of long-term sampling programmes of species composition, abundance, and distribution in the SOIS (Constable et al., 2018).

Since its inception in 1991, the SCAR Southern Ocean Continuous Plankton Recorder (SO-CPR) survey has been the dominant large-scale zooplankton time series in the Southern Ocean (Hosie et al., 2003). It aims to document zooplankton diversity and distribution, understand seasonal, annual and long-term variability, and examine the changes in abundances of Antarctic krill larvae produced each year (Hosie et al., 2003; Takahashi and Hosie, 2020). Over the past decades, the SO-CPR survey has delivered data on taxonomy, life histories, and distribution of individual species (e.g., Takahashi et al., 2002; Hunt and Hosie, 2003; 2005; Meilland et al., 2016), as well as a comparison to DNA-based monitoring programmes (e.g., Deagle et al., 2018; Suter et al., 2021), and contributed to large-scale bioregionalization (e.g., Takahashi et al., 2010; Godet et al., 2020; Pinkerton et al., 2020; Sugioka et al., 2021; Takahashi et al., 2021). In addition to monitoring

large-scale zooplankton distribution, the SO-CPR has been collecting information on phytoplankton as the phytoplankton colour index (Takahashi and Hosie, 2020). In recent years, the phytoplankton analysis has moved from noting the colour gradient to a more detailed identification to taxon-level by the Australian Antarctic Division and the University of Tasmania, Australia (L. Brokensha, personal communication, 17/12/2024). To date, the majority of the SO-CPR observations have been concentrated in the SOIS region primarily between 60°E and 160°E south of the Sub-Antarctic Front (**Figure 5A**). This region includes areas near sub-Antarctic archipelagos such as Prince Edward, Crozet, and the Kerguelen Islands, as well as along several transects in the western sectors, mainly from South Africa to the Antarctic coast. The western and more north-central regions of SOIS are not as well covered (Takahashi and Hosie, 2020).

In addition to the SO-CPR survey, several other long-term and short-term zooplankton research programmes in the SOIS are noteworthy. One example is the ongoing initiative ‘Long-term monitoring of zooplankton community structure and productivity in the sub-Antarctic Prince Edward Islands Marine Protected Area’ established in 2013 and led by South Africa, (Verheye and Makhado, 2014). Another example is the Southern Ocean seasonal Experiment (SCALE), an interdisciplinary initiative led by South Africa (Ryan-Keogh and Vichi, 2022). Voyages on the SA *Agulhas II* occurred in the winter and spring of 2019, allowing for investigations of zooplankton in the SOIS marginal ice zone, specifically related to the relationships between seasonal sea-ice dynamics and zooplankton abundance and productivity. Similarly, the Indian Southern Ocean Research Program, initiated in 2004, has completed 11 expeditions to date, underscoring India’s commitment to long-term oceanographic and biological research in the SOIS (Narayana Pillai et al., 2020). France and Australia have also made significant contributions, particularly in studying the zooplankton systems in the vicinity of the Crozet archipelago and Kerguelen Islands (e.g., Matsuno et al., 2020; Cotté et al., 2022).

Other in situ methods such as multinet, WP-2, and bongo net sampling, in combination with other methods such as acoustic backscatter measurements and laser optical plankton counters, are also used to collect and observe zooplankton organisms during occasional samplings (e.g., Labat et al., 2002; Escobar-Flores et al., 2018) and/or long-term monitoring programmes in the SOIS, including in the open ocean of several hydrographic zones (e.g., Takahashi et al., 1998; Venkataramana et al., 2020; Yang et al., 2022) and near archipelagos such as the sub-Antarctic Prince Edward Islands (e.g., Pakhomov and Froneman, 1999; Stirnimann et al., 2021). In contrast to the CPR samples, these approaches provide an improved vertical resolution of zooplankton to understand, for example, the impacts of oceanographic fronts on mesopelagic distributions (Venkataramana et al., 2019; Venkataramana et al., 2020), carbon export by zooplankton (Halfter et al., 2020; Halfter et al., 2022), the island mass effect on zooplankton distribution and productivity (Stirnimann et al., 2021),

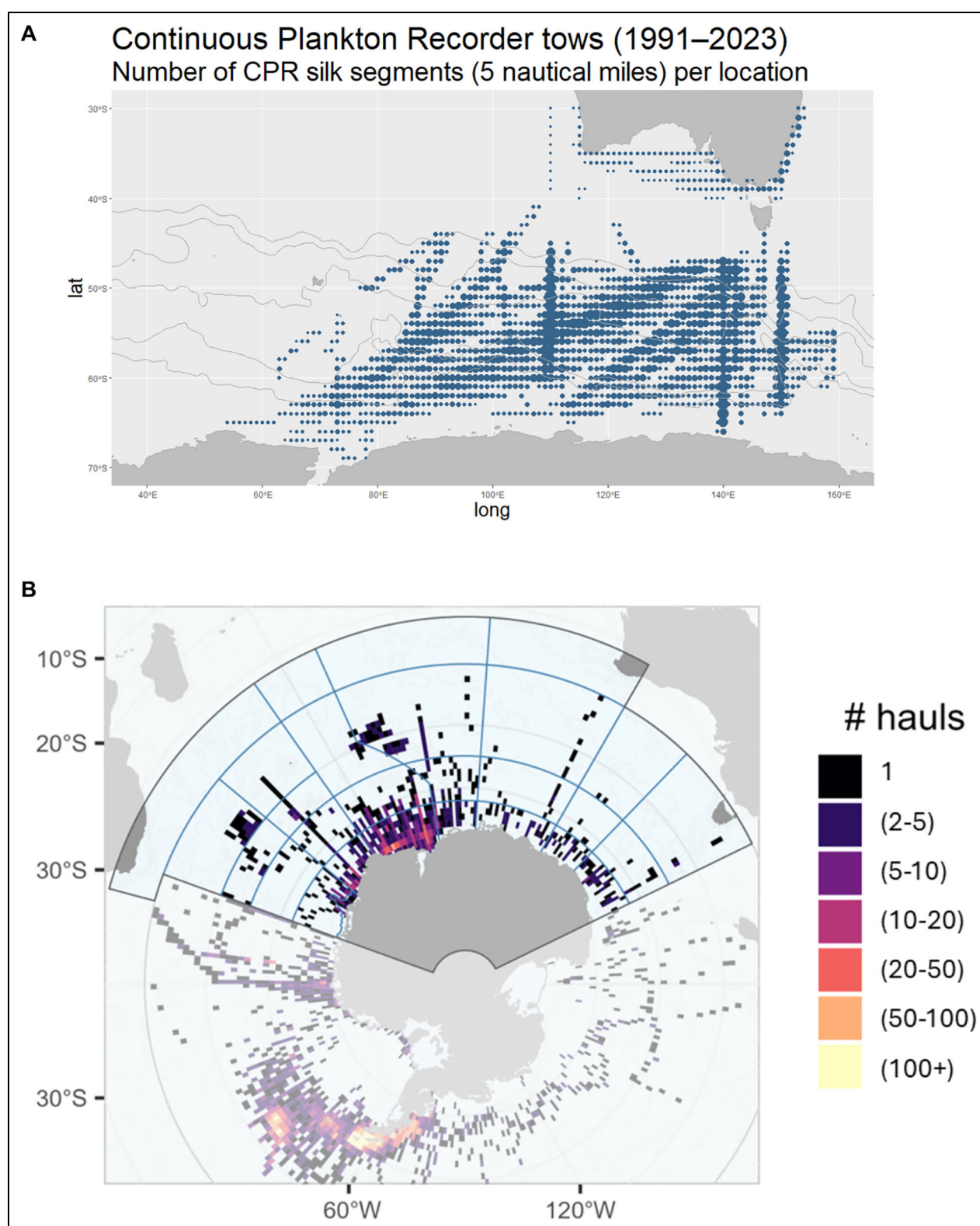


Figure 5. Examples of sustained ocean observations of plankton in the Indian Sector of the Southern Ocean. (A) Observation density of plankton data in the Southern Ocean Continuous Plankton Recorder database, as number of silk segments per location (1991–2023). Grey lines show Southern Ocean fronts (**Figure 1A**). (B) Data coverage, that is, binned total number of net hauls, recorded in KRILLBASE with a focus on the SOIS.

and variability in the distribution and biogeochemical activity of zooplankton, including key Antarctic species such as Antarctic krill and salps (Yang et al., 2021; Yang et al., 2022).

Stable isotope analysis can be a powerful tool to understand trophic interactions, marine productivity rates, and biogeochemical cycles within pelagic plankton ecosystems. However, analysis of nitrogen and carbon stable

isotopes (i.e., $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$) in zooplankton body tissues remains limited to point measurements, with research focused primarily on niche variations (e.g., Weldrick et al., 2019; Yang et al., 2021) and lower trophic system food web structures (Hunt et al., 2021). As a result, there is a growing need within the scientific community to enhance observations of the less described zooplankton isoscapes in the SOIS, which could facilitate the generation of isotopic baselines for food web analysis and support the development of spatial biogeochemical models based on satellite observations or mechanistic models (Buchanan et al., 2021; St John Glew et al., 2021).

Antarctic krill (*Euphausia superba*) are among the most monitored organisms in the Southern Ocean, including in the Indian Sector, due to their significant contribution to Southern Ocean food webs and their commercial importance as a fishery resource. In 2017, KRILLBASE, a temporal-spatial krill database, was published for the Southern Ocean to facilitate research in biogeochemistry, ecology, higher predator foraging, food web modelling, fisheries management, and conservation (Atkinson et al., 2017; **Figure 5B**). While data collection is ongoing, more recent survey data since 2017 are not captured in the current version of KRILLBASE. Regular surveys of the krill population in the SOIS are conducted, primarily by Australia, and often utilise multiple methods, such as acoustics, net surveys, underway sampling, and recently the deployment and collection of specialised moorings to examine krill distributions at depth (Krill Observational Mooring for Benthic Investigation system; Cox et al., 2024). A significant number of the scientific cruises undertaken in the SOIS by Australia specifically target krill, krill predators and their environment, for example, the ENRICH (2019) and the TEMPO (2021) voyage on the RV *Investigator*.

Despite the extensive zooplankton monitoring in the SOIS, data density from the winter season, within the sea-ice zone, and subsurface (>200 m) is still low, due to the logistical constraints of the environment and the lack of voyages in winter. While important studies have elucidated zooplankton biomass, abundance, distribution, and trophic role in the marine food web (e.g., Atkinson et al., 2012; Yang et al., 2022), comprehensive syntheses of the environmental drivers for zooplankton dynamics and their changes in future ocean conditions remain limited (Johnston et al., 2022). Voyage-based surveys are not only constrained temporally by season but are often limited to sampling the upper ocean due to acoustic echo depths, net deployment times, and the focus on the euphotic zone in the upper 200 m. As many of the net and acoustic surveys are focused on krill observations, many other zooplankton taxa are undersampled or caught opportunistically at best, thus giving sporadic data points to estimate trends, understand distributions, and extrapolate population estimates.

Gelatinous zooplankton, comprising cnidarians (i.e., medusae and siphonophores), ctenophores, and pelagic tunicates (i.e., salps, pyrosomes, and appendicularians; Pagès, 1997), play a key trophic role in marine ecosystems (reviewed by Hays et al., 2018) and contribute significantly to carbon sequestration as ‘jelly falls’ (Lebrato et al., 2012;

Lebrato et al., 2019; Luo et al., 2020). Despite their importance, gelatinous zooplankton remain largely understudied compared to hard-bodied zooplankton (e.g., Smith and Schnack-Schiel, 1990; Pauly et al., 2009). In the Southern Ocean, research has focused on salps, as an increase in salps compared to krill is predicted in the Antarctic Peninsula region (Loeb et al., 1997; Pakhomov et al., 2006; Atkinson et al., 2019). In the SOIS, interactions between salps and krill are less understood (Constable et al., 2018), partially due to the low sampling effort for gelatinous organisms in general (Collins et al., 2008; Lindsay et al., 2015; Panasiuk et al., 2019) and because traditional survey methods, such as CPR and nets, damage soft-bodied organisms often beyond recognition (Takahashi et al., 2002; Hosie et al., 2003; Hunt and Hosie, 2003; Licandro et al., 2015). The lack of surveys targeting gelatinous organisms and using appropriate sampling methodologies leads to a lack of long-term baseline data and prevents the detection of climate change-driven trends in gelatinous community dynamics, with unknown consequences for the SOIS ecosystem.

3.5. Higher trophic levels

Marine birds and mammals offer a unique perspective on ocean processes and the effects of climate change on the Southern Ocean. Knowledge of higher trophic levels in the SOIS is vital for informing decisions on marine living resource management and conservation policy (McMahon et al., 2021). Tracking the spatial distribution of marine predators at sea has already helped in identifying areas of ecological significance in the SOIS (**Figure 6**; Raymond et al., 2015; Reisinger et al., 2018; Hindell et al., 2020). Furthermore, using tracking data to identify key foraging habitats for bird species allows the analysis of the potential overlap between important bird areas and fisheries (Delord et al., 2014) and hotspots of other anthropogenic activities, such as tourism (Becker et al., 2025). To consolidate the already collected tracking data for meso- and top predators in the Southern Ocean, SCAR initiated the research project ‘Retrospective Analysis of Antarctic Tracking Data’ co-led by expert groups on birds and marine mammals and Antarctic biodiversity informatics (Ropert-Coudert et al., 2020). This publicly available dataset aims to fill some of the knowledge gaps mentioned above and support conservation management and modelling of predator distributions under future climate change. For example, the dataset recently enabled the definition of 30 potential key biodiversity areas throughout the Southern Ocean (Becker et al., 2025).

In the SOIS, marine birds and mammals are monitored on several sub-Antarctic islands, including Marion, Crozet, and Kerguelen islands, and the Antarctic continent (Brasier et al., 2019). Existing monitoring programmes in the region showed various trends, from increasing (e.g., fur seal or Adélie penguin) to decreasing populations (e.g., Emperor penguin), interannual variations (Chinstrap penguin), and contrasting trends (e.g., for ice-breeding and Elephant seals; Weimerskirch et al., 2018; Brasier et al., 2019). While long-term monitoring has increased in importance over the last few decades (e.g., towards the

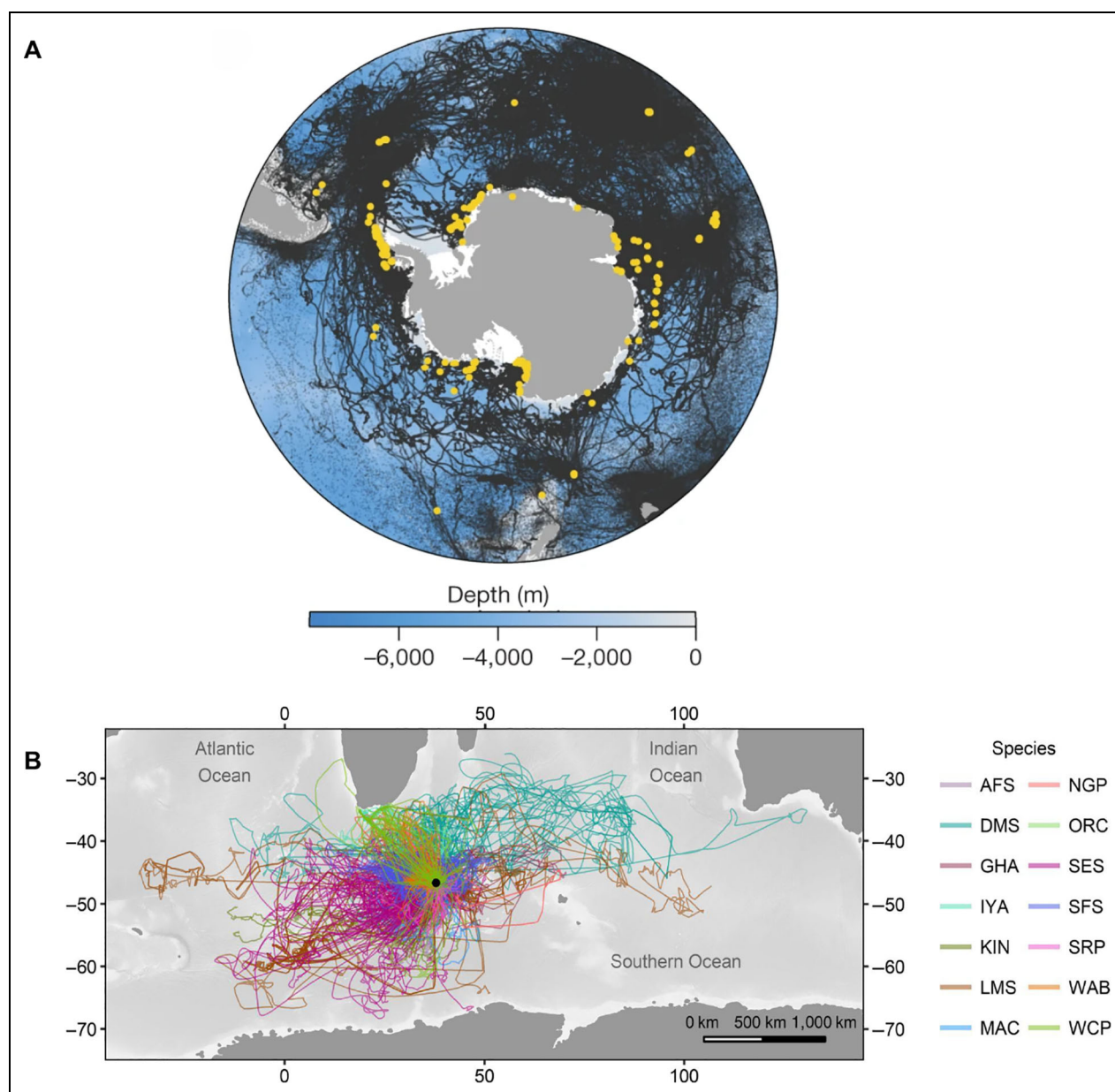


Figure 6. Examples of available tracking data of higher trophic levels in the Southern Ocean. (A) Tracking data from 17 marine predator species synthesised by Hindell et al. (2020). Black points indicate tracking data, and yellow points are tagging locations. (B) Tracking deployments on 14 species of marine predators at the Prince Edward Islands, synthesised by Reisinger et al. (2018); the Islands are marked with a filled black point. The species are Antarctic fur seal (AFS), sooty albatross (DMS), grey-headed albatross (GHA), Indian yellow-nosed albatross (IYA), king penguin (KIN), light-mantled albatross (LMS), Macaroni penguin (MAC), northern giant petrel (NGP), killer whale (ORC), southern elephant seal (SES), sub-Antarctic fur seal (SFS), rockhopper penguin (SRP), wandering albatross (WAB), and white-chinned petrel (WCP). Further information on methodology and data availability can be found in the respective reviews. Reproduced with permission.

Ecosystem Monitoring Program of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR; Agnew, 1997), demographic and foraging datasets are still limited for many species in the SOIS, for example, toothed whales and gentoo penguins (Brasier et al., 2019) among others. Typically, data on free-ranging species (i.e., cetaceans) and life stages (e.g., juveniles and nonbreeders) are less available than colony-based marine predators. However, these datasets are necessary to detect changes in breeding habits, phenology, and foraging distribution and

in separate influences by natural fluctuations from anthropogenic forcing (Orgeret et al., 2022). Remote sensing technologies, such as satellites and others, could help to develop cost-effective monitoring approaches in the future and acquire more (frequent) data, while being less invasive for the animal (McMahon et al., 2014; LaRue et al., 2021).

Despite advances made in biologging technologies, studying animals of higher trophic levels at sea remains challenging, especially linking animal performance, available prey/resources, and environmental variation to

animal life history and vital rates (i.e., survival and fecundity). For instance, correlative approaches such as species distribution models perform poorly when used to predict important habitat for unsampled populations (Torres et al., 2015), presumably because they are unable to capture causal environment-prey-predator linkages underlying predator foraging behaviour. Likewise, while there has been considerable work linking horizontal movements of higher marine predators to surface ocean variables, an understanding of how biophysical processes structure the vertical distribution and availability of prey for these predators remains limited. Quantifying these links and informing the transfer functions between the individual elements in this process is not straightforward, given that detailed long-term information is needed to achieve these goals (Schick et al., 2013; New et al., 2014; Bost et al., 2015; McHuron et al., 2018). Developing full predictive capacity for marine predator populations will require integrating information on the energetic requirements and foraging habitats of predators with information on physical forcing (McMahon et al., 2021), biological productivity, modelled prey niches, and predator-prey linkages (Green et al., 2020; Reisinger et al., 2022; Green et al., 2023a). Predictive capacity could be further advanced through the integration of this empirically derived process understanding into mechanistic modelling frameworks resolved at the food web (McCormack et al., 2020; Subramaniam et al., 2020a), population (Volzke et al., 2024), or even individual levels (Goedegebuure et al., 2018).

Other significant research and knowledge gaps include intra- and inter-specific competition, trait-specific data (e.g., physiology and diet), age classes, and seasonal variation (i.e., lack of observations over the winter/non-breeding period; Orgeret et al., 2022). Moreover, individual variation in diet and foraging strategies within populations needs to be evaluated. Advances in biomolecular methods, including stable isotope analysis (Walters et al., 2014; Connan et al., 2019), genetics (Hoffman et al., 2022), sensors (McMahon et al., 2021), and hormone analysis (Bestley et al., 2020), lead the way to assess physiology, diet, foraging ecology, and population history information more regularly. By their nature of integrating information from lower trophic levels, these techniques also offer a practical and cost-effective approach for characterising and monitoring change in the structure and function of SOIS marine ecosystems. However, continued work is needed to identify sentinel species and approaches that provide the clearest information on the trophic pathways they represent.

In the SOIS, marine predators equipped with biological and physical sensors have been used as autonomous environmental samplers (Harcourt et al., 2019; McMahon et al., 2021). They provide long-term data on key marine environmental variables, such as hydrography, animal behaviour and ecology, and changes in the distribution, abundance, and composition of the prey community (McMahon et al., 2019; McMahon et al., 2021). They can provide direct physical measurements in areas that are currently under-sampled and inaccessible for ship-based research, using deployments from sub-Antarctic islands and the Antarctic continent (e.g., Casey or Davis stations;

Charrassin et al., 2008; Fedak, 2013; Roquet et al., 2014; Pauthenet et al., 2018; McMahon et al., 2021; Ribeiro et al., 2021). In addition to physical measures, we can also collect essential biogeochemistry data, such as fluorescence and dissolved oxygen (Jaud et al., 2012; Xing et al., 2012; Blain et al., 2013; Bailleul et al., 2015). With sonar and light sensors, prey encounters at sea, density and distribution (Tournier et al., 2021; Chevallay et al., 2023), and predator-prey interactions (Vacqu  -Garcia et al., 2017) can be quantified. Beyond the collection of essential ocean variables, equipped marine predators can provide additional capacity for monitoring anthropogenic activity such as illegal, unreported and unregulated fishing within the region (e.g., Weimerskirch et al., 2020).

3.6. Benthos

While observations of benthic fauna in the Southern Ocean date back to the Challenger Expedition (1872–1876), they are still comparatively rare (Jansen et al., 2023). Sampling the seafloor consumes considerable time and requires specialised equipment, meaning benthic fauna is usually only sampled during dedicated surveys (Baishnab et al., 2023; Bhaumik et al., 2023) and is rarely done opportunistically. Most commonly, benthic fauna is sampled using either photographic surveys or physical sampling techniques such as benthic trawls, sleds, or grabs. While physical sampling techniques have been used historically, photographic surveys are much more common these days as they do not disturb the habitat, images can be more easily stored and shared, and frameworks exist to analyse images in a consistent way (Althaus et al., 2015). We focus here on giving an overview of the benthic imagery collected in the SOIS to date, but note that physical sampling will remain required for the taxonomic description of new species or molecular samples to further explore the biodiversity of benthic communities. Additionally, infaunal studies still require physical samples, as these habitats are inaccessible for photographic surveys.

Benthic imagery in the SOIS is sparse and patchy, both in space and time. The most comprehensive survey imagery exists for the sub-Antarctic Prince Edward Islands, consisting of downward-facing camera images from surveys in 1988–1989, followed by ongoing biannual (alternate years) forward-facing still image surveys initiated in 2013 (**Table 1**). On the Antarctic continental shelf, individual surveys have focused on the Mertz Glacier region, the Sabrina Coast, and in the proximity of the Australian Antarctic Stations at Casey and Davis (Jansen et al., 2023). On the Antarctic continental shelf in the SOIS, we have neither identified any surveys from the same year covering different regions nor any repeat surveys that target the same locations, which would allow investigating temporal changes in benthic fauna. Without more spatially and temporally comprehensive data on the benthic fauna, setting baselines is difficult and monitoring for changes through time is subject to high uncertainty.

3.7. Anthropogenic activities in the SOIS

Fishing for the Patagonian and Antarctic toothfish (*Disostichus eleginoides* and *D. mawsoni*, respectively) has

Table 1. Overview of seafloor image surveys and data access, organised by region in the SOIS

Survey ^a	Region or Site	Depth (m)	Year(s)	Camera Properties	Access or Reference
CEAMARC–Mertz	Mertz Glacier	200–1500	2007–2008	Stills, forward	Contact Jan Jansen (IMAS/UTAS, Australia)
RV <i>Aurora Australis</i> –Mertz	Mertz Glacier	200–1500	2011	Stills, downward	Smith (2017)
Under-ice shelf images (poor quality)	Amery Ice Shelf	775	2003	Stills, downward	Riddle et al. (2007); Post et al. (2014)
TEMPO voyage	Amery Ice Shelf	NA	2021	Stills, downward	Suter and Brasier (2024)
GA0348	Casey Station	<40	2014–2015	Video and stills	Carson (2015)
Casey benthic survey	Casey Station	<30	1998	Video and stills	Contact Jonathan Stark (Australian Antarctic Division, Australia)
GA0357	Davis Station	<300	2017	Video, downward	Smith (2020)
Davis benthic surveys	Davis Station	<30	1985, 1989, 2010, 2019	Video and stills	Contact Jonathan Stark (Australian Antarctic Division, Australia)
RV <i>Aurora Australis</i> voyage	Dalton Polynya and Mertz Glacier	NA	2014–2015	Video, downward	Symons (2020)
IN2017_V01	Sabrina Coast	480–1680	2017	Stills, forward	Post (2018)
Prince Edward Islands (University of Cape Town surveys)	Prince Edward Islands	31–750	1988–1989	Stills, downward	Branch et al. (1993) or contact Lara Atkinson (South African Environmental Observation Network, South Africa)
Prince Edward Islands (SAEON–LTBM)	Prince Edward Islands	56–550	2013–2022 (biennial)	Stills, forward	Von Der Meden et al. (2017) or contact Lara Atkinson (SAEON, South Africa)

^aCollaborative East Antarctic Marine Census (CEEAMARC), South African Environmental Observation Network (SAEON), Trends in Euphausiids off Mawson, Predators and Oceanography (TEMPO).

been prevalent around the sub-Antarctic islands and close to the Antarctic continent since 2000 and continues either constantly or intermittently (Welsford et al., 2012; CCAMLR, 2023). Moreover, Mackerel icefish (*Champsocephalus gunnari*) has been harvested consistently on Heard and McDonald islands since 1997 (AFMA Report, 2023; CCAMLR, 2023). The Antarctic krill fishery was historically high in the SOIS, particularly close to the Antarctic continent, but the fishery in this region closed in the 1990s (Nicol and Foster, 2016; Kawaguchi and Nicol, 2020). The krill fishery restarted in the SOIS in the 2016–2017 season, focusing more broadly on regions in the southwest, as well as around the Kerguelen Islands and the continent. Currently, the krill fishery in the SOIS is dominated by Chinese companies, due to its closeness to their ports and processing centres (Constable et al., 2018; Kawaguchi and Nicol, 2020). With the increase in fishing in the SOIS since 2016–2017 (Kawaguchi and Nicol, 2020), there has also been an increase in bycatch (CCAMLR, 2021). The reduction of adults in a fish or krill population will have widespread impacts on the ecosystem, but colonies and populations of marine predators closest to fishing

operations will be those most at risk (Barbraud et al., 2012; Corbeau et al., 2021; Queirós et al., 2021). A possible threat in future to the SOIS ecosystem is the development of new fisheries of mesopelagic organisms, for example, myctophids and squid that are prey items for marine predators (Bestley et al., 2020). Fishing activities took place in the Indian Sector for the first time in early 2017 (Constable et al., 2018), but the spatial and temporal distribution in the future and the magnitude of ecosystem-level impacts are currently unknown (Bestley et al., 2020).

Research on plastics distribution in the SOIS has been most prevalent from 2010 onwards (Isobe et al., 2017; Caruso et al., 2022; Li et al., 2022; Pattiaratchi et al., 2022), but a few studies occurred in the 1980s–1990s, particularly around the South African coastline and many of the SOIS sub-Antarctic islands (Ryan, 1987; Cooper and Condry, 1988; Kriwoken et al., 1989). Historically, the research focus was on the impact of plastics on larger organisms such as birds and seals in the SOIS (Ryan, 2008; Ryan et al., 2016; Perold et al., 2020; Robin et al., 2024), but recently the focus has been on microplastics in sediments (Nair et al., 2023) and underway plastic sampling in sea ice (Kelly et al., 2020a). No major

study has yet been conducted within the SOIS on marine plastic levels or distribution; trends in relation to plastic levels are unknown for the SOIS marine sector. However, marine plastic debris being found around the Antarctic coastline in the SOIS is increasing, as seen in Convey et al. (2002) and Barnes et al. (2010).

Studies on the impacts of research bases, both on the continent and on the sub-Antarctic islands within the SOIS, have been conducted at all Australian, French, and South African stations (Walton and Shears, 1994; Deprez et al., 1999; Stark et al., 2016; Crossin et al., 2020). Studies of human activities in the SOIS have been focused on fuel spills, pollution from effluent runoff, human disturbance of wildlife (Coetzee and Chown, 2016), and humans as vectors for invasive species to be introduced to the region (Frenot et al., 2005; Whinam et al., 2005; Tin et al., 2009). Currently, there are no known invasive marine animal species in the SOIS region. Detailed records for invasive terrestrial species, however, are available for the sub-Antarctic islands, including rabbits and cats, vascular plants, and several invertebrate species (e.g., Macquarie Island, Bergstrom et al., 2009, and Marion Island and Prince Edward Island, Ryan et al., 2003; Greve et al., 2017).

Tourism within the SOIS is limited due to the lack of close ports for ships and cruises and the few sub-Antarctic islands compared to the South Atlantic sector (Riffenburgh, 1998; Grant et al., 2021; Tejedo et al., 2022). However, many of the tourist operations in this region occur via air traffic, which brings its own unique challenges and environmental impacts, including the management of ice runways and aerosol particles. While some of the tourist flights do not land in Antarctica and only ‘fly-over’, and these styles of flights limit other contaminants and pollutants entering Antarctica, they also increase other anthropogenic inputs via carbon emissions, aerosolised particles, and increasing demand for tourism through social media posts and outreach.

4. Synergies between modelling and observations

Although very different in character, there is a high level of co-dependence between modelling and observing systems, whether the focus is on the representation of physical, chemical, or ecosystem processes. All models, even those based on fundamental physics, require a degree of tuning to ensure that their outputs are representative and utilise parameterisations of the key processes. This tuning can only be achieved if there are sufficient observations of the relevant rates and states against which the model can be evaluated. Uncertainties are greatest for biogeochemical and biological components due to the paucity of observations and often incomplete mechanistic understanding. This requirement is likely to increase in importance as more advanced machine-learning techniques are applied to model tuning (Fox-Kemper et al., 2019). Given complete spatial and temporal coverage, models can be used to place observations into context by documenting important variability or processes, testing hypotheses, highlighting the observations likely to have the most predictive power for model evaluation, or simulating the response

of an observing network (e.g., autonomous floats) over time (Fujii et al., 2019; Talley et al., 2019). Models are also essential in forecasting longer-term impacts of environmental changes on different aspects of the ocean system to inform policy-making (IPCC, 2022).

The most direct synthesis of modelling and observations involves reanalyses and state estimates, which combine model physics with direct observations to give a best-guess representation of the ocean. Recently, this approach has been used to implement a physics-biogeochemical estimate of the Southern Ocean, B-SOSE (Verdy and Mazloff, 2017). Compared to the ocean's physical state, biogeochemical modelling is more challenging due to the reliance on an incomplete theory of key processes. Model evaluation usually relies on concentrations of model tracers, such as nutrients or indicators of phytoplankton biomass (e.g., Chl-a). For some key aspects, like the distributions of the limiting nutrient iron, there can be substantial mismatches (Tagliabue et al., 2016).

All modelling efforts in the SOIS are hampered to some extent by the spatial sparsity and the summer bias of observations highlighted in this article and previous reports (Constable et al., 2018; Newman et al., 2019). For physical modelling, the most critical data gaps occur on the Antarctic continental shelf. As models move to much higher spatial and vertical resolution (**Figure 7A**), their accuracy becomes constrained by the accuracy of local bathymetry; this constraint also holds for open ocean regions where topography modulates mixing (Nikurashin et al., 2013), for example, the Kerguelen Plateau. Additionally, Antarctic ice-ocean interactions are unique in the global ocean, but the dearth of year-round observations presents a challenge to evaluating how well models simulate these processes.

For biogeochemical models, the emergence of BGC-Argo floats may start to fill some gaps, especially with the increased use of the nitrate sensor. However, other key nutrients cannot be determined autonomously yet. This issue is even more problematic for dissolved iron measurements, which, although significantly improved by the GEOTRACES programme, still have substantial spatio-temporal data gaps. Due to the difficulties of winter in situ sampling, assessments of phytoplankton activity via Chl-a have relied on satellite data, but satellite retrievals can require region-specific algorithms due to the unique bio-optical properties of Antarctic phytoplankton (Brown-ing et al., 2014). BGC-Argo floats offer a potential advantage here, as well as instrumented marine mammals and gliders, but still only cover a small suite of relevant biogeochemical parameters. These new datasets have yet to be integrated into BGC model evaluations. These knowledge gaps hamper the ability of BGC models to represent nutrient and trace metal cycling accurately, with implications for marine ecosystem modelling.

In addition to simulating the physical and chemical state of the ocean, our understanding of Southern Ocean ecosystems is also assisted by synthesising observations within ecosystem models (McCormack et al., 2021). Through models, we can better understand ecosystem structure and function, and how environmental and

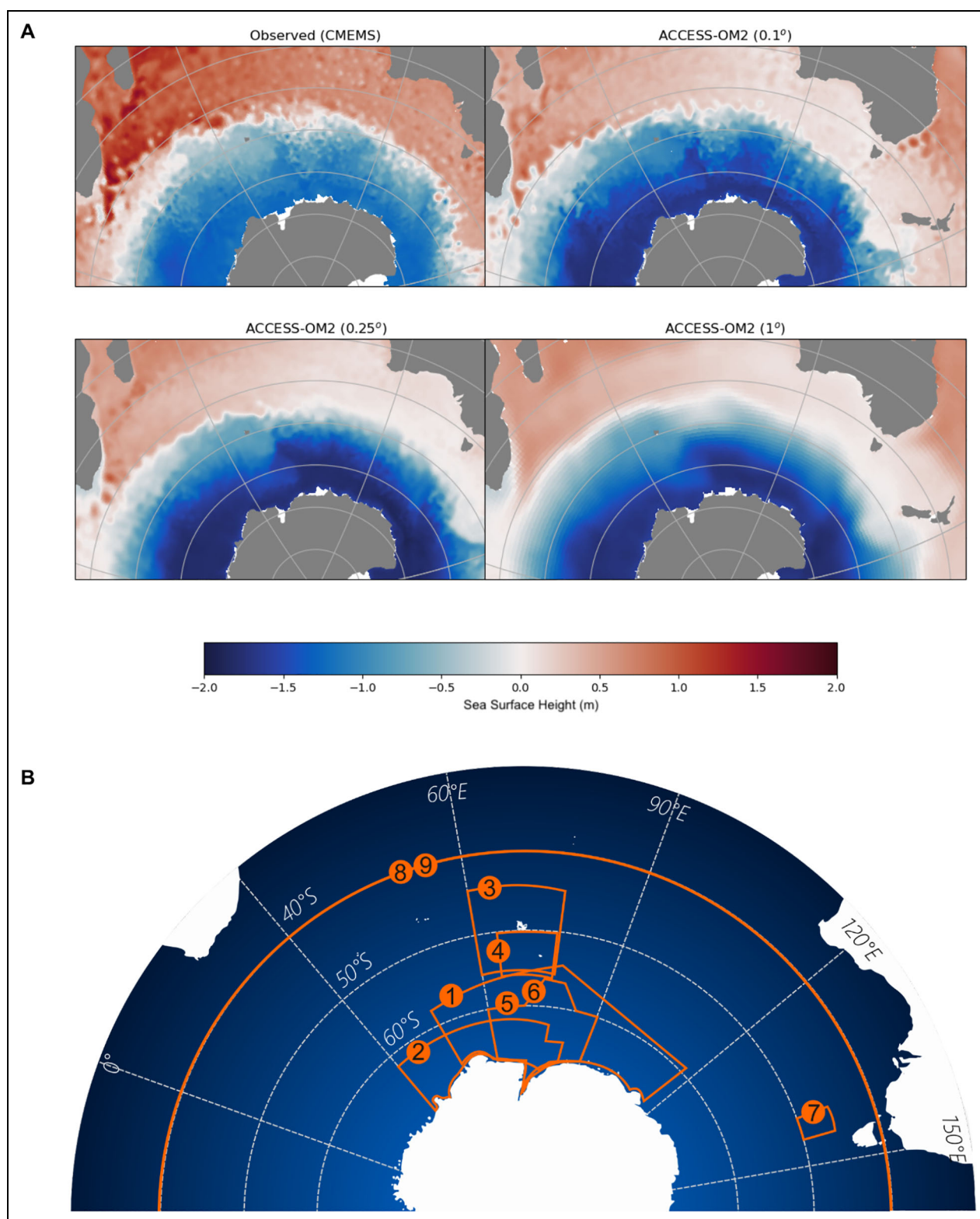


Figure 7. Examples of ocean-sea ice and ecological models in the SOIS. (A) Varying resolutions of in situ observations in comparison with ocean models. As an example, the observed sea surface height, accessed from Copernicus Marine Service, is displayed in the top left panel, in comparison to modelled sea surface height with the ACCESS-OM2 in 0.1° (top right), 0.25° (bottom left), and 1° (bottom right) resolution. (B) Overview of regional ecosystem models: (1) East Antarctic Atlantis, (2) East Antarctica Ecopath with Ecosim (EwE), (3) Kerguelen EwE, (4) Heard and McDonald Islands Mizer (multi-species dynamic size spectrum modelling in R), (5) Prydz Bay EwE, (6) Prydz Bay Mizer, (7) Southern Ocean Time Series Mizer, (8) Southern Ocean Models of Intermediate Complexity, and (9) KRILLPODYM. Further information and references can be found in Table S1.

anthropogenic drivers (like fishing and pollution) impact Southern Ocean ecosystems. Therefore, models are useful tools for supporting management decisions, policy-making, and conservation strategies and have the added functionality of hindcasting or forecasting ecosystem dynamics to further understand impacts on the ecosystem (McCormack et al., 2021). Since the SOOS SOIS workshop in 2017 (Constable et al., 2018), models have significantly progressed ecosystem understanding (**Figure 7B**; McCormack et al., 2021), mostly in areas of high data availability and interest, and associated with land-based research stations (Brasier et al., 2019; McCormack et al., 2021). In the SOIS, these areas are the sub-Antarctic islands and areas close to the continent and adjacent to research stations, such as Prydz Bay and the Mawson Sea.

A variety of data are required to develop an ecosystem model (Fulton and Link, 2014), some of which can be difficult to collect or standardise for use in model parameterisation (Newman et al., 2019). Major data gaps for the SOIS (and the Southern Ocean in general) are squid, fish, and other mesopelagic prey, which are patchy yet important to ecosystem function (Brasier et al., 2019; De La Chesnais et al., 2019; McMahon et al., 2019; McCormack et al., 2020; Subramaniam et al., 2020a; Caccavo et al., 2021). Fewer benthic assessments have been conducted in the SOIS compared to other sectors; as a result, benthic systems are not well represented in trophic or whole-of-ecosystem models (Brasier et al., 2019; McCormack et al., 2021). Further, the bias towards summer observations means that the seasonality of the Southern Ocean processes that influence ecosystems is not well represented in models. Broader spatio-temporal coverage of key ecological processes through sustained observations will significantly improve ecosystem representation in models and the utility of models for observing strategies (Addison et al., 2018; Newman et al., 2019).

5. Recommendations

5.1. Improve mechanistic understanding of drivers and processes

We recommend more research on the drivers of environmental changes to improve their monitoring at the regional, sector-wide, and circumpolar levels. Rising temperatures, ocean acidification, water column stratification, sea ice and glacier melting, changes in regional currents, and shifts in frontal zones are predicted to impact the availability of nutrients and biogeographic distribution, physiology, and ecology of Southern Ocean species from microbes to penguins. While large-scale environmental drivers are typically defined (see Section 2), their impact on ecosystem processes, especially on a regional basis, is usually less understood. For example, a lack of comprehensive scenarios of key physical, chemical and ecological drivers and a limited understanding of the impacts of these drivers on zooplankton are named as two of the largest gaps that need to be closed to understand future trajectories of the group in the future (Johnston et al., 2022). Similarly, the mechanistic understanding of links between sea ice processes and the resulting community

composition, both sympagic and pelagic, needs to be improved (Swadling et al., 2023).

5.2. Increase the use of new methods, sensors, and technologies

We recommend the increased use of new methods, sensors and technologies to enhance the ocean observing system while continuing validation and comparison studies between novel and traditional methods whenever possible.

New methods, sensors, and technologies can significantly increase the data collection by the ocean observing system in the SOIS. For example, the use of floats and instrumented seals vastly increased the availability of year-round oceanographic and biogeochemical datasets. The use of optical methods as well as biogeochemical tracers, such as eDNA, also significantly reduces the environmental impact of in situ sampling, for example, of vulnerable benthic communities, and time spent at sea. New sensors, for example, the addition of pH sensors or Underwater Vision Profiler-6 to BGC-Argo floats, significantly enhance the data collection below surface waters and beyond the summer season. While novel methods and technologies should be embraced by the SOIS research community, attention needs to be paid to validating and comparing novel methods with traditional approaches and long-term time series. For example, comparing sensor-based primary productivity measured in situ with laboratory-based incubation approaches allows better validation of satellite data products. Similarly, validating eDNA sampling with abundance data from nets remains necessary in many cases.

5.3. Standardise data collection and improve data accessibility

We recommend a focus on more standardisation in the data collection, especially for biological data, as well as following the FAIR (findable, accessible, interoperable, reusable) data principles whenever possible. While progress has been made in the standardisation and accessibility of physical and biogeochemical data, biological data lag behind. For example, for the purpose of benthic monitoring using optical methods, more data exist than shown in **Table 1**, but they are not publicly discoverable or accessible. Despite the high value of long-term time series to understand the spatial and temporal dynamics of a species, the limited accessibility of qualitative and quantitative datasets (including metadata) for many species restricts any exploration of trends and trajectories. Increased accessibility of data is also necessary to further facilitate model development and improvement (Addison et al., 2018; Newman et al., 2019). Examples of initiatives to improve the accessibility of biological data are KRILLBASE (though not updated since 2016; Atkinson et al., 2017), the Southern Ocean Dietary and Energetics Database (Scientific Committee on Antarctic Research, 2023), and Myctobase, a circumpolar database of midwater trawl sampling (Woods et al., 2022). In addition to data accessibility, the sampling protocols for biological data collection are often inconsistent and vary, even between field campaigns of the same national programme, an issue to be resolved by adopting sampling methods based on approved best

practices (e.g., the World Meteorological Organization (WMO) CIMO guide for measurements of cryospheric variables; WMO, 2018). An increased standardisation of methods and metrics used in the data analysis will be necessary to enable cross-sector comparisons.

5.4. Sustained observations of mid-trophic levels beyond krill and hard-bodied zooplankton

We recommend an increased focus on sustained observations of mid-trophic levels, by updating KRILLBASE, focusing on gelatinous zooplankton, continuing efforts such as Myctobase (see Section 5.3) to explore alternative energy pathways, and developing standardised databases for acoustic and optical observations. While Antarctic krill is often the focus of biological studies and long-term monitoring in the SOIS, we need to consider other mid-trophic links, such as myctophids, squid, or salps, that might be essential for top predators, as highlighted by McCormack et al. (2020) and Subramaniam et al. (2020a). KRILLBASE is an important database for both krill and salp observations in the Southern Ocean in general, but it requires updating with newer observations since 2017 or even a shift towards a living database rather than a published dataset. The Southern Ocean Continuous Plankton Recorder is one of the largest and longest plankton time series in the world, but it under-samples migrating, sub-surface, and gelatinous zooplankton species. Acoustic observations of micronekton and fish can be valuable to understanding their large-scale and vertical distribution; however, we currently lack a central database of openly accessible and quality-controlled acoustic data. Similarly, the few benthic observations, nowadays focusing on optical rather than on trawl or grab data, are not stored in a single database either and are often only accessible upon request (Table 1).

5.5. Observing the Southern Ocean sea-ice zone

We recommend emphasis on cross-disciplinary, international longitudinal observing systems deployed at scientific hotspots and integrating from the Antarctic continent, via coastal, on-shelf (including sea-ice zone) to the deep ocean (including year-round bluewater zone) to obtain year-round well-conceived observational data sets. Future directions for observing Antarctic sea ice will hinge on cross-disciplinary, international collaborations with a focus on sustained long-term in situ observations, building on CryoNet of the Global Cryosphere Watch, focusing on key regions and enabling longitudinal networks, that observe from the continental and near-coastal Antarctic across the sea-ice zone into the blue ocean, to provide process information as well as link across spatial scales and regions (Brooks et al., 2021; Heil et al., 2023). Increasingly, the emphasis for polar and sub-polar regions is on comprehensive and synchronous observations with broad coverage to improve our understanding of anthropogenic impacts on the wider Earth system. This emphasis includes broad agreement on standardised observing protocols and adherence to best practices and open data. This approach will be embodied within upcoming international initiatives such as the Antarctica InSync (2027–2028) of the

UN Ocean Decade and the WMO- and SCAR-endorsed 5th International Polar Year (2032–2033).

5.6. Monitoring of direct anthropogenic impacts beyond fisheries

We recommend focusing on improved monitoring of fisheries, but also other current and upcoming anthropogenic impacts, such as plastics, non-native species, and pollution. Fisheries in the SOIS are managed under CCAMLR, which not only monitors impacts on fish stocks but also on potential bycatch and higher trophic levels. However, with the restarting of the fisheries for Antarctic krill as well as potential mesopelagic fisheries in the sector, monitoring needs to focus on the fishery impacts on the food web and associated processes, such as downward carbon flux. In addition, changes in marine predator colonies due to climate change have to be taken into consideration by management as well to adjust to new conditions. Other direct human pressures, such as (micro-)plastics or the introduction of non-native marine species, are currently not monitored in a standardised or sustained way. Similarly, pollution, for example through shipping traffic or around research bases, is still evaluated case-by-case instead of in a network of selected monitoring sites. With the advance of eDNA, better large-scale tracking of non-native species will be possible in future (Nester et al., 2024). In general, the pathway from the detection of environmental changes to an adjustment of the management of anthropogenic activities needs to be more efficient. Emergency responses to developing threats, for example, the recent spread of avian influenza H5N1, are only possible within a comprehensive monitoring and observation network, and an effective science-policy interface (e.g., see Hughes et al., 2023).

5.7. Fill in temporal observation gaps during winter

We recommend a focus on filling observational gaps in winter by continuing the multi-platform approach for oceanographic and biogeochemical observations, considering more widespread year-round moorings, and developing biological observation methods that do not require a ship. For many in situ observations, winter still represents a data-poor time of the year. Anything requiring a ship, for example, CTDs, plankton net tows, shipboard experiments, short- and mid-term glider deployments, is focused on the summer season when the Southern Ocean is logistically accessible. While permanent research stations or one-off campaigns such as SCALE allow for limited datasets during the winter, the observations are often restricted in space. Even upcoming initiatives, such as Antarctica InSync, currently focus on filling the spatial knowledge gaps rather than the temporal ones. Nevertheless, progress has been made, especially for oceanographic and biogeochemical observations. The advances of floats with additional sensors and instrumented mammals are a step towards a better understanding of seasonal dynamics in the water column. Similarly, surface and deep-sea moorings, such as at the Southern Ocean Time Series site, allow a unique understanding of the air-sea interface and water column processes, as well as particulate flux in the

SOIS outside the summer season. Biological observations that require in situ observations, for example, CPR and net deployments or ship-based acoustics, still lag behind in terms of year-round observations, although acoustic sensors are increasingly attached to moorings (Trull et al., 2019).

5.8. Fill spatial observation gaps

We recommend a focus on closing the spatial observation gaps in the northern SOIS, the sea ice-covered waters, as well as in subsurface waters. The spatial knowledge gaps that emerge from this review are not necessarily unique to the SOIS but are often exacerbated due to the size of the sector, as well as the diversity of regions to cover by the observation system and the participating national programmes. For example, the northern SOIS (latitudes lower than 45°S–55°S, depending on the longitude) appears to be understudied, for example, fisheries are not managed by CCAMLR but are considered high seas with a lack of associated monitoring, tracks of instrumented seals are not available (bottom row of **Figure 3**) and, with a few exceptions, ship-based research campaigns do not often focus on this region. Likewise, large knowledge gaps of water column processes exist at high latitudes in waters covered by sea ice (both land-fast ice and in the marginal ice zone; Fraser et al., 2023). Sites with more observations are usually centred around the sub-Antarctic islands, along the transits to research stations of resupply missions and around research stations themselves. Floats, gliders, and other remotely operated methods (i.e., not reliant on a ship) have started to fill spatial knowledge gaps (top and middle rows of **Figure 3**). When connected with long-term, sustained observations using other platforms, these remotely operated methods allow a determination of the representativeness of a long-term observation site for a larger region in the SOIS (e.g., Yang et al., 2024). For many biological observations, large spatial knowledge gaps are still apparent, for example, in microbial diversity and benthic communities. Spatial gaps also include observations below the surface, as large-scale monitoring often focuses on the upper 100–200 m of the water column, rather than the deep sea.

5.9. Improved models to support an ocean observing system in the SOIS

We recommend the integration of new ocean observation data to improve models, work towards model ensembles, a focus on the East Indian Sector when developing regional models, and a better coupling of ecosystem models with physical and biogeochemical models. Improving models will be essential to support sustained ocean observations in the SOIS, while novel observational technologies can help resolve current uncertainties in ecosystem models. In the future, information from new data streams needs to be integrated into models to better contextualise disparate observations, incorporate seasonality, and represent groups that were previously underrepresented in traditional data collection methods (Fulton et al., 2019; Newman et al., 2019). Uncertainties within a model framework will be further resolved through building capabilities

towards model ensembles, which identify ongoing data gaps and areas in need of improvement regarding ecosystem understanding and projections of change (Addison et al., 2018; Newman et al., 2019; Pethybridge et al., 2020). Additionally, developing less data-reliant models using dynamical systems theory or equation-free non-linear approaches may resolve remaining data gaps and uncertainties (McCormack et al., 2021). Most regional models focus on the Central Indian Sector, while the East Indian Sector remains less studied. Common models used in the different regions around the Southern Ocean will allow a better generalisation of processes and impacts, which is especially relevant for marine predators that migrate between regions. Work towards coupling ecosystem models to physical and biogeochemical models (or incorporating key elements from these models) and, in cases where it is possible, coupling them to detailed higher trophic level models (such as dynamic energy budget models) will significantly improve our understanding of ecosystem processes in the SOIS.

6. Conclusion and outlook

This review summarises the current state of ocean observations in the Indian Sector of the Southern Ocean, a region with a unique ecosystem and an important role for the global climate. We provide examples of available methods, accessible datasets, and initiatives to improve our understanding of climate change and its impact on oceanography, sea ice, biogeochemistry, air–sea flux, lower, mid- and higher trophic levels, and the benthic community. The multidisciplinary ocean observing system in the Indian Sector of the Southern Ocean has advanced in recent years, especially with the progress in multi-platform and multi-sensor observations, such as floats, gliders, and instrumented marine mammals. Many more traditional methods are still used to observe the ocean in the Indian Sector, for example, moorings at the Southern Ocean Time Series site, ship-based sampling along established transects, deployments of the CPR, or population monitoring of sub-Antarctic bird colonies. However, the widespread deployment of newer technologies, methods, and sensors helps close temporal and spatial gaps in observations and significantly increases the real-time availability of ocean data. Moreover, much effort has focused on making already collected data accessible to the Antarctic research community, which substantially improves our understanding of environmental change in the Indian Sector.

While progress has been made over the past decades, temporal and spatial gaps remain for many components of the ocean observing system in the Indian Sector, including microbial diversity, benthic ecology, microplastic distribution, and many more. Therefore, we recommend: (1) improving our mechanistic understanding of drivers and processes affected by climate change, (2) further increasing the use of new methods, sensors, and technologies, (3) standardising data collection and improving data accessibility, (4) increasing sustained observations of mid-trophic levels beyond krill and hard-bodied zooplankton, (5) focusing on observing the sea-ice zone, (6) better

monitoring direct human pressures, (7) filling temporal observational gaps during winter, (8) resolving spatial gaps, for example, underneath the sea ice and in the northern SOIS, and (9) improving our suite of models to support the ocean observing system in the sector.

International and national collaborations continue to play an important role in further improving the temporal and spatial extent of observations, for example, by targeting specific seasons, regions, or processes. Upcoming initiatives, such as Antarctica InSync and the 5th International Polar Year (2032–2033), are the next opportunities for the international research community and other Southern Ocean stakeholders to collaborate, integrate different observational methods, and increase data sharing within and across research disciplines and knowledge systems. These initiatives aim to support better coordination of resources and logistics for shared fieldwork campaigns to tackle emerging issues in the Southern Ocean and Antarctic environment. A sustained and effective ocean observing system in the Indian Sector of the Southern Ocean will be vital to advancing our understanding of climate change and its widespread impacts in this globally significant region.

Supplemental files

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

Supplementary Material.docx

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Competing interests

The authors declare no competing interests.

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