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The Southern Ocean carbon and climate observations and modeling (SOCCOM) project: A review

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A R T I C L E I N F O

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A B S T R A C T

The Southern Ocean serves as the primary gateway through which the intermediate, deep, and bottom waters of the ocean interact with the surface ocean (and thus the atmosphere), and it has a profound influence on the oceanic uptake of anthropogenic carbon and heat as well as nutrient resupply from the abyss to the surface. Yet it has been the least observed and understood region of the world ocean. The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project was implemented in 2014 with a goal to help remedy this deficit in observations and understanding. The SOCCOM project is based on two major advances that have the potential to transform understanding of the Southern Ocean. The first is the development of new biogeochemical sensors mounted on autonomous profiling floats that allow sampling of ocean biogeochemistry in 3-dimensional space. Floats may detect processes with a temporal resolution that ranges from hours to years. The second is that the climate modeling community finally has the computational resources and physical understanding to develop fully coupled climate models that can represent crucial, mesoscale processes in the Southern Ocean, as well as corresponding models that assimilate observations to produce a state estimate. The observational component, based on deployment of profiling floats with oxygen, nitrate, pH and bio-optical sensors, is generating vast amounts of new biogeochemical data that provide a year-round view of the Southern Ocean from the surface to 2000 m. The modeling effort is applying these observations and enhancing our understanding of the current ocean, and reducing uncertainty in projections of future carbon and nutrient cycles and climate. After nine years of operation, including a project renewal in the sixth year, the SOCCOM project has deployed more than 260 profiling floats. These floats have collected over 27,000 vertical profiles throughout the Southern Ocean. A data-assimilating biogeochemical state estimate model has been implemented. Here, the design of the SOCCOM project is reviewed and the scientific results that have been obtained are described. The project's capability to help meet the observing system priorities outlined for a notional UN Decade for Ocean Sciences Southern Ocean observing system is assessed.

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1. Introduction

In 2014, the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) project was initiated with a vision to enable a transformative shift in scientific and public understanding of the role of the Southern Ocean in global carbon biogeochemistry and the associated effects on climate. A strategic mix of innovative and sustained observations of the physical and biogeochemical elements of the carbon cycle, as well as mesoscale eddying model simulations linked to the observations formed the nucleus of the project. The project focused on the Southern Ocean because of its outsized role in regulating the global cycles of carbon and heat and the climate of the earth. Prior results suggested that:

- the Southern Ocean south of 44°S accounts for up to half of the annual oceanic uptake of anthropogenic carbon dioxide (CO_2) from the atmosphere (cf., Gruber et al., 2009);
- vertical exchange in the Southern Ocean south of about 40°S supplies nutrients that fertilize up to three-quarters of the biological production in the global ocean north of 30°S (Sarmiento et al., 2004; Marinov et al., 2006);
- the Southern Ocean is warming rapidly (Gille, 2002; Levitus et al., 2012) and recent work suggests that the region south of 30°S accounts for about 75%±22% of the excess heat that is transferred from the atmosphere into the ocean each year (Frölicher et al., 2015); and
- Southern Ocean winds and buoyancy fluxes are the principal source of energy for driving the global large-scale deep meridional overturning circulation (e.g., Toggweiler and Samuels, 1998; Marshall and Speer, 2012).

Model studies also projected that changes in the Southern Ocean would have a profound influence on future climate trends, with corresponding alteration of the ocean carbon cycle, heat uptake, and ecosystems. Projections included:

- due to acidification, the Southern Ocean south of ~ 60°S will become undersaturated in aragonitic calcium carbonate by ~ 2030 (McNeil and Matear, 2008; Feely et al., 2009), with potentially large impacts on calcifying organisms and Antarctic ecosystems (Bednaršek et al., 2012); and.
- The vertical exchange of deep and surface waters may either increase or decrease. Projected increases in winds over the Southern Ocean will decrease stratification and increase vertical exchange, whereas projected increases in rainfall and meltwater input will increase stratification and decrease vertical exchange. More vertical exchange would be expected to result in more anthropogenic carbon uptake from the atmosphere, but less storage of carbon through biological cycling (cf. Sarmiento et al., 1988), while its impact on heat uptake depends on whether it brings anomalously warm or cold waters to the ocean surface.

The two overarching goals of SOCCOM were:

- Goal 1: Quantify and understand the role of all regions of the Southern Ocean in carbon cycling, acidification, nutrient cycling including oxygen, and heat uptake, on seasonal, interannual, and longer time scales.
- Goal 2: Develop the scientific basis for projecting the contribution of the Southern Ocean to the future trajectory of carbon, acidification, nutrient cycling, and heat uptake.

To achieve these ends, we proposed a three-pronged approach, consisting of:

- a novel autonomous biogeochemical observing system for the Southern Ocean;
- high-resolution state estimation that would incorporate biogeochemical processes and assimilate the new data sets; and
- Earth System Model analyses, data/model assessment metrics, and development of a Southern Ocean Model Intercomparison Project.

The proposed observing system was to span all sectors of the Southern Ocean and extend from the surface to depths of two kilometers (Fig. 1). It was to be capable of measuring the processes outlined in Goal 1 with the skill needed for internally consistent observations spanning decades.

The modeling and state estimation components leveraged large external resources. The most expensive part of SOCCOM by far has been the observing system simply because of the cost of instrumentation, deployment, and data management. This observing system was necessary because, despite the significance of the Southern Ocean in the carbon cycle and climate-related processes (Martin et al., 1990), it has been one of the least observed basins of the global ocean (Bakker et al., 2016, Johnson et al., 2017b). To remedy this deficiency, the SOCCOM project proposed to deploy an array consisting of roughly 180 Biogeochemical-Argo (BGC-Argo) profiling floats (Johnson, 2017; Riser et al., 2018; Claustre et al., 2020) throughout the Southern Ocean over a 6-year interval beginning in 2014. The size of the array was based on several assessments described in Section 2.2. As floats are lost due to system failures or battery exhaustion, additional floats must be deployed to sustain the array. A subsequent renewal of the program funded an additional 120 floats over 4 years to maintain the array. This renewal began in 2020 and ends in 2024. Finally, the project aspired to educate a new generation of ocean scientists trained in both ocean observation and simulation, and to develop a sophisticated outreach effort to disseminate results to the broadest possible community.

As SOCCOM was developing, planning also began in 2017 for the United Nations Decade of Ocean Science, with the theme “the science we need for the ocean we want”. In conjunction with the UN Decade, it was argued (Pendleton et al., 2020) that scientific research in the ocean has not kept pace with changing social and environmental conditions. Pendleton et al. (2020) called for fundamental changes in ocean science and ocean observing to equip society with the necessary information to manage marine systems. A UN Decade working group for the Southern Ocean (Hofmann et al., 2020) defined a series of priorities for an observing system in the Southern Ocean that would enable the UN goals to be achieved (Table 1). Many of the observing system priorities outlined in the UN report align closely with the design and objectives of the SOCCOM program. Given the significance of the UN Decade of Ocean Science effort, this review will incorporate the observing system priorities identified in the UN Decade Southern Ocean Workshop Report (Hofmann et al., 2020; hereafter UN Southern Ocean Report). This enables a comparison that serves, in part, as an assessment of the capability to build and operate an observing system compatible with UN Decade of Ocean Science goals and that would also achieve the goals outlined in the SOCCOM proposal.

The first part of this paper describes the SOCCOM observation and modeling implementation strategy followed by our major biogeochemical and modeling results, and then assessment of public outreach. This structure reflects the design of the SOCCOM project. SOCCOM operated with teams focused on observations, modeling, and broader impacts, rather than teams that might focus on a specific science topic, such as carbon cycling. This structure ensured that communications between groups always covered a broad range of topics, rather than permitting smaller groups with a single focus to become isolated. In each section that addresses a priority in the UN Southern Ocean Report (Table 1), those priorities are reiterated to emphasize the coherence between SOCCOM and the desired observing system. In a “SOCCOM in the Future” section, new applications of SOCCOM data are described.

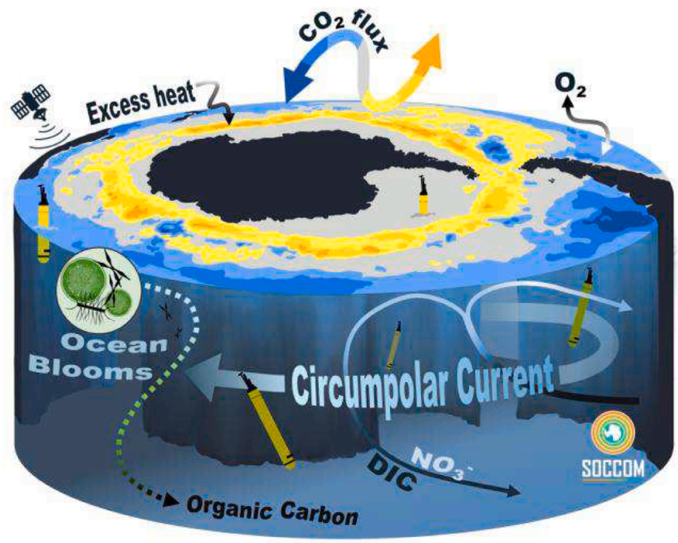

Fig. 1. The SOCCOM observing system concept. An array of profiling floats spanning all sectors of the Southern Ocean. The profiling floats would carry sensors that enable fluxes and stocks of carbon, oxygen, and nitrate to be assessed, along with the major biological and physical processes that contribute to the fluxes. Data would be delivered in real time, via satellite, for assimilation in state estimates and scientific analysis. Surface shading represents the air-sea CO_2 flux in August 2017 (Bushinsky et al. 2019a,b). Graphic by Emily Clark, MBARI.

Table 1
Priorities of the UN Decade of Ocean Science Southern Ocean Report (Hofmann et al., 2020) addressed by the SOCCOM project design.

Theme 1: Healthy and Resilient Ocean
Priority 1: Improve understanding of key drivers of change and their impacts on Southern Ocean species and food webs.
Priority 2: Improve understanding of sea ice, including its role in ecological processes of the Southern Ocean.
Priority 3: Improve understanding of Southern Ocean biogeochemical cycling. The Southern Ocean plays a key role in biogeochemical cycling, particularly in regulating air-sea exchange of carbon dioxide in the global carbon cycle.
Priority 4: Improve societal understanding of Southern Ocean issues and appreciation of the Southern Ocean for its global value in Earth systems and unique environment.
Theme 2: Predicted Ocean
Priority 1: Enhance and expand observational capability to support predictions.
Priority 2: Improve and enhance Southern Ocean modeling capability.
Theme 3: Sustainable Productive Ocean
Priority 1: Increase the suite, types and reliability of measurements, including those focused on ecosystem change, needed to inform management and policy.
Priority 3: Ensure science-based and effective MPAs and uphold sustainable fisheries management.
Cross Cutting Themes
Priority 3: Implement a coordinated, international, circumpolar observational program to elucidate processes that 1) allow life histories of key species in the Southern Ocean ecosystem to be quantified, 2) allow a total carbon budget to be developed, 3) provide coverage of the annual cycle, and 4) quantify the role of sea ice in regulating ecosystem productivity.
Priority 5: Enhance predictive skill across climate, circulation, cryosphere, and ecosystems. The Southern Ocean community can add scenarios, such as freshwater inputs in the Southern Ocean, to understand climate sensitivity. End-to-end integration across ecosystems is needed to improve estimations of carbon fluxes, understand the effects of multiple stressor on ecosystems, identify biological hotspots, and evaluate the effects of living resource extraction on biological productivity. This requires working across disciplines, comprehensive observational systems, community engagement, and resources.

2. SOCCOM implementation strategy

2.1. Observational strategy

The SOCCOM observational program was designed to provide circumpolar biogeochemical observations throughout the year, within the Southern Ocean (Talley et al., 2019), by deployment of a large array of BGC-Argo profiling floats (Fig. 2). The BGC-Argo program is described in Claustre et al. (2020). The quality controlled data would be served in real time (Maurer et al., 2021). The SOCCOM float array was also designed to provide crucial year-round profile data in the large seasonal sea ice zone south of 60°S. Argo-type profiling floats are free drifting, battery-powered platforms that cycle between 2000 m depth and the surface (Johnson, 2017; Riser et al., 2016, 2018; Roemmich et al., 2019). A typical profile cycle is shown in Fig. 3. Floats ascend from depths near 2000 m to the surface at defined time intervals (typically 10.08 days). Physical and chemical measurements are made during the ascent at programmed depth intervals (typically 70 depths for chemical measurements and every 2 m for physical measurements in SOCCOM floats). Once at the surface, the float position is determined by GPS, and the observed data are then transmitted via the Iridium communication system to a shore-based server. The data are immediately processed. This includes any necessary corrections for sensor calibration offsets or sensor drift (Maurer et al., 2021). Data suitable for scientific analysis are then made available through publicly accessible databases on the Internet (https://soccom.princeton.edu/content/data-access) and the Argo data system (Wong et al., 2020) within 24 h. The float then returns to a parking depth at 1000 m before repeating the cycle.

The current status of the SOCCOM BGC-Argo float array is shown in Fig. 4a. SOCCOM has achieved circumpolar coverage, with many floats operating in the Antarctic sea ice zone. SOCCOM also sought from the start to achieve sampling in all dynamical and BGC regimes of the Southern Ocean (Talley et al., 2019). The Antarctic Circumpolar Current (ACC) fronts are shown for context in Fig. 4a; SOCCOM has also achieved this regime-defined coverage which has enabled studies of the zonal and meridional dependence of carbon, productivity and air-sea fluxes. After 9 years of deployments, floats in the earliest years of SOCCOM have become inactive due to battery lifetime, such that about half of the floats deployed are active at this time (Fig. 4b).

The observing system implemented for the SOCCOM project aligns closely with the UN Southern Ocean Workshop Report priorities:

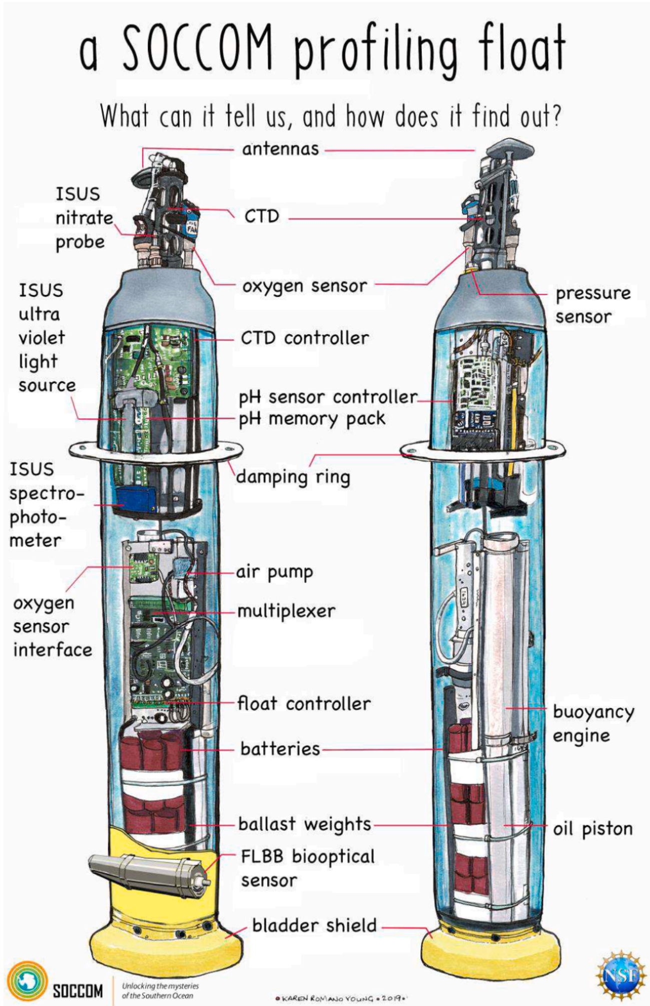

Fig. 2. Schematic of a SOCCOM profiling float showing component views of the float (left) and rotated by 180° (right). This sketch, created by Karen Romano Young, is widely used in SOCCOM's K-12 outreach program. The original drawing, with additional detail, was designed for a poster size and is available on the SOCCOM website (https://soccom.princeton.edu).

- *Enhance and expand observational capability to support predictions.*
- *Increase the suite, types and reliability of measurements, including those focused on ecosystem change, needed to inform management and policy.*

2.2. Array size

A variety of methods have been applied to assess the optimum number of floats in the SOCCOM array. One of the primary tools has been Observing System Simulation Experiments (OSSE). Majkut et al. (2014) sampled CO_2 fluxes in the GFDL-ESM2M 'historical' simulation (years 1995–2000) with synthetic floats. This OSSE found that a large uncertainty reduction in reconstruction of the air-sea CO_2 flux in the Southern Ocean (south of 30°S) was obtained with approximately 200 floats. Kamenkovich et al. (2017) subsampled oxygen in CM2.6 to assess observing system design and also identified 200 floats as being an optimal choice. Taking a different approach, Mazloff et al. (2018) estimated the correlation scales in the Southern Ocean for carbon flux and content on seasonal time-scales and longer using an ocean model. These findings suggest that, ideally, approximately 100 floats would be deployed with one every 20° longitude by 6° latitude. In practice, however, this deployment spacing is impossible to achieve due to advection that aggregates floats in some regions and removes them from others, making the required float number greater than 100. An additional caveat for all these studies is that constraining the higher frequency signals (i.e. subseasonal) may require far more than 200 floats. For example, Prend et al. (2022c) found that much of the Southern Ocean chlorophyll variability occurs at sub-seasonal time scales that would require a much larger float array to characterize. Chlorophyll has a very short turnover time that leads to a patchier distribution than tracers such as DIC (Mahadevan and Campbell, 2002). A float array cannot resolve the short length scales that characterize ocean chlorophyll. But the analysis of Mazloff et al (2018) shows that a float array can resolve the DIC length scales. This implies that a float array can quantify processes such as net community production from DIC (or nitrate) drawdown. Further, we have shown (Johnson and Bif, 2021) that float arrays can resolve primary productivity signals quantitatively, but at low spatial and temporal resolution.

The goal in the initial SOCCOM proposal was to deploy 180 floats south of 30°, based on Majkut et al.'s (2014) results. It was presumed that international partners would supply the remainder. A uniform distribution of floats was desired to meet the goals outlined in the BGC-Argo Science and Implementation Plan (Biogeochemical-Argo Planning Group, 2016) with floats in all basins of the Southern Ocean. Fig. 4b shows the number of SOCCOM floats that were operating in each year and the cumulative number deployed by the project. The highest population of active floats was achieved in year 6 of the project (2020) with 152 floats. This number fell short of the 180 float goal due a fault in APEX float (the primary float-type deployed) power management that led to premature failure of the float batteries at around 150 vertical profiles. The fault was not recognized until floats had been in the water nearly 4 years. The power management fault has since been resolved and APEX floats deployed since 2020 are capable of making ~ 275 vertical profiles before battery depletion. The resolution of this problem was followed immediately by the Covid-19 pandemic, which limited production and deployment capabilities. The array population then fell to ~ 120 floats operating each year. The number of operating floats, now at 137, will gradually increase at planned deployment rates of 30 floats per year.

Observing system design work continues with similar and expanded approaches, including the use of transition matrices to project information forward in time (Chamberlain et al., 2023). The prospect of utilizing covariance information from other observables to reduce observational demands is also being explored (Giglio et al., 2018; Liang et al., 2018). Finally, other groups have been applying OSSEs for other BGC variables. For example, Valsala et al. (2021) considered observing system design for pCO_2 in the Indian Ocean. Ford (2021) assessed the effect of assimilation for chlorophyll, oxygen, pH and nitrate in the global ocean. These studies all find significant reduction in error through use of a large array of biogeochemical floats.

2.3. SOCCOM float sensors

Major advances in sensor technology have enabled SOCCOM floats to measure nitrate and oxygen concentrations and bio-optical properties from profiling floats (Riser and Johnson, 2008; Johnson, 2017; Johnson et al., 2013, 2017b; Körtzinger et al., 2005; Boss et al., 2008; and Bittig et al., 2018a). Newly developed pH sensors have now been successfully integrated onto the profiling float platform with measurements to 2000 m depth (Johnson et al., 2016, 2017b; Williams et al., 2017).

Oxygen is measured with optode sensors that determine concentration from the effect of oxygen partial pressure on luminescence lifetime of an embedded fluorophore (Bittig et al., 2018a). The large number of deployments in SOCCOM have enabled a robust demonstration of the capability to recalibrate the optode sensors with air oxygen measurements (Johnson et al., 2015). Nitrate is measured using direct UV spectrophotometry (Johnson et al., 2013). pH is measured with an Ion Sensitive Field Effect Transistor (Johnson et al., 2016). Both the nitrate and pH sensor output must be corrected for offsets in the initial calibration that may arise during the many months between laboratory

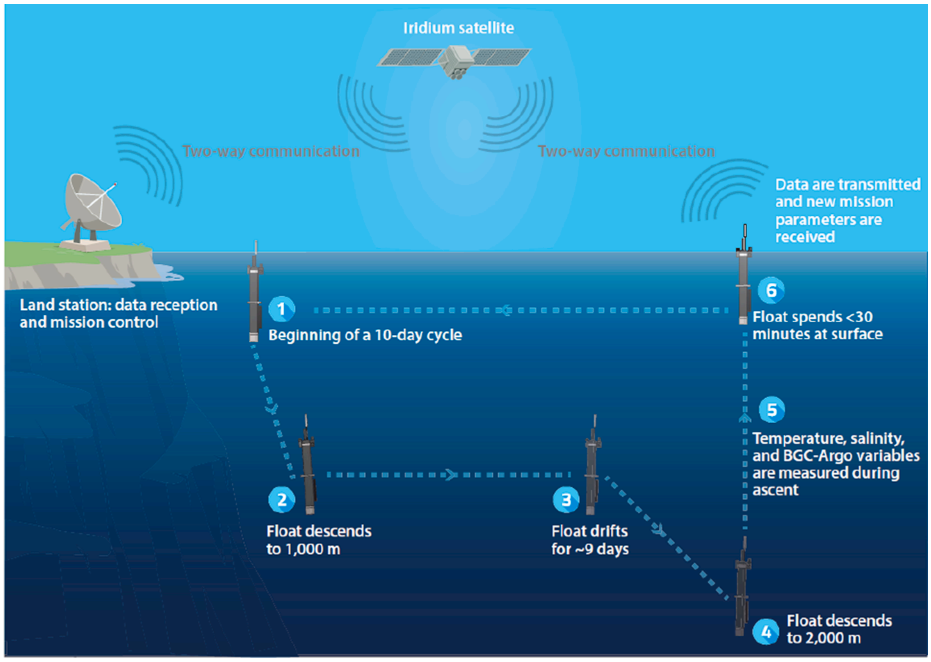

Fig. 3. Typical profile cycle for a SOCCOM Argo float. From Claustre et al. (2020).

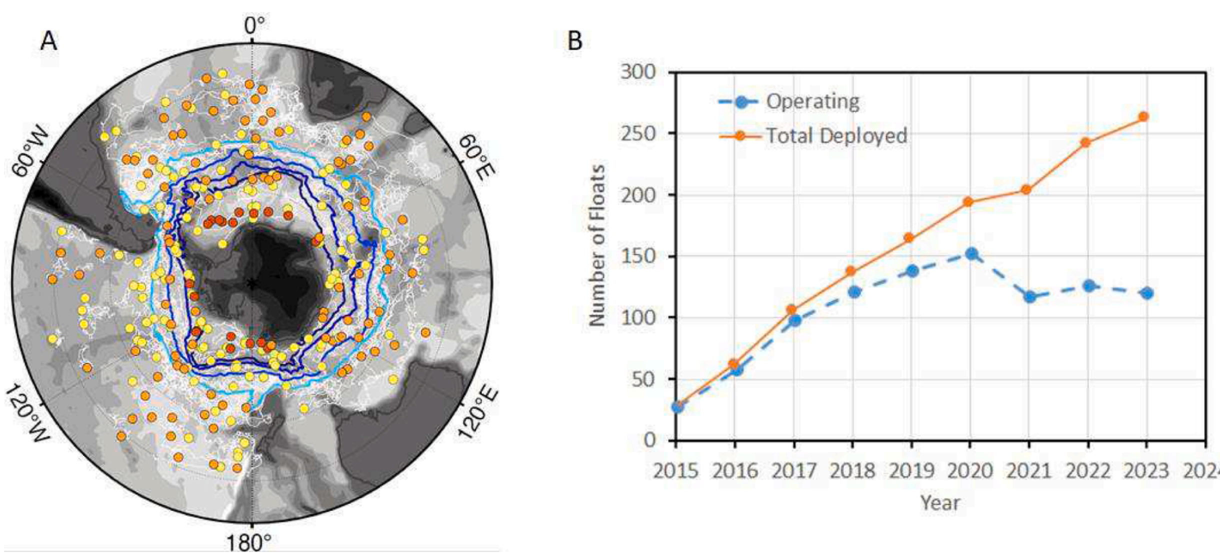

Fig. 4. A) SOCCOM float locations as of December 2022. Active floats: orange. Under-ice floats: dark orange. Inactive floats: yellow. Trajectories of all floats shown as white lines. Antarctic Circumpolar Current frontal positions are shown as solid lines: Subantarctic Front (light blue), Polar Front (medium blue), Southern ACC Front (dark blue), Southern Boundary of the ACC (black), from north to south (positions from Kim and Orsi, 2014). B) Number of floats operating in each year of the SOCCOM project and total number of floats deployed.

calibration and deployment, as well as correction for offsets or drifts that occur after deployment. Protocols were developed for these corrections (Johnson et al., 2017b; Maurer et al., 2021) and these are described further in Section 2.6.1. Particle abundance (primarily phytoplankton and their detritus in the open ocean; Graff et al., 2015) is measured using optical backscatter. Chlorophyll fluorescence is measured by in situ fluorometry (Roesler et al., 2017). These sensors are all capable of operating for years through the pressure and temperature extremes experienced by Argo floats (Johnson et al. 2017b). Fig. 5 shows one example of the data records in the upper 300 m from all of these sensors. This record spans four years on a SOCCOM float (WMO 5904468) operating in the seasonal ice zone of the Weddell Sea (Claustre et al., 2020).

2.4. Float performance

The SOCCOM project utilizes both APEX and Navis profiling floats. The APEX floats used in SOCCOM are constructed at the University of Washington from components purchased from Teledyne/Webb Corporation. They carry batteries capable of powering the floats for about 250 profiles to 2000 m. However, due to a power management fault in early floats used by the project, the batteries failed shortly after 150 cycles. This fault was corrected in floats that were built after 2019. The mortality of the floats used in SOCCOM is somewhat higher than analogous floats used throughout the world ocean in Argo and other programs (Riser et al., 2018). About 50% of the SOCCOM floats have survived about 4 years, or 150 profiles. For longer times, the survivability

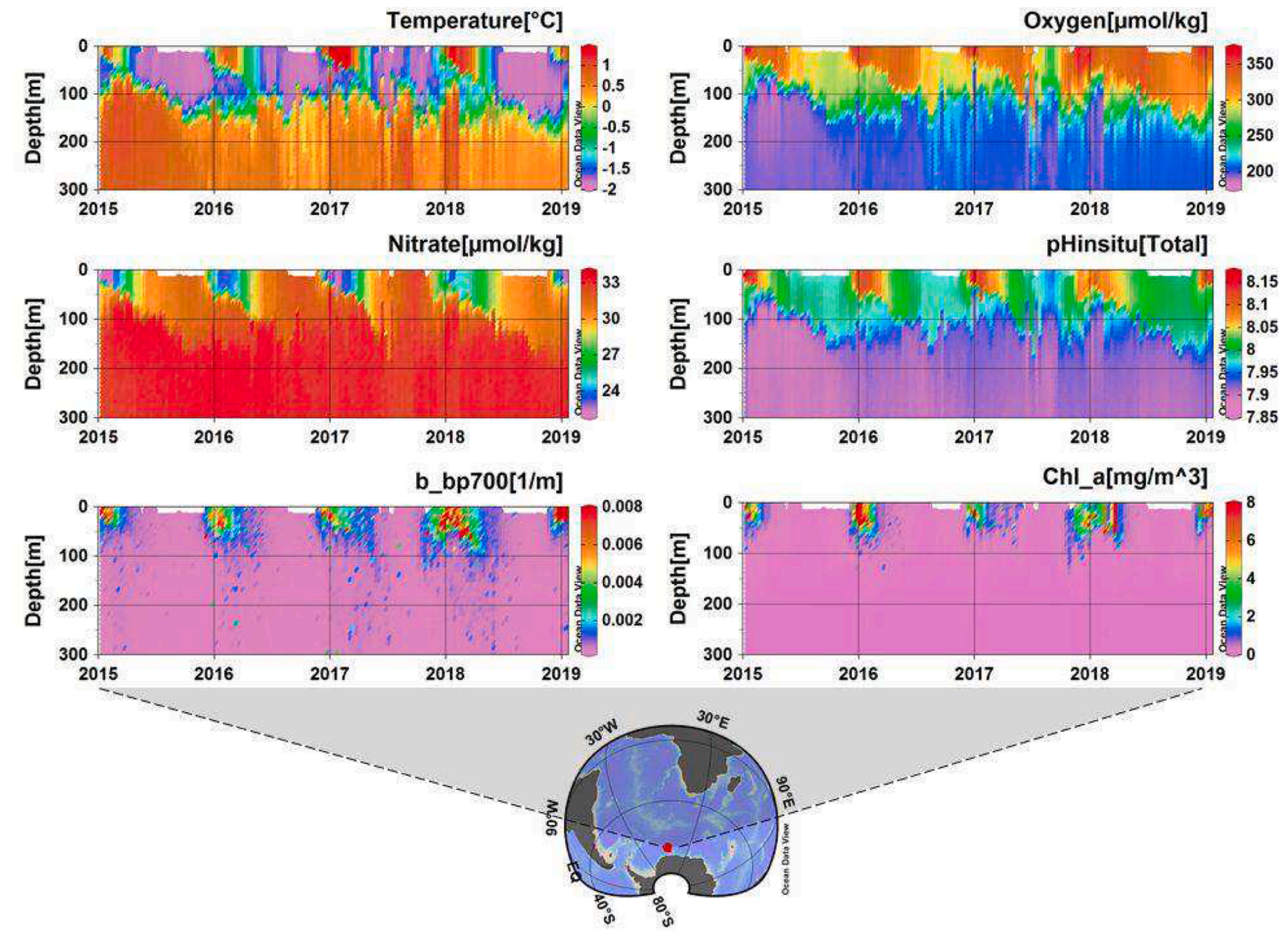

Fig. 5. Sensor data gathered by World Meteorological Organization (WMO) float number 5904468 in the upper 300 m of the Atlantic sector of the Southern Ocean. Note that the float acquired data under ice (during the periods identified by white sectors in the surface layer) and then transmitted them when the ocean surface became ice free (adapted from Claustre et al., 2020).

decreases, largely due to the power management fault, and only about 30% of the floats continue to operate for 250 profiles. The technical details and performance characteristics of the floats used in SOCCOM are discussed in Riser et al. (2018). The Navis floats are acquired in completed form from Sea-Bird Scientific and used after a thorough inspection that now includes disassembly of complete floats to check internal components.

Argo floats, including the BGC-Argo floats deployed by the SOCCOM project, are regularly operating under ice-covered water (Wong and Riser, 2011; Riser et al., 2018; Chamberlain et al., 2018). Sixty-six SOCCOM floats have operated under seasonal sea ice and collected over 2600 vertical BGC profiles in the seasonal ice zone. The survival rate for APEX floats operating in ice is moderately lower (93% survival/year) versus floats outside the seasonal ice zone (96%/year).

Like all Argo floats, SOCCOM floats cannot determine position from GPS when operating under ice. The Argo default is linear interpolation between available profiles with GPS fixes. Acoustic receivers have been added to limited sets of Argo floats for under-ice tracking in the insonified Weddell Sea (Klatt et al., 2007). However, the rough sea ice bottom interferes with acoustic range. As part of SOCCOM, Chamberlain et al. (2022a) developed a Kalman smoothing method for improved acoustic tracking and applied it to the Weddell Sea floats. While this work is promising, expansion of the existing Weddell array of moored sound sources to the full Southern Ocean is prohibitively expensive at present. Chamberlain et al. (2018) used a set of acoustically-tracked Argo floats to quantify the uncertainty in the linear interpolation of float locations. The location error is approximately 100 km for a 9-month sojourn under the ice. This is of comparable size to other sources of representation error (e.g. “eddy noise”). As a result, acoustic receivers have not been incorporated on SOCCOM floats.

2.5. Float deployments

SOCCOM has operated with essentially no dedicated ship time (Talley et al., 2019). Float deployments have occurred from ships of opportunity in nearly all cases. The primary exception has been the assignment of several days of ship time to SOCCOM for float deployments on US research vessels making transits between ports. At this time, floats have been deployed from 19 different ships. Fifteen of these ships have been from other nations, including Australia, Germany, Japan, Korea, New Zealand, Russia (on a Swiss charter), South Africa, Spain, and the United Kingdom. This international collaboration has been essential to the development of the SOCCOM array by providing access to all regions of the Southern Ocean.

Although SOCCOM has not used dedicated ships for the most part, the deployment platforms have played a key role in the success of the project. A SOCCOM policy was to collect a hydrocast with high quality measurements of oxygen, nitrate, carbonate parameters (pH, titration alkalinity, dissolved inorganic carbon), HPLC measurements of photosynthetic pigments, and particulate organic carbon whenever possible

(Talley et al., 2019). The shipboard chemical measurements are used to validate the data obtained from float sensors. Nearly all deployments have occurred from research vessels, as a result. Nearly 50% of the deployments have been on GO-SHIP cruises (Talley et al., 2016) to take advantage of the high quality data generated by this program. The data from these hydrographic stations taken at float deployment sites has provided convincing evidence of the quality of the float observations (Section 2.6.1). The validation data was also a key contribution to the development of the quality control methods by providing a quantitative metric for improvements to data processing. As sensors evolve, continued collection of validation data will be essential to demonstrate their improvement. The SOCCOM project encourages the collection of this type of supporting data whenever possible.

As batteries in a profiling float are depleted, the float is lost at depths near 2000 m when the external bladder can no longer be inflated to change its buoyancy. Each profiling float, with a mass near 30 kg, thus contributes to marine waste. However, when compared to the impacts from operation of an ocean going research vessel that may burn five tons of fuel each day, a 30 kg profiling float that operates 4 to 6 years is an extremely low impact observing system. A further assessment of the environmental impacts of Argo floats can be found in Riser and Wijffels (2020).

2.6. Data system

Parameters observed by SOCCOM floats (temperature, salinity, dissolved oxygen, nitrate, pH, chlorophyll and particulate backscatter) are Essential Ocean Variables (EOVs) and contribute to our understanding of the Southern Ocean and its response to a changing climate. Profiling float data are provided in real-time (<24 h) to the community with equal access to all. The SOCCOM website (https://soccom.princeton.edu) provides a direct link to these data resources. Although the SOCCOM data system was developed before the FAIR concept for data accessibility was published (Wilkinson et al., 2016), it adheres closely to the principles of findability, accessibility, interoperability, and reusability. The success of the SOCCOM system in achieving the FAIR principles can be assessed through the number of external publications that use the observations and model output, as described in Section 3.6. SOCCOM data are provided to users through multiple format options, including both NetCDF files and human-readable text files that contain estimates of derived carbon parameters (dissolved inorganic carbon (DIC), total alkalinity (TAlk), partial pressure of carbon dioxide (pCO2) and particulate organic carbon (POC)). The provision of such value-added products, calculated in a standardized way, facilitates analysis across a broad user base. A key objective of the SOCCOM program has been to supply the data in a way that fosters direct and efficient ingestion by users. SOCCOM scientists have collaborated with the sister Global Ocean Biogeochemistry Array (GO-BGC) to make toolboxes available in a variety of computer languages (Matlab, Python, R; https://go-bgc.org) to further facilitate data access. These toolboxes include instructional videos and examples.

SOCCOM is integrated into the larger One Argo program framework, a program that serves as the backbone to both the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS) (Roemmich et al, 2019; Owens et al., 2022). SOCCOM deployments represent up to 15 percent of annual Argo deployments in the ocean south of 30°S and, on average, close to 70 percent of total BGC-Argo floats deployed in this region annually. This has established SOCCOM as an integral part of the Core Argo program to observe ocean temperature and salinity and of the BGC-Argo global networks. All SOCCOM data are delivered to Argo Global Data Assembly Centers via the US Argo Data Assembly Center within 24 h of successful transmission to shore. SOCCOM has become the dominant source of in situ biogeochemical observations in the Southern Ocean (Table 2). SOCCOM and partner international programs that comprise BGC-Argo have become essential for observing biogeochemical changes in the ocean interior as the amount of such data collected from ships has declined precipitously in recent decades (Fig. 6). The expanded ocean coverage in space and in time is enabling a transformation in ocean observing similar to the transformation Argo has provided for physical measurements (Wong et al., 2020). This was especially true during the COVID-19 pandemic when ship activity was constrained but deployed floats continued to collect data (Boyer et al., 2023).

Table 2
Number of profiles to at least 900 m depth over an 8-year span reported by SOCCOM floats or by ships. The float data includes only profiles with data quality marked good. Ship data was obtained from World Ocean Database (https://www.ncei.noaa.gov/products/world-ocean-database).

Property	SOCCOM 2015–2022	Ships South of 30°S 2010–2017	Ships North of 30°S 2010–2017
Oxygen	21,420	1,764	3,032
Nitrate	20,564	1,651	2,840
pH	12,603	1,054	1,976

2.6.1. Data quality

The goal of the SOCCOM float program is to produce a climate-quality data record for carbon, oxygen, and nitrate cycling. This is a "time series of measurements of sufficient length, consistency and continuity to determine climate variability and change" (National Research Council, 2004). Such a record requires sensors that are well characterized and calibrated to the property of interest before deployment, and whose calibration is assessed at deployment with high quality hydrographic measurements, or in which post-deployment calibration is possible. Meeting project goals requires continuous reviews to ensure that the profiling float data are of high quality and consistency. Further, as SOCCOM is one element of the BGC-Argo array, these efforts should be well documented and capable of implementation at all Argo Data Assembly Centers (DACs). To meet these sensor goals, novel methods were developed to ensure sensors were accurate and could be corrected for post-deployment drift in calibration (Maurer et al., 2021).

Körtzinger et al. (2005) and Bittig and Körtzinger (2015) demonstrated the potential for optical oxygen sensors to be calibrated in air when floats surface. This work was limited to a small number of floats. Using nearly 50 SOCCOM and Argo Canada floats, the SOCCOM project built on this work to establish that air oxygen calibration could reduce oxygen concentration errors below 1% of surface saturation values for large arrays (Johnson et al., 2015). These capabilities were built into a software package, the SOCCOM Assessment and Graphical Evaluation (SAGE-O2) tool, which is now in widespread use at Argo DACs (Maurer et al., 2021). The air oxygen measurements enable assessment of sensor calibration and calibration drift in time.

Errors arising in nitrate and pH sensor calibrations are corrected using methods that build on the techniques developed in the Core Argo program to assess change in salinity sensor calibration (Owens and Wong, 2009). Sensor measurements at depths between 1000 and 2000 dbar, where conditions change only slowly in time, are compared to high quality shipboard observations. Differences are assigned to sensor offsets or drifts. In the case of salinity, there are sufficient ship-based observations to use objective mapping to predict salinity values at float profile locations. There are too few ship-based observations of nitrate and pH to allow direct mapping of these observations to float profile locations. Instead, software was developed to interpolate shipboard observations using the well-known relationship between oxygen and nitrate or pH that is encapsulated in the Redfield Ratio (Anderson and Sarmiento, 1994). Initially, locally interpolated regressions (LIR) were built using the GLODAPv2 dataset (Carter et al., 2018). The LIRs allow nitrate and pH to be predicted at depth using profiling float oxygen, date, and position data with biases less than 0.00 ± 0.47 (1 SD) μmol kg^{-1} and 0.001 ± 0.006 pH at depths near 2000 m. Subsequent work using neural networks has provided improved spatial resolution in fitted

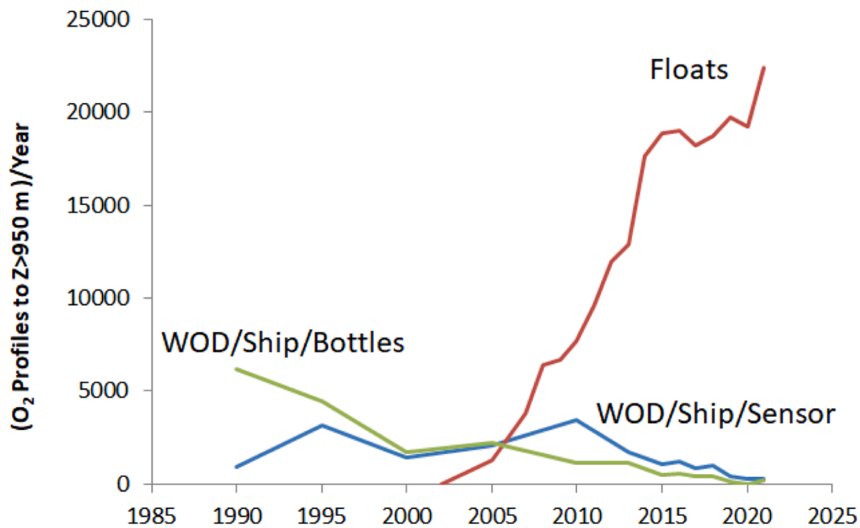

Fig. 6. Oxygen profiles in the global ocean to a depth of at least 950 m per year. Values for analyses of water collected on bottle casts (green) and for oxygen sensors on CTD casts from ships (blue) are from the NOAA/NCEI World Ocean Database. Values for Argo profiling floats are from the Argo Global Data Assembly Center and are for all BGC-Argo floats.

deep reference data (Bittig et al., 2018a,b; Carter et al., 2021). These tools are used in the SAGE software application to quality control and adjust nitrate and pH sensor data (Maurer et al., 2021).

The accuracy of the adjusted and quality-controlled data collected by SOCCOM floats has been assessed by comparing sensor values from the first float profile with data from standard laboratory analysis methods applied to water samples collected during a conventional hydrocast coincident with the float deployment. Such shipboard measurements of oxygen, nitrate, pH, HPLC pigments and particulate organic carbon (POC) have been made alongside nearly all SOCCOM float deployments. Note that SOCCOM sensor calibrations are made independently of the accompanying shipboard measurements. Oxygen sensors use air oxygen measured by the floats for the final sensor calibration (Johnson et al., 2015). pH and nitrate data are adjusted by applying an offset based on a deep, stable reference field (Johnson et al., 2013; 2016; 2017a, 2017b; Maurer et al., 2021) predicted with global algorithms fitted to high quality ship data (Carter et al., 2018; Bittig et al., 2018b). Both the raw and adjusted sensor data are always reported.

Statistical comparison of float sensor data with shipboard data (Fig. 7) yields the overall accuracies quoted for SOCCOM float BGC sensors (Maurer et al., 2021). Some of the statistical uncertainty in the validation comparisons is due to hydrographic differences between float and shipboard sampling times and locations. Validation matchups across the array are an average of 23 h and 8 km apart in time and space. Assuming that half of the standard deviation in the bottle minus float differences (Fig. 7) is from natural ocean variability, float data uncertainties are 3 μmol kg^{-1}, 0.5 μmol kg^{-1}, and 0.007 for oxygen, nitrate, and pH, respectively. These uncertainties correspond to coefficients of variation near 1.5% for oxygen and nitrate concentrations near their mean values. The assumption that half of the error is due to oceanographic processes is consistent with alternate assessments of data quality, such as a comparison of sensor nitrate concentrations in surface water with temperature >24 °C, excluding equatorial regions. The expected nitrate concentration in these conditions is near 0. The observed surface nitrate concentration for all profiles that meet these conditions from floats supported by the UW/MBARI group is 0.2 ± 0.5 μmol kg^{-1}. This standard deviation is similar to one half of the value for nitrate in Fig. 7. These uncertainties meet or exceed targets for sensor performance set in the original proposal.

Note that when chemical concentrations are near zero, both the oxygen and nitrate sensors will report negative values. A negative concentration is physically impossible. However, the values returned by a sensor are an estimate of concentration and estimates can be negative (Thompson, 1988). At concentrations near zero, half the estimates of concentration will be negative. The SOCCOM project has elected to retain these negative values in the dataset with a quality flag of good to

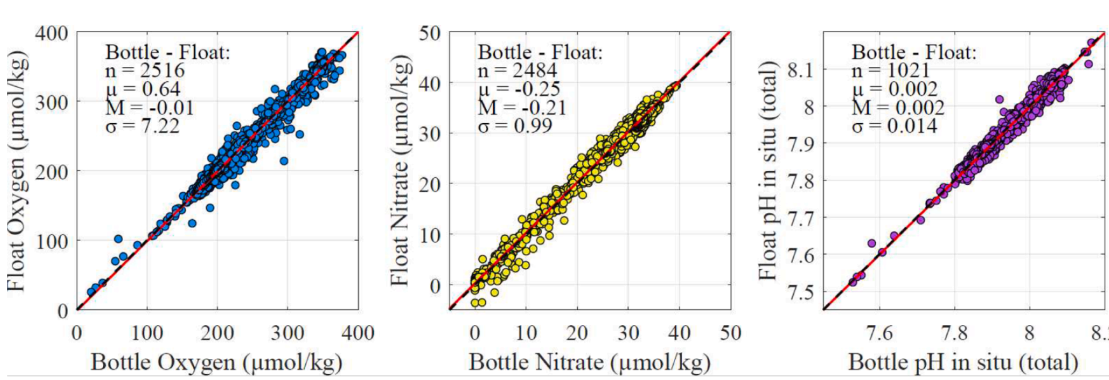

Fig. 7. Comparison of profiling float oxygen, nitrate, and pH sensor values versus values measured on board ship in samples collected from a hydrocast made near the time of float deployment. Statistics for number of comparisons (n), mean difference (μ), median difference (M), and standard deviation (σ) are shown for each property. Adapted from Maurer et al. (2021) after updating to all data available through 2022.

avoid a bias known as "left censoring" of the data (Newman et al., 1989). Left censoring results in unrealistic estimates of error near zero concentration. The user must make their own decision on how to utilize these negative values.

The long term stability of the adjusted sensor data has been assessed by comparing the quality controlled sensor values to shipboard profile measurements when floats pass within 20 km of a station in the GLODAPv2 database (Johnson et al., 2017b; Maurer et al., 2021). Offsets in the comparisons change with the age of the shipboard observations. The rate of change for both pH and oxygen are consistent with known ocean acidification or deoxygenation rates (Johnson et al., 2017b; Maurer et al., 2021). The nitrate comparisons are invariant with the age of the shipboard observations. These results indicate that the quality controlled float data are stable in time.

These statistical adjustments relative to deep ocean data that may slowly change in time require a continuous update of the deep, ship-based reference data. In essence, the float measurements provide a record of the large, seasonal changes in upper ocean chemistry (Fig. 5) relative to a deep, ship-based observational product. As such, projects such as SOCCOM require a decadal scale set of repeated hydrographic section measurements, such as those conducted in the GO-SHIP program (Talley et al., 2016), to produce a climate quality dataset.

In addition to the chemical sensor measurements, SOCCOM floats have also collected chlorophyll fluorescence and optical backscatter data. The conversion of chlorophyll fluorescence to chlorophyll concentration is fraught with uncertainty (Roesler et al., 2017). Measurements of chlorophyll pigments by High Performance Liquid Chromatography in samples collected at float deployment show large variability in the relationship between chlorophyll fluorescence and chlorophyll (Johnson et al., 2017b). Despite this uncertainty the chlorophyll fluorescence data have proven to be extremely useful in a variety of SOCCOM studies (e.g., Carranza et al., 2018; Haëntjens et al., 2017; Von Berg et al., 2020). The optical backscatter data show a robust relationship with Particulate Organic Carbon (POC) concentration in samples collected at float deployment (Johnson et al., 2017b). This has enabled estimates of POC throughout the Southern Ocean (Haëntjens et al., 2017; Johnson et al., 2017a; Arteaga et al., 2020).

2.7. Biogeochemical-Southern Ocean state estimate

An integral strategy in the SOCCOM design was to assimilate the observational data into a state estimate model. Data assimilating models are computationally expensive, especially for biogeochemistry. Ample and sustained data constraints are required in order to justify the task of operating a large-scale ocean model that assimilates data. The SOCCOM array has provided this data source. The Biogeochemical Southern Ocean State Estimate (B-SOSE; Verdy and Mazloff, 2017) assimilates physical and biogeochemical data into the MIT ocean general circulation model using an adjoint method developed by the consortium for Estimating the Climate and Circulation of the Ocean (ECCO; Stammer et al., 2002; Forget et al., 2015). The biogeochemical model in B-SOSE is the nitrogen version of the Biogeochemistry with LIght, Nutrients and Gases model (NBLING; evolved from Galbraith et al., 2010). B-SOSE provides a complete, budget-closing analysis of Southern Ocean biogeochemical and physical processes. Similar data assimilation efforts are now appearing elsewhere (Fennel et al., 2019).

The B-SOSE objective is to yield a baseline estimate of the large-scale Southern Ocean biogeochemical, sea ice, and physical properties, and a framework to understand this baseline. Nudging (i.e. reinitializing) models allows one to fit eddy signals, but the B-SOSE aim is to have closed budgets, and thus there is no nudging included. The gridded model solution aims to capture the seasonally varying properties by adjusting the atmospheric state and initial conditions, with eddies represented in a statistical sense. The first state estimate produced was a 1/3° resolution solution for the period 2008–2012. Validation, analysis, model inputs, code, and comprehensive diagnostics have been published. This demonstrates the maturity of BGC state estimation (Verdy and Mazloff, 2017). A subsequent 2013–2021 SOCCOM era state estimate was produced at higher-resolution (1/6°).

B-SOSE offers a gridded product consistent with model physics and constrained to the large-scale signals observed by the SOCCOM array. A first study with B-SOSE was an intensive analysis of the dissolved inorganic carbon budget (Rosso et al., 2017). B-SOSE has also had smaller regional models nested inside to inform the impact of resolution on the carbon cycle (e.g. Jersild et al., 2021; Swierczek et al., 2021a) and its predictability (Swierczek et al., 2021b). The B-SOSE resource has been used as an essential component of numerous studies, which are noted throughout the remainder of this review.

2.8. Earth system models

The Southern Ocean is notoriously difficult to simulate consistently. At every stage of the Coupled Model Intercomparison Project (CMIP), sponsored by the Intergovernmental Panel on Climate Change (IPCC), there have been significant inter-model differences as well as a lack of observationally-based metrics on which to discern the overall quality of each model (Russell et al. 2006a, 2006b, 2018; Meijers et al., 2012; Beadling et al. 2019, 2020; Kajtar et al., 2021; Bourgeois et al., 2022). To address this issue, a climate and biogeochemistry modeling component, including the Geophysical Fluid Dynamics Laboratory (GFDL) mesoscale eddying coupled climate models (e.g. "CM4") and Earth System Models (e.g., "ESM4"), has been a core SOCCOM element. This enables the program to translate our evolving understanding of the current ocean into a greatly improved projection of the future with an emphasis on the role of the Southern Ocean in the global climate. The benefits of the SOCCOM joint observation and modeling approach are clear, as important spatially- and temporally-resolved data have been assimilated into our state estimates and metrics of biogeochemical and physical ocean properties that provide consistent benchmarks have been established (Beadling et al., 2020).

The state estimation and global modeling components address the UN Southern Ocean Report priority:

- *Improve and enhance Southern Ocean modeling capability.*

3. Major SOCCOM biogeochemical results

Here we review SOCCOM results that improve our understanding of biogeochemical cycles in the Southern Ocean. These results advance the UN Southern Ocean Report priorities:

- *Improve understanding of Southern Ocean biogeochemical cycling. The Southern Ocean plays a key role in biogeochemical cycling, particularly in regulating air-sea exchange of carbon dioxide in the global carbon cycle.*
- *Implement a coordinated, international, circumpolar observational program to elucidate processes that 1) allow life histories of key species in the Southern Ocean ecosystem to be quantified, 2) allow a total carbon budget to be developed, 3) provide coverage of the annual cycle, and 4) quantify the role of sea ice in regulating ecosystem productivity.*

3.1. Southern Ocean air-sea gas fluxes

Autonomous profiling floats have enabled year-round observations of biogeochemical parameters such as oxygen, nitrate, pH, and bio-optics in large regions of the ocean that previously were undersampled (Hennon et al. 2016; Briggs et al. 2018; Arteaga et al. 2019, 2020; Johnson and Bif 2021). In sufficient numbers, profiling floats can provide the quasi-continuous data needed to calculate air-sea gas exchange over broad regions through full annual cycles.

3.1.1. Oxygen fluxes

Bushinsky et al. (2017) demonstrated the capability to resolve basin-scale gas exchange processes by calculating air-sea oxygen fluxes in the major zones of the Southern Ocean using the data in Fig. 8. They found a Southern Ocean oxygen sink of -221 ± 57 Tmol O_2 yr^{-1} south of 30°S, nearly double prior estimates (Gruber et al., 2001). The increased sink is due, in part, to strong uptake in partially ice covered waters of the Seasonal Ice Zone.

3.1.2. CO_2 fluxes

Few autonomous vehicles have been deployed that are capable of constraining the carbonate system through the full water column (Bushinsky et al. 2019b). The deployment of autonomous profiling floats equipped with pH sensors requires one other carbon parameter to enable determination of the complete carbon system. Fortunately, titration alkalinity can be estimated with reasonable accuracy using a variety of models fitted to shipboard data sets such as GLODAPv2 (Olsen et al., 2020). pCO_2 values determined using pH are not particularly sensitive to the titration alkalinity estimate (Williams et al., 2017). Estimates of pCO_2 and Dissolved Inorganic Carbon (DIC) using measured pH and estimated alkalinity have the potential to greatly increase our understanding of the wintertime carbon cycle (Williams et al., 2018), spatial patterns of carbon uptake (Johnson et al., 2022), and the influence of sub-surface processes on gas fluxes (Prend et al., 2022b; Chen et al., 2022).

The first Southern Ocean study using float-based estimates of carbonate system parameters to explore the seasonal drivers of carbonate changes (Williams et al., 2018) found variable agreement with prior studies based on shipboard observations (Takahashi et al., 2014). There is reasonable agreement between float-based estimates of pCO_2 and DIC in the more northerly Subtropical and Subantarctic zones (Fig. 9; Williams et al. 2018). However, in the poorly sampled Polar Frontal Zone and Antarctic Southern Zone there are large offsets in pCO_2 (Fig. 9). These offsets were suspected to result from undersampling in the ship-based data. Fay et al. (2018) compared pCO_2 estimates from SOCCOM floats going through the Drake Passage with nearby, shipboard observations from the Drake Passage Time-series (Munro et al., 2015). They found that the float estimates of pCO_2 agreed, within their estimated relative error of 2.7%, with the shipboard observations.

Estimates of the air-sea CO_2 flux using data from the first 3 years of SOCCOM float observations led to a calculated Southern Ocean net annual flux south of 35°S of only -0.08 ± 0.55 Pg C yr^{-1} (negative into the ocean), relative to the ship-based estimate of approximately –1.1 Pg C yr^{-1} (Gray et al. 2018). To obtain a more comprehensive assessment, these float data were combined with Surface Ocean CO_2 Atlas (Bakker et al., 2016) observations and gridded using previously established mapping and interpolation methods. The merged data (Fig. 10a) yields a contemporary Southern Ocean flux of -0.75 ± 0.22 Pg C yr^{-1} (Bushinsky et al. 2019a). This represents an approximately 0.4 Pg C yr^{-1} reduction in the contemporary Southern Ocean sink, relative to estimates based only on SOCAT data. Independent estimates of the Southern Ocean anthropogenic carbon sink from observations of ocean interior carbon concentrations coupled with inverse modeling approaches indicate that the anthropogenic flux is -1.1 Pg C yr^{-1} (DeVries 2014; Mikaloff Fletcher et al. 2006; Gruber et al. 2019). A contemporary flux of -0.75 Pg C yr^{-1} implies that the Southern Ocean natural outgassing flux is likely positive and on the order of several tenths of a Pg yr^{-1}, changing the prior understanding of a neutral natural carbon flux with uptake in the subtropical north balancing upwelling-driven outgassing South of the Antarctic Circumpolar Current (ACC; Gruber et al. 2019).

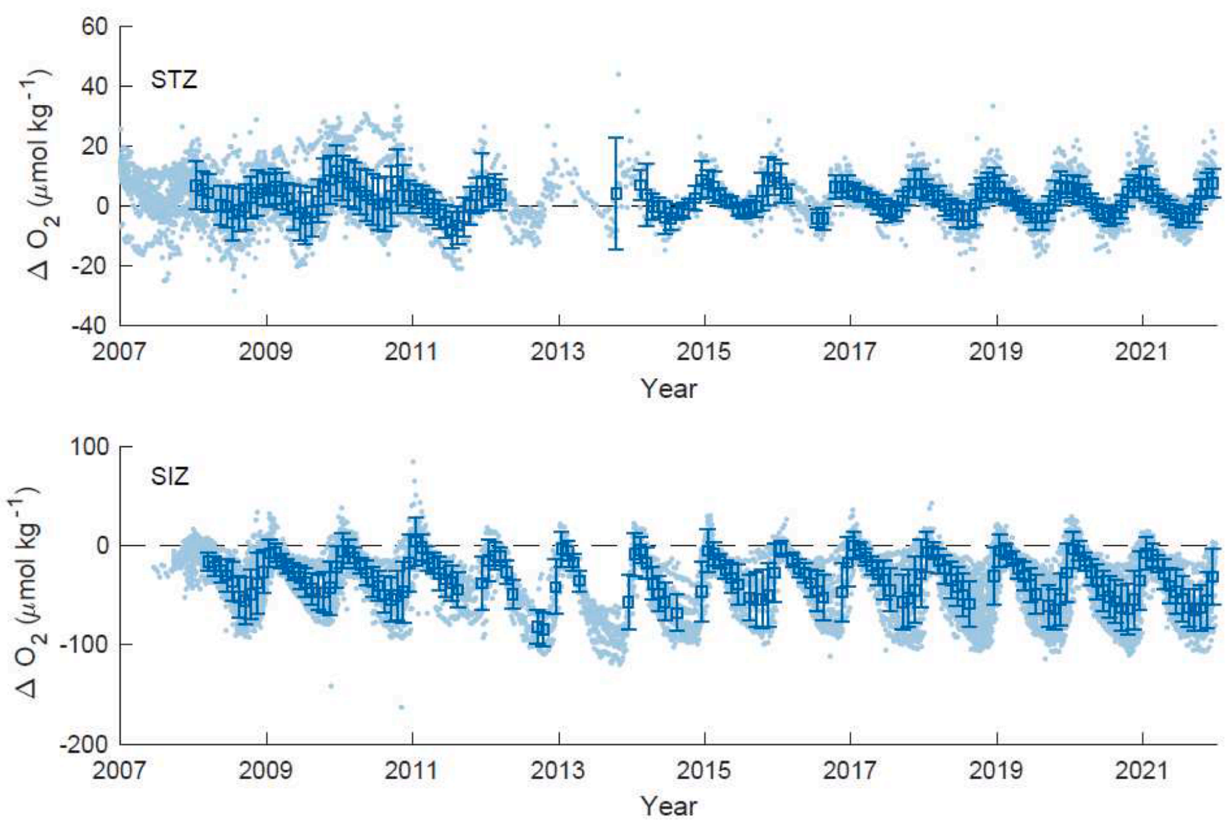

Fig. 8. Oxygen concentration difference from saturation ($\Delta O_2 = [O_2]_{measured} - [O_2]_{saturation}$) for the Subtropical Zone (STZ) and Sea ice Zone (SIZ). Updated from Bushinsky et al. (2017) with data through 2022. Light blue points indicate mixed layer concentrations from individual profile averages. Blue squares and error bars are monthly means ± 1 SD when average float temperature agreed with the NOAA Optimal Interpolation Sea Surface Temperature product as a check on data coverage.

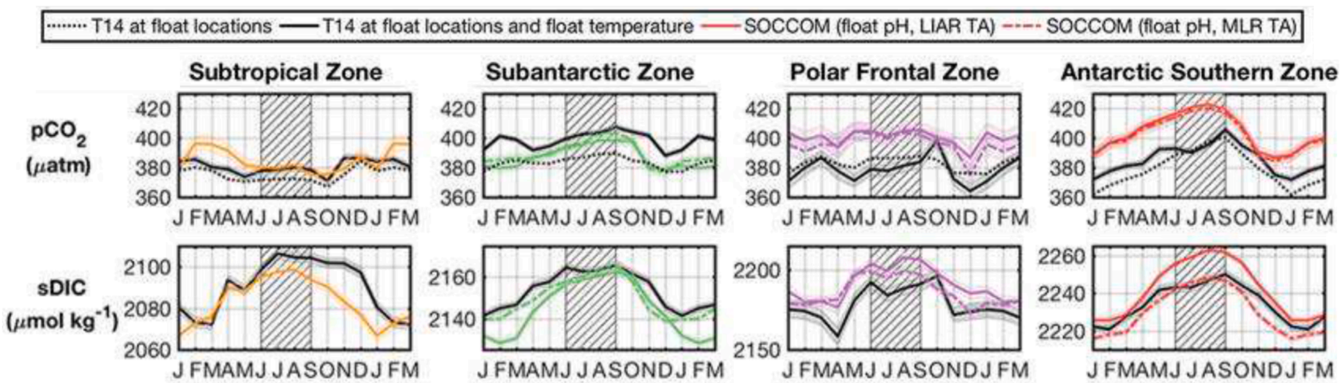

Fig. 9. Seasonal cycles of pCO_2 and salinity normalized DIC (sDIC) in the Subtropical, Subantarctic, Polar Frontal, and Antarctic Southern Zones. Float data are shown as solid, colored lines. The climatological values reported by Takahashi et al. (2014) for the year 2005 (T14 on figure), were adjusted to the present. The mean of all Takahashi et al. (2014) data at each float location are shown as black dotted lines and a filtered data set, with values selected only when float and climatology temperatures were similar, are shown as solid black lines.
Adapted from Williams et al. (2018)

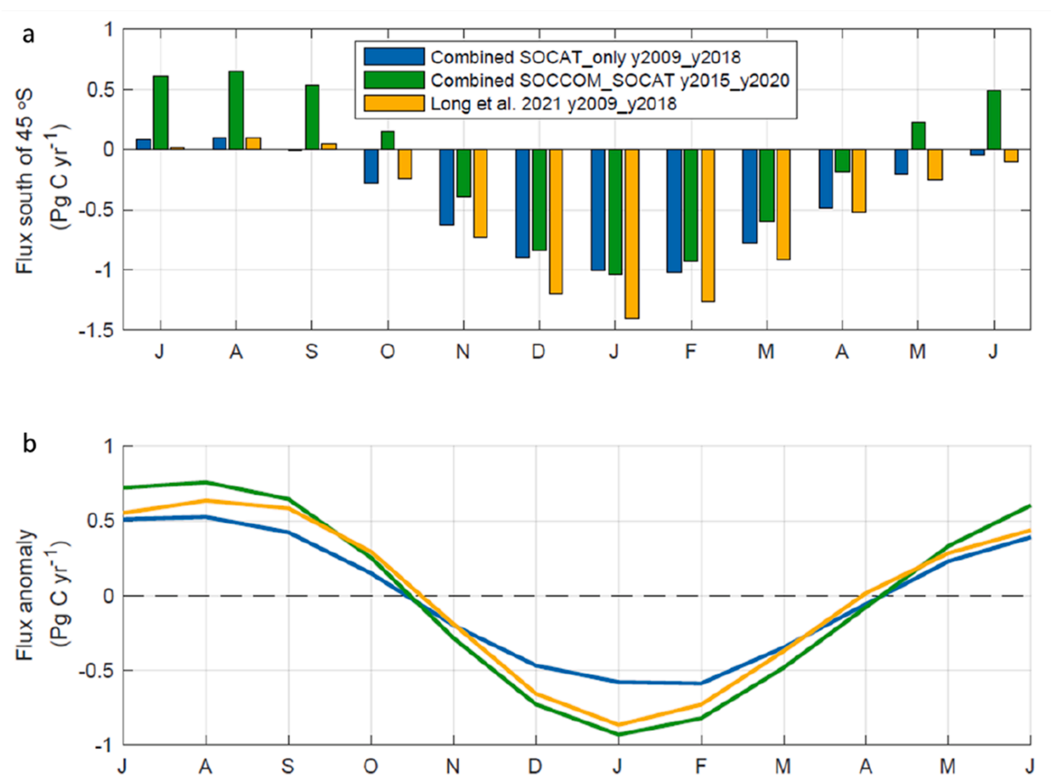

Fig. 10. Monthly mean sea to air CO_2 fluxes south of 45°S (positive values for flux from sea to air). (a) Values reported by Long et al. (2021) for 2009 to 2018 are shown as yellow bars. Values determined from the MPI SOM-FFN method (Landschützer et al., 2017) fitted to SOCAT shipboard data only for 2009 to 2018 are shown as blue bars. Values from the MPI SOM-FFN method fitted to the combined SOCAT and SOCCOM profiling float datasets (Bushinsky et al. 2019a,b) for 2015 to 2020 are shown as green bars. (b) The same data from panel a) are shown as monthly anomalies from the overall mean of each data set.

A recent study used aircraft and ground station measurements of atmospheric pCO_2 with atmospheric inversion models to develop a new constraint on air-sea CO_2 fluxes south of 45°S (Long et al. 2021). These fluxes, derived primarily from vertical gradients in atmospheric pCO_2 observations, agree more closely in annual magnitude with prior ship-only estimates. This may suggest a systematic bias in float based pCO_2 fluxes that would arise if float pH were consistently low around 0.005 to 0.010 pH. However, it is also clear that the flux based on the merged float and SOCAT data yield a seasonal cycle much closer to the values derived from atmospheric measurements than do the SOCAT only fluxes. This is shown by a plot of the anomaly from the annual mean in seasonal cycles from the atmospheric data, the shipboard only data and the shipboard plus float data (Fig. 10b). The SOCCOM float data appear to add significant information regarding the timing and amplitude of the seasonal cycle, relative to the SOCAT only dataset. The merged SOCCOM and SOCAT data yield a seasonal flux cycle that agrees closely with the aircraft data in seasonal amplitude and timing (Fig. 10b). The seasonal cycle would be difficult to obtain from sparse, shipboard observations in the Southern Ocean that are heavily biased to observations in summer (Bushinsky et al., 2019a).

Independent studies such as Long et al. (2021), Wu et al. (2022), and MacKay and Watson (2021) suggest that there may be a systematic offset in pCO_2 values that are derived from profiling floats of 5 to 10 μatm. It should be possible to identify and correct such a systematic error. Possible sources of systematic error include biases in carbon system thermodynamics (Fong and Dickson, 2019) or a systematic error in calibration protocols (Johnson et al., 2016). Resolving a potential bias will clearly lead to more precise and accurate air-sea CO_2 fluxes. The potential need for improvements in the profiling float pH and derived pCO_2 accuracy are reminiscent of the work required to make shipboard pCO_2 observations from different research groups consistent with each other (Körtzinger et al., 2000).

As the SOCCOM array has grown to cover the Southern Ocean in all of its most distinctive regimes, it has become possible to document regional differences within circumpolar regimes (Williams et al., 2018). These spatial and temporal variations can then be related to physical and biological processes. Chen et al. (2022) documented the connection of the deep water reservoirs of high carbon to the near-surface in the southern part of the Antarctic Circumpolar Current, using both SOCCOM float and historical hydrographic data (Olsen et al., 2020) and the property potential pCO_2 (PCO_2). The PCO_2 is the pCO_2 a parcel of water would have if raised to the sea surface (Broecker and Peng, 1982), and better characterizes the potential for air-sea exchange than the DIC concentration. Prend et al. (2022b) connected this high subsurface PCO_2 to the sea surface. Using SOCCOM air-sea carbon fluxes, they showed preferential outgassing in the Indian and Pacific sectors of the Southern Ocean compared with the Atlantic (Fig. 11). The initial hypothesis for the asymmetry was the lower PCO_2 observed for Atlantic deep water compared with Indo-Pacific Deep Water. However, Prend et al. (2022b) showed that stronger winter entrainment of high PCO_2 waters into the mixed layer is the proximate cause. Thus, a future with strengthening westerly winds and deepening mixed layers (e.g. Sallée et al., 2021)

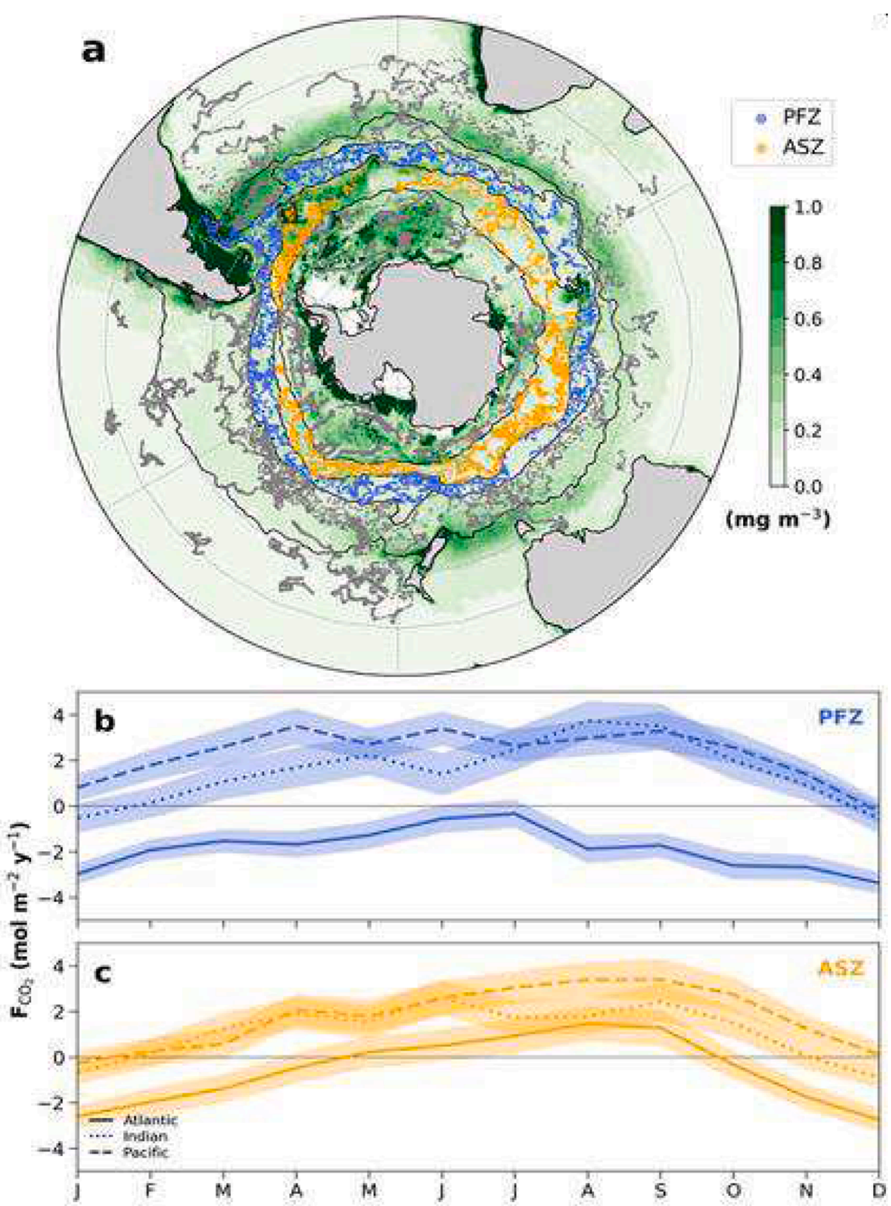

Fig. 11. (a) SOCCOM float profile locations sorted by frontal zone (PFZ: Polar Frontal Zone; ASZ: Antarctic Southern Zone). The color shading shows austral summer surface chlorophyll (mg/m3) from a 2002 to 2019 satellite ocean color climatology (NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group, 2018). (b) Monthly climatology of air-sea CO2 flux (mol C/m2/yr) in the PFZ from float profiles in the Atlantic, 65°W–25°E (solid line), Indian, 25°E − 150°E (dotted line), and Pacific, 150°E − 65°W (dashed line) sectors. Float profiles were made between 2014 and 2020. Panel (c) same as panel (b), but for the ASZ. Adapted from Prend et al. (2022b).

would lead to greater carbon outgassing.

Prend et al. (2022a) demonstrate the capability of SOCCOM profiling float pH observations to assess the processes that drive pCO_2 seasonal cycles. There is a change from a summer maximum of pCO_2 in the subtropics to a winter maximum in the polar regions. They find this shift is driven by a reduction in the amplitude of the seasonal temperature change at high latitudes, rather than biological processes.

3.2. Primary production and seasonal biomass cycles

3.2.1. Primary productivity

The transformation of dissolved inorganic to organic carbon during photosynthesis in the ocean, i.e., primary productivity, fuels marine ecosystems and plays an essential role in the global carbon cycle. Global marine net primary productivity (NPP) (defined as gross carbon fixation minus autotrophic respiration) is commonly inferred from ocean color remote sensing observations. Satellite observations provide information on water optical constituents and the available light field to infer phytoplankton biomass and division rates (Behrenfeld and Falkowski, 1997). The calibration of these satellite productivity models relies on scarce in situ observations of productivity determined from incubations of seawater samples with added $H^{14}CO_3^-$. The in situ observations are mostly constrained to low latitude regions (Buitenhuis et al., 2013; Marra et al., 2021).

Alternatively, primary productivity can be quantified by tracking the production of oxygen through photosynthesis. BGC-floats with oxygen sensors, including all floats within the SOCCOM array, permit the direct measurement of in situ gross oxygen production (GOP), albeit at coarse spatial scales. Although profiling floats cycle at ~ 10 day intervals, the diel cycle of oxygen can be detected by a float array if the individual floats surface at different times of the day (Fig. 12; Johnson and Bif, 2021). In this case, the set of profiling floats act as a dispersed chemical sensor array. The GOP computed from the diel cycle in oxygen concentration can then be converted to NPP, yielding a globally integrated value of 53 ± 7 (1 standard error) Pg C yr^{-1}. This value is consistent with the previous mean estimate of 50.7 Pg C yr^{-1} obtained from multiple ocean color and general circulation models (Carr et al., 2006). The diel oxygen method developed in SOCCOM has been extended to include diel cycles of particulate organic carbon in a study using SOCCOM data (Stoer and Fennel, 2022).

In addition to chemical sensors, SOCCOM floats have been equipped with bio-optical instruments that allow the estimation of phytoplankton chlorophyll and carbon biomass from measurements of fluorescence and particle backscattering that are combined with the models used to calculate productivity from remote sensing observations. These bio-optical observations are used to constrain phytoplankton physiology in response to nutrient and light limitation and to extend the computation of NPP beyond the mixed ocean surface and past the first optical depth (Arteaga et al., 2022), where most satellite sensors are unable to retrieve bio-optical information. Within the surface ocean observed by satellites, the increasing availability of float bio-optical observations is enabling the evaluation of ocean color remote sensing products (Bisson et al., 2019, 2021). For example, an assessment of estimates of chlorophyll and particulate organic carbon from NASA's Ocean Color Index (OCI) algorithm based on retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) and (VIIRS) showed a good agreement with float-based estimates of these variables in the Southern Ocean (Haëntjens et al., 2017).

3.2.2. Bloom dynamics

The incorporation of bio-optical sensors together with the float's biogeochemical measurements has increased our capacity to assess the role of ocean physics in setting the necessary nutrient and light preconditions needed for phytoplankton to grow and blooms to develop. Prend et al. (2019) coupled float data with the B-SOSE model to show that the large bloom in the Scotia Sea is linked to an unusually shallow mixed layer. This is due to a Taylor column over a topographic feature supporting early bloom formation. von Berg et al. (2020) show that the initiation and magnitude of blooms in the seasonal ice zone are linked to the timing of sea ice retreat. Uchida et al. (2019) and Arteaga et al. (2020) examined the phenology of phytoplankton blooms from the in situ observations of SOCCOM floats, a complementary approach to prior satellite-based assessments. Over the last ten years, studies based on satellite information have suggested that the temporal evolution of phytoplankton blooms cannot be fully understood from abiotic environmental properties controlling phytoplankton division rates (Behrenfeld and Boss, 2018). In situ observations of phytoplankton biomass from SOCCOM float bio-optical sensors have revealed a temporal gap between the seasonal cycle of phytoplankton division rates and actual biomass accumulation, which highlights the role of biomass-loss processes (e.g., grazing, viruses, sinking) as important drivers of bloom initiation and termination (Arteaga et al., 2020).

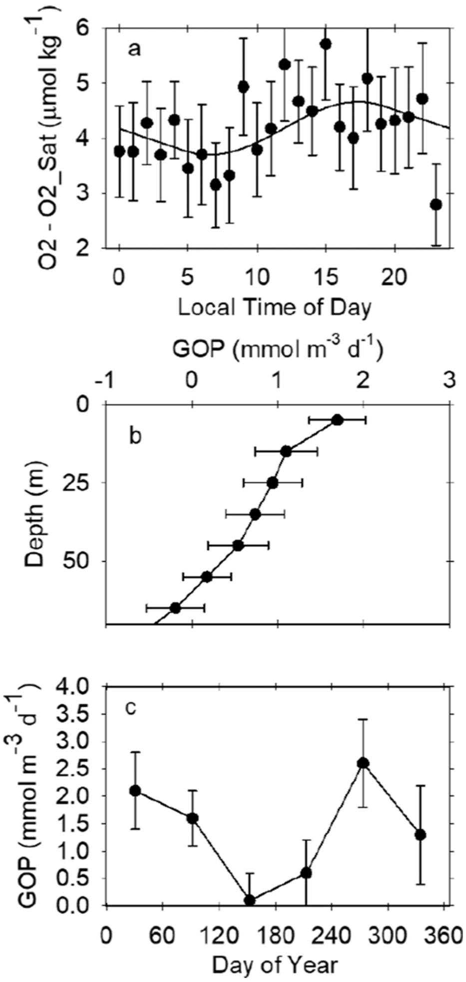

Fig. 12. Diel oxygen productivity from 30°S to 60°S following Johnson and Bif (2021). (a) Diel cycle of oxygen in the upper 20 m for all SOCCOM floats on days 0 to 61. (b) Vertical profile of Gross Oxygen Production (GOP). (c) Seasonal cycle of GOP in the upper 10 m. Error bars are 90% confidence intervals.

3.2.3. Linking to elements of the global ocean observing system

Profiling floats operate in synergy with all elements of the global ocean observing system. They are dependent on ships for deployments, sensor validation, and mapped products for sensor adjustment (Maurer et al., 2021). They complement earth observing satellites such as ocean color sensors and altimeters by providing observations with vertical resolution under clouds and ice, and during dark winter periods. Satellite-based communication systems are required to transmit data.

These synergies are illustrated in Fig. 13. The figure emphasizes the role that floats add to the observing system. They extend ship-based observations in time. They extend satellite observations in depth. They provide a consistent set of in situ observations that can effectively link these systems. For example, Haëntjens et al. (2017) have demonstrated consistency between SOCCOM profiling float chlorophyll values and the concentrations determined from ocean color satellites. Arteaga et al. (2022) used SOCCOM profiling float bio-optical data to extend NPP values computed with the Carbon-Based Productivity Model (Westberry et al., 2008), developed to support ocean color satellites, into waters deeper than can be resolved by ocean color satellites. They find that the vertical extrapolations necessary with ocean color satellite data have systematic biases in the Southern Ocean that affect vertical integrals of NPP.

The spatial density of profiling float observations cannot approach that obtained by ocean color satellites. However, processes that operate at higher temporal and spatial scales than those that floats sample at are aliased into the float data. In many cases, these signals can be recovered from the analysis of large numbers of float profiles. In addition to the above example of diel oxygen production by phytoplankton (Johnson and Bif, 2021), Carranza et al. (2018) used SOCCOM profiling float bio-optical sensors and satellite wind sensors to examine the effects of Southern Ocean storms on the vertical structure of plankton communities and their ability to develop vertical structure during quiescent wind periods.

3.3. Biological carbon pump

The biological influence on air-sea carbon flux is controlled by the downward flux of organic matter produced by phytoplankton in the surface ocean. This export and transfer of carbon from the surface to depth is termed the biological carbon pump. It is one of the main regulators of global atmospheric CO_2 levels (Volk and Hoffert, 1985). In most cases, the amount of carbon exported by the biological carbon pump will equal the annually integrated net community production (NCP), where NCP is the amount of primary production minus respiration at all trophic levels. SOCCOM floats have observed NCP from the seasonal drawdown of nitrate (Johnson et al., 2017a; Arteaga et al., 2019) and DIC (Briggs et al., 2018) in all regions of the Southern Ocean, providing comprehensive assessments of the net carbon production that is subsequently exported. This work allows the first, systemwide rate observations with the potential for annual resolution.

These analyses of NCP and the biological carbon pump generally make simplifying assumptions regarding potential biases due to ocean physics. As the number of floats increase, more effective use of the observational data may be made by incorporating the results with data assimilating models such as B-SOSE. Such an approach was used to study the mismatches in NCP rates determined from DIC and nitrate that may occur in oligotrophic systems. Elevated rates of DIC uptake may occur without corresponding nitrate uptake (Johnson et al., 2022) in oligotrophic systems. This study, which merged observations of 234 seasonal cycles of nitrate and DIC from floats with the corresponding results in B-SOSE, implies that much of the DIC uptake north of about 40°S is due to the production of dissolved organic matter containing little or no nitrogen. Seasonal declines in oxygen concentration observed by SOCCOM floats in the mesopelagic zone (depths between 100 and 1000 m) have been used to determine consumption rates of exported carbon (Arteaga et al., 2018, 2019; Hennon et al., 2016). The decreases in oxygen are driven by respiration of sinking organic carbon.

The ocean near the Polar Front (~50° S), a region of extremely low iron concentrations, appears to be an area of elevated biogenic carbon export relative to the rest of the Southern Ocean (Arteaga et al., 2019; Johnson et al., 2017a; Fig. 14). Prior studies have suggested differences in the remineralization and grazing efficiency by bacteria and zooplankton as a potential driving mechanism (Cavan et al., 2015; Laurenceau-Cornec et al., 2015; Le Moigne et al., 2016). An alternative hypothesis derived from the analysis of SOCCOM float-based export estimates and satellite productivity algorithms is that iron limitation promotes silicification in diatoms, which is evidenced by the low silicate to nitrate ratio of surface waters around the Antarctic Polar Front

Fig. 13. Illustration of the SOCCOM float observing system embedded within the framework of ship-based observations and satellite remote sensing and communications. Floats deployed from the ship extend elements of the diverse laboratory data out in time. Floats extend the high spatial resolution of ocean color data in the first optical depth of the ocean down in the vertical, while depending on satellites for data communications. Credit: SOCCOM Project, Princeton University.

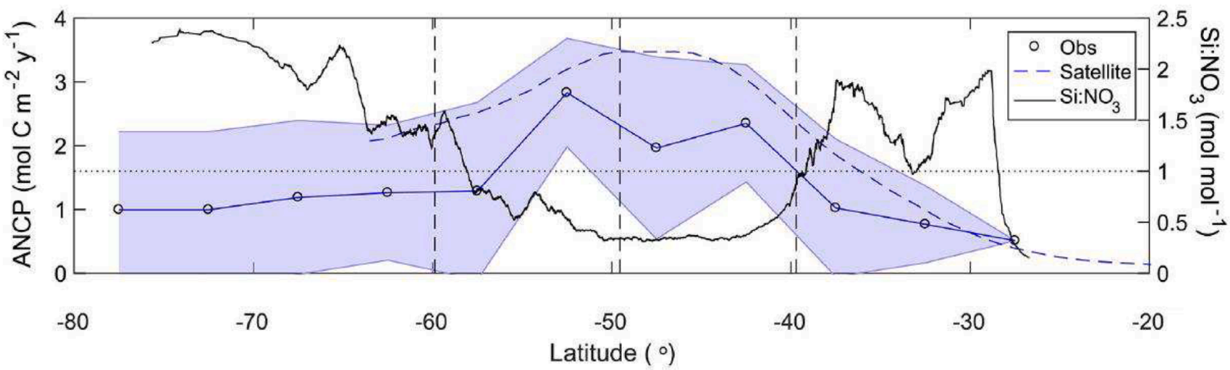

Fig. 14. Meridional pattern in export production (inferred from annual net community production - ANCP). Export production inferred from float oxygen and nitrate profiles (open blue circles and blue solid line), and satellite observations (blue dashed line). The Silicate to nitrate ratio (black solid line) was obtained from float nitrate observations and the World Ocean Atlas (2013) silicate climatology (Garcia et al., 2014).
Adapted from Arteaga et al. (2019)

(Arteaga et al., 2019). High diatom silicification increases the ballasting effect of particulate organic carbon and overall annual net community production in this region (Arteaga et al., 2019).

3.4. Floats in the seasonal ice zone

A hallmark of the Southern Ocean is the presence of seasonal sea ice south of about 60° S. Biogeochemical observations under sea ice have been rare, particularly during winter. SOCCOM has greatly improved sampling of both biogeochemistry and temperature/salinity in the sea-ice zone around the Antarctic continent with thousands of vertical profiles through all times of the year. These observations have allowed for unprecedented views of the under-ice water column properties in winter and the evolution of biogeochemical properties throughout an annual cycle (Briggs et al., 2018).

The SOCCOM floats operating in the seasonal ice zone enable a number of the observing system priorities identified in the UN Southern Ocean Report to be advanced. These include:

- *Improve understanding of sea ice, including its role in ecological processes of the Southern Ocean.*
- *Enhance predictive skill across climate, circulation, cryosphere, and ecosystems.*

3.4.1. Ice-ocean interactions

While SOCCOM was designed as a circumpolar observing system, its unprecedented year-round coverage has led to important contributions to more regional studies in the sea-ice zone as well (Wilson et al., 2019). In 2016 and again in 2017, a relatively large, open-ocean polynya appeared in the Weddell Sea region around Maud Rise (Campbell et al., 2019). This was in the same area occupied by the very large Weddell polynya of the mid-1970s. The 2016–17 polynya events were the largest since those observed in the mid-1970s (e.g. Gordon, 1978). SOCCOM floats over Maud Rise showed that the upper ocean in this region was only marginally statically stable during the events, with a mixed layer salinity approaching the limit for deep convection in late summer of both 2016 and 2017. The polynyas in both years were triggered by the passage of strong atmospheric storms, initiating mixing and heat loss from the subsurface ocean. Analysis of the stratification and climate forcing between the 1970s and 2016 indicated that this combination of weak stratification and strong climate forcing in the intervening years was rare (hence no polynya formation). The BGC sensors on the Maud Rise floats and in the northern Weddell Sea provided a comparison of productivity in the two regions, showing much higher productivity in the circulation trapped over Maud Rise, suggesting greatly enhanced vertical mixing that transports nutrients to the mixed layer.

Haumann et al. (2020) used a combination of under-ice profiles from both Core Argo floats and SOCCOM BGC-Argo floats, as well as ship-based and animal borne profiles, to investigate the details of temperature anomalies under and near sea ice. Surprisingly, a number of cases were found of water at temperatures below the in situ freezing point, termed supercooled, and water that would have been below the freezing point if it were raised to the sea surface, termed potential supercooled. Haumann et al. showed that nearly 6% of the profiles under the ice appeared to be supercooled, especially close to the Antarctic continent. The cause was attributed to melting of ice shelves and the existence of convective plumes during the formation of sea ice in winter. Such plumes might have important implications in the vertical transport of properties such as nutrients and carbon. An idealized modeling study nested in B-SOSE demonstrated the importance of ice shelf melt rates on spatial patterns of productivity (Twelves et al., 2021). These works suggest a need for a more focused observational study in these regions near the ice shelves.

3.4.2. Climatologies of BGC properties

The under-ice observations (from both Core Argo floats, with temperature and salinity data; and SOCCOM floats, with temperature, salinity, and BGC data) have been combined to produce a climatology of the wintertime under-ice regime around the continent, as can be seen in Fig. 15. Here we show the climatology in the wintertime surface mixed layer ($\sigma_\theta = 27.4$ and ~ 50 m deep in summer; $\sigma_\theta = 27.7$ and 100–120 deep in winter). The climatologies shown in this figure were formed by averaging and gridding the float data in an equal-area, scalable Earth projection, in order to avoid problems with convergence of meridians near the pole.

Mazloff et al. (2023) used the profiling float pH profiles and the B-SOSE model to create a monthly, mapped pH product for the Southern Ocean from 30°S to 70°S. The pH product was then compared to pH measurements made from ships prior to 2014. The differences in the climatology and shipboard measurements show that pH is decreasing most rapidly near the surface at a rate of -0.02 pH decade^{-1}, consistent with the rate of atmospheric CO_2 increase. The rate of decrease is not uniform horizontally, with some regions showing little change. The observed pattern of pH rate of change is consistent with the overturning circulation. Regions with low acidification rates are areas where Southern Ocean winds drive upwelling, which brings older, less acidified water to the surface and this decreases the rate at which pH declines.

3.4.3. Sea ice and phytoplankton

Sea ice plays a central role in structuring the productivity and

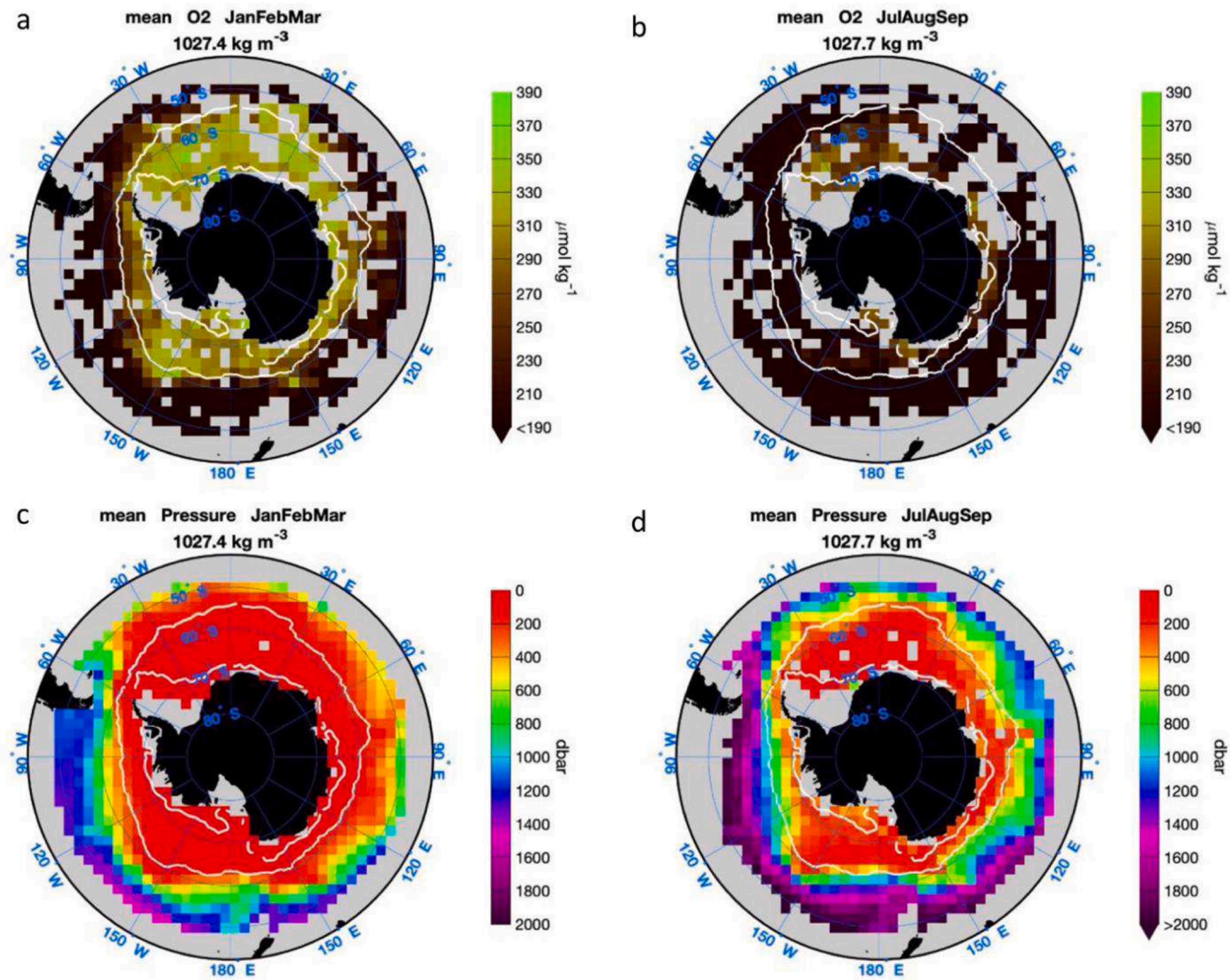

Fig. 15. Under ice climatology for oxygen. Dissolved O_2 (μmol kg^{-1}) determined from SOCCOM float data in summer (panel a) and winter (panel b) on the pressure (decibars) surfaces shown in panels c ($\sigma_\theta = 27.4$) and d ($\sigma_\theta = 27.7$). These pressure surface lie at the base of the mixed layer in summer and winter and the O_2 concentrations represent values in the surface mixed layer. The inner and outer white contours represent the summer and winter limits of the sea ice zone. The climatologies are gridded using an equal area scalable Earth projection that preserves the gridding in cells near the pole.

ecology of marine polar ecosystems. Observations in the Southern Ocean have long shown that sea ice communities are highly productive and diverse (Garrison 1991; Smith and Garrison, 1990). It has also been hypothesized that sea ice plays a critical role in adjacent pelagic communities (Smith and Nelson 1986), which represent a significant proportion of the annual primary productivity, and underpins trophic dynamics and biogeochemical cycles of the Southern Ocean (Arrigo et al. 2008).

Under-ice observations from SOCCOM floats revealed that Antarctic phytoplankton in ice covered regions begin to bloom (net increase in biomass accumulation) in early winter (Prend et al., 2019; von Berg et al., 2020; Arteaga et al., 2020), well before sea ice starts to retreat (Fig. 16). Under-ice blooming has been observed at local scales in the Arctic (Arrigo et al., 2012) and near Antarctica (Gibson and Trull, 1999; Arrigo et al., 2017), but the SOCCOM float dataset demonstrates that this phenomenon is a common feature of the seasonal ice zone. This is a remarkable event given the low light levels at which the bloom appears to begin (less than1 E m^{-2} d^{-1}). Biomass loss must be very low to permit phytoplankton to accumulate despite very low cellular division rates (Arteaga et al., 2020). These blooms deplete nitrate and DIC and, as light increases, they rapidly produce oxygen (Briggs et al., 2018). These observations show that respiration in winter nearly balances summer production with little net carbon export.

3.5. Circumpolar circulation

SOCCOM investigators worked on describing and understanding the pathways of the deep waters to the sea surface in the Southern Ocean (Morrison et al., 2015). This work was inspired by the findings of unexpectedly large carbon outgassing in the southern Antarctic Circumpolar Current (Section 3.1) that are driven by upwelling of high carbon deep waters. To explore the upwelling deep waters, Lagrangian tracking in multiple computer simulations revealed a southward and upward spiraling pathway (Tamsitt et al., 2017, 2018; Drake et al., 2019). Deep waters exiting the Atlantic, Pacific, and Indian Oceans were shown to be localized to the western and eastern boundaries and to mid-ocean ridges. These waters enter the eastward-flowing ACC, and mingle with each other and with ventilated waters from south of the ACC. While the net upward pathway is related to Ekman suction, most of the actual upwelling occurs in eddy fields at topographic features that are encountered by the ACC. This topographically-facilitated upwelling is active up to near the base of the surface mixed layers. The last step of

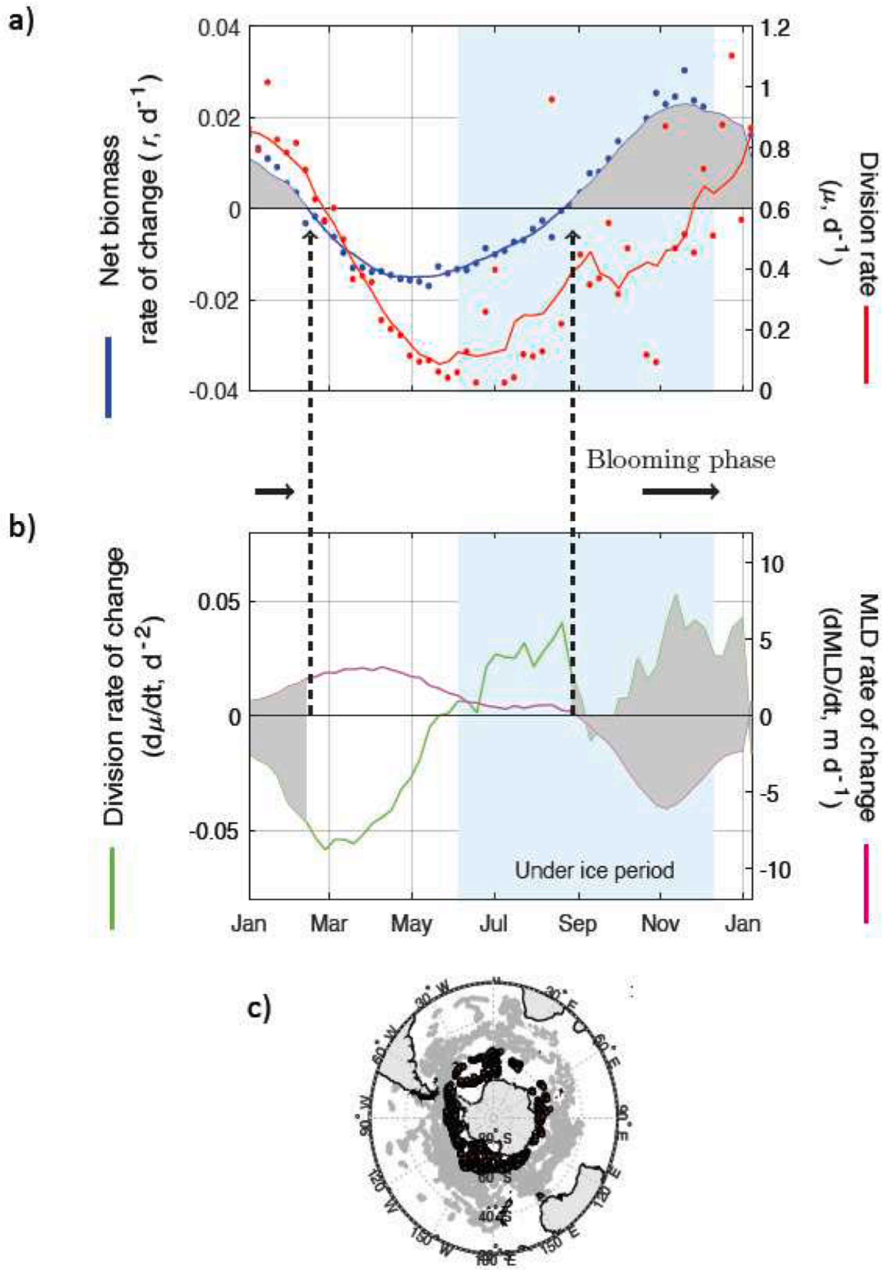

Fig. 16. Climatological phytoplankton bloom cycle in the Antarctic seasonal ice zone (SIZ). (a) Annual cycle of net phytoplankton biomass rate of change (r, blue line) and division rates (μ, red line). Individual points are weekly averaged observations and the continuous line is the result of a smoothing temporal filter. (b) Averaged time series of the temporal derivative of μ (dμ/dt, green line) and of the mixed layer depth (MLD) (dMLD/dt, magenta line). The blooming phase (r greater than 0) is highlighted by the gray shaded periods. The light blue shaded section indicates the period where 50% or more profiles were under ice. (c) Location of float profiles in the STZ and SIZ.
Adapted from Arteaga et al. (2020)

incorporation into the mixed layer is decoupled from these topographic features, and instead is dominated by surface-forced mixed layer entrainment. This process is most vigorous where winter mixed layers are deep, in the Indian and Pacific sectors of the ACC (Prend et al., 2022b).

Thus carbon outgassing in the southern ACC is driven by the conjunction of two processes – upwelling of high-carbon, northern deep waters to just below the surface layer, and vigorous winter entrainment that incorporates this water. There are many steps of this process that remain to be detailed, but the framework is now clear. After the northern deep waters upwell to near the sea surface, they split into the lower and upper limbs of the Southern Ocean's overturning circulation. The lower limb is fed by the densified surface layer, fueled by brine rejection from sea ice formation. In the upper limb, surface waters and sea ice are exported northward through Ekman transport. Freshwater from melted sea ice provides enough buoyancy to allow the upwelled water to move northward and warm, eventually reaching the northern ACC where it subducts into the thermocline (Haumann et al., 2016). This upper limb water carries high nutrients and carbon which become the source of nutrients for the thermocline (Sarmiento et al., 2004, Verdy and Mazloff 2017). This split between the upper and lower limbs has been quantified and localized in SOCCOM studies utilizing the B-SOSE output (Abernathey et al. 2016; Masich et al. 2018). Abernathey et al. 2016 showed the importance of freshwater transport via sea-ice in setting the structure of this overturning circulation (Fig. 17).

3.6. SOCCOM biogeochemical data as a community resource

A major focus of the SOCCOM program was to provide open access data to the community that was easily accessible outside of the program participants to ensure maximum influence. There are numerous publications by scientists outside the SOCCOM program who have used these data. Here we focus on just three topical examples; the effect of eddies on biogeochemical processes, studies of carbon export, and studies of plankton blooms under sea ice.

The open access SOCCOM dataset has played a seminal role in studies that illustrate the role of eddies on biogeochemical processes. This work has been performed completely by scientists outside of the project (Su et al., 2021; Cornec et al., 2021), illustrating both the Findability and Accessibility principles of a FAIR dataset (Wilkinson et al., 2016). These authors used the large SOCCOM dataset, as well as other floats in the BGC-Argo system, to assign float profiles to their location in cyclonic and anticyclonic mesoscale eddies that were mapped with satellite altimeters (an illustration of the FAIR Interoperability principle). This allowed them to test hypotheses regarding the role of eddy circulation in sustaining enhanced chlorophyll in these systems. Chlorophyll fluorescence in the deep chlorophyll maximum of eddies may increase due to biomass accumulation or photo-adaptation. Cornec et al. (2021) find, in a study with a global span, that in cyclonic eddies the fluorescence increase is primarily due to biomass accumulation, while in anti-cyclonic eddies it results primarily from photo-adaptation. Su et al. (2021) focused on the Indian Ocean sector of the Southern Ocean, where they found fluorescence increases generally resulted from both biomass accumulation and photo-adaptation. They show the importance of eddy pumping for sustaining elevated biomass in cyclonic eddies, as expected from prior studies. Supporting studies at the scale of eddies was not one of the original goals of SOCCOM, illustrating the FAIR principle of data Reusability.

SOCCOM floats have also played a significant role as a data source for studies of carbon export (Dall'Olmo et al., 2016; Stukel and Ducklow, 2017; Llort et al., 2018; Su et al., 2022). There is a growing appreciation that transport of organic carbon into the deep sea may occur by a variety of mechanisms (Boyd et al., 2019) in addition to the gravitational sinking of particles (the biological carbon pump; Ducklow et al., 2001). The broad distribution of SOCCOM floats allowed carbon export processes observed at the Long Term Ecological Research Station on the Palmer Peninsula to be extrapolated across the Southern Ocean (Stukel and Ducklow, 2017). Vertical mixing appeared to contribute one quarter of the biological carbon pump. In a global study, using many SOCCOM floats, Dall'Olmo et al. (2016) demonstrated that deep winter mixing is an important transport mechanism that detrains particles from surface waters to the deep-sea, a process labeled the seasonal mixed-layer pump. Llort et al. (2018) used SOCCOM floats to demonstrate that vertical motions along mesoscale eddies can further transport particulate carbon into the deep-sea, a process they termed the carbon eddy-pump. Su et al. (2022) used all of the available Southern Ocean oxygen profiles to compute oxygen consumption rates between the euphotic zone and 1000 m throughout the Southern Ocean. They obtained Annual Net Community Production rates by presuming the vertically integrated respiration rates are balanced by surface production and export. Their values are 1.1 to 2.8 times higher than found in prior studies.

The ability of the SOCCOM profiling floats to collect year-round data under sea ice has become a novel data resource that is being well utilized by the broader community. Jena and Pillai (2020) used SOCCOM floats, which fortuitously surfaced in the Weddell Polyna (Campbell et al., 2019), to examine the processes controlling plankton blooms in ice free regions of the seasonal ice zone. Hague and Vichi (2021) used SOCCOM float data to test the hypothesis that blooms in the seasonal ice zone form when meltwater stabilizes the water column. They found that significant growth occurred under ice and before there was a large salinity decrease. Bisson and Cael (2021) examined the relationship between phytoplankton abundance detected by SOCCOM floats and remotely sensed sea-ice properties to assess the role of ice in plankton growth. Horvat et al. (2022) used the SOCCOM data to demonstrate that under-

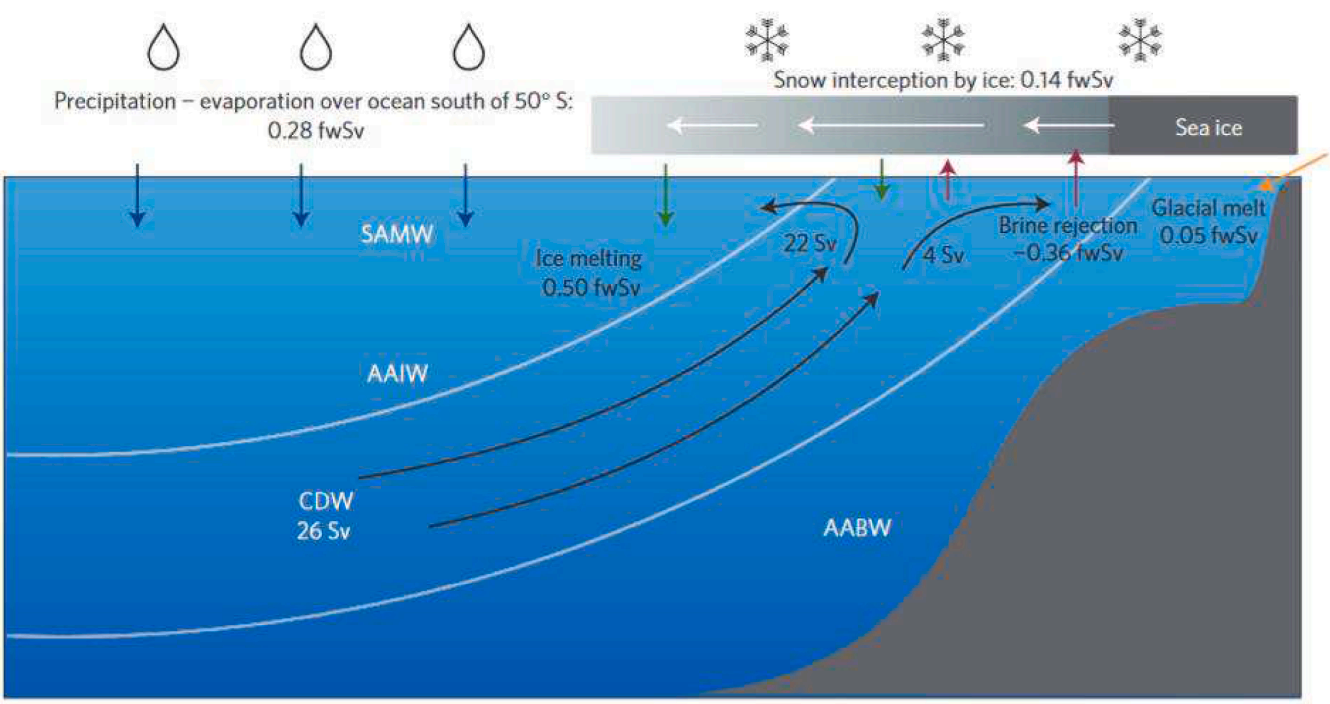

Fig. 17. Schematic depicting the various bulk contributions to the freshwater exchange at the ocean surface south of 50° S (positive downward). Net fluxes are given in units of freshwater sverdrups: 1 fwSv = 10^6 m^{-3} freshwater s^{-1} = 3.15 × 10^4 Gt freshwater per year. For reference, 1 fwSv = 1.9 mm d^{-1} of rainfall distributed over the region. From (Abernathey et al., 2016).

ice phytoplankton blooms are widespread in the Southern Ocean. Nearly all profiles under compact ice (80–100% coverage) showed large blooms during austral spring. Moreau et al. (2020) examined the fate of the carbon produced in ice-edge and under-ice blooms. Herbivory accounts for 90% of the losses and downward POC export is less than 10%.

These papers are just a subset of the analyses now produced by members of the ocean science community that are not directly associated with the program, but who are using the SOCCOM float data and B-SOSE output. They illustrate the role that SOCCOM is playing in becoming a major data resource that will enable both process studies and long-term assessments of the Southern Ocean response to climate forcing.

The SOCCOM observing system also fulfills a broader role through its synergism with other Southern Ocean observing systems and research programs. Examples of synergism with other programs include use of data from marine mammals that have been instrumented by the Marine Mammals Exploring the Oceans Pole to Pole (MEOP) program. The B-SOSE data assimilation system uses MEOP data as a constraint, which is particularly valuable in waters that are shallower than the 2000 m limit at which most floats are deployed. A SOCCOM study of the effect of storm driven mixing on bio-optical gradients used both profiling float and MEOP data (Carranza et al., 2018). Another SOCCOM study of the distribution of supercooled water used profiling float, MEOP, and ship-based measurements from the NOAA World Ocean Database (Haumann et al., 2020). Other major programs use the SOCCOM data in a variety of applications. For example, the Palmer Long Term Ecological Research (LTER) project is using SOCCOM float to provide an open ocean end member to assess the changes in shelf productivity driven by the precipitous declines in sea ice. Close interaction with focused programs such as Ocean Regulation of Climate by Heat and Carbon Sequestration and Transports (ORCHESTRA) resulted in benefit to both programs through float deployments and data exchange (Meredith et al., 2017). SOCCOM profiling float data have been used in Marine Ecosystem Assessment of the Southern Ocean (MEASO) to understand the ecological significance of subsurface chlorophyll maxima (Baldry et al., 2020). Of course, the SOCCOM program is closely intertwined with the international GO-SHIP program, which has deployed many of the SOCCOM floats and which is an irreplaceable source of validatation data for float sensors. These programs have formed an essential base for the success of the SOCCOM project.

4. Modeling the current and future state of the Southern Ocean and climate

Initial work with Earth System Models has focused on improving understanding of several important drivers of ocean change (Shi et al., 2018). This work addresses the UN Southern Ocean Report priority:

- *Improve understanding of key drivers of change and their impacts on Southern Ocean species and food webs.*

A critical component of SOCCOM modeling and the associated observations has been assessing the impacts of known model deficiencies and biases related to freshwater forcing, in addition to wind effects. Meltwater from the Antarctic Ice Sheet is projected to cause up to one meter of sea-level rise by 2100 under the highest greenhouse gas concentration trajectory (RCP8.5) considered by the Intergovernmental Panel on Climate Change (Oppenheimer et al., 2019). However, the effects of meltwater from the ice sheets and ice shelves of Antarctica are not included in the widely used CMIP5 or CMIP6 climate models, which may introduce bias into IPCC climate projections. Work using B-SOSE (Abernathey et al., 2016) highlights the importance of understanding and incorporating the effects of freshwater inputs on Southern Ocean circulation.

The Southern Hemisphere surface westerly winds are the main driver of the Southern Ocean circulation, mixing and air-sea exchanges. These strong westerly winds drive vertical mixing between surface and deep waters. An increase and poleward shift in these westerly winds, due to both the cooling of the stratosphere and the warming of the troposphere, has been inferred from reanalyses since 1980 (Swart and Fyfe 2012). The effects of meltwater provide a significant positive feedback on these changes. Models from both CMIP5 and CMIP6 still underestimate these historical trends (Beadling et al., 2020). The SOCCOM-led Southern Ocean Model Intercomparison Project (SOMIP) addresses this wind issue directly by imposing a "corrective perturbation" to the wind stress felt by the ocean.

4.1. Meltwater and wind

Antarctic Ice Sheet meltwater discharge into the Southern Ocean is generally neglected in most CMIP simulations (Pauling et al., 2016). Bronselaer et al. (2018), however, found that accounting for this discharge substantially affected the rest of the climate system. Including meltwater discharge slows the rate of global atmospheric warming, delaying the realization of both 1.5 °C and 2 °C warming by more than ten years. Ice sheet meltwater into the Southern Ocean during future simulations also drives a northward shift of the Inter-Tropical Convergence Zone (ITCZ), which results in reduced drying over Northern Hemisphere landmasses and enhanced drying in the Southern Hemisphere, relative to future simulations that neglect the meltwater. These SOCCOM results suggest that a feedback mechanism is in operation, whereby the meltwater added at the surface induces subsurface warming. That in turn leads to enhanced melting underneath ice shelves, potentially causing further meltwater-related climate effects (Fig. 18). The results demonstrate that meltwater discharge from the Antarctic Ice Sheet not only contributes to sea-level rise but also influences the global climate throughout most of the twenty-first century, emphasizing the importance of ocean and ice-sheet feedbacks on the climate system.

Wind increases and meltwater increases have opposing effects on Southern Ocean biogeochemistry. Additional meltwater causes a local reduction in ventilation that decreases subsurface oxygen levels. On the other hand, reduced ventilation increases subsurface nitrate concentrations along the continent through the accumulation of nutrients in more poorly ventilated waters and reduces nitrate export out of the Southern Ocean in newly formed intermediate water. The reduction in nitrate concentrations therefore propagates to low latitudes. In opposition, the wind-induced increase in ventilation causes an increase in oxygen concentrations throughout the upper 1,000 m of the Southern Ocean, while at the same time increasing surface nutrients and nutrient export through increased upwelling of deep, nutrient-rich waters. The balance between competing effects of wind and meltwater on ventilation will therefore influence future projections of ocean biogeochemistry.

Future climate change beyond 2100 is expected to cause nutrient trapping in the Southern Ocean through increases in surface stratification and poleward-shifting westerlies, starving the world-wide ocean of nutrients. Bronselaer et al. (2020) find that adding meltwater at the surface strongly amplifies Southern Ocean nutrient accumulation south of 60°S (Fig. 19). Previously, Pauling et al. (2016) concluded that adding meltwater at the surface or at ice shelves had little difference. Bronselaer et al. (2020) also find that increasing both wind and meltwater leads to significantly decreased nutrients north of 60°S as well (Fig. 19). While Southern Ocean nutrient trapping is found to be important in the twenty-second century, our results suggest that accounting for Antarctic meltwater and wind can cause similar effects in the twenty-first century, suppressing global biological productivity sooner than otherwise expected.

4.2. Buoyancy forcing, wind, and circulation changes

Strong westerly winds are a hallmark of the Southern Ocean and the primary driver of the ACC (Munk and Wunsch, 1998; Paparella and

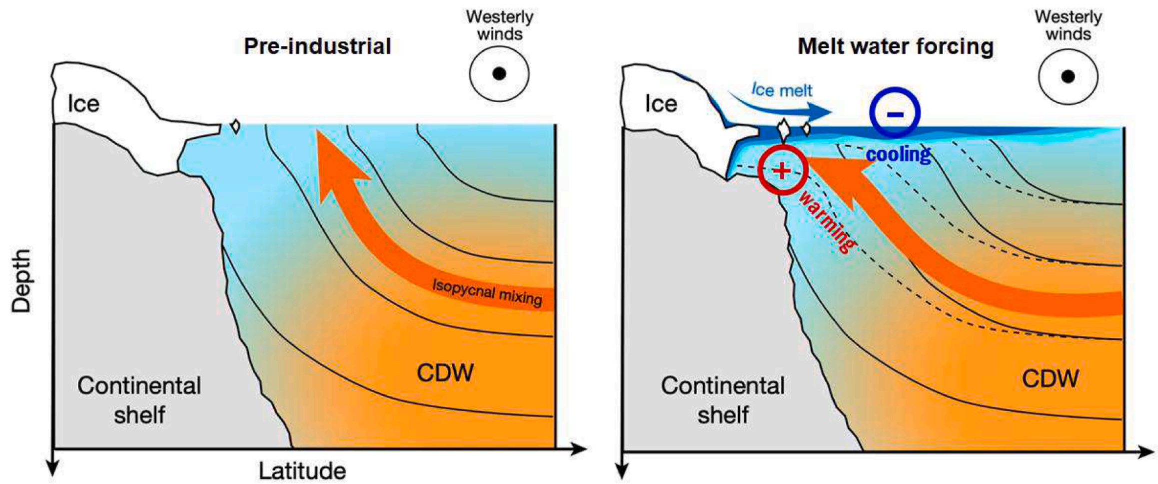

Fig. 18. Schematic showing subsurface warming in response to increased melt water is added to the surface of the Southern Ocean in an earth system model. After Bronselaer et al. (2018).

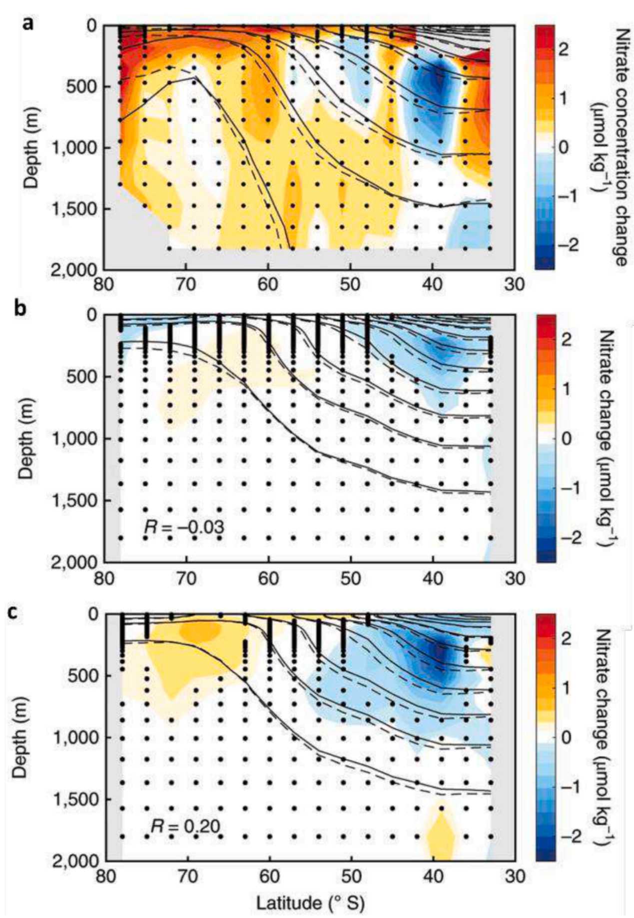

Fig. 19. Zonal-mean change in nitrate concentration. a) Observed nitrate change, SOCCOM float data 2014 to 2019 minus Ship data pre-2005. b) The decadal change of nitrate in the RCP 8.5 ESM2M simulation (2014 to 2019 mean minus 1985 to 2005 mean). c) The decadal change of nitrate in a SOMIP simulation with altered wind and meltwater (2005 to 2025 mean) minus the RCP 8.5 ESM2M simulation mean for 1985 to 2005. After Bronselaer et al. (2020).

Young, 2002). These winds are intensifying and shifting poleward, which may sustain an important feedback mechanism on the global carbon cycle (Russell et al., 2006b) and ocean warming (Armour et al., 2016). Much of the increased wind energy on the ocean appears in the mesoscale eddy field at locations determined by topographic interactions (Cai et al., 2022). Increased wind did not seem to appear in the mean flow. The weak effect on mean flow led to a concept known as eddy saturation (Straub, 1993; Munday et al., 2013).

In a SOCCOM supported study, Shi et al. (2020) used the Community Earth System Model (CESM) to examine climate driven controls on the ACC flow. They demonstrated that a changing buoyancy flux across the ACC was an important process regulating the ACC. To the north of the ACC, increasing ocean temperature produces a large buoyancy flux that has increased in time. Strong upwelling to the south of the ACC limits warming there. In a combined observational and modeling study, Shi et al. (2021) examined this process further. They used profiling floats, shipboard hydrography, and satellite altimetry with a careful statistical analysis to conclude that the zonally averaged ACC flow is accelerating, rather than remaining static. The increased baroclinicity due to the asymmetric buoyancy flux is a major driver of the increased flow, while strengthened wind stress is of secondary importance.

5. Broader impacts

SOCCOM's Broader Impacts vision is to transform training of oceanographers, expand public understanding of the Southern Ocean and its impact on climate change and living conditions on the planet, and enable broad access to the technology and findings of the SOCCOM initiative. The SOCCOM website, https://soccom.princeton.edu, was developed to enable much of this vision to be communicated to the public. The website includes access to profiling float data, model output, and a variety of multimedia resources including videos, photos, and graphics. Resources for an Adopt-A-Float program, including lesson plans for teachers are available. Some of these programs and resources are described in more detail below.

5.1. Public understanding

SOCCOM has a mission to drive a transformative shift in the scientific and public understanding of the outsized role of the ocean–and the Southern Ocean in particular–within our global climate system. In addition to deepening public understanding of the ocean's key role as a climate change buffer, the real-time monitoring of ocean health being done by SOCCOM provides critical information to policy makers, providing an ongoing assessment of carbon uptake and an independent way to effectively track progress on emission targets. This SOCCOM mission aligns with the UN Southern Ocean Report priority:

- *Improve societal understanding of Southern Ocean issues and appreciation of the Southern Ocean for its global value in Earth systems and unique environment.*

SOCCOM's Broader Impacts activities include use of social media, an Adopt-a-Float program, an array of multimedia content (lesson plans, videos, animations, and fact sheets), and capacity-building workshops to help researchers effectively apply float data (Matsumoto et al., 2022). The Adopt-a-Float program (Fig. 20) partners with teachers and classrooms around the world by enabling classes to adopt a profiling float with a goal to inspire and educate students about the Southern Ocean and climate change. Elementary- to college-level classes have the opportunity to give a soon-to-be-deployed float a name, and follow its progress at sea through online data visualizations and, sometimes, blogs written by their paired SOCCOM scientists. Students can find their float on the adopted floats table and explore data collected via a special Adopt-a-Float visualization application. Beginning with just one classroom in 2015, the program now has 180 adopted floats in classrooms across 42 states and seven countries (Chile, Canada, Australia, UK, Saudi Arabia, Japan, and Poland). Multimedia content is available through the SOCCOM YouTube channel that is linked on the SOCCOM website.

Outreach to communicate these key points has been part of the SOCCOM program since its inception and has helped scientists, teachers, students, and the public better understand the ocean's role in climate change while shining a light on the Southern Ocean.

5.2. Educating the next generation of Southern Ocean scientists

The SOCCOM project has contributed directly to the training and education of 19 postdocs, 22 graduate students, and 50 undergraduate students who have been actively engaged in our research program at SOCCOM institutions. Over half (59%) of these junior researchers have been female and nearly 9% have been participants from under-represented groups, with highest participation of under-represented groups at the undergraduate level. These students and postdocs are an integral part of the program. Many of the publications cited above are the direct result of research by postdocs, graduate students and undergraduates. As part of their training, SOCCOM early career personnel participate in regular research webinars as well as the SOCCOM annual meeting, where they present their research and take part in professional development activities. Ten SOCCOM-supported Ph.D. students have successfully defended their dissertations and have moved on to postdoctoral and faculty positions.

In addition to our program alumni, SOCCOM has established connections with dozens of ocean BGC researchers affiliated with the project partners through associate researcher and early career scientist groups. The program has also helped expand the community of BGC float and model data users through public training workshops on biogeochemical float and sensor technology, BGC data processing and QC, climate model data analysis and verification, and use and applications of the B-SOSE model.

5.3. SOCCOM in public policy

The SOCCOM program has been influential in shaping national

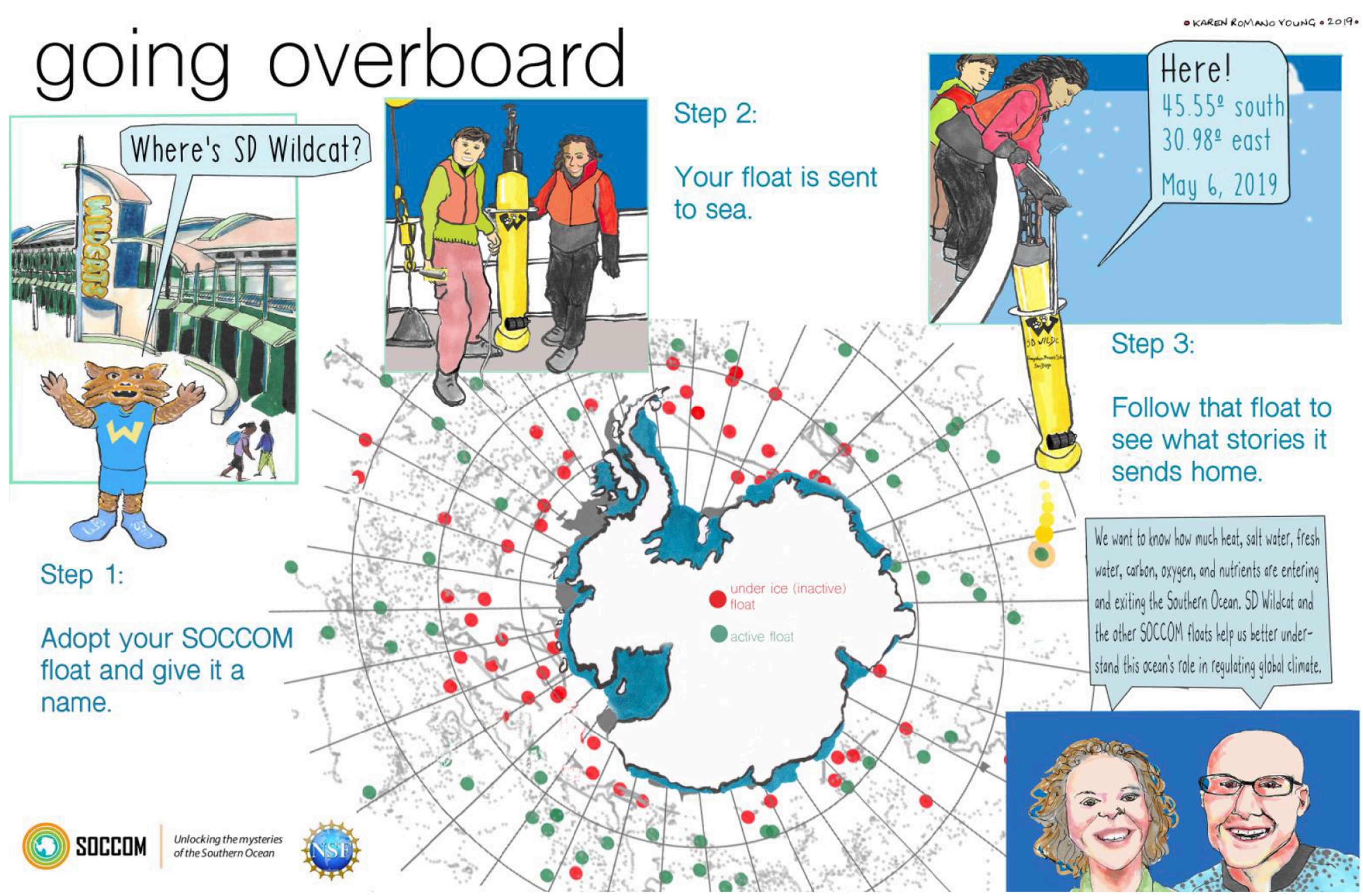

Fig. 20. The SOCCOM team partners with teachers and classrooms across the country to inspire and educate students about global ocean biogeochemistry and climate change through the "Adopt-A-Float" initiative. This illustration provides step-by-step instructions for adopting a float. Credit: Karen Romano Young for SOCCOM. The original drawing, with additional detail, was designed for a poster size and is available on the SOCCOM website (https://soccom.princeton.edu).

research policy. The second decadal plan for US ocean science, "Science and Technology for America's Oceans: A Decadal Vision" (NSTC, 2018), prominently features the SOCCOM project in the discussion on modernizing R&D infrastructure. The "Mid-Term Assessment of Progress on the 2015 Strategic Vision for Antarctic and Southern Ocean Research" (NAS, 2021) describes the role of SOCCOM in providing year-round observations of the Southern Ocean and the discoveries that have resulted. The role of SOCCOM in an international ocean carbon observing system has been discussed (IOC-R, 2021). Results from SOCCOM have been frequently included in the Bulletin of the American Meteorological Society Annual State of the Climate Assessment (Meredith et al., 2017; Swart et al., 2018; Meijers et al, 2019; Tamsitt et al., 2021).

6. SOCCOM in the future

The science performed in the SOCCOM program has evolved in scale as the profiling float array has grown. Initial studies were focused on one or a few floats (e.g., Williams et al., 2017; Briggs et al., 2018). The rapid growth of the array then enabled studies that encompassed the entire Southern Ocean, but without zonal resolution (e.g., Johnson et al., 2017a, 2017b; Bushinsky et al., 2017; Gray et al., 2018; Arteaga et al., 2019). As the array has progressed to more than 200 floats, studies with zonal resolution that reveal differences between processes in the Atlantic, Pacific, and Indian basins of the Southern Ocean are now possible (Prend et al., 2022b; Chen et al., 2022). Contrasting regional variability is also now possible. For example, Rosso et al. (2020) used machine learning techniques to classify profiles from the Indian Ocean sector of the Southern Ocean based on the vertical distribution of properties. The classification was then used to sort profiles into common groups. The grouping reproduced the expected frontal zone structure, but also showed significant differences with position relative to the Kerguelen Plateau. Such machine learning techniques will play an increasing role in studies of the growing SOCCOM dataset.

An immediate challenge for the SOCCOM system is sustaining the observations long enough to detect the effects of climate variability on biogeochemical processes. The time scales for detection of climate driven changes in biogeochemical cycles are typically greater than 15 years and often multiple decades (Henson et al., 2010; 2016; Schlunegger et al., 2020). The SOCCOM project has clearly established the capability to observe major elements of ocean biogeochemical cycles and their spatial variability over seasonal and internannual time scales (Bushinsky et al., 2017, 2019a; Johnson et al., 2017a, 2022; Gray et al., 2018; Arteaga et al., 2019; Prend et al., 2022a,b; Mazloff et al., 2023). However, with records that are typically less than 10 years in length, it is not yet reasonable to expect climate driven change to be detected unless float data is merged with prior, ship-based observations (Bronselaer et al., 2020; Mazloff et al., 2023). As the SOCCOM array operations are extended it will be critical to demonstrate that the data collected from profiling floats retain long-term consistency and can be used to directly detect climate driven change. Sustaining such a record will be a major challenge.

As the ocean warms (Roemmich et al., 2015, Cheng et al, 2022), it is likely that changes in primary productivity will result (Boyd et al., 2014) with significant effects throughout the ecosystem (IPCC, 2019). "Greening" of the Southern Ocean, quantified as an increase in chlorophyll detected by remote sensing (Del Castillo et al., 2019), has been suggested to result from warming. An enhanced focus on ecosystem properties, through bio-optical observations, is necessitated by these changes. Future SOCCOM efforts will continue to incorporate bio-optical sensors for both chlorophyll and optical backscatter, as well as adding downwelling irradiance. Each of these parameters provides information on changing biomass and phenology. A sustained array of these observations will provide a novel view of ecosystem change in the Southern Ocean.

Irradiance has not previously been a focus of SOCCOM. The radiometer, which is used to measure downwelling irradiance, will provide a scientifically valuable addition to the SOCCOM suite of measurements. The intensity of incident solar radiation varies substantially over the annual cycle in the Southern Ocean. In ice covered waters, there is considerable interest in the light level that enables the onset of the spring bloom (Horvat et al., 2022). The attenuation of downwelling irradiance is also a useful measure of integrated chlorophyll stocks (Xing et al., 2011). The combination of irradiance and chlorophyll fluorescence can be used to assess nutrient stress in phytoplankton (Schallenberg et al., 2022). The depth dependence of light attenuation also provides important insight into upper ocean heating (Ohlmann et al., 1996). Adding radiometers to the floats deployed in SOCCOM should provide valuable information on these issues across all zones of the Southern Ocean. Within a few years, most SOCCOM floats will carry radiometers, in addition to the five BGC sensors now carried. The addition of more advanced bio-optics, such as Underwater Vision Profilers (Picheral et al., 2022) and hyperspectral radiometers (Organelli et al., 2021), are being tested on profiling floats. These instruments provide additional capabilities for assessing higher trophic levels or plankton functional groups.

The SOCCOM project was explicitly designed as a program to examine the physical and chemical properties of the Southern Ocean at sites with depths in excess of 2000 m. Nearly all SOCCOM and Argo floats deployed to date in the Southern Ocean have adhered to this constraint. The program has the opportunity to expand these goals and objectives as a second renewal proposal is prepared. One of these future objectives is to expand the array into shallower, ice covered waters typical of the very highest latitudes in the Ross Sea, a core part of the Ross Sea Marine Protected Area (MPA). Buoyancy driven gliders are frequently deployed in this region (Jones and Smith, 2017; Kaufman et al., 2014; Meyer et al., 2022) and have provided valuable information on biological process including bloom dynamics and carbon export. However, glider deployments are generally limited to a few months, which requires ships to deploy and recover them. That presents significant logistical challenges if observations are to be sustained. Gliders also have carried a limited suite of sensors, typically bio-optics and oxygen sensors. While Argo floats are generally not intended to operate at depths less than 2000 m, eight UW-produced Argo floats were deployed on the Ross Sea shelf in a region less than 500 m deep late in 2013 (Porter et al., 2019). The float technology and ice-avoidance software proved to be robust, with seven of the floats continuing to operate on the shelf for 4 years or more. The resulting data yielded a unique view of the heat and freshwater budgets on the Antarctic continental shelf over an extended period of time, including new information on the contribution of land-based ice to these budgets (Porter et al., 2019).

These shallow, Ross Sea float deployments open the window for sustained, year-round profiling float operations in waters that had been accessible only in summer. They have led to questions of what such floats might observe if they were equipped with a full BGC sensor suite. In order to investigate the biogeochemical processes in this shelf region, and their links to the physical characteristics of the site, SOCCOM has deployed a set of 5 floats in the same region studied by Porter et al. (2019) that are equipped with O_2, NO_3, pH, Chl, and backscatter sensors, as well as a standard CTD. While both SOCCOM and GO-BGC are intended to be deep water observation networks, the continental shelf around the Antarctic continent is a unique region, where local water mass formation and carbon fluxes may have global implications. Thus, we hope to be able to observe these processes on the Ross Shelf in the near future using profiling float technology. Operation of floats in these shallow waters will provide a unique view into ecosystems, as there are few observations made year around.

The measurements in shallow waters of the Ross Sea MPA will support the UN Southern Ocean Report goal:

- *Ensure science-based and effective MPAs and uphold sustainable fisheries management.*

7. Conclusions

7.1. Lessons learned in operating a basin-scale array

Early planning for BGC-Argo, sponsored by the US Ocean Carbon and Biogeochemistry program, found that deployment of a regional profiling float array would be the next step towards a global system (Johnson et al., 2009). This regional project needed to demonstrate three essential capabilities. The float sensors had to generate "climate-research-quality" data. The system would have to be capable of inter-operating with other components of the ocean observing system including satellites, ships, and data-assimilating models. There had to be an integrated data management system operating in real-time. The SOCCOM project became an early model for this regional system. Along the way, a number of valuable lessons were learned about the effort to go to regional and then global arrays.

Lesson 1: Expanding operations involves many risks that do not manifest themselves until the expansion is well underway. A comment frequently made to SOCCOM personnel about the goal of expanding BGC-Argo to a much larger array was not to start until all aspects were ready. As practical as that advice seems, one cannot assess whether one is ready until the regional, and then global, arrays are built and relatively large numbers of sensors are deployed. For example, as a project transitions from small scale operations to something more akin to mass production a variety of new issues arise. Instruments that were hand built by the engineers and scientists who designed them must now be assembled by a less experienced production team. Inevitable miscommunications in construction of the platforms and sensors will arise with a detrimental effect on operations. When that is combined with an increasing demand for hardware to meet frequent cruise dates and data expectations from users, there will be system failures.

Lesson 2: Systemic failures will occur and vigilant monitoring of an expanding array is required to detect such failures as early as possible. Even in mature programs such as Core-Argo, very small manufacturing changes have resulted in widespread system failures in mature components such as pressure sensors (Barker et al., 2011; Wong et al., 2020) and salinity sensors (Wong et al., 2020). These systemic failures typically span multiple years before they are identified, understood, re-engineered, and then upgraded float deployments are resumed. In the case of pH sensors manufactured at MBARI, a modest manufacturing change resulted in widespread failures of pH sensors deployed in both 2017 and 2018, which illustrates the time scale of these problems. An unrelated problem is now affecting pH sensors manufactured at Sea-Bird Scientific. The extent of real-time monitoring and assessment of system operation which was required was a somewhat unexpected task. If the expectation is that such problems must be cured before basin to global-scale arrays are deployed, then no large scale system would be built.

Lesson 3: A rigorous approach to sensor data validation in the field is an extremely valuable contribution to program success. Much of the success in SOCCOM has resulted because of efforts such as collecting high quality hydrographic data to validate sensor performance (Section 2.6.1). These efforts also identified early sensor performance issues (Johnson et al., 2017b). The validation data guided our development of data adjustment procedures. Such efforts are essential to demonstrate the long-term stability of data.

Lesson 4: The cheapest way to obtain more high quality data is to transfer knowledge to the community. As lessons are learned while scaling up production and data processing, a very effective way to multiply this effort is to transfer that understanding as broadly and quickly as possible. In SOCCOM, several software tools, SAGE (SOCCOM Assessment and Graphical Evaluation) and SAGE-O2 were developed to streamline the quality control of nitrate and pH, and oxygen, respectively (Maurer et al., 2021). These tools are open source and they are now widely used in the BGC-Argo system. This contributes to the amount of high quality data available for research.

In parallel with this effort, a large amount of BGC-Argo data remained in the raw state at the start of SOCCOM without quality control or adjustments. Quality control of data in the Argo system is the responsibility of the principal investigator that deploys the float. However, Argo Data Assembly Centers set up to process Core-Argo temperature and salinity data may not have the complete expertise to quality control biogeochemical data. To mitigate this problem, SOCCOM developed the Argo Oxygen Audit. This program surveys all of the BGC-Argo data, performs an automated assessment of the consistency of the data through several metrics, computes sensor gain correction factors, and then reports these results to each Argo Data Assembly Center. This audit is performed 2 to 3 times per year. It has resulted in an increase in the percentage of quality controlled Argo oxygen data (Argo Adjusted Mode or Argo Delayed Mode data types) from 35% in 2019 to a value of 91% today.

Lesson 5: Expect the unexpected and have a strong management structure to enable rapid solutions. While the SOCCOM project could not anticipate an event such as the Covid-19 pandemic, they seem to find the program. Sole source components for instruments will become unavailable, requiring rushed research and engineering to find alternatives. Cruises will be canceled due to medical or engineering issues on ships. The SOCCOM Executive Team met weekly using remote video platforms from the beginning of the project. These meetings facilitated early recognition of unexpected events and the rapid development of solutions. The management structure helped prevent these problems from becoming frustrations.

7.2. Did SOCCOM meet its goals?

After nine years of operation, the SOCCOM project has established the observing system that was outlined in the initial proposal. Over 260 floats have been deployed. Thousands of profiles have been collected (Table 2) in all regions of the Southern Ocean (Fig. 4). The sensor data have been quality controlled, and made freely available (Maurer et al., 2021). These data extend observations in the Southern Ocean, particularly in the seasonal ice zone, throughout the year. A data-assimilating Biogeochemical Southern Ocean State Estimate has been developed and is now routinely assimilating SOCCOM profiling float data, as well as data from an array of other sources (Verdy and Mazloff, 2017). Insights from the profiling float data and B-SOSE have been used to understand factors that limit the performance of coupled climate models (Beadling et al., 2020, 2020; Bronselaer et al., 2018, 2020).

The profiling float data have been applied to studies of carbon, oxygen, and nitrate cycling, as well as a variety of ecosystem processes throughout the Southern Ocean and over complete annual cycles. More than 170 peer-reviewed papers acknowledge funding from the SOCCOM project. Dozens of papers have been written by scientists outside of the SOCCOM project using data generated by profiling floats of the SOCCOM array, as well as the products of the B-SOSE model. The access by scientists outside of the project demonstrates both the facile access to data and the confidence that the community has in this resource.

The SOCCOM array, and BGC-Argo (Claustre et al., 2020) in general, have demonstrated the robustness of autonomous observations during the height of a global pandemic. The onset of the Covid-19 pandemic led to a suspension of research ship operations in March of 2020. This included cancelation of the GO-SHIP A13.5 cruise, for which SOCCOM floats had already been shipped. Thus, float deployments were directly affected. However, the array of deployed robotic profiling floats continued to collect data (Boyer et al., 2023). The year 2020 will have few biogeochemical ocean records collected from ships. In comparison, there were 19,235 such oxygen profiles collected by all BGC-Argo floats in 2020.

While 2020 was an extraordinary year due to Covid-19, there is a continuing, downward trend over time in biogeochemical observations of essential ocean variables, such as oxygen, that are being reported from ships. Robotic observing systems are required to offset the lack of shipboard data, and the SOCCOM array demonstrates that such arrays can operate at the extent of an ocean basin. Operation of systems such as SOCCOM are an essential tool for observation of change in the ocean interior. Sustaining the operation of this system will be necessary to observe ocean change driven by climate processes.

In summary, SOCCOM has made very significant progress towards its very aspirational goals:

- Goal 1: Quantify and understand the role of all regions of the Southern Ocean in carbon cycling, acidification, nutrient cycling including oxygen, and heat uptake, on seasonal, interannual, and longer time scales.
- Goal 2: Develop the scientific basis for projecting the contribution of the Southern Ocean to the future trajectory of carbon, acidification, nutrient cycling, and heat uptake.

The project has met its three primary objectives to: generate climate research quality data, develop a system capable of inter-operating with the broader ocean observing system, and develop a data system that delivered science quality data in real-time. However, fully achieving the SOCCOM goals will require operating the system for longer periods of time to observe and quantify the emerging, climate driven signals that are expected.

The features of the SOCCOM system clearly address many of the priorities outlined in the UN Southern Ocean Report. While that report was largely aspirational, the SOCCOM project demonstrates that the development of comprehensive observing systems is possible. SOCCOM can stand as a model for observing systems in other basin-scale, sustained ocean observing systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data sources are identified in the manuscript

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Data Availability

All profiling float data generated by the SOCCOM project are available in a permanent archive at the University of California San Diego digital library with a digital object identifier (10.6075/J0TX3C9X). The archive is updated approximately three times each year. The real-time, quality controlled data are also uploaded, typically within 24 hours of receipt, to the Argo data system where they are available from the Argo Global Data Assembly Centers. See https://argo.ucsd.edu/data/ for a description of the Argo data system. In addition, real-time data with added data products such as computed total alkalinity, dissolved inorganic carbon and pCO2 are available from ftp://ftp.mbari.org/pub/SOCCOM/FloatVizData/.

Shipboard observations made to validate SOCCOM float deployments are available from the CLIVAR and Carbon Hydrographic Data Office (CCHDO; https://cchdo.ucsd.edu) by searching on the keyword SOCCOM.

B-SOSE model output is available from http://sose.ucsd.edu.

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