BAMS
Meeting Summary

Future Priorities for Observing the Dynamics of the Southern Ocean

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Observing the Dynamics of the Southern Ocean: Present Challenges and Future Strategies

What: A workshop funded by NSF's Office of Polar Programs to recommend research and fieldwork priorities for Southern Ocean physical oceanography.
When: 17–19 April 2024
Where: Scripps Institution of Oceanography, San Diego, California, and online

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1. Introduction

The Southern Ocean has an outsized influence on the global climate. The region takes up a disproportionate amount of anthropogenic heat and CO_2, mediates the transport of heat to the Antarctic ice sheet that influences ice sheet melt rates, impacts global atmospheric weather patterns and climate feedbacks, and supports global marine ecosystem via the upwelling and transport of nutrients (Sarmiento et al. 2004; Frölicher et al. 2015; Gruber et al. 2019; IPCC 2019; Gray 2024). Despite significant scientific and observational advances over the past few decades, the region's dynamics remain a major source of uncertainty in climate projections of global surface warming and sea level rise over the next century. The Southern Ocean also remains sparsely sampled, especially during the winter months in regions covered by sea ice. With the recent downsizing of the icebreaker fleet operated by the U.S. Antarctic Program (USAP), there is heightened urgency for the Southern Ocean research community to prioritize its scientific objectives and future observational needs.

To address these challenges, an NSF-funded workshop was held on 17–19 April 2024, at the Scripps Institution of Oceanography. Attendees were tasked to highlight recent advances in Southern Ocean physical oceanographic research, identify key knowledge gaps, and outline an ambitious but achievable set of research and observational priorities for the coming years. The workshop included three science sessions focused on (i) the open Southern Ocean, (ii) the seasonal sea ice zone, and (iii) the Antarctic continental shelf. Additional sessions addressed equity, diversity, and inclusion (EDI) in fieldwork, as well as data management. Each session featured presentations and breakout discussions to gather input on key scientific goals and observational strategies. There were approximately 60 participants, including over 20 virtual attendees. A visual summary of the workshop's key outcomes is provided in Fig. 1.

2. Key outcomes and perspectives

a. Research priorities. Workshop attendees agreed on the following high-priority research objectives for the next 5–10 years:

1) Constrain the magnitude and spatiotemporal variability of ice shelf melt rates to reduce uncertainty in global sea level rise projections over the next century. The ocean circulation along the Antarctic margins delivers heat to ice shelves, impacting melt rates and global sea level rise (Pritchard et al. 2012; Thompson et al. 2018). While satellite measurements have provided valuable constraints on ice shelf mass loss, the ocean processes

impacting sea level rise outcomes are poorly observed. A major research priority is observing the seasonal variations in ocean heat content and transport, which necessitates full-depth wintertime measurements over the continental shelf that are currently lacking. In addition to closing the on-shelf heat and freshwater budgets, it is necessary to understand how inter-shelf-sea exchange influences the ocean's circulation, stratification, and heat content variations over interannual to decadal scales. Key choke points, such as the boundary between the Amundsen and Ross Seas, are identified as critical areas for studying boundary current interactions. Additionally, the potential for hydrographic changes caused by ice-shelf melt in West Antarctica to propagate westward and affect the melting of the East Antarctica Ice Sheet is an open question. Studying these along-shelf interactions will require more measurements from the sparsely observed shelf seas in front of Wilkes Basin, East Antarctica. Given the inherently coupled dynamics governing the Antarctic Ice Sheet mass balance, attendees recommend increasing collaborations between the oceanography, glaciology, and atmospheric science communities.

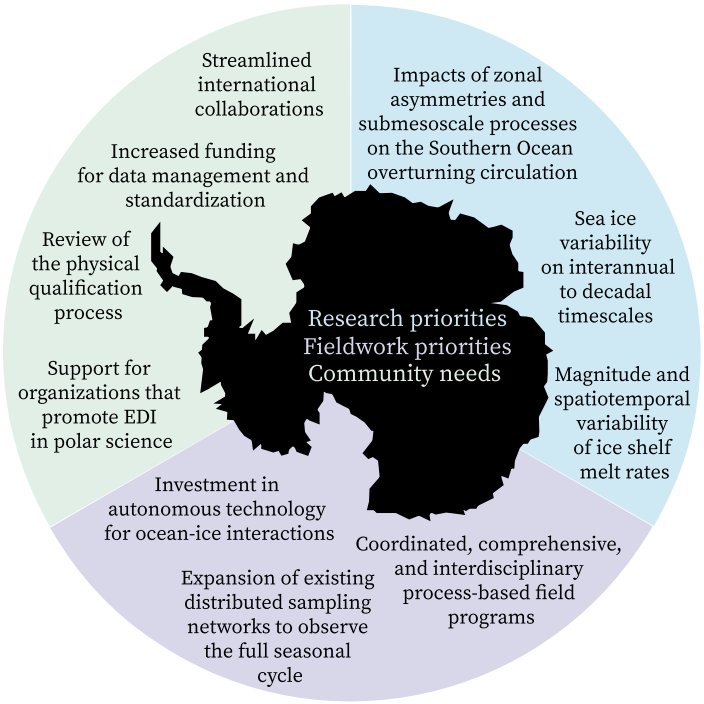

Fig. 1. A visual summary of the workshop's outcomes. Further details are provided in the text.

2) Develop a mechanistic understanding of sea ice variability on interannual to decadal time scales and its broader impacts on the regional climate. Antarctic sea ice is a crucial intermediary between the open Southern Ocean and the Antarctic margins. The growth, drift, and melt of sea ice play a key role in the region's dynamics, influencing—and being influenced by—oceanic and atmospheric circulation, as well as biogeochemical processes and ecosystem dynamics (Massom and Stammerjohn 2010; Hobbs et al. 2016). Over the past decade, there has been tremendous progress in observing the Antarctic sea ice zone. Recent advances in satellite capabilities and data processing have provided an emerging view of Antarctic sea ice thickness and its overlying snow depth, although validation of remote sensing estimates with in situ observations remains sparse (Maksym and Markus 2008; Kacimi and Kwok 2020). Significant gaps remain in the under-ice ocean observational network, which have been exposed by the unexpected and poorly understood dramatic decline in Antarctic sea ice extent in recent years (Purich and Doddridge 2023; Wang et al. 2024). Workshop attendees emphasized the need for a more robust, mechanistic understanding of the variability of sea ice extent, thickness, and motion on seasonal to decadal time scales. Additionally, there is growing appreciation for the importance of small-scale ocean processes, including turbulent mixing under ice and heat transport by submesoscale currents, particularly near the sea ice edge; wave–ice interactions; and the impact of intermittent, high-intensity atmospheric storms in setting large-scale sea ice properties. There is also a need to better constrain how sea ice impacts other components of Earth system, such as ocean water mass transformation rates, local ecosystem dynamics, and air–sea gas exchange.

3) Improve our understanding of how zonal variations and submesoscale currents influence the Southern Ocean's overturning and transport pathways. The open Southern Ocean, extending from the Antarctic shelf break to more northern ice free latitudes, plays a central role in modulating climate variability through its influence on ocean–atmosphere exchange. Recent studies have highlighted the importance of small-scale turbulence and zonal asymmetries of the Southern Ocean's three-dimensional circulation, particularly its standing meanders and localized regions of intense eddy activity, in modulating the zonally integrated meridional overturning circulation (Tamsitt et al. 2017; Dove et al. 2021; Youngs and Flierl 2023; Hague et al. 2024). These insights have been derived from limited in situ observations from ships and autonomous instruments, data-assimilating numerical simulations, and theoretical frameworks. Future research efforts should clarify the mechanisms governing zonal asymmetries in the regional circulation and small-scale mixing in ocean's surface boundary layer, elucidate how these dynamics impact coupled climate dynamics, and evaluate and improve their representation in climate models. A related priority is improving our understanding of how ocean turbulence and air–sea exchange at small scales (<100 km), during high-frequency events (e.g., storms), determine ocean ventilation rates.

b. Observational priorities. To achieve these research objectives, workshop attendees identified the following fieldwork priorities for the Southern Ocean:

1) Maintain and expand the existing distributed sampling network to ensure sustained monitoring of key ocean state properties and fluxes. With the downsizing of USAP's icebreaker fleet, the community stresses the need for autonomous platforms that provide year-round subsurface measurements across the Antarctic Circumpolar Current (ACC) and sea ice–covered Southern Ocean, such as those provided by the OneArgo Array [core, biogeochemical (BGC), and deep Argo] and CTD-tagged seals. There is strong support for continuing long-term surveys, like Palmer Long-Term Ecological Research (LTER) and decadal hydrographic transects, which provide a localized and rich view of ocean dynamics and biogeochemical processes. These long-term surveys are also essential for calibrating autonomous sensors. Attendees expressed enthusiasm for launching a new long-term survey in the Ross Sea marine protected area (MPA) as well as expanding the network of profiling floats along the Antarctic continental shelf. There is also a strong need for expanding bathymetric surveys on the continental shelf, which is crucial for constraining model-based estimates of ocean heat transport to the Antarctic Ice Sheet.
2) Execute collaborative, targeted field campaigns to constrain key physical processes. Attendees emphasized an urgent need for integrative, process-based field campaigns that synchronize with other international efforts (e.g., Antarctica InSync; https://www.antarctica-insync.org/) and simultaneously tackle multiple scientific questions. In particular, workshop attendees recommend prioritizing studies that constrain the following:
   (i) Cross-shelf ocean heat and freshwater fluxes along the continental shelf on daily to seasonal time scales, specifically near ice shelf fronts and across the continental slope: This effort would extend previous work that has focused on heat and freshwater content, a measure of the ocean's state, to quantify the flux or rate of spatial transport of these quantities. Two key locations were suggested for this type of study: (i) across the face of one or more ice shelf cavities and (ii) along a cross-shelf transect that captures key boundary currents at the coast, shelf break, and potentially over the continental slope (e.g., southern boundary of the Ross Gyre). A major priority is to combine in situ observations with altimetry [e.g., Surface Water and Ocean Topography (SWOT) and *ICESat-2*] and other remote sensing measurements to monitor

heat transport. We advocate for future focused, collaborative efforts between NASA and NSF to constrain ocean–ice dynamics for the Antarctic margins.

(ii) The three-dimensional evolution of sea ice and its interaction with the oceanic eddy field, with an emphasis on vertical thermodynamic processes across the air–snow–ice–ocean interface: Such a study would make comprehensive measurements of the atmosphere–ice–ocean system across a range of spatial scales, from centimeter-scale upper ocean turbulence to the mesoscale dynamics on the order of tens of kilometers. The Salinity and Stratification at the Sea Ice Edge (SASSIE) and Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) field expeditions within the Arctic Ocean seasonal ice zone provide examples of what could be accomplished by combining remotely sensed observations with an intensive, ship-based campaign (Drushka et al. 2024; Rabe et al. 2022). Attendees additionally envisioned a more limited but valuable study utilizing distributed autonomous platforms to facilitate the concurrent measurement of meteorological conditions, sea ice and snow properties, and the ocean state across the ice edge and into the main ice pack. The group expressed interest in a collaborative NSF–NASA effort that could support the validation of sea ice and snow remote-sensing capabilities.

(iii) The role of zonal asymmetries in the ACC and submesoscale processes on setting the structure of the Southern Ocean overturning circulation: The group discussed a field campaign analogous to the Ocean Surface Mixing, Ocean Submesoscale Interaction Study (OSMOSIS) conducted in the North Atlantic (Buckingham et al. 2016; Erickson and Thompson 2018; Thompson et al. 2016; Yu et al. 2019). Among several possible target regions, the group highlighted the Pacific sector of the ACC as particularly opportune since it features standing meanders that eventually diverge to influence the Antarctic margins along the Ross and Amundsen Seas further downstream (Prend et al. 2024). The imagined field campaign would include moorings and gliders in conjunction with floats and satellite observations. In situ assets would be maintained over multiple seasons of multiple years to capture how upper ocean turbulence and overturning circulation evolve under different atmospheric conditions. Though executing a field project of this scale in the Southern Ocean will inevitably be challenging, past field campaigns, such as the DIMES project, demonstrate the viability of an intensive multiyear regional study of the ACC (Gille et al. 2012; Sheen et al. 2013).

3) Support technological developments and infrastructure to advance our understanding of ice–ocean interactions. While many of the proposed field priorities are feasible, the group identified several observational limitations and recommended prioritizing technological developments to achieve the following scientific objectives:

(i) Autonomous measurements of the drifting Antarctic sea ice pack and underlying ocean: Few, if any, autonomous platforms provide direct estimates of sea ice properties, such as its thickness, snow cover, and vertical temperature profile, concurrent with measurements of the ocean state below. While platforms such as ice-tethered profilers and ice mass balance buoys have been widely deployed in the Arctic to great effect, deployments in the Southern Ocean are rare. This is in part due to the region's remoteness and the lower fraction of perennial sea ice to anchor these relatively expensive instruments. Thus, the community urges the development of affordable, resilient, and buoyant autonomous drifting platforms that can be frozen into the Antarctic sea ice pack, can continue measurements after ice melts, and could be deployed on a large scale. A model for such a platform is the Upper Layer Temperature of the Polar Oceans (UpTempO) ocean temperature buoy that has been successfully deployed in the Arctic Ocean and, in a more limited capacity, the Southern Ocean (Castro et al. 2016).

(ii) Hydrographic surveys within ice shelf cavities: Sustained under-ice shelf measurements, throughout an ice shelf cavity, especially near the grounding zone, were seen as an extremely high priority and a critical step for constraining melt rates and future sea level change. The group perceived that technology capabilities were a bottleneck at this stage and that future discussion is needed to identify how funding agencies can most effectively support both U.S. development of these new technologies and collaborations with other countries that are advancing this issue.

(iii) Large-scale deployment of profiling floats along the Antarctic continental shelf: Workshop attendees were supportive of an Argo-like effort, with coordinated interactions between different national Antarctic programs, to seed the continental shelves with profiling floats. These floats would periodically ground and would have adaptive sampling capabilities to avoid sea ice and icebergs, as are implemented on sea ice zone profiling Argo floats. The shelf floats would provide critical wintertime measurements of shelf heat and freshwater content, even without precise positioning. Such an approach has recently been implemented on the Ross Sea continental shelf by the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program (Cao et al. 2024), based on an earlier, serendipitous grounding of Argo floats in the same region (Porter et al. 2019). This approach has the benefit of being relatively inexpensive and straightforward to implement collaboratively with other Antarctic programs in an environment with limited ship resources.

c. Community needs. Attendees highlighted several policies and community practices that lead to inequitable distribution of fieldwork opportunities and the benefits derived from the collected data. The group proposed the following actionable priorities for NSF and the Southern Ocean research community at large:

1) Review the physical qualification process for USAP-supported fieldwork and increase transparency on factors that lead to medical exclusions. Attendees expressed concerns about the NSF Physical Qualification (PQ) process, which many found to be burdensome and opaque. The current PQ process makes little distinction between different types of fieldwork (e.g., remote fieldwork with limited access to professional medical assistance versus a short summertime stay at a well-equipped Antarctic field station). The lack of transparency in the PQ process as well as its short turnaround time could undermine the community's trust in this system. The community also emphasizes the need for more transparent health standards so that researchers are aware of the health requirements to participate in Southern Ocean fieldwork.
2) Increase funding for community-based organizations that promote EDI principles and provide support for researchers from underrepresented groups in the polar sciences. The complex logistics and expensive nature of Antarctic and marine research present a barrier to participation in polar marine science. Sexual, racial, and homophobic harassment aboard USAP vessels remain pressing concerns, especially for students and early career researchers (Nash 2021). Attendees acknowledged that the positive efforts led the NSF-supported Polar Science Early Career Community Office (PSECCO) and urge expanded financial support for grassroots community groups (e.g., Accessibility in Polar Research and Polar Impact) that facilitate community-building, mentorship, and outreach and skills training for under-represented and under-resourced groups in the polar sciences.
3) Implement and enforce data standardization and protocols to ensure that all Antarctic programs conform to Findable, Accessible, Interoperable, and Reusable (FAIR) principles. Given the multitude of challenges around obtaining polar data, it is necessary to make

these data accessible to the scientific community for equitable outcomes. Data reuse is a current priority of the NSF Office of Polar Programs, but it is only possible when data are archived in searchable repositories and are interoperable, meaning they are stored in common data formats (e.g., netCDF files) with the appropriate metadata. Any information about quality control or complementary datasets should also be documented and made available alongside the data.

4) Increase funding for data management personnel and infrastructure. While established programs such as Argo, Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), and SOCCOM have well-documented and robust data collection and accessibility protocols, standards for smaller programs and efforts led by individual principal investigators vary widely. Data management is often labor-intensive and thus needs explicit funding support to ensure that acceptable standards are met. Improving these inconsistencies will enhance information discoverability, foster more integrative research studies (e.g., validation of climate models), and streamline operational endeavors.
5) Streamline and promote international collaboration, both at the individual PI and agency levels. Despite immense interest in international collaborations, funding schemes and administrative barriers for such collaborations are often prohibitively complex. One potentially effective solution is expanding NSF's Lead Agency Opportunity (LAO) program, which provides a pathway for proposers from the United States and selects countries to submit a joint proposal that will undergo a single review by the lead science agency. The U.S.-based Southern Ocean research community would benefit from enhanced collaboration with other countries with Antarctic seagoing programs, such as South Korea, Australia, South Africa, and Japan.

3. Conclusions

Given the current resource limitations within the NSF and USAP, the Southern Ocean research community in the United States, as represented by workshop attendees, realizes the need to leverage precious ship resources. The community prioritizes continued monitoring of in situ ocean properties through autonomous platforms and collaborative field studies aligned with international efforts. Attendees also see the potential for significant advances in understanding ocean–ice interactions through the combined analysis of remotely sensed data products and in situ observations as well as dedicated collaborative NASA–NSF field campaigns. Fully leveraging these data requires a transformative approach to data management. Funding agencies must increase their investment in tools and personnel to ensure timely archiving and accessibility of data for the broader research community. Last, the community calls for greater transparency in the NSF Physical Qualification process, which restricts the pool of qualified researchers who can participate in field campaigns. We hope the dissemination of these proceedings will encourage further dialogue and stimulate coordinated efforts to advance our understanding of this critical component of our global climate.

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Data availability statement. Further details about the workshop and complete schedule of the meeting can be accessed at https://sites.google.com/ucsd.edu/soworkshop2024/home.

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