https://doi.org/10.5194/egusphere-2026-213
Preprint. Discussion started: 22 January 2026
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Opinion: Status, Plans and Needs of Southern Ocean Modelling

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Abstract. In preparation for the *SOOS/OCEAN:ICE Workshop on ice-ocean observation harmonization and future priorities agenda*, a survey targeting the modelling community was conducted to assess research priorities for the Southern Ocean and Antarctica. This initiative specifically supports the design of field activities from the open Southern Ocean to the Antarctic shelf for the forthcoming *Antarctica InSync* campaign and is aligned with broader strategic planning efforts ahead of the next International Polar Year (IPY). The survey results are a useful basis to further communication between modeling and observing science communities. We believe this is crucial for optimizing campaign planning, achieving enhanced data usage and improving numerical experiments.

1 Background

The Southern Ocean is responsible for 83% of the global ocean heat and more than 40% of global ocean anthropogenic carbon uptake (Frölicher et al., 2015; Williams et al., 2024) and ocean heat is a major driver of the current Antarctic ice sheet mass imbalance (Adusumilli et al., 2020; Bell & Seroussi, 2020; Noble et al., 2020). Nevertheless, this part of the world ocean features some of the most severe and long-standing biases present in state-of-the-art climate models with far reaching implications for climate projections (Stouffer et al., 2017; Beadling et al., 2020; Moreno-Chamarro et al., 2022; Zhang et al., 2023).

Full understanding of the processes and feedbacks of climate change in the Southern Ocean and Antarctica can only be gained by combining in-situ observations, satellite reconnaissance and numerical modelling. The region is difficult to access, especially where ice covered, and direct observations thus remain sparse. Remote sensing is limited to the surface, at least for the ocean. And models are valuable tools but never perfect. The upcoming Antarctica InSync and the IPY programs are centered around field campaigns, which resides in the need for strategically planning ship schedules and equipment acquisition years in advance. Model development and numerical experiment design follow different cycles and routines. Nevertheless, coordinating efforts across these science communities and intensifying

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exchange between them from early on in these major programs will be crucial for turning advanced process understanding into improved projections of the future climate in and beyond the southern high latitudes. Therefore, the survey initiative documented here supports a push for early integration of and engagement by the modeling community in these observation-driven efforts.

The survey was designed with a primary focus on the ocean modeling community. Although particular attention was initially given to realistic regional Southern Ocean configurations and CMIP-class global climate and Earth system models, input was solicited from modelers working across a range of spatial and temporal scales, and model complexities. While the survey emphasized physical oceanographic processes, coupled interactions with other components of the climate system, for example, sea ice, ice shelves and atmospheric dynamics were considered as well. Contributions related to biogeochemical processes and ecosystem modeling were also encouraged though not covered comprehensively. For pragmatic reasons, we defined the Southern Ocean as the region south of approximately 50°S in the survey context.

The survey was a rather spontaneous effort and thus of ad hoc design. Despite being launched just before the northern hemisphere summer break, it received a relatively large number of completed responses (98), representing a broad cross-section of the ocean and climate modeling community. This great turnout is also owed to the endorsement by SOOS(https://www.soos.aq/), the Southern Ocean Observing System and CLIVAR (https://www.clivar.org/), Climate and Ocean Variability, Predictability, and Change offices and Scientific Steering Groups, who spread the call in the SOOS Update (Issue 31) and the CLIVAR Bulletin, respectively, in August 2025 as well as the sharing of the call across mailing lists of Antarctica InSync (https://www.antarctica-insync.org/) modelling, APECS (https://www.apecs.is/), ASPeCt(https://aspectsouth.org/), BEPSII (https://sites.google.com/site/bepsiiwg140/home), BioEcoOcean(https://bioecoocean.org/), Polar-CORDEX (https://climate-cryosphere.org/polar-cordex/about/), Cryolist(https://lists.cryolist.org/mailman/listinfo/cryolist), the EU Polar Cluster (https://polarcluster.eu/), ICED(https://www.iced.ac.uk/), IMBeR (https://imber.info/), IMECaN (http://imecan/), MISOMIP2(https://misomip.github.io/misomip2/), ObsSea4Clim (https://obssea4clim.eu/), Ocean & Carbon Biogeochemistry(https://www.us-ocb.org/), OCEAN:ICE (https://ocean-ice.eu/), CLIVAR's Ocean Modeling Development Panel(https://www.clivar.org/clivar-panels/omdp) and Southern Ocean Region Panel (https://www.clivar.org/clivar-panels/southern), POGO (https://pogo-ocean.org/), SCAR (https://scar.org/), SCOR (https://scor-int.org/), SOCCOM(https://soccom.org/), the CLIVAR task team and Community-MIP SOFIA (https://sofiamip.github.io/), and TipESM(https://tipesm.eu/). This positive engagement yielded a valuable and unprecedented dataset that offers quantitative insights into current priorities and gaps in Southern Ocean research and modeling. It provides a robust foundation for ongoing and future strategic discussions regarding the alignment of modeling and observational efforts.

The following summary presents key findings of the survey. While the dataset (https://doi.org/10.5281/zenodo.17289776) (Martin et al., 2025) can be further explored, a first look already holds significant potential for informing cross-disciplinary planning and collaborative program development in the Southern Ocean and Antarctic research landscape.

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2 Who participated?

About half of the 98 survey participants [48%] identified as oceanographers, others see themselves as experts in coupled climate [13%], sea ice [12%], ice shelf cavity [10%] and land ice [8.2%] modelling. Colleagues studying processes at basin to global scales and from annual to centennial scales contributed two-thirds of the replies; less than a quarter indicated a research focus on mesoscale (10-100 km) processes with periods of months to seasons.

3 Survey results and discussion

3.1 Model status and evolution

We asked the participants for the most problematic ocean model bias allowing a single choice only aiming for a clear emergence of the most pressing issue from the survey. About a quarter identified processes of the Antarctic continental margin (shelf seas, slope current, ice shelf cavities) as requiring most attention (Figure 1). Further, open ocean deep convection and water mass transformation [both 14.3%] and mixing were highlighted. Individual free text answers mentioned deep ocean circulation, modeling of biogeochemical cycles and the carbon pump, planetary boundary layer of ice-covered seas, and impacts on benthic ecosystems as other major model biases, which are not displayed in Figure 1. The respondents related such biases in particular to global coupled climate [38%] and ocean models [28%] in general such as those used for the Climate Modelling Intercomparison Project (CMIP); this may reflect the dominant area of expertise of the participants however. Moreover, the respondents identified a dozen specific ocean models and state estimates as well as specifically high resolution model versions that include some of these major biases (see published survey data for details; Martin et al., 2025). We emphasize that moving towards finer grid resolution alone may yield individual improvements but will not solve all the biases—as is documented in Moreno-Chamarro et al. (2022).

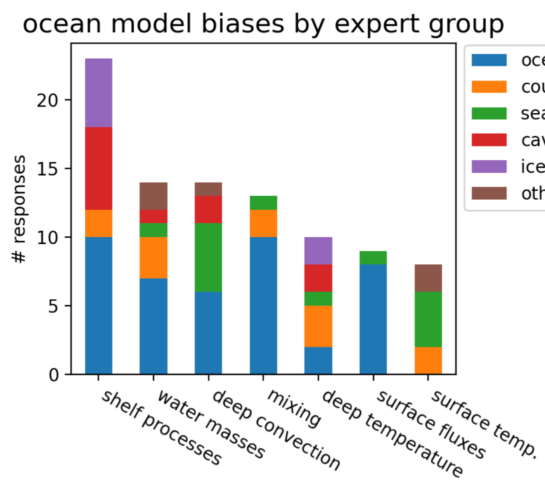

Figure 1: "What is the most problematic ocean model bias?" Eight well-known issues were listed as pre-defined, single-choice answers to ensure emergence of the most pressing problems. In this distribution of the responses we merged seasonality of surface fluxes and air-sea CO_2 flux into surface fluxes. The 91 responses (of 98 in total) are color-coded with respect to the area of expertise provided by the respondents. Here, "other" refers to all areas of expertise not explicitly listed, e.g. atmosphere and ecosystem.

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It is important to understand that open ocean deep convection—while physically not unrealistic (Gordon, 1978)—is dramatically overestimated in many coarse resolution climate models with consequences for ocean to atmosphere heat redistribution, sea ice coverage, bottom water characteristics, and eventually also internal climate variability (Reintges et al., 2017; Heuzé et al., 2021). In reality, Antarctic bottom water (AABW) is formed on the continental shelf where sea ice formation and ice shelf melt play key roles in the transformation of upwelled deep water (Silvano et al., 2023) and so does mixing for its transformation into Antarctic intermediate water (AAIW) further equatorward (Li et al., 2022). To this end, nearly three-quarters of all participating experts pointed out biases that are inter-connected and play an imminent role in the formation of water masses, such as AABW and AAIW, crucial for the global overturning circulation and for the natural sequestration of heat and anthropogenic carbon.

Hence, it is no surprise that implementation of ice shelf cavities [20%], convection parameterization [18%], scale aware (mixing) parameterizations [15%] and overflow parameterization [13%] were listed as most urgent model development targets. There has been remarkable advancement in these directions over the past two decades (e.g., De Rydt et al., 2024; Legg et al., 2009; Bruciaferri et al., 2024). And it has been demonstrated that these new developments can mitigate model biases in the Southern Ocean even at relatively coarse resolution despite remaining issues (e.g. for ice shelf cavities see Hutchinson et al., 2023). However, there is often significant delay or inaction in implementing such advancements, as model development is rarely funded directly by dedicated research projects. The push for rapid research outcomes tends to favor easily implemented targets — the 'low-hanging fruit' — over more complex, long-term efforts.

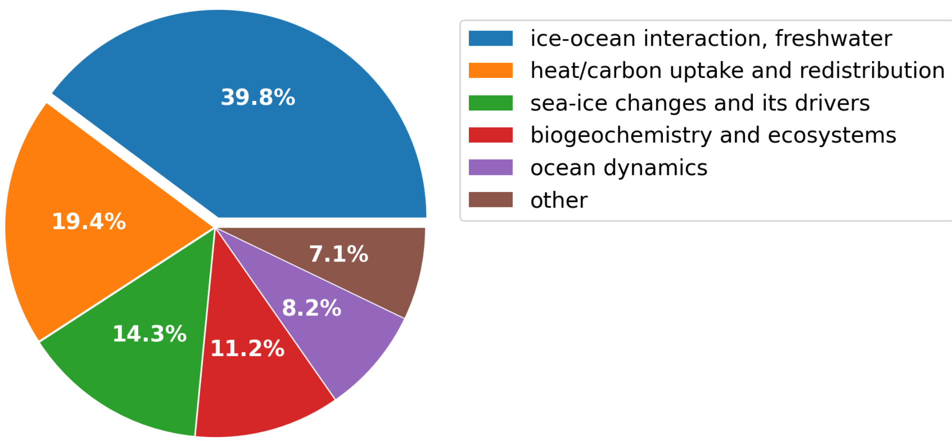

Figure 2: "What is in your view the singular key science topics in the Southern Ocean?" The five most frequent answers were provided as part of seven examples and could be simply ticked. Pre-defined answers less picked were air-sea exchange and extreme events. Additional topics were given by the respondents as free text input. These include, amongst others, cloud-radiation processes, carbon uptake and storage, nutrient redistribution and cross-disciplinary topics, and are collated as 'other'.

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This behavior is evident in the responses on near-term model evolution. Among those, increasing model complexity [27%] and spatial resolution [24%] stand out. Other goals such as improving or developing novel parameterizations and including artificial intelligence based modules are only considered by 11-13% of the participants. In this case multiple answers were possible and participants ticked or listed 2-3 responses on average. It seems that preference is given to model complexity—evolving climate models into Earth system models by coupling more components, for example, ice sheets or biogeochemistry modules—over improving model physics. However, this could also be a sign of a more diversified, cross-disciplinary science landscape. As compute power keeps growing, resolving model issues by enhancing grid resolution appears to be a possible avenue to reduce biases (e.g., Rackow et al., 2022). But this is a costly option and impractical for applications on centennial time scales since proper representation of mesoscale dynamics in the high latitudes of the Southern Ocean requires grid spacing of 1/8˚-1/20˚ (and finer on the continental shelf), to properly resolve the Rossby radius (Hallberg, 2013, their Fig. 1). New observations supporting model development could thus lead to improved and yet affordable simulations on a large range of spatial and temporal scales.

3.2 Scientific focus

Reducing the major model biases and advancing ocean and climate models as laid out above will be essential to address the key research topics identified in the survey responses. Freshwater, heat and carbon budgets are high on the scientific agenda of the modelling community (Figure 2). Questions on process understanding and future evolution of the Antarctic ice sheet, its ice shelves and their interaction with the ocean through heat and meltwater dominate the results [40%]. While this is research at the continental margin, heat and carbon uptake where the low latitude Southern Ocean plays a major role was named second [19%], followed by interest in the recent and future sea ice trends [14%]. On the one hand, these results are somewhat biased by the research areas of the participants. On the other hand, scientific interest has migrated poleward in the Southern Ocean, where major challenges have been identified, such as knowledge gaps in ice-ocean interaction affecting global sea level rise projections, and where new observational techniques for under-ice sampling and mesoscale ocean simulations have become available.

The results suggest that oceanic processes themselves, such as dynamics from mesoscale eddies to large-scale circulation, tides, waves and mixing are not part of the big questions anymore despite remaining issues and a dependence of, for example, biogeochemical modeling on the quality of the representation of the physical drivers. However, we assume that the underrepresentation of biogeochemical and ecosystem research as well as atmospheric process understanding, most prominently clouds and aerosols, is likely a consequence of questionnaire design and the focus group addressed.

3.3 Observations used and needed

Before going into a discussion on the observational needs of the modelling community, we would like to call attention to the data sources actually used. There is an unbroken preference by modellers to use gridded data products [28%], i.e. statistically interpolated fusions of observations from various sources, and reanalysis or state estimates [21%], which are based on a numerical model and incorporate observations through, e.g. assimilation techniques. Likely also due to their extensive spatial coverage, satellite-borne remote sensing products are favored as well [15%]. Data from ship-borne instruments, moorings, and floats are less

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valued [10-13%]. The latter often feed into the gridded products though. It is important to note that modelers tend to validate their simulations against "observations", which in fact are advanced data products and certainly not viewed as actual observations by the observing, sea-going science community. Modelers tend to lean on derived products, such as reanalyses and state estimates, because (1) there is a persistent lack of observations, (2) formats and platforms used to share observational data are still not optimally accessible to users despite ongoing efforts, and (3) there is a lack of understanding regarding observational data and their application for model validation making modelers reluctant to use original measurements. Especially item two and three can be addressed by strengthening communication between the science communities and by offering educational programs, such as summer schools, for the next generation of modelers.

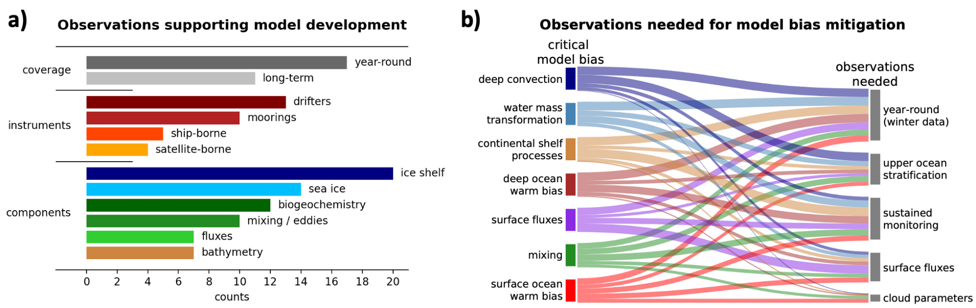

Figure 3: (a) "Which kind of observations would further this [model] development?" (without pre-defined answers). Free text responses were grouped by key words (right hand side bar labels) and sorted into groups of temporal coverage, instrumentation/sensors/platform and Earth system components (left hand side labels). In total 130 responses were identified. (b) Linking the two questions "What is the most problematic ocean model bias?" and "Which observations could help understanding biases or further the process understanding?" by the same respondent. In both cases pre-defined answers were provided but free text replies also possible; multiple choice was allowed. Overall 200 responses were cross-linked. The number of responses on the left side are normalized, see Fig. 1 for specific numbers.

For reducing observational gaps, especially with mitigating model biases in mind, modelers should be given and take the opportunity to provide input to evolving observational programs early in the planning phase. This would ensure multiple use of the data collected in the end. In contrast to the above given numbers, which indicate lesser use of in-situ data by modelers, Figure 3a shows observations desired for bias mitigation. Here, in-situ observations are clearly dominating over remote sensing data. We interpret this as a need for in-situ data for better process understanding then leading to improved model parameterizations whereas data of larger spatial coverage, like gridded products and satellite data, are preferred for model validation. Moreover, the scientific goals and observational plans of Antarctica InSync appear to be very much in line with the needs of the modelling community wishing for year-round data especially in ice-covered seas and combining physical and biogeochemical measurements (Figure 3a). The strong desire for winter observations and year-round monitoring in the Southern Ocean [29%] is independent of the main model bias the respondents care most about (Figure 3b). As is already discussed by the Antarctica InSync community, building capacity for sustained monitoring in preparation for the International Polar Year in 2032/33 and beyond would also strongly support model improvement and advancement [25%]. Observations of the upper ocean stratification and surface fluxes would enable a better process understanding of the mixed layer and help to constrain

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vertical/diapycnal mixing parameterizations in models. Interestingly, the role of other climate system components causing biases in the ocean, for example, sea ice and snow, clouds and radiative processes, was not highly considered. This could be a bias in the focus group addressed. However, it also hints at a need for improved fundamental understanding and acknowledgement of coupled mechanisms and feedbacks by the oceanography-centered community, not only in models but also in reality. Having better records of magnitude and variability of Southern Ocean surface fluxes of both physical and chemical quantities will help this significantly. Similarly, any observations in support of heat and freshwater budgets especially with a focus on ice-ocean interaction will be instrumental in advancing models and improving climate projections. And last but not least, high-resolution bathymetry data of the Southern Ocean from the Antarctic Circumpolar Current to the continental margin and into the ice shelf cavities is direly needed. Topography is a key ingredient for realistic simulations of the ocean circulation, specifically the import of warm deep water and the export of dense bottom waters, and therefore crucial for reliable projections of ice shelf melting.

4 Conclusions and Outlook

In conclusion, surveys like this provide a valuable overview of the current status, plans, and data needs not only for the Southern Ocean but also for the global modeling community. With the Antarctica InSync program in active planning and IPY approaching, we hope the results presented—with additional data available (Martin et al., 2025)—will inform both the scientific community and stakeholders to advance observations and models. The findings already contributed to the *SOOS/OCEAN:ICE Workshop* discussions and conclusions. Research priorities include ice–ocean interactions, Southern Ocean heat and carbon uptake, and the recent major changes in sea ice. Addressing these challenges requires model developments such as ice-shelf–ocean coupling, biogeochemistry, and higher resolution, alongside improved understanding of continental shelf processes and upper-ocean stratification. This, in turn, requires new observations in key regions with ice shelves most vulnerable to warm water intrusions and ocean circulation choke points. Further, the survey results call for stronger communication between the modeling and observing communities and dedicated data-use training for early-career modelers. Antarctica InSync offers a major opportunity to advance such efforts.

Data availability

The survey results are available through Zenodo (Martin et al., 2025), https://doi.org/10.5281/zenodo.17289777.

Author Contributions

TM received the original idea of conducting the survey, lead the analysis and produced all figures. All authors contributed to the survey design, its content and writing of this manuscript. AMH explored different survey platforms and distributed the survey call.

Competing Interests

The authors declare to have no competing interests.

Acknowledgement

The authors thank SOOS and CLIVAR for their support and endorsement of the survey facilitating this study. We thank all the scientific networks and coordinators for widely spreading the survey call and all the participants for responding yielding such great turnout.

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Helpful comments on the questionnaire design by Chris Danek, Ivy Frenger, Alexander Haumann, Qian Li, Lavinia Patara, Ariaan Purich, David Stevens were much appreciated. The survey was conducted using Google Forms and we made use of the initial visualization of the statistics provided by this platform in material provided by Martin et al. (2025). AJSM was supported by Ocean Cryosphere Exchanges in Antarctica: Impacts on Climate and the Earth system, OCEAN ICE, which is funded by the European Union, Horizon Europe Funding Programme for research and innovation under grant agreement Nr. 101060452, 10.3030/101060452; OCEAN ICE contribution number 49; he was also funded by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding Guarantee [grant number 10048443]. SOOS is a joint initiative of the Scientific Committee on Oceanic Research (SCOR) and the Scientific Committee on Antarctic Research (SCAR). SOOS sponsors include SCAR and SCOR, the Tasmanian State Government, CSIRO, the Australian Antarctica Program Partnership (AAPP), the Alfred Wegener Institute (AWI), OCEAN:ICE, the Swedish Polar Research Secretariat and the TÜBİTAK MAM Polar Research Institute. The SOOS International Project Office is hosted by the Institute for Marine and Antarctica Studies, University of Tasmania.

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