

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. While this initiative was tailored mostly towards physical ocean and ice modelling, its outcome 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*. 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 content increase over the historical period and more than 40% of global ocean anthropogenic carbon uptake (Frölicher et al., 2015; Huguenin et al., 2022; Williams et al., 2024). 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).

Recently, two major programs have been launched, [Antarctica InSync](https://www.antarctica-insync.org/) (<https://www.antarctica-insync.org/>) and the [5th International Polar Year](https://ipy5.info/) (<https://ipy5.info/>) (IPY5), to advance understanding of polar climate change and synchronize research across nations and disciplines. For both, coordinated observational campaigns with broad international participation are planned to take place in Antarctica and the Southern Ocean in 2027–2030 and 2032–2033, respectively. Research activities will expand beyond in-situ observations to, amongst others, Earth observations and numerical modelling. Especially for

50 Antarctica InSync an effort has been made to include modelling groups from the beginning,
51 which lead to the survey presented here.

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53 Full understanding of the processes and feedbacks of climate change in the Southern Ocean
54 and Antarctica can only be gained by combining in-situ observations, satellite reconnaissance
55 and numerical modelling. The region is difficult to access, especially where ice covered, and
56 direct observations thus remain sparse. Remote sensing is limited to the surface, at least for
57 the ocean. And models are valuable tools but never perfect. The upcoming Antarctica InSync
58 and the IPY5 programs are centered around field campaigns, which is logical, considering the
59 need for strategically planning ship schedules and equipment acquisition years in advance.
60 Satellite missions and model development follow again different cycles and routines, partly
61 on even longer schedules. Dedicated numerical experiments can be accomplished on a much
62 shorter time scale, though. Nevertheless, coordinating efforts across these science
63 communities and intensifying exchange between them from early on in these major programs
64 will be crucial for turning advanced process understanding into improved projections of the
65 future climate in and beyond the southern high latitudes. Therefore, the survey initiative
66 documented here supports a push for early integration of and engagement by the modeling
67 community in these observation-driven efforts.

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

94

95 The survey was designed with primarily the physical ocean modeling community in mind and
96 thus pre-defined answers often highlight physical oceanographic processes (see Appendix).
97 Although leaning towards such processes, coupled interactions with other components of the
98 climate system, such as sea ice, ice shelves, and the atmosphere were considered as well.
99 Contributions related to biogeochemical processes and ecosystem modeling were also

100 encouraged though not covered comprehensively. It turns out that a more careful selection of
101 the pre-defined answers would have been advantageous and likely beneficial for a broader
102 coverage of these coupled processes. Relatively little use was made of the “Other” free text
103 option by the respondents. Similarly, the survey started out with an emphasis on probing
104 modelling groups using realistic regional Southern Ocean configurations and CMIP-class
105 global climate and Earth system models to study the historical period and maybe 21st century
106 projections. But it evolved into covering a much broader range of spatial and temporal scales,
107 and model complexities, for which the respondents did make use of the free text comment
108 fields. For pragmatic reasons, we limited the geographical region and defined the Southern
109 Ocean as the area south of approximately 50°S in the survey context.

110
111 The following summary presents key findings of the survey. While the [dataset](https://doi.org/10.5281/zenodo.17289776)
112 (<https://doi.org/10.5281/zenodo.17289776>) (Martin et al., 2025) can be further explored, a
113 first look already holds significant potential for informing cross-disciplinary planning and
114 collaborative program development in the Southern Ocean and Antarctic research landscape.

115

116 **2 Who participated?**

117

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

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124 **3 Survey results and discussion**

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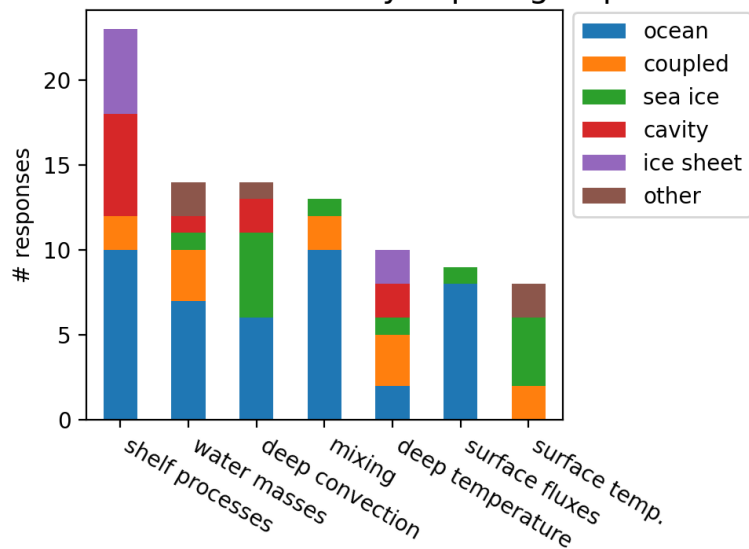
126 **3.1 Model status and evolution**

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

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ocean model biases by expert group

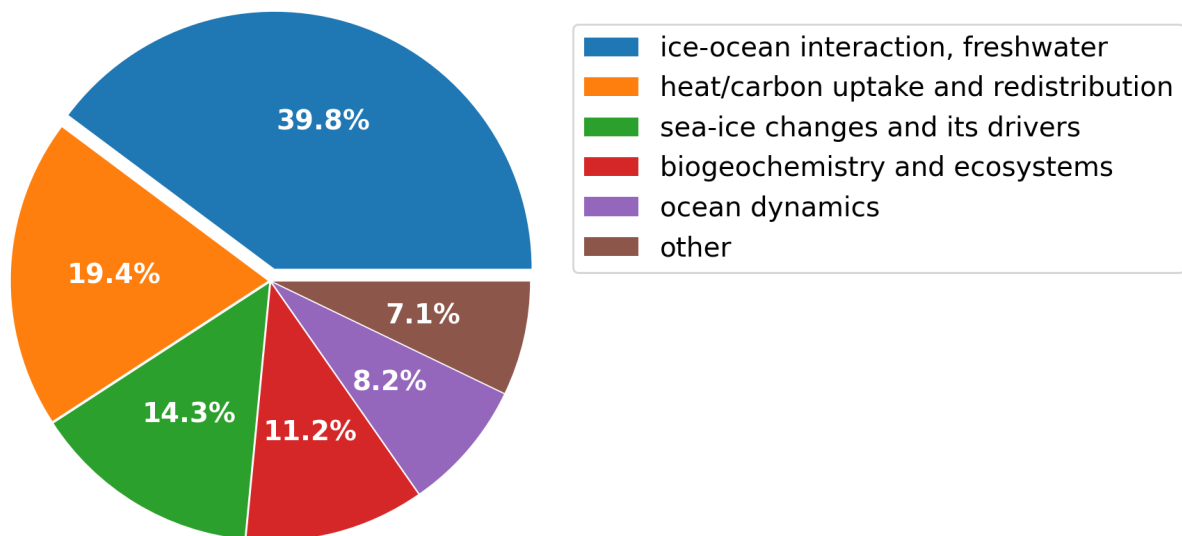


145
 146 *Figure 1: “What is the most problematic ocean model bias?” Eight well-known issues were listed as pre-*
 147 *defined, single-choice answers to ensure emergence of the most pressing problems. In this distribution of the*
 148 *responses we merged seasonality of surface fluxes and air-sea CO₂ flux into surface fluxes. The 91 responses (of*
 149 *98 in total) are color-coded with respect to the area of expertise provided by the respective respondents. Here,*
 150 *“other” refers to all areas of expertise not explicitly listed, e.g. atmosphere and ecosystem.*

151
 152 It is important to understand that open ocean deep convection—while physically not
 153 unrealistic (Gordon, 1978)—is dramatically overestimated in many climate models,
 154 specifically those of coarse resolution, with consequences for ocean to atmosphere heat
 155 redistribution, sea ice coverage, bottom water characteristics, and eventually also internal
 156 climate variability (Reintges et al., 2017; Heuzé et al., 2021). In reality, most Antarctic
 157 Bottom Water (AABW) is formed on the continental shelf where sea ice formation and ice
 158 shelf melt play key roles in the transformation of upwelled deep water (Silvano et al., 2023)
 159 and so does mixing for its transformation into Antarctic Intermediate Water (AAIW) further
 160 equatorward (Li et al., 2022). To this end, nearly three-quarters of all participating experts
 161 pointed out biases that are inter-connected and play an imminent role in the formation of
 162 water masses, such as AABW and AAIW, crucial for the global overturning circulation and
 163 for the natural sequestration of heat and anthropogenic carbon.

164
 165 Hence, it is no surprise that implementation of ice shelf cavities [20%], convection
 166 parameterization [18%], scale aware (mixing) parameterizations [15%] and overflow
 167 parameterization [13%] were listed as most urgent model development targets. There has
 168 been remarkable advancement in these directions over the past two decades (e.g., De Rydt et
 169 al., 2024; Legg et al., 2009; Bruciaferri et al., 2024). It has been demonstrated that these new
 170 developments can mitigate model biases in the Southern Ocean even at relatively coarse
 171 resolution despite remaining issues (e.g. for ice shelf cavities see Hutchinson et al., 2023).
 172 However, we believe there is often significant delay or inaction in implementing such
 173 advancements, as model development is rarely funded directly by dedicated research projects.
 174 The push for rapid research outcomes tends to favor easily implemented targets — the 'low-
 175 hanging fruit' — over more complex, long-term efforts.

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177
 178 *Figure 2: “What is in your view the singular key science topic in the Southern Ocean?” The five most frequent*
 179 *answers were provided as part of seven examples and could be simply ticked. Pre-defined answers less picked*
 180 *were air-sea exchange and extreme events. Additional topics were given by the respondents as free text input.*
 181 *These include, amongst others, cloud-radiation processes, extreme events, nutrient redistribution and cross-*
 182 *disciplinary topics, and are collated as ‘other’.*

183
 184 This behavior is evident in the responses on near-term model evolution. Among those,
 185 increasing model complexity [27%] and spatial resolution [24%] stand out. Other goals such
 186 as improving or developing novel parameterizations and including artificial intelligence
 187 based modules are only considered by 11-13% of the participants. In this case multiple
 188 answers were possible and participants ticked or listed 2-3 responses on average. It appears
 189 that preference is given to model complexity—evolving climate models into Earth system
 190 models by coupling more components, for example, ice sheets or biogeochemistry modules—
 191 over improving model physics. However, we think this could also be a sign of a more
 192 diversified, cross-disciplinary science landscape. As computing power keeps growing,
 193 resolving model issues by enhancing grid resolution appears to be a possible avenue to reduce
 194 biases (e.g., Rackow et al., 2022). But this is a costly option and impractical for applications
 195 on centennial time scales since proper representation of mesoscale dynamics in the high
 196 latitudes of the Southern Ocean requires grid spacing of $1/8^{\circ}$ - $1/20^{\circ}$ (and finer on the
 197 continental shelf), to properly resolve the Rossby radius (Hallberg, 2013, their Fig. 1). We
 198 suggest that new observations supporting model development could thus lead to improved
 199 and yet affordable simulations on a large range of spatial and temporal scales.

200 201 **3.2 Scientific focus**

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

214 global sea level rise projections, and where new observational techniques for under-ice
215 sampling and mesoscale ocean simulations have become available.

216

217 The results suggest that oceanic processes themselves, such as dynamics from mesoscale
218 eddies to large-scale circulation, tides, waves and mixing are not “big questions” by
219 themselves anymore despite remaining issues and their important role in current “grand
220 challenges” like ice-ocean interaction, warm water intrusion onto the continental shelf and
221 biogeochemical modeling. Further, we assume that the underrepresentation of
222 biogeochemical and ecosystem research as well as atmospheric process understanding, most
223 prominently clouds and aerosols, is likely a consequence of questionnaire design and the
224 focus group addressed.

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226 **3.3 Observations used and needed**

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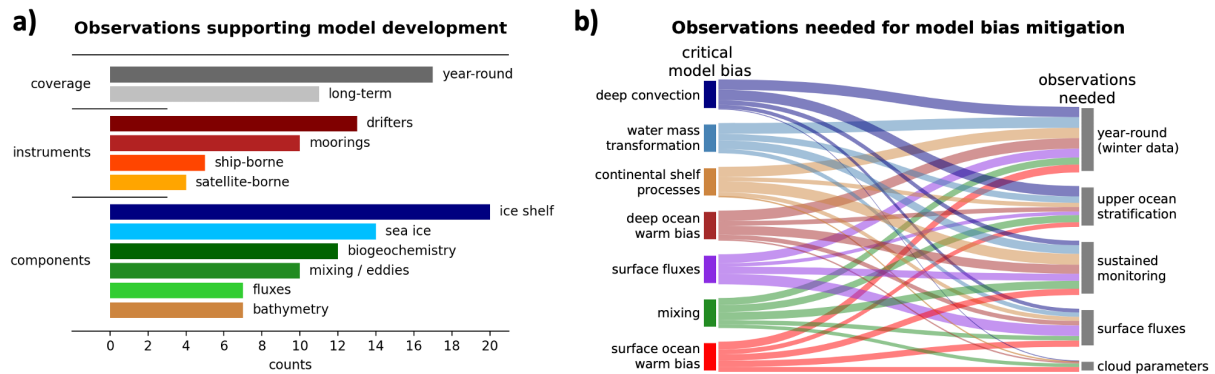
228 Before diving into a discussion on the observational needs of the modelling community, we
229 would like to call attention to the data sources actually used. There is an unbroken preference
230 by modellers to use gridded data products [28%], i.e. statistically interpolated fusions of
231 observations from various sources, and reanalysis or state estimates [21%], which are based
232 on a numerical model and incorporate observations through, e.g. assimilation techniques.
233 Likely also due to their extensive spatial coverage, satellite-borne remote sensing products
234 are favored as well [15%]. Data from ship-borne instruments, moorings, and floats appear to
235 be used less often directly [10-13%]. We acknowledge that observational data of all kinds, in
236 particular including in-situ data, feed into the gridded products. Nevertheless, it is important
237 to note that modelers tend to validate their simulations against these kind of “observations”,
238 which in fact are advanced data products and rather not viewed as actual observations by the
239 observing, sea-going science community. Further, any in-situ data that are not included in
240 such gridded products is likely less used or even overlooked by modelers and thus does not
241 contribute as much to the improvement of models.

242

243 Based on our personal experience, modelers tend to lean on derived products, such as
244 reanalyses and state estimates, because (1) observations are typically sparse and direct
245 comparisons require complex subsampling of model output, (2) formats and platforms used
246 to share observational data are still not unified and easily accessible to users despite ongoing
247 efforts, and (3) original measurements require advanced background knowledge and
248 interpretation for use in model validation. These issues can be mitigated by, for instance,
249 providing open-source validation packages along with the measurements and the
250 development of virtual instruments, i.e. tool boxes allowing for the subsampling of model
251 output in ways emulating specific observational instruments. Further, we suggest that
252 communication between the science communities should be strengthened. Additionally,
253 educational programs, such as summer schools, could introduce instruments, proper data
254 handling and aforementioned tool boxes to the next generation of modelers.

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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 were 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.

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For reducing observational gaps, especially with mitigating model biases in mind, modelers should be given and should take the opportunity to provide input to evolving observational programs early in the planning phase. In the end, this would ensure multiple use of the data collected. Figure 3a shows observations desired for bias mitigation with in-situ observations clearly dominating over remote sensing data. This preference can be interpreted as a need for better process understanding in which in-situ data are considered actual “ground truth” and often provide higher resolution in space and time, which is useful in several aspects, such as model validation, identifying of processes resolved at a given grid spacing, improving model parameterizations, etc. Another interpretation is that modellers are well aware of in-situ measurements being crucial for better quality gridded products. And while such products are preferred in the actual validation process, the dire need for more ground truth data in a changing climate is acknowledged and its collection valued.

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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 linked nearly equally to all major biases identified (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 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 is likely owed to the limited choice of pre-defined answers we provided and the behavioral bias of the respondents preferring to tick one of those rather than entering individual answers. Nevertheless, we take this as an opportunity to point out the need for improved fundamental understanding and acknowledgement of coupled mechanisms and feedbacks within and beyond the focus group. Having better records of magnitude and variability of Southern Ocean surface fluxes of both physical and chemical quantities will help significantly. Similarly, any observations in

299 support of heat and freshwater budgets, especially with a focus on ice-ocean interaction, will
300 be instrumental in advancing models and improving climate projections. And last but not
301 least, high-resolution bathymetry data of the Southern Ocean from the Antarctic Circumpolar
302 Current to the continental margin and into the ice shelf cavities are urgently needed.
303 Topography is a key ingredient for realistic simulations of the ocean circulation, specifically
304 the import of Warm Deep Water and the export of dense bottom waters, and therefore crucial
305 for reliable projections of ice shelf melting.

307 **4 Conclusions and Outlook**

308
309 In conclusion, surveys like this provide a valuable overview of the current status, plans, and
310 data needs not only for the Southern Ocean but also for the global modeling community.
311 There are also some experiences to take away from this exercise, in particular how the pool
312 of respondents shapes the usefulness of the survey, how to ask targeted questions without
313 being exclusive, how pre-defined multiple-choice answers simplify the analysis but reduce
314 the variety of responses, and which meta-information really is instrumental for interpreting
315 the responses. All of this is well known and demonstrates the importance to involve experts
316 on questionnaire design rather than constructing an ad hoc survey. Nevertheless, the feedback
317 by the community to our survey has been very positive indicating that such surveys can be a
318 valuable tool for future international program planning.

319
320 With the Antarctica InSync program in active planning and IPY5 approaching, we hope the
321 results presented—with additional data available (Martin et al., 2025)—will inform both the
322 scientific community and stakeholders to advance observations and models. The findings
323 already contributed to the *SOOS/OCEAN:ICE Workshop* discussions and conclusions.
324 Research priorities include ice–ocean interactions, Southern Ocean heat and carbon uptake,
325 and the recent major changes in sea ice. Addressing these challenges requires model
326 developments such as ice-shelf–ocean coupling, implementing biogeochemical processes,
327 and applying higher resolution grids, alongside improved understanding of continental shelf
328 processes and upper-ocean stratification. This, in turn, requires new observations in key
329 regions with ice shelves most vulnerable to warm water intrusions and ocean circulation
330 choke points. Further, the survey results call for stronger communication between the
331 modeling and observing communities and dedicated data-use training for modelers.
332 Antarctica InSync offers a major opportunity to advance such efforts.

335 **Appendix A**

336 Here we reproduce for convenience the survey introduction and questions along with the
337 response options. A screenshot of the original questionnaire website is available at
338 <https://doi.org/10.5281/zenodo.17289777>.

340 **Southern Ocean modelling: status, plans and needs**

341 In preparation of the *SOOS/OCEAN:ICE/Antarctica InSync workshop* on ice-ocean
342 observation harmonisation and future priorities agenda, which will be held in Copenhagen in
343 September this year and also serves for the planning of [Antarctica InSync](#) activities, we
344 kindly ask for your input.

345 All of the 12 questions below focus on the Southern Ocean region (south of ~50°S), physical
346 ocean processes are prioritised but immediate interaction with other system components can
347 be addressed (atmosphere, sea ice, ice shelves, biogeochemistry, ecosystem etc.), and the
348 applications we have in mind range from realistic regional models in the Southern Ocean to
349 CMIP-type global climate models (with or without further coupled components like ice
350 shelves or biogeochemistry).

351 **Please select from the multiple choice items or add an alternative item as "other".**
352 **This should not take more than 10 minutes.**

353 Note, the first three questions on expertise and scales may help to "set the stage" for the
354 answers of the other questions. If you work on very different scales, you may consider
355 answering the questionnaire twice for different cases. A link for another response is provided
356 after submitting the first one.

357 ***Please respond until September 15. (deadline extended)***

358 Thank you for your time and effort.

359 Torge Martin (OMDP), Carolina Dufour (SORP), Andrew Meijers (SOOS), Alyce Hancock
360 (SOOS)

361 *This questionnaire is supported by SOOS and CLIVAR panels SORP and OMDP. The*
362 *anonymous(!) data may be used by these panels for planning of further activities beyond the*
363 *above mentioned workshop.*

364 <https://www.soos.aq>, <https://www.clivar.org/clivar-panels/southern>,
365 <https://www.clivar.org/clivar-panels/omdp>

366

367 **1) What is your primary area of expertise?**

368 This is independent of a focus on physical, biological or other processes.

- 369 Ocean
370 Sea ice
371 Ice-shelf cavity
372 Ice sheet/ice shelf/icebergs
373 Atmosphere
374 Coupled climate modelling
375 Other: _____
376

377 **2) What spatial scales do you work on?**

- 378 Submesoscale (<10 km)
379 Mesoscale (10-100 km)
380 Basin-scale (>100 km)
381 Global impacts
382

383 **3) What temporal scales do you work on?**

- 384 Days to weeks
385 Months to seasons
386 Years to decades
387 Decades to centuries

388 ○ Beyond centuries

389

390 **4) What is in your view the singular key science topic in the SO?**

391 ○ Ocean dynamics (sub-/mesoscale eddies to large-scale circulation)

392 ○ Ice sheet/shelf–ocean interaction, fresh water

393 ○ Heat and/or carbon uptake and redistribution

394 ○ Sea-ice change and drivers/consequences thereof

395 ○ Air-sea exchange, incl. carbon/trace gasses

396 ○ Marine biogeochemistry and ecosystems

397 ○ Extreme events

398 ○ Other: _____

399

400 **5) What kind of observational data do you preferably use?**

401 *[multiple answers allowed]*

402 ○ Campaign based data (e.g. ship transects, gliders, ...)

403 ○ Stationary, year-round data (e.g. moorings)

404 ○ Varied spatial and temporal coverage (e.g. Argo-Floats)

405 ○ Gridded data products integrating various data sources

406 ○ Reanalysis/ocean state estimate products

407 ○ Remote sensing data (please specify below)

408 ○ Other: _____

409

410 **If you selected “Remote sensing data” above, please specify the variable and**
411 **product here:**

412 _____

413

414 **6) What is the most problematic ocean model bias?**

415 ○ Surface warm bias, too small sea ice extent

416 ○ Deep warm bias

417 ○ Mixing

418 ○ Seasonality of surface fluxes

419 ○ Air-sea CO₂ flux

420 ○ Water mass formation and characteristics (AABW, AAIW, ...)

421 ○ Open-ocean convection (polynyas)

422 ○ Shelf processes (e.g. slope current, ice shelf cavities, overflows, ...)

423 ○ Other: _____

424

425 **7) Which type of model did you have in mind when answering the last question**
426 **on biases?**

427 For example, list model complexity, grid resolution, application case, or anything
428 else.

429 _____

430

431 **8) Which observations could help understanding biases or further the process**
432 **understanding? [multiple answers allowed]**

433 ○ Winter data (year-round observations)

434 ○ Upper ocean stratification

435 ○ Surface fluxes

- 436 ○ Cloud observations
437 ○ Sustained monitoring
438 ○ Other: _____
439

440 **9) Where do mismatches exist between traditionally observed quantities and**
441 **model diagnostics (e.g. mixed layer depth)?**
442 _____
443

444 **10) What is the most pressing ocean model development?**

445 *[multiple answers allowed]*

- 446 ○ Implementation of ice shelf cavities
447 ○ Overflow parameterization, vertical coordinates
448 ○ Convection parameterization, vertical mixing
449 ○ Scale-aware parameterization, e.g. for eddies
450 ○ Biogeochemistry module
451 ○ Coupled ecosystem module
452 ○ Surface waves and/or tides
453 ○ Sea ice dynamics
454 ○ Other: _____
455

456 **11) Where will you or your collaborators evolve ocean models towards over the**
457 **next decade?**

458 *[multiple answers allowed]*

- 459 ○ Coupling more Earth system components (ice sheets, biogeochemistry, ...)
460 ○ Including more processes (tides, waves...)
461 ○ Novel parameterizations (submesoscale, scale-aware...)
462 ○ Higher resolution (horizontal and/or vertical)
463 ○ Unstructured grids, variable topography (wetting/drying, ice shelf cavity
464 shape)
465 ○ AI-based model components (parameterizations, emulators, ...)
466 ○ Other: _____
467

468 **12) Which kind of observations would further this development?**
469 _____
470

471
472 **Voluntary option:** provide your contact details for further discussion regarding Antarctica
473 InSync modeling activities: **name, affiliation, e-mail** (comma delimited please).
474 _____
475

476
477

478 **Data availability**

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

481

482 **Author Contributions**

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

486

487 **Competing Interests**

488 The authors declare to have no competing interests.

489

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513 **References**

- 514 Adusumilli, S., H. A. Fricker, B. Medley, L. Padman & M. R. Siegfried (2020). Interannual
515 variations in meltwater input to the Southern Ocean from Antarctic ice shelves. *Nat.*
516 *Geosci.* 13, 616–620, <https://doi.org/10.1038/s41561-020-0616-z>.
- 517 Beadling, R. L., Russell, J. L., Stouffer, R. J., Mazloff, M., Talley, L. D., Goodman, P. J.,
518 Sallée, J. B., Hewitt, H. T., Hyder, P., & Pandde, A. (2020). Representation of Southern
519 Ocean properties across coupled model intercomparison project generations: CMIP3 to
520 CMIP6. *J. Climate*, 33, 6555–6581, <https://doi.org/10.1175/JCLI-D-19-0970.1>.
- 521 Bell, R. E. & H. Seroussi (2020). History, mass loss, structure, and dynamic behavior of the
522 Antarctic Ice Sheet. *Science* 367, 1321–1325, <https://doi.org/10.1126/science.aaz5489>.
- 523 Bruciaferri, D., Guiavarc'h, C., Hewitt, H. T., Harle, J., Almansi, M., Mathiot, P., &
524 Colombo, P. (2024). Localized general vertical coordinates for quasi-Eulerian ocean
525 models: The Nordic overflows test-case. *Journal of Advances in Modeling Earth Systems*,
526 16, e2023MS003893, <https://doi.org/10.1029/2023MS003893>.

527 De Rydt, J., Jourdain, N. C., Nakayama, Y., van Caspel, M., Timmermann, R., Mathiot, P.,
528 Asay-Davis, X. S., Seroussi, H., Dutrieux, P., Galton-Fenzi, B., Holland, D., & Reese, R.
529 (2024). Experimental design for the Marine Ice Sheet–Ocean Model Intercomparison
530 Project – phase 2 (MISOMIP2), *Geosci. Model Dev.*, 17, 7105–7139,
531 <https://doi.org/10.5194/gmd-17-7105-2024>.

532 Frölicher, T. L., J. L. Sarmiento, D. J. Paynter, J. P. Dunne, J. P. Krasting, & M. Winton
533 (2015). Dominance of the Southern Ocean in Anthropogenic Carbon and Heat Uptake in
534 CMIP5 Models. *J. Climate*, 28, 862–886, <https://doi.org/10.1175/JCLI-D-14-00117.1>.

535 Gordon AL (1978). Deep Antarctic convection west of Maud rise. *J. Phys. Oceanogr.*,
536 8(4):600–612, [https://doi.org/10.1175/1520-0485\(1978\)008<0600:DACWOM>2.0.CO;2](https://doi.org/10.1175/1520-0485(1978)008<0600:DACWOM>2.0.CO;2)

537 Hallberg, R. (2013). Using a resolution function to regulate parameterizations of oceanic
538 mesoscale eddy effects, *Ocean Modelling*, 72, 92-103,
539 <https://doi.org/10.1016/j.ocemod.2013.08.007>.

540 Heuzé, C. (2021). Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models,
541 *Ocean Sci.*, 17, 59–90, <https://doi.org/10.5194/os-17-59-2021>.

542 Huguenin, M.F., Holmes, R.M. & England, M.H. (2022). Drivers and distribution of global
543 ocean heat uptake over the last half century. *Nat. Commun.*, 13, 4921,
544 <https://doi.org/10.1038/s41467-022-32540-5>

545 Hutchinson, K., Deshayes, J., Éthé, C., Rousset, C., de Lavergne, C., Vancoppenolle, M.,
546 Jourdain, N. C., & Mathiot, P. (2023). Improving Antarctic Bottom Water precursors in
547 NEMO for climate applications. *Geosci. Model Dev.*, 16, 3629–3650,
548 <https://doi.org/10.5194/gmd-16-3629-2023>.

549 Legg, S., B. Briegleb, Y. Chang, E. P. Chassignet, G. Danabasoglu et al. (2009). Improving
550 Oceanic Overflow Representation in Climate Models: The Gravity Current Entrainment
551 Climate Process Team. *Bull. Amer. Meteor. Soc.*, 90, 657–670,
552 <https://doi.org/10.1175/2008BAMS2667.1>.

553 Li, Z., S. Groeskamp, I. Cerovečki, and M. H. England (2022). The Origin and Fate of
554 Antarctic Intermediate Water in the Southern Ocean, *J. Phys. Oceanogr.*, 52, 2873–2890,
555 <https://doi.org/10.1175/JPO-D-21-0221.1>.

556 Martin, T., Dufour, C., Meijers, A., & Hancock, A. (2025). Southern Ocean modelling survey
557 (1.0) [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.17289777>.

558 Moreno-Chamarro, E., Caron, L.-P., Loosveldt Tomas, S., Vegas-Regidor, J., Gutjahr, O.,
559 Moine, M.-P., Putrasahan, D., Roberts, C. D., Roberts, M. J., Senan, R., Terray, L.,
560 Tourigny, E., & Vidale, P. L. (2022) Impact of increased resolution on long-standing biases
561 in HighResMIP-PRIMAVERA climate models, *Geosci. Model Dev.*, 15, 269–289,
562 <https://doi.org/10.5194/gmd-15-269-2022>.

563 Noble, T. L., Rohling, E. J., Aitken, A. R. A., Bostock, H. C., Chase, Z., Gomez, N., et al.
564 (2020). The Sensitivity of the Antarctic Ice Sheet to a Changing Climate: Past, Present, and
565 Future. *Reviews of Geophysics*, 58, e2019RG000663,
566 <https://doi.org/10.1029/2019RG000663>.

567 Rackow, T., S. Danilov, H. F. Goessling, H. H. Hellmer, D. V. Sein, T. Semmler, D.
568 Sidorenko & T. Jung (2022). Delayed Antarctic sea-ice decline in high-resolution climate
569 change simulations. *Nat Commun* 13, 637, <https://doi.org/10.1038/s41467-022-28259-y>.

570 Reintges, A., T. Martin, M. Latif, & W. Park (2017). Physical controls of Southern Ocean
571 deep-convection variability in CMIP5 models and the Kiel Climate Model, *Geophys. Res.*
572 *Let.*, 44, <https://doi.org/10.1002/2017GL074087>.

573 Silvano A, Purkey S, Gordon AL, Castagno P, Stewart AL, Rintoul SR, Foppert A, Gunn KL,
574 Herraiz-Borreguero L, Aoki S, Nakayama Y, Naveira Garabato AC, Spingys C, Akhoudas
575 CH, Sallée J-B, de Lavergne C, Abrahamsen EP, Meijers AJS, Meredith MP, Zhou S,
576 Tamura T, Yamazaki K, Ohshima KI, Falco P, Budillon G, Hattermann T, Janout MA,
577 Llanillo P, Bowen MM, Darelius E, Østerhus S, Nicholls KW, Stevens C, Fernandez D,
578 Cimoli L, Jacobs SS, Morrison AK, Hogg AM, Haumann FA, Mashayek A, Wang Z, Kerr
579 R, Williams GD and Lee WS (2023). Observing Antarctic Bottom Water in the Southern
580 Ocean. *Front. Mar. Sci.*, 10:1221701, <https://doi.org/10.3389/fmars.2023.1221701>.

581 Stouffer, R. J., V. Eyring, G. A. Meehl, S. Bony, C. Senior, B. Stevens, & K. E. Taylor
582 (2017). CMIP5 scientific gaps and recommendations for CMIP6. *Bull. Amer. Meteor. Soc.*,
583 98, 95–105, <https://doi.org/10.1175/BAMS-D-15-00013.1>.

584 Williams, R.G., Meijers, A.J.S., Roussenov, V.M. et al. (2024). Asymmetries in the Southern
585 Ocean contribution to global heat and carbon uptake. *Nat. Clim. Chang.* 14, 823–831,
586 <https://doi.org/10.1038/s41558-024-02066-3>.

587 Zhang, Q., Liu, B., Li, S., & Zhou, T. (2023). Understanding models' global sea surface
588 temperature bias in mean state: From CMIP5 to CMIP6. *Geophysical Research Letters*, 50,
589 e2022GL100888. <https://doi.org/10.1029/2022GL100888>.

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