BAMS
Meeting Summary

Determining the Freshwater Fluxes from Antarctica with Earth Observation Data, Models, and In Situ Measurements: Uncertainties, Knowledge Gaps, and Prospects for New Advances

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Workshop on Antarctic Ice Shelf Processes in Models and Earth Observation

What: The meeting brought together 25 scientists specializing in diverse fields related to Earth Observation (EO), in situ data, and numerical modeling to share their latest research findings on freshwater fluxes from Antarctica.

When: 23 and 24 May 2023

Where: Copenhagen, Denmark

Theme: The workshop identified relevant datasets and gaps in the current understanding of mass budget estimates and freshwater flux processes from the Antarctic ice sheet (AIS). Presentations included process studies and evaluation of atmosphere, ocean, and ice dynamical models. In addition, new approaches were presented using machine learning methods for assessing mass change, enhancing satellite remote sensing data, and developing blended hybrid datasets. Finally, we developed recommendations for future work.

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1. The importance of freshwater fluxes from the AIS

Freshwater fluxes from Antarctica are a key source of sea level rise accounting for ~10% of global mean sea level rise observed since 1993. The ESA/NASA Ice sheet Mass Budget Intercomparison Exercise (IMBIE) estimates that the ice sheet has on average experienced a net loss of ~109 Gt ± 56 Gt a^{-1} over the last 30 years (The IMBIE Team 2018) and models project an increase in contribution over the next century. Figure 1 illustrates the most important processes by which Antarctica gains and loses mass, as well as different techniques used to assess and quantify these processes. Freshwater is lost from Antarctica mostly by solid ice discharge over the grounding line followed by basal melting under floating ice shelves and by the calving of icebergs from the front of ice shelves or directly from ocean-terminating glaciers (primarily on the Antarctic Peninsula). A small amount of mass is also lost by surface meltwater runoff, and blowing snow sublimation and evaporation. The surface runoff component of mass loss is likely to become more important under climate warming. Antarctica gains mass from precipitation with estimates from regional climate models (RCMs), suggesting around 2000 Gt of precipitation falls on grounded ice in Antarctica each year (Mottram et al. 2021). In future, it is likely that increased snow accumulation will partly compensate for increased dynamical ice loss (Nicola et al. 2023).

Basal melting under ice shelves is an important source of freshwater at depth and contributes directly to Antarctic Bottom Water (ABW), an important component of global circulation. Icebergs transport freshwater far beyond the continent and slowly release that water to the ambient ocean.

2. Assessing AIS freshwater export from Earth observation data

Earth observation data are crucial for quantifying Antarctica's freshwater fluxes. Continent-wide measurements of grounding line discharge (Rignot 2023; Davison et al. 2023a), calving (Greene et al. 2022), and submarine melt fluxes (Paolo et al. 2023; Adusumilli et al. 2020) are now available at monthly to annual temporal resolution from at least the mid-1990s. They are not all produced operationally, but, e.g., routine grounding line discharge estimates are, since the launch of the Sentinel-1 constellation, feasible (Davison et al. 2023b, manuscript submitted to *Earth Syst. Sci. Data*), but dependent on the operation of a single satellite so are vulnerable to failure. New estimates of ice shelf basal melt rates are provided intermittently (Zinck et al. 2023) but require further research and development to account for changes in ice flux divergence, to resolve small ice shelves, and to account for partial flotation near the grounding line. Only one estimate of pan-Antarctic calving flux exists that has not assumed stationary calving fronts (Greene et al. 2022), largely due to the difficulty in delineating the calving fronts at scale. Several machine learning (ML) approaches (Baumhoer et al. 2023; Zhang et al. 2023) have been developed in recent years that provide promising progress toward

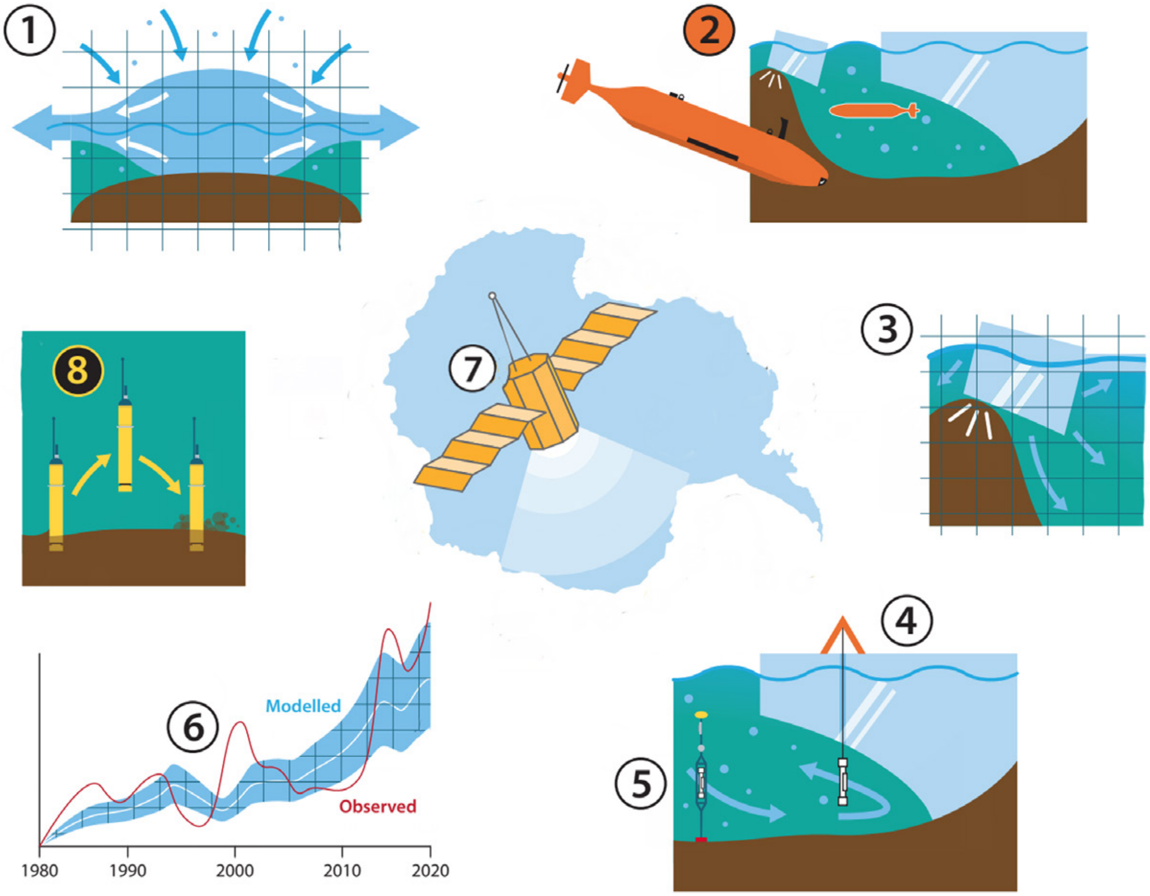

Fig. 1. **Overview of the topics of the workshop illustrating key challenges in Antarctic mass budget. 1) AIS budget is driven by incoming precipitation (blue arrows) that together with mass loss at the margins and under ice shelves drives ice flow (white arrows). 2) Mass loss from Antarctic ice shelves is driven by ocean processes, where in situ observations are scarce, but new autonomous vehicles are bringing new data. 3) Iceberg calving is a process that EO data have shown is increasingly important in the total mass budget but is still poorly modeled. 4) In situ observations (e.g., via ApRES) under ice shelves of melt, thinning, and 5) water properties adjacent to the ice shelf are crucial for testing both models and EO datasets. 6) Climate models have shown improved progress in resolving AIS climate processes, but, especially with coupled models, challenges remain. The development of ML approaches brings both models and data closer together. 7) EO data are a game-changer in the monitoring of AIS mass budget and in process understanding. 8) Monitoring the deep Southern Ocean via Argo floats and other instruments further afield is crucial to identify the far-field effects of the AIS.**

routine measurements of calving front position change. Despite this progress, assimilating measurements into ocean circulation models to quantify the impact of freshwater on the Southern Ocean is still rare (Swart et al. 2023) in spite of the assessed importance of these processes (Hellmer et al. 2012).

At present, surface meltwater runoff comprises a small, but poorly known proportion of Antarctica's overall freshwater fluxes (Bell et al. 2018). Meltwater volumes are difficult to assess from space, but robust methodologies have produced datasets of ponded water (Tuckett et al. 2022) and slush extent (Dell et al. 2022). Despite the significance of both for the melt-albedo feedback, neither are currently included explicitly in surface energy balance models, and Earth Observation (EO) estimates of meltwater production may be inaccurate (Husman et al. 2023) though still of value to the modeling community for evaluation (van Wessem et al. 2023).

Workshop participants identified some important biases in existing EO datasets, including that ice thickness datasets produce ice that is unrealistically thin (given observed velocities) in many places, probably due to lack of direct observations and as an artifact of inversion modeling. This bias has knock-on impacts for grounding line discharge calculations, which often provide discharge values that equate to net Antarctic ice sheet (AIS) mass gain using input–output methods [i.e., grounding line discharge is lower than the long-term mean surface mass balance (SMB)]. Some of the newest versions of RCMs presented have a higher SMB than older versions giving a wide uncertainty on input–output methods and illustrating the importance of close collaboration between modeling and EO communities to determine mass budget. Underestimates in basal topography also extend to estimates of ocean depth, with similar consequences for mass flux estimates, ice sheet modeling, and ocean forcing estimates on the ice shelves. Finally, there is uncertainty related to the firn air correction applied to convert elevation to ice thickness (Veldhuijsen et al. 2023).

Combining in situ observations with EO data is a critical calibration and validation check on EO datasets. A particularly striking example at the workshop compared basal melt from Autonomous Phase-Sensitive Radio Echo Sounder (ApRES) with EO-derived melt rates (Vaňková and Nicholls 2022). Ice shelf basal melt driven by oceanographic processes varies highly in the ApRES time series of direct observations, and while these rates also vary enormously spatially in the EO datasets, there are critical areas of disagreement where, e.g., satellite observations suggest refreezing in contradiction of in situ observations. However, the source of the disagreement is unclear as key assumptions relate to ice processes and ice flux divergence in the in situ observations and the use of firn air content corrections and modeled SMB in the EO data. All of which require further investigation. It is also possible that the contradictions between datasets relate to temporal and/or spatial averaging and the workshop identified as a key question the minimum averaging time scale that is required to get better agreement between the different types of observations. Concrete suggestions (see also conclusions below) include expanding and interpolating in situ data, rigorous assessment of modeled mass budget data, and improved evaluation of EO solutions.

Solid ice discharge from Antarctica is not confined to ice shelves. Observational data revealed seasonal trends in ice velocity on the Antarctic Peninsula (AP) with a 12.4% speed variability on average and an increase in calving activity in the summer (Wallis et al. 2023; Boxall et al. 2022). This seasonal trend may be important to account for, particularly on the AP. Peak speed at Cadman Glacier coincides with peak ocean heat and peak runoff, and the onset of acceleration coincides with melt onset but may also relate to calving activity. EO data are not conclusive in other factors that promote the seasonal velocity cycle. This part identified new processes that are not yet understood or are not incorporated into models. For example, following Larsen B collapse, fast ice formed in the Larsen B embayment and remained there for a decade, eventually reaching a thickness of order 10 m, until it broke up in February 2022. Subsequent but delayed acceleration of the glacier ice behind suggests that land-fast sea ice affects the dynamics of grounded glaciers (Ochwat et al. 2024), but the slow response (Sun et al. 2023) and lack of modeled speed up (Surawy-Stepney et al. 2024) suggest that sea ice did not provide buttressing in the same manner as an ice shelf. Instead, fast ice may have permitted glacier advance and ice tongue formation by resisting rotational forces at the terminus and delaying calving. The use of EO data to track mélange processes is an important avenue of future research to understand how future loss of ice shelves will change ice sheet dynamics (Mercer 1978). EO data have also identified a widespread increase in areas of crevassing (Colgan et al. 2016), termed "damage," across Antarctica (Surawy-Stepney et al. 2023; Izeboud and Lhermitte 2023). While not strictly a freshwater export, damage is a useful dataset for ice sheet modeling, indicating areas of weakness or changing ice dynamics where future mass loss rates may increase.

3. Modeling freshwater fluxes from Antarctica

The second part of the workshop covered modeling with global and RCMs, ice sheet models, and ocean models. The possibility to run models incorporating well understood climate processes contributed a number of important insights in understanding the AIS. Models largely agree (within ~20%) on accumulation for the present day, but unpublished data presented (C. Amory et al. 2024, unpublished material) indicated a wide divergence in projected future melt rates from RCMs. We conclude that while RCMs may be overly tuned to present-day conditions, there are also considerable uncertainties in important processes including cloud phase and snow and firn model initialization (Hansen et al. 2024). Surface meltwater runoff directly contributes to freshwater fluxes, and an increase in surface meltwater production may also increase an ice shelf's vulnerability to collapse through hydrofracturing (Banwell et al. 2023; van Wessem et al. 2023). Partial or complete ice shelf collapse, occurring in regions that actively buttress the flow of grounded ice, will result in an increase in freshwater export (Fürst et al. 2016). van Wessem et al. (2023) showed that melt area can expand rapidly in Antarctica because it occurs over flat ice shelves, but wet and mild ice shelves have different vulnerabilities to firn saturation and subsequent melt ponding, compared to cold and dry ice shelves. It remains an open question, how much runoff there is from Antarctica at the present day, and assessing melt volume, while challenging, remains a key priority for EO data.

The AIS is part of the global climate system, and insights presented from Orr et al. (2023) showed how large-scale circulation patterns including El Niño–Southern Oscillation (ENSO) and Southern Annular Mode (SAM) play an important role in modulating melt patterns over ice shelves. The magnitude and timing of polar climate change is determined by the equilibrium climate sensitivity (ECS) of the Earth system model (ESM) with consequent effects on SMB and other processes like ocean melting. As CMIP6 models show a wide range of ECS values, careful analysis prior to ESM selection for downscaling future projections is required. EO data can play an important role in the evaluation of global climate models for selection for downscaling. Williams et al. (2023), for example, used sea ice area as a key metric. It is challenging to reproduce realistic ice sheet model configurations with fully coupled ESMs, as biases in the driving ESM impede a direct coupling, implying an unrealistic representation of key climate processes in Antarctica. Numerous studies (Heuzé 2021; Beadling et al. 2020; Meijers 2014) have noted significant biases in the Southern Ocean in ESMs including warm biases in SST and circumpolar deep water, sea ice extent and thickness, shelf properties, and dense water formation. Freshwater fluxes are presently not well defined in CMIP6 (Eyring et al. 2016) as no models within the Diagnostic, Evaluation and Characterization of Klima (DECK) experiments include two-way coupled ice sheets. Instead, ice sheet freshwater fluxes are generally set to equal net precipitation flux over Antarctica and incorporate simplistic runoff distribution schemes. While some modeling groups are now implementing coupled models, or exploring the impact of more realistic ice sheet melt (Swart et al. 2023), there are still only a handful of ESMs that incorporate fully coupled ice sheets (Siahaan et al. 2022), and realistic ice sheet configurations will need flux corrections (Manabe and Stouffer 1988; Sausen et al. 1988). Furthermore, ice sheet models lack or use simplified process descriptions that may be important for ice sheet dynamics (e.g., calving). EO data can help to constrain and validate coupled models and provide boundary conditions for ice sheet model inversions, but in situ ocean observations were also noted as a particularly problematic gap. Baseline observations, particularly in winter and under sea ice and shelves, are needed to provide observational constraints and dynamical understanding for model improvements in the representation of the Southern Ocean.

4. Developments in machine learning applied to Antarctic ice

The final part of the workshop was devoted to new developments in ML to assist automated data analysis of EO datasets and to develop modeling tools and parameterizations. The vast potential of ML models to extend data analysis and climate modeling will likely lead to much future collaboration between communities. As one presenter commented, “The deep learning part is very easy, it’s all about the training data.” The EO community are uniquely positioned to supply this training data, and the numerical modeling groups represented have also explored the approach, for example, to develop ocean melt parameterizations (Burgard et al. 2022; Rosier et al. 2023). Strong feedbacks between melt rate and geometry of ice shelf cavities cannot be captured by simple basal melt parameterizations in models. Comparably small neural networks perform well emulating basal melt rates in a cross-validation framework and in adapting to evolving geometries; however, neural networks struggle in simulating future changes in a warmer climate, so blended approaches using both physically based numerical models and neural networks offer promise. A similar approach for surface mass balance emulation at a high resolution based on global and RCMs (van der Meer et al. 2023) similarly shows promise for developing large ensembles of SMB but also fails when external driving conditions change. Deep learning emulators are therefore complementary to complex physical models. Accuracy assessment is key, but the gain in speed and in being able to access many more simulations will greatly assist in climate change impact assessment. The diverging futures in modeled SMB over Antarctic ice shelves are, for example, a potential target for future investigation to use these techniques.

The development of blended EO and model data products is already well advanced, and a striking example is the use of “super-resolution” to fill in a surface melt product using input from a high-resolution modeled area applied to a lower-resolution model (Husman et al. 2023). In Hu et al. (2022), a pure image superresolution approach was contrasted with an advanced physics-informed approach combining albedo and elevation blended with RCM output. Other presented applications have, e.g., used the Reference Elevation Model of Antarctica (REMA) digital elevation model to derive basal mass budget at 50-m resolution (Davison et al. 2023b, manuscript submitted to *Earth Syst. Sci. Data*). Resolving the conflict between model estimates and EO data will also help develop physical parameterization schemes as firn layer properties and saturation of the firn layers are highly model dependent (Hansen et al. 2022).

5. Bringing together EO and climate models

Assessing freshwater fluxes from the AIS requires a combined observational and modeling approach. Remote sensing is pivotal to quantify grounded and floating ice thickness, to assess solid ice flux over the grounding line, ice shelf basal melt, and surface melt occurrence, and to evaluate numerical models. However, current remote sensing techniques fall short when it comes to quantifying surface melt rate, firn versus ice thickness change, and mass change of floating ice and for producing future projections. We note that model and data products can together create enhanced datasets though with the proviso that both data and models include biases and uncertainties and both need to be improved with better process understanding. In situ observations are therefore key. Biases and missing data in key basic datasets such as basal topography and ice shelf extent also have implications for estimates of ice sheet mass budget as well as models and observations because their deficiencies are propagated through both EO datasets and climate models. Particularly egregious are the uncertainties on grounding lines that are difficult to measure and difficult to model. Developing definitive datasets would be advantageous for modelers and mass budget estimates. Based on the workshop discussions, we make the following recommendations for future work on the AIS.

1) Reducing the clear mismatch between satellite observations, in situ data from ApRES, and climate models when it comes to basal melt processes under Antarctic ice shelves is crucial. Work is needed to explore assumptions in EO-derived basal melt as well as interpretation of ApRES data and will ideally combine modeling, observational data, and ocean melt expertise.

2) A comprehensive dataset of calving fronts with an operationalized update (as in Davison et al. 2023a,b, manuscript submitted to *Earth Syst. Sci. Data,*; Greene et al. 2022) is a priority to assess ongoing changes in Antarctica and to potentially act as an early warning system for ice sheet instability. We note that, for example, expanding the IceLines dataset (Baumhoer et al. 2023) to all ice shelves or the annual calving front datasets from Andreasen et al. (2023) would allow this to be a "quick-win."
3) Earth observation datasets from different researchers, including melt, calving front location, and ice thickness, can have widely diverging estimates in key areas like Thwaites Glacier. Systematic comparisons between datasets to reduce the estimated spread should cover at least maps of damage, surface melt, basal melt, and basal mass budget. Community standards integrating these into standardized shapefiles or masks will help evaluate physical models.
4) Good data management practice means that data should be Findable, Accessible, Interoperable, and Reproducible (FAIR) and licensed using open science criteria. We also urge scientists to publish using DOIs in data journals where datasets can be updated and published in a more polished format later if necessary. Linking via data integrators [e.g., European Marine Observation and Data Network (EMODnet) and Southern Ocean Observation System (SOOS)] and sharing sample scripts to process and re-project datasets are useful for reproducibility and can easily be published on open platforms such as Zenodo.
5) For models, choices around model initialization, physiographic datasets, and driving fields can give very different results and procedures need to be made clear for all types of models via specific protocols under, e.g., CMIP. Updated EO datasets can also improve physiographic fields and provide standardized model evaluation data.
6) The development of ML tools can boost both EO and model products. Current generation data products will help produce many scientific insights in the near term.
7) Basic in situ observations are lacking over most of the AIS and surrounding ocean, especially in some important and fast-changing parts of Antarctica. Coordination [e.g., via Scientific Committee on Antarctic Research (SCAR)/SOOS and the WCRP Climate and Cryosphere (CliC)/WMO] can help build up the necessary long-term observational data. Building on up-and-coming programs to reduce logistics costs will be crucial as is the need for technological development to improve under ice observations.

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Data availability statement. OCEAN:ICE is committed to FAIR data, and a brief report of the workshop and lightly edited copies of all presentations at the workshop are available in the Zenodo open-access repository under the OCEAN:ICE community page at https://zenodo.org/communities/oceanice.

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