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Data initiatives for ocean-driven melt of Antarctic ice shelves

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Abstract

Ocean-driven melt of Antarctic ice shelves is an important control on mass loss from the ice sheet, but is complex to study due to significant variability in melt rates both spatially and temporally. Here we assess the strengths and weakness of satellite and field-based observations as tools for testing models of ice-shelf melt. We discuss how the complementary use of field, satellite and model data can be a powerful but underutilised tool for studying melt processes. Finally, we identify some community initiatives working to collate and publish coordinated melt rate datasets, which can be used in future for validating satellite-derived maps of melt and evaluating processes in numerical simulations.

1. Ocean-driven melt of Antarctic ice shelves

Ocean-driven melt of the floating ice shelves around Antarctica is a primary mechanism of mass loss from the ice sheet, and a key component in understanding the continent's future (Rignot and others, 2013; Adusumilli and others, 2020). Accurately predicting the magnitude and spatial pattern of ice-shelf melt rates is vital to accurately project the ice sheet's contribution to global sea level over the coming centuries (Dinniman and others, 2016), as melt of floating ice shelves affects their ability to buttress grounded ice upstream.

Due to the diverse properties of water masses entering ice-shelf cavities around Antarctica, rates of ocean-driven melt differ considerably between ice shelves, and can be highly variable within an ice-shelf cavity. The melting point of ice is pressure dependent, meaning that melt rates are often highest near the grounding line of an ice shelf, where the ice-ocean interface is at its deepest, and this is also where melt rate changes have the strongest effect on overall ice sheet dynamics (Reese and others, 2018). Melt rates can also be higher then the shelf-average near the calving front, as solar warming increases the temperature of surface water, which is then drawn underneath the shelf front (Stewart and others, 2019). Ice-shelf melt rates are highest where warm Circumpolar Deep Water (CDW) is able to cross the continental shelf and reach the ice-shelf cavity (e.g. Davis and others, 2018; Shean and others, 2019). However, the majority of ice-shelf cavities are dominated by water masses formed from cold shelf waters, leading to low melt rates and in some areas freezing of seawater to the ice-shelf base (Dinniman and others, 2016; Thompson and others, 2018).

Ocean-driven melt of ice shelves can also be highly variable temporally, with timescales and magnitudes of variability differing between and within ice shelves. Understanding the timescales over which melt rates vary is important to properly distinguish long-term climate trends from short-term variability (e.g. Paolo and others, 2015). Melt rates can vary over hours to weeks due to tidal currents and changes in ocean heat, salt and current speeds caused by waves and eddies (e.g. Vaňková and others, 2020a; Davis and others, 2018). Seasonally, changes in sea ice coverage, solar flux and wind stress can drive changes in the dominant water masses entering ice-shelf cavities, causing variations in melt rate (e.g. Lindbäck and others, 2019). On longer timescales, interannual melt rate variability can often be linked to well-known climate oscillations such as the Indian Ocean Dipole, the Southern Annular Mode or El Niño-Southern Oscillation (Dutrieux and others, 2014). The relative importance of each of these processes is expected to vary significantly across different ice shelves.

Three broad strategies have been used to study ocean-driven melt of ice shelves: in-situ observations of melt from field studies; melt rates derived from satellite observations; and simulated melt rates from numerical ice-shelf/ocean models. While models allow us to understand ice-shelf melt rate sensitivity, connections with other parts of the climate system, and to make future projections, observational studies are key to understand current ice sheet mass balance and present day variability, providing data to evaluate and constrain numerical models. In this paper we examine the strengths and weaknesses of current techniques for observing ice-shelf melt, make the case for the complimentary use of field, satellite and model data as a powerful tool for studying melt processes, and present some ongoing community initiatives designed to make available coordinated melt rate datasets to improve our ability to integrate data across different approaches.

2. Techniques for observing ice-shelf melt

2.1. Satellite method

To map the spatial distribution of ice-shelf melt using satellite data, studies use repeat observations of surface elevation, which are converted into a change in thickness by assuming that the ice shelf is freely floating (in hydrostatic equilibrium). This method can be applied using repeat Digital Elevation Models (DEMs) derived from stereo satellite imagery or SAR interferometry (e.g. Shean and others, 2019; Bevan and others, 2021). This method can measure change in surface elevation at high spatial resolution (tens of metres) but is expensive to apply over large areas. Basal melt has more commonly been measured using surface elevation observations derived from satellite altimetry missions such as ERS-1, ERS-2, Envisat and Cryosat (e.g. Rignot and others, 2013; Adusumilli and others, 2020). Repeat-track satellite altimetry can produce circum-Antarctic maps of surface elevation change, although the spatial resolution is limited by the distance between tracks.

The conversion from surface elevation change to basal melt rate is not straightforward, and requires multiple supporting data sources. The observed surface elevation change is first corrected for change in ocean surface height from tides and varying atmospheric pressure, and then the basal melt rate can be calculated using a continuity equation of the form:

$$\frac{dh}{dt} = \frac{(\rho_w - \rho_i)}{\rho_w}\left(\frac{M_s}{\rho_i} - \nabla \cdot (H_i \mathbf{v}) - w_b\right) + \frac{dh_{air}}{dt}, \qquad (1)$$

where h is the ice-shelf surface height relative to the height of the ocean surface, ρ_w and ρ_i are the densities of seawater and ice, M_s is the surface mass balance (typically derived from climate reanalysis), and w_b is the basal melt rate. $\nabla \cdot (H_i \mathbf{v})$ combines terms for ice-shelf divergence ($H_i \nabla \cdot \mathbf{v}$) and advection of ice ($\mathbf{v} \cdot \nabla H_i$), and is calculated from the velocity at the ice surface ($\mathbf{v}$) and the effective ice thickness (H_i), which is adjusted for the firn air content (h_{air}, derived from firn densification modelling). If surface elevation measurements are densely-spaced, a Lagrangian reference frame can be used, allowing the advection term to be dropped (Moholdt and others, 2014). Where the Lagrangian method cannot be applied, the along-flow advection of features such as rifts tends to create artefacts in the data (Rignot and others, 2013; Moholdt and others, 2014). Other processes such as salinity changes in ice-shelf cavities and spatial rearrangement of ocean currents can also affect ice-shelf surface elevation, but are likely a lower order influence and are not sufficiently well-known to be corrected for.

The biggest advantage of the satellite method is its wide spatial coverage, with datasets covering all Antarctic ice shelves (e.g. Rignot and others, 2013; Adusumilli and others, 2020). It can be used to identify key spatial patterns of ice-shelf melt, such as the elevated melt rates near grounding zones and calving fronts of large, cold cavity ice shelves (e.g. Fig. 1a). Where high-resolution DEMs are used, melt can be mapped on even smaller spatial scales. For example, Shean and others (2019) used this method to identify differences in melt between the troughs and keels of basal channels on Pine Island Glacier. However, uncertainties in the derived melt rate can be significant because many of the data sources needed to convert surface elevation change to basal melt are poorly constrained. The method also relies on the assumption that the shelf is in hydrostatic equilibrium. This condition is typically broken around basal channels, crevasses and near the grounding line (Fricker and Padman, 2006), which is also a region of particular interest as it often experiences the highest melt rates.

Using multiple repeat passes of a satellite can also allow a timeseries of melt rates to be developed. Recent studies have used four European Space Agency radar altimeter satellite missions (ERS-1, ERS-2, Envisat and Cryosat) to build a quarterly timeseries of elevation change on Antarctic ice shelves from 1994–2018 (Paolo and others, 2015; Adusumilli and others, 2020). The results have demonstrated a relationship between ice-shelf height anomalies in the Amundsen Sea sector and the El Niño-Southern Oscillation which causes variability in both ocean and atmosphere in the region (Paolo and others, 2018). However, converting timeseries of surface elevation change into timeseries of basal melt is challenging. The method requires multiple measurements of ice velocity, which often do not cover the necessary time period (Adusumilli and others, 2020), and corrections for snowfall and firn compaction derived from climate reanalysis data have high uncertainties. This creates an ongoing need for validation of satellite-derived melt timeseries.

2.2. Field methods

Ice-shelf melt rates can be measured more directly using field-based techniques, including range finding from under-ice

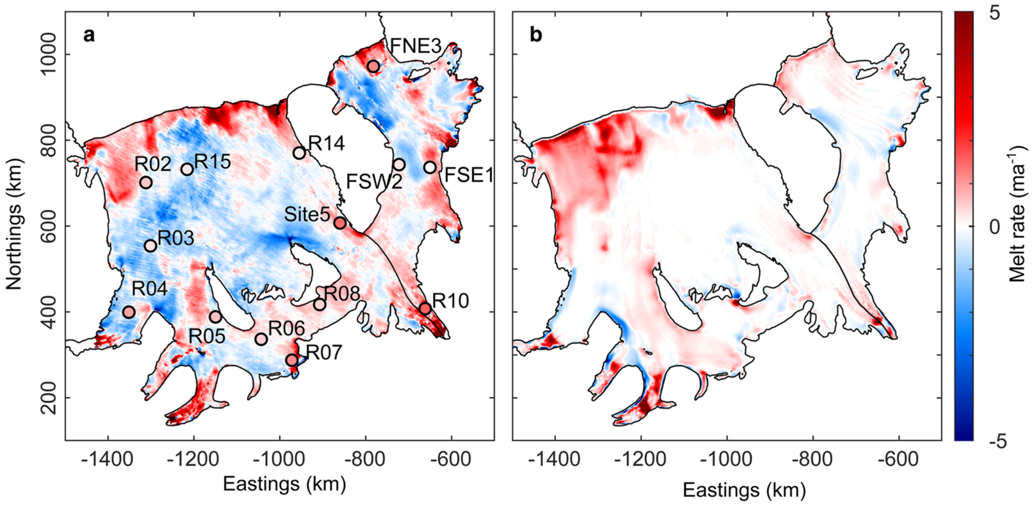

Fig. 1. Melt rates on Filchner-Ronne Ice Shelf, from (a) satellite data (Adusumilli and others, 2020) with point measurements from ApRES (Vaňková and Nicholls, 2022) and (b) the Whole Antarctic Ocean Model (WAOM v1.0, Richter and others, 2022). The model captures elevated melt rates at the grounding line and calving front, but may underestimate the extent of refreezing in the centre of the ice shelf as it does not contain frazil dynamics known to be important during freezing (Galton-Fenzi and others, 2012). However, in situ measurements suggest that the satellite method overestimates refreezing on the western side of the shelf.

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moorings (e.g. Stewart and others, 2019; Rosevear and others, 2022a) and surface radar instruments (e.g. Jenkins and others, 2006; Vaňková and Nicholls, 2022; Zeising and others, 2022). In this paper we focus on a single instrument/method: the Autonomous phase-sensitive Radio Echo Sounder (ApRES, Nicholls and others, 2015), which is becoming the most common way of measuring melt in situ due to its low cost and ease of deployment. The ApRES is designed to run autonomously in the field for a period of one or more years. It recurrently emits a burst of chirps, typically every few hours, each of which is used to produce a record of amplitude and phase versus depth. Combining these records together into a timeseries, we can track internal layers and use their change in phase over time to determine their motion relative to the radar unit. By tracking the motion of internal layers in the ice as well as the base of the ice shelf, the method allows us to measure snow/firn compaction and internal thickness change. These can then be removed from the total thickness change of the ice shelf to produce a measurement of ocean-driven melt without relying on additional supporting datasets. The timeseries produced has up to millimetre-scale precision, depending on the strength of the signal and the nature of the ice base.

Possibly the greatest strength of the ApRES method is its ability to measure changes in melt rate over a variety of timescales from hourly to interannual. Given ideal conditions, the method can measure variability in melt on timescales as short as the M2 (12.4 hour) tidal component (Vaňková and others, 2020a). A further advantage is that by measuring both total and internal thickness change components independently, the method can be applied in areas such as the grounding zone where the hydrostatic assumption used in satellite methods breaks down. However, the instrument performs best when located in an area with a low rate of vertical shear in ice velocity and a smooth, flat ice base. Uncertainties can become large if the instrument is placed in an area of complex basal topography, where off-nadir signals complicate interpretation of the basal reflector (e.g. Vaňková and others, 2021a). Uncertainties can also increase if the vertical strain profile is non-linear, particularly if this non-linearity is time-dependent such as under tidal flexure (e.g. Jenkins and others, 2006; Vaňková and others, 2020a). Unlike range-finding methods, the ApRES is only able to accurately measure rates of melt and not refreezing. In areas with a thick layer of basal marine ice, increased absorption of radar wave energy may make the basal reflector difficult to detect. Where refreezing is intermittent, changes in impedance contrast at the ice base during periods of freezing cause a phase shift which interferes with the measurement of thickness change. Despite this, intermittent freezing periods can be identified and mean freezing rate inferred using amplitude and phase change measurements and their variation as a function of ApRES frequency (Vaňková and others, 2021b).

As a field-based instrument, the cost of field logistics limits the spatial sampling that can be achieved with ApRES. Similarly, the need for maintenance visits to keep an instrument running for more than one to two years has limited the length of the timeseries collected, with the longest installation to date being only a few years compared to the 25-year satellite record of melt rates achieved by Adusumilli and others (2020). However, where data are available they are a powerful tool for validating satellite-derived measurements of melt, and for testing numerical simulations of melt over a range of timescales.

3. Integrating observations and simulations

Each of the observational methods described has the potential to enhance understanding of the ocean conditions around Antarctica and how they affect ice sheet flow via ice-shelf melt rates. The utility of each method can be enhanced by integrating data from different sources, particularly when combined with output from ice-shelf cavity-resolving ocean models that allow the melt rates to be put into context of ocean drivers.

3.1. Utilising spatial patterns of melt

The extensive spatial coverage of melt rates measured using satellite data makes them a useful tool for evaluating models of ice-shelf melt. Observed spatial patterns of melt can be informative in assessing an ocean model's ability to simulate realistic water mass properties and circulation beneath ice shelves (e.g. Fig. 1,2). Examples of this include a spatial comparison between simulated and observed melt rates by Pelletier and others (2022), which used low simulated melt rates in the Bellingshausen and Amundsen Seas to infer issues with the applied ice-shelf geometry, while Comeau and others (2022) used spatial patterns of melt to assess model success in accurately predicting intrusions of CDW onto the continental shelf. The spatial patterns of melt observed on a shelf can also indicate important processes that should be included in ice-shelf cavity models. For example, Nakayama and others (2021a) showed that including subglacial discharge in an ice-shelf cavity model of Pine Island Glacier is important for capturing high melt rates observed near the grounding line. Ice shelf melt rates are only one tool for testing model performance, and other observations such as ship-based and seal-tagged CTD measurements, moorings and satellite sea-ice concentration estimates are critical tools for testing ocean model performance more broadly. These oceanographic observations have been the basis for recent efforts in data assimilation to optimise ocean model performance (e.g. Nakayama and others, 2021c), which in future could potentially also include ice shelf melt as a parameter.

Satellite-derived maps of ice-shelf melt can also be a powerful tool for effectively targeting field campaigns toward particular melt processes, or for avoiding locations where the equipment might fail, such as areas with basal marine ice, which quickly attenuates ApRES signal at depth. Conversely, field deployments can be used to validate and potentially improve spatial maps of melt. In situ measurements would be particularly valuable for validation where different satellite estimates diverge, or where uncertainties in the satellite method are high. Particular targets include regions where the hydrostatic assumption of the satellite method breaks down (principally around the grounding line and above

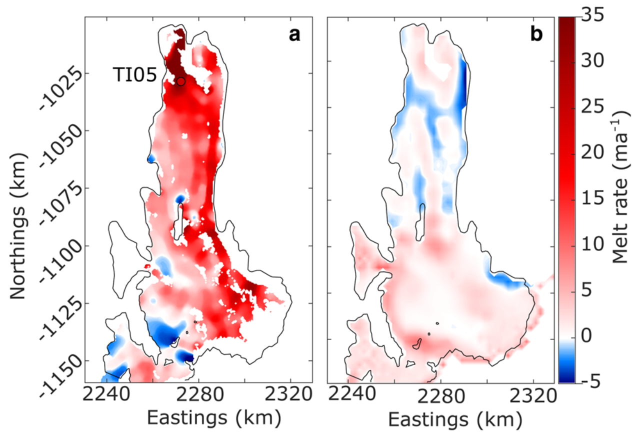

Fig. 2. Melt rates on Totten Glacier Ice Shelf, from (a) satellite data (Adusumilli and others, 2020) and ApRES (Vaňková and others, 2021a) and (b) the Whole Antarctic Ocean Model (WAOM v1.0, Richter and others, 2022). The model does not capture elevated melt rates on Totten Glacier Ice Shelf, most likely because of underestimation of CDW crossing the continental shelf, noting that WAOM was not specifically 'tuned' for any one region, unlike focussed regional modelling studies which show better agreement (e.g. Gwyther and others, 2014, 2018).

basal channels), or where the input datasets required for the satellite method have high uncertainties or biases, for example due to known issues in modelling surface mass balance on ice shelves surrounded by complex and steep topography (Lenaerts and others, 2016).

The use of field measurements for validating satellite melt products has been very limited to date, leaving satellite datasets largely untested. A recent study on Filchner-Ronne Ice Shelf found that the satellite method overestimated refreezing rates on the west of the shelf, indicating that uncertainties in the satellite data were under-reported (Fig. 1a, Vaňková and Nicholls (2022)). Another study on the same shelf using a non-autonomous (repeat visit) application of ApRES found that agreement between in situ and satellite-derived melt rates could be improved by careful selection of the velocity dataset used to derive vertical strain rates in the satellite method (Zeising and others, 2022). This illustrates how field data could be used in the future to improve satellite melt rate data, by guiding the selection of input datasets.

3.2. Utilising temporal variability in melt

Measuring the change in ice-shelf melt over time as well as its spatial variability can allow us to assess the importance of time-dependent processes such as seasonal changes in ocean properties, climate forcing variability and intermittent transport of CDW into ice-shelf cavities. ApRES measurements of ice-shelf melt are particularly useful for this type of analysis, due to their high temporal resolution. Deployments of ApRES on Pine Island Glacier (Davis and others, 2018), Nivlisen Ice Shelf (Lindbäck and others, 2019) and Roi Baudouin Ice Shelf (Sun and others, 2019) have been instrumental in identifying timescales and causes of melt variability, including diurnal, weekly and seasonal melt rate drivers. As with satellite data, field-based measurements of melt can be a useful tool for evaluating ice-shelf ocean cavity models (e.g. Bull and others, 2021). For example, the ApRES deployment on Pine Island Glacier has been used to test a high-resolution ocean cavity model, confirming that the model reproduced the observed 7–10 day fluctuations in melt rate successfully (Nakayama and others, 2019). However, there still remains further potential for using field observations to evaluate model behaviour over subannual timescales.

Satellite-derived timeseries of ice-shelf melt also have potential for studying interannual variations in melt rate (e.g. Adusumilli and others, 2018, 2020). Nakayama and others (2021b) compared modelled and satellite-derived melt rates for Totten Glacier, finding a strong agreement in interannual variability caused by intrusions of warm modified CDW into the ice shelf cavity. However, the high uncertainties in satellite-derived melt rates mean that the observed variability can be unreliable, particularly in regions of low melt or refreezing. A recent study comparing satellite-derived timeseries of melt with data from field observations on Filchner-Ronne Ice Shelf found poor agreement in both the phase and magnitude of temporal variability, with the satellite method significantly overestimating variability on both seasonal and interannual timescales (Fig. 3, Vaňková and Nicholls (2022)). While further testing and development of the satellite-derived timeseries is clearly required, the longer melt record provided by satellite instrumentation (up to 25 years at present) has the potential to provide important context for evaluating the importance of short-term variability relative to long-term trends.

4. Community data initiatives

Both the observed temporal variability in melt rates and the interplay between different techniques are currently under-utilised in studying ice-shelf melt, at least in part because of the challenges of finding high-quality data in an accessible format. Of the three data types, satellite-derived observations of melt are the most readily available, particularly the open access dataset produced by Adusumilli and others (2020). While field data are often published, they rarely share the same data portal or format, while model outputs are rarely made open access because of their large data volume. The FAIR data principle (that data should be findable, accessible, interoperable and reusable) could significantly benefit the community studying ice sheet-ocean interactions. While much work remains to be done, community initiatives are making progress on some of these issues.

The NECKLACE project is an international effort to collate ice-shelf melt rates measured by ApRES into a combined data product suitable for validation and evaluation of satellite-derived melt rates and numerical ocean models (https://necklaceproject.com). Beyond the collation and quality-control of existing data, the project team works to promote the collection of new field data by providing assistance with equipment procurement, set-up and data processing. By providing a standardised data format and single point of access, the project aims to make field data easier to find and use. The improved accessibility of ice-shelf melt data has obvious benefits to end users, but also benefits the originator by increasing citation rates and impact. Developments in data assimilation capability in ice-shelf/ocean models will also drive a need for open data access.

Information on existing NECKLACE ApRES deployments is available through SOOSmap (http://www.soomap.aq), a tool for sharing Southern Ocean observational data facilitated by the Southern Ocean Observing System (SOOS, Newman and others, 2019). Production of the first melt rate dataset is underway,

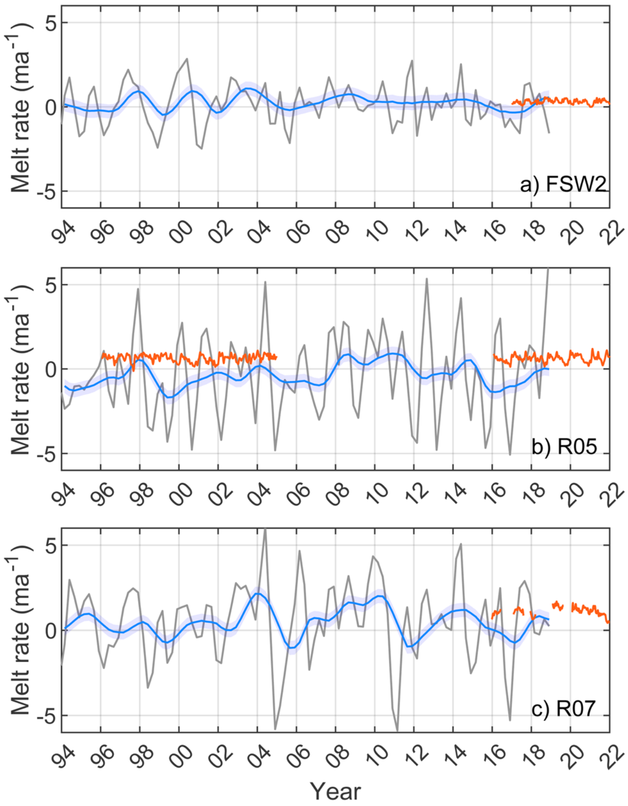

Fig. 3. Melt rate timeseries from three of the named sites on Filchner-Ronne Ice Shelf (see Fig 1 for locations). In situ data (red) are from a sub-ice shelf mooring pre-2015 and ApRES post-2015; satellite data shown quarterly (grey) and 1-year low-pass filtered (blue, shading shows reported uncertainty of 0.4 ma^{-1}). The satellite method generally overpredicts variability in melt in these locations.

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which will initially provide monthly-averaged melt rates, with the aim to increase this to daily measurements as processing techniques continue to develop. An important component of the project is to ensure that raw ApRES data are also made open access, so that improvements in data processing over the coming years can be retroactively applied to existing datasets to update the collated data product. Ultimately the project aims to create a circum-Antarctic dataset of high-resolution melt timeseries, covering locations with a wide range of melt processes. A further goal is to publish supporting data processing software, as an open-access, version-controlled resource for future ApRES deployments.

The WCRP-supported Realistic Ice-sheet/ocean State Estimates (RISE) project is a complementary initiative targeted at evaluating circum-Antarctic numerical ice-shelf/ocean models. RISE builds from earlier intercomparison projects such as ISOMIP+ which used semi-idealised domains (Asay-Davis and others, 2016; Gwyther and others, 2020). Instead, RISE draws on realistic, whole-Antarctic applications, with an emphasis on open participation without a prescribed experimental design. Model analysis will initially focus on collating and comparing simulated ice-shelf melt rates from a range of numerical ocean models, to understand how choices such as different surface forcing, melt parameterisations and model-specific numerics and discretisation affect simulated melt rates. In parallel, an ongoing regional model evaluation will be undertaken by the MISOMIP2 intercomparison project, which will focus on the Amundsen and Weddell Seas to complement internationally-coordinated field activities.

RISE further aims to coordinate an evaluation of model results against observations, including melt rates from both satellite data and ApRES, and to make available synthesis datasets which can be used for designing field programmes. Model output can help to target field deployments efficiently, by identifying likely timescales of variability which can inform sampling strategies, and highlighting areas where model results deviate from each other, allowing field campaigns to be designed to maximise utility to the modelling community. Model outputs are often not made openly available, but sharing at least some model output in data formats familiar to remote sensing and field scientists would significantly benefit the community. This should be a point of consideration in future model intercomparison initiatives.

While each of the data sharing initiatives described here will improve the utilisation and co-function of existing datasets, observations of ice-shelf melt alone are only one tool for improving understanding of ice-shelf ocean interactions. To accurately project melt rates into the future, ocean cavity models must capture ocean dynamics and water mass properties around the continent and their changes over time. Observations of a wide range of ocean state variables are important as a tool for testing ocean model behaviour (e.g. Mazloff and others, 2010) and developments in data assimilation provide a means of using observational data to improve model performance (Nakayama and others, 2021c). As observations of ice shelf melt improve, they can become one tool in this process of model optimisation.

Similarly, models of ocean-driven melt rely on parameterisation of fine-scale processes at the ice-ocean boundary. Co-deployment of field instruments for measuring basal melt with sub-ice shelf moorings measuring ocean temperatures and currents would allow more in-depth testing of basal melt parameterisations. These type of co-measurements are currently limited in number (Jenkins and others, 2010; Rosevear and others, 2022b), and data collected from a broader range of melt environments would have the potential to significantly advance the field. By taking care to understand how field measurements can best support other data users, the impact of field studies can be greatly enhanced, driving developments in the field.

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