Ice-Ocean Melt: Future Research Directions

Report on the first JCIOI workshop on ice-ocean interactions (17-19th October 2022)

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1. Introduction

The latest IPCC report estimates that mass loss from the Antarctic and Greenland Ice Sheets is likely to raise global mean sea level by up to 25 cm by the end of this century under scenarios of unmitigated climate change (Fox-Kemper, 2022). Moreover, high-end projections of up to 15 m over the coming 2000 years cannot be ruled out, largely due to uncertainty in processes that could invoke rapid ice loss from the Antarctic Ice Sheet.

A key driving force behind Antarctica's mass loss is ocean melt beneath the ice shelves (Fig. 1), which causes thinning, grounding line retreat, and the acceleration of grounded ice into the oceans (Colleoni et al., 2018; Khazendar et al., 2016). A similar mechanism operates at Greenland's marine-terminating glaciers (Fig. 2), where ocean melt is thought to have driven between one third and one half of Greenland's current ice mass loss (Enderlin et al., 2014; Benn et al., 2017). This ocean-driven melting is governed by boundary layer physics (Holland & Jenkins, 1999) – transport of heat and salt on centimeter scales – that are themselves determined by the wider ocean circulation that varies on scales of meters to hundreds of kilometers (Holland et al., 2020). Understanding these processes, and hence reducing uncertainties in projections of future ocean-driven ice mass loss, will be achieved through advances in observational technologies and numerical modeling that can cover the vast temporal and spatial scales over which ice-ocean interactions occur.

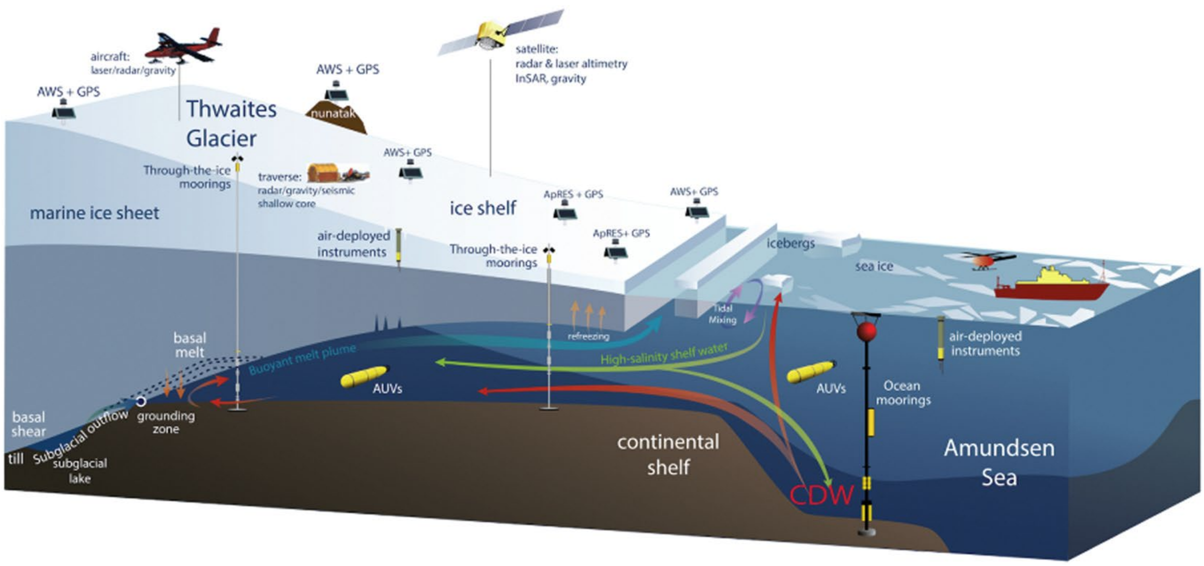

Figure 1: Schematic of Thwaites Glacier, Antarctica, showing key ice-ocean processes and techniques to measure them. From Scambos et al. (2017).

The Joint Commission on Ice-Ocean Interactions (JCIOI) was formed in 2021 as an IUGG joint working group between the International Association of Cryospheric Sciences (IACS) and the International Association for the Physical Sciences of the Oceans (IAPSO). JCIOI held its first workshop in October 2022, aiming to: (1) identify critical knowledge gaps surrounding processes that govern ocean-driven melt of ice sheets across a range of spatio-temporal scales; (2) identify options to address these knowledge gaps through observing, parameterizing, and modeling ice-ocean interactions, and their impacts on ice mass loss and ocean dynamics; and (3) bring together the community interested in ice-ocean interactions. The workshop was held online in five x 2-hour sessions taking place over a week. The first four sessions focused on a specific theme within ice-ocean interactions, and each of these sessions was structured with 2 x half-hour solicited talks followed by 1 hour of discussion in break-out rooms. The 8 solicited speakers were invited on the basis of their expertise in the given research area. The last session focused on linkages and community initiatives with a number of shorter talks. All sessions were well-supported with over 280 registered participants from 26 countries across 6 continents and across career stages.

This Report provides a synopsis of the workshop activities. We first summarize the solicited talks in each of the four themed sessions, describing the current state of knowledge of (i) the physics of the ice-ocean boundary, (ii) the role of glacial melt in the wider ocean, (iii) the impact of ocean-driven melt on glacier and ice sheet mass balance, and (iv) new and emerging technologies for studying ice-ocean interactions. On the basis of these talks, and from the discussion sessions which followed, we then discuss community-defined key future research directions in ice-ocean interactions research. As part of this discussion, we highlight the need for an internationally-coordinated approach to tackle this complex problem.

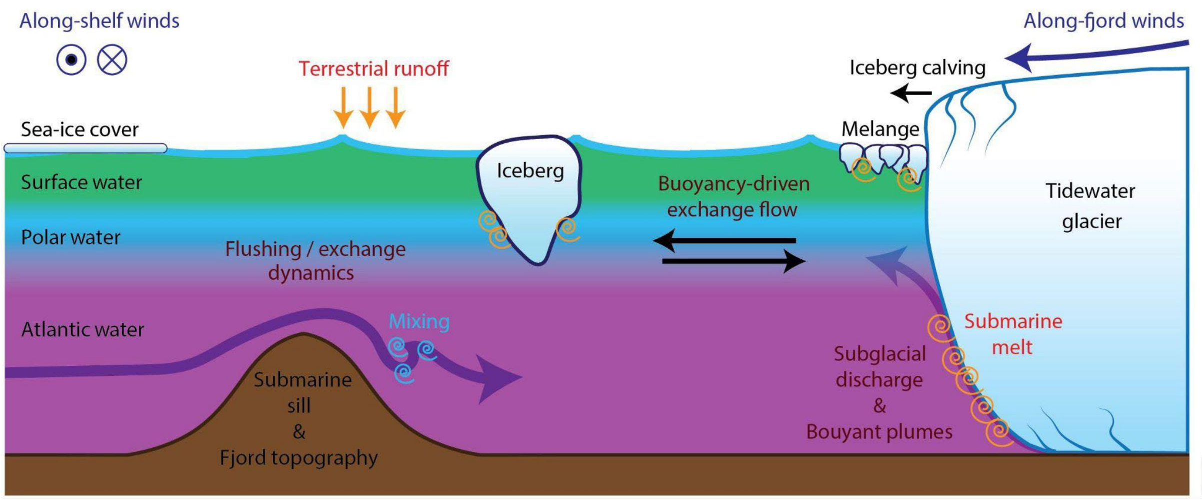

Figure 2: Schematic of a Greenland glacier/fjord system showing key ice-ocean processes. From Straneo et al. (2019).

2. The Physics of the ice-ocean boundary

2.1 Zooming in on the ice-shelf ocean boundary (solicited speaker: Madelaine Rosevear)

The relationship between local, sub-ice shelf conditions and basal melting is determined by small-scale processes within the ice shelf-ocean boundary layer (ISOBL) – a turbulent layer that regulates the transport of heat and salt to the ice and sets the basal melt rate. Existing ice-ocean parameterizations assume that the ISOBL is “shear-driven” (i.e. generated by friction between the stationary ice and moving ocean), and express the melt rate as a function of the thermal driving and the local current speed (Holland & Jenkins, 1999; Jenkins et al., 2010). However, recent laboratory and numerical studies have examined other “buoyancy-driven” regimes, in which basal melting and boundary layer dynamics are dominated by convection (Kerr & McConnochie, 2015; Gayen et al., 2016) or double-diffusive convection (Middleton et al., 2021; Rosevear et al., 2021), raising questions about the accuracy and ubiquity of existing parameterizations (e.g. see summary in Malyarenko et al., 2020). Additionally, recent studies show that meltwater tends to suppress turbulence beneath horizontal ice shelves, making heat transport in the ISOBL less efficient (Vreugdenhil & Taylor, 2019) and insulating the ice from warm water below (Rosevear et al., 2022). Both these factors decrease melting, and are not currently included in parameterizations.

Overall, observations of the sub-ice shelf ocean are sparse. However, the data that we do have show a wide range of ocean conditions beneath ice shelves, and suggest that both shear- and buoyancy-driven melting regimes are relevant. Some in-situ observations of melting and ocean observations from cold, tidally-dominated cavities indicate that shear-driven melting is occurring (Jenkins et al., 2010; Davis & Nicholls, 2019). However, at warmer, more quiescent conditions, observed melting is significantly overestimated by shear-dependent parameterizations and is instead better explained by convective (Malyarenko et al., 2020; Rosevear et al., 2022) or double-diffusive convective (Kimura et al., 2015; Middleton et al., 2022) processes.

Despite significant recent progress, many gaps remain in our understanding of how to best parameterize basal melting. Some relate to the ISOBL physics, such as the effects of basal roughness and critical thresholds for moving between buoyancy and shear-dominated melting regimes, while others relate to the sub-ice shelf environment, including the shape, slope and roughness of the ice base, as well as the ocean conditions. Further sub-shelf observations are desperately needed and should target boundary layer processes by measuring ocean conditions including turbulence close to the ice base.

2.2 Zooming out from the ice-shelf ocean boundary (Adrian Jenkins)

Melting at the base of an ice shelf generates relatively cold, light waters that flow along the ice-ocean interface because of their buoyancy and the large-scale slope of the ice shelf (Jenkins, 2016). The resulting current can grow in thickness as the freshening caused by melting diffuses away from the interface. Once the thickness of the current exceeds that of the Ekman layer (the layer in which there is force balance between the Coriolis, pressure gradient, and turbulent drag forces), the current itself determines the far-field properties that drive heat, freshwater and momentum exchange across the planetary boundary layer (Jenkins, 2021). The melt rate then depends on heat transfer across the pycnocline that separates the boundary current from the waters below and heat transport by the current itself. The latter two processes, along with the heat transfer across the turbulent boundary layer (discussed in section 2.1), set the overall distribution of melting and freezing at the ice shelf base. Basal freezing, which is widespread beneath the larger ice shelves, is a clear indicator of the importance of heat advection within the boundary current. Mixing across the pycnocline supplies heat to the boundary current and is the process that delays or prevents freezing as the boundary current flows towards regions of shallower ice draft.

Little is known about the roles of either heat advection within the boundary current or the turbulent heat flux across the pycnocline at its base, largely because of a lack of observations. The boundary currents are analogous to the katabatic winds that form over the ice sheet and understanding of those flows has been built on a rich dataset of coincident temperature and wind profiles (Jenkins, 2016). Just as synoptic weather conditions add a background pressure gradient forcing that influences the katabatic winds, so the deviation of the ice shelf from its level of free flotation creates a background flow that adds to the buoyancy driven flow of the boundary current. Obtaining observations of current profiles along with the density and surface elevation distributions that force them would enable a major step forward in understanding ice-ocean boundary processes.

3. The role of glacial melt in the wider ocean

3.1 Submarine melting at tidewater glaciers: linking observations with theory (Rebecca Jackson)

Tidewater glacier-fjord systems are common across the Arctic, in Greenland and in West Antarctica. Their termini are grounded and relatively vertical. Freshwater fluxes from glaciers arise from iceberg calving, submarine melt, and subglacial discharge (Straneo & Heimbach, 2013). Observations of submarine melt are limited due to the difficulty in acquiring measurements (Motyka et al., 2003; Rignot et al., 2010; Inall et al., 2014). The approaches currently used to observe submarine melt therefore have high associated uncertainties and few succeed in providing information of how melt is changing over time (Motyka et al., 2013; Sutherland et al., 2019; Jackson et al., 2022). Therefore, understanding the process of submarine melting relies heavily on developing theories and testing them in models (Jenkins, 2011; Xu et al., 2013; Magorrian & Wells, 2016; Catania et al., 2020).

The most common framework for describing submarine melt combines buoyant plume theory and the three-equation formulation for melting (e.g. Jenkins, 2011). The resulting “plume-melt theory” has been used to model melt in many ways over the past decade (Carroll et al., 2017; Oliver et al., 2020; Slater et al., 2022), and in regions where it is applicable (i.e. within plumes), it has provided significant theoretical gains in how melt is related to properties such as ocean temperature, grounding line depth and seasonality. However, the ability of plume-melt theory to capture melt over the wider calving front remains uncertain. In particular, some observational evidence suggests that plume-melt theory underestimates the magnitude of calving front-averaged melt at tidewater glacier fronts (Sutherland et al., 2019; Jackson et al., 2022).

Additionally, some aspects of plume-melt theory require further testing with observations. For example, the properties, structure, and geometry of the plume are generally poorly constrained (Mankoff et al., 2016; Fried et al., 2015; Everett et al., 2021). Furthermore, uncertainty surrounds whether upwelling plumes are the dominant source of velocity adjacent to the ice (Slater et al., 2018; Jackson et al., 2019). Therefore, there is a need for new observing platforms and approaches to further test and constrain plume-melt theory as a model for submarine melting.

3.2 Ice shelves in ocean models (Nicolas Jourdain)

After three decades of ocean modeling under the Antarctic ice shelves, are the models good enough to provide melt rates to ice sheet models and to represent freshwater fluxes in climate models? A representation of the largest ice shelf cavities at relatively coarse resolution (~1°) in a circumpolar ocean model is sufficient to simulate the formation of Ice Shelf Water in the Ross and Weddell Seas (Beckmann et al., 1999). However, ice shelf basal melt rates near the grounding lines require much higher resolution, and even 1-2 km resolution may not be sufficient. This is a concern for driving ice sheet simulations, which are much more sensitive to melt rates in these areas than anywhere else (Walker et al., 2008; Goldberg et al., 2018). Furthermore, ice shelf-ocean model intercomparison (early ISOMIP+) results show a high diversity of melt patterns across ocean models even with very constrained model parameters. More work is needed to parameterize melt rates where it matters for ice sheet models, that is, in the region near the grounding zone.

Another concern is the temporal variability in melt rates. Some models are tuned to reach a realistic mean state but have a variability that is much weaker than observed (Siahaan et al., 2022). In contrast, some parameter choices can lead to spurious tipping points without any climate perturbation (Hellmer et al., 2017). Hence, it remains difficult to have high confidence in the models' ability to represent the future evolution of ice shelf melt rates.

Melt rate biases in ocean models that resolve ice shelf cavities can have wide consequences, including impacts on coastal circulation, sea ice thickness, and the stratification of the Southern Ocean (e.g. Jourdain et al., 2017; Mathiot et al., 2017; Roach et al., 2018). Making advances in melt rate parameterizations, and the conditions under which they apply, will significantly improve our capacity to model ice-ocean interactions accurately.

4. The impact of ocean-driven melt on glacier and ice sheet mass balance

4.1 Research directions for large-scale modeling of ice-ocean interactions (Carolyn Begeman)

Uncoupled ice and ocean models have been used extensively by the modeling community to capture climate variability and change in evolving ice and ocean simulations. In addition to the resolution problem described above, uncoupled models do not capture the feedbacks between the ocean and the ice sheet that result in ice shelf geometry changes (Naughten et al., 2021). This has motivated the recent use of coupled ice-ocean models (Seroussi et al., 2017; Gladstone et al., 2021; Favier et al., 2019), in which higher resolution ocean properties are fed into the melt rate parameterization to better simulate melt rate distributions and geometry feedbacks.

Nevertheless, coupled models come with their own set of challenges. For example, coupled ocean models inherit geometry changes from the ice sheet model, but inconsistencies may arise in mass conservation as new water columns are created and are assigned extrapolated ocean properties. Furthermore, we currently have difficulty resolving which shelf regions are dominated by warm circumpolar deep water and which are dominated by colder denser water (Morrison et al., 2020). Responding to this challenge might involve focusing on higher resolution modeling in critical regions and improving mesoscale mixing parameterizations. A further challenge is the representation of iceberg calving in these coupled models, highlighting the need to improve understanding of calving physics (Benn & Åström, 2018).

Overcoming these challenges associated with coupled models could facilitate research focused on accurately reproducing large-scale relationships between ocean thermal forcing, melt rates and grounding line changes.

4.2 What current models can and cannot tell us about ice-ocean interactions (Dan Goldberg)

The timescales over which the ocean drives ice sheet melt can vary significantly from the natural response timescales of the ice sheet (Robel et al., 2018), which might be relatively short (decades) or very long (centuries to millennia). Due to the significant computational cost of running high resolution ocean models on these longer timescales, ice sheet modelers seek physically motivated parameterizations of varying complexity to describe the behavior at the boundary layer. Coupled ice-ocean models use fully developed ice sheet dynamics with a three-dimensional ocean model to describe how ocean cavities evolve over time (Favier et al., 2019). However, due to the higher resolution of ocean properties and inclusion of geometry, coupling issues can arise where errors in the ice sheet model are amplified by the ocean model (Hanna et al., 2020; Goldberg & Holland, 2022). One tool that can help inform coupled ice-ocean models is observational data such as satellite altimetry which allows us to calibrate certain properties that are difficult or impossible to directly observe, and understand variable dependencies in model equations.

Often ocean models inaccurately represent melt rates near the grounding line (Berger et al., 2017; Dutrieux et al., 2013). The consequence of this is that models will fail to accurately predict the behavior of the grounding line over time if melt rates there are poorly simulated. A deeper understanding of physical processes at the grounding line and of the coupled interactions between the ice sheet and ocean is needed, which will ultimately improve the capacity of ice-ocean models to accurately predict rapid ice loss in real systems.

5. New and emerging technologies for studying ice-ocean interactions

5.1 Observing and understanding variability in sub-ice-shelf circulation and basal melting (Irena Vaňková)

The key observable for quantifying ice-ocean interactions beneath ice shelves is the basal melt rate. There has been recent progress on two main fronts. The increasing amount of satellite data and advancements in processing techniques have resulted in a continuous improvement in pan-Antarctic satellite-derived melt rate estimates, including efforts to detect temporal melt rate variability (Rignot et al., 2013; Adusumilli et al., 2020). In parallel, the development of an autonomous, ground-based phase-sensitive radar (Nicholls et al., 2015) has led to the ability to measure millimeter-scale temporal changes in basal melting (Stewart, 2018; Vaňková et al, 2020).

The increasing volume and diversity of remote sensing and in situ data provide much needed opportunities for validating melt rate estimates, and bridging melt processes across a range of spatial and temporal scales (Cook et al., 2023). Complementary in-situ data can add confidence to melt rate estimates, especially if they help draw a consistent picture based on physical understanding of the ice-ocean system. For example, co-located seismic measurements of sub-ice shelf water column thickness can provide constraints on ocean circulation, and therefore on the spatial pattern of basal melting (Smith et al., 2020). Time series of ocean temperatures and velocities from moored instruments have proven to be extremely valuable for interpreting measured temporal variability of melt rates (Davis et al., 2023). Furthermore, for some ice shelves, differences in spatial melt patterns between satellite and ground-based estimates have been reconciled by identifying the most accurate remotely-sensed ice-velocity field products (Zeising et al., 2022).

At the same time, there are some important discrepancies that still need to be reconciled. For example, for ice shelves with low melt rates, satellite-derived estimates can overestimate melt rate variability by an order of magnitude, posing a problem for the utility of these data for forcing ice-sheet models and validating sub-ice shelf cavity ocean models (Vaňková et al., 2022). This highlights the need for new and continued long-term ground-based monitoring of melt rates for key shelves, an effort that would greatly benefit from coordination of the ice-ocean community.

5.2 The hunt for the secrets below the ice (Anna Wåhlin)

There are large areas under Antarctic ice shelves that have so far been unexplored and unmapped. Detailed maps of bathymetry and ocean properties are crucial to understanding the complex ice-ocean interactions occurring in these areas. To better observe these regions, a diverse range of sensory techniques must be employed to map bathymetry, ice thickness and structure, hydrology in and out of cavities, and ice-ocean variability.

Techniques currently in use include gliders and shipborne sensors, which provide information on hydrography and full-depth currents, as well as airborne surveys, which give ice thickness data and ocean turbulence patterns in front of ice shelves (e.g., Wåhlin et al., 2020). Ocean properties such as temperature, salinity, dissolved oxygen, and pH can also be measured by newly developed semi-autonomous underwater instruments. Seals tagged with instrumentation can help monitor ocean properties within the range of their dives (McMahon et al., 2021). One advantage of this form of observation is that it can provide data through the entire winter. Large projects that deploy robotic vehicles through holes drilled through the ice shelf also provide crucial information at key regions such as grounding zones that have previously been difficult to access (Schmidt et al., 2023). However, these projects require significant time and resources.

The technology required to gather more observations beneath ice shelves has already been developed. The greatest challenge now is overcoming the difficulty associated with getting suitable technologies out into the field. Cruises need to facilitate observational equipment and coordinate operations for more observational data to be collected.

6. Summary and future directions

Several broad themes emerge from the sections above, including the need for:

1. Observational data to establish and constrain boundary layer melt rate equations and the physics of ice-ocean interactions, particularly at the grounding line and calving front;
2. Development, comparison and testing of coupled and uncoupled models at all scales, including through reconciling model outputs with theory and observations;
3. Sensitivity studies to understand the implications of model simplifications and resulting uncertainties;
4. Long-term monitoring to establish the mean state and variability in ice sheet and ocean properties;
5. Development of methods to reconcile data streams that cross a broad range of temporal and spatial scales;
6. Coordinated international collaboration to deploy technologies into the field, particularly in regions difficult to access.

These are broad challenges, too large to be tackled by an individual or single research group. Ongoing research initiatives are already making progress in leveraging international support to advance some of these issues:

- International collaboration on field logistics is enabling projects of large scale, allowing deeper understanding of physical processes by thoroughly observing a single geographical location (e.g., the International Thwaites Glacier Collaboration ITGC).
- Several data initiatives are working to improve accessibility and interoperability of datasets. For example, SCAR's Antarctic RINGS Action Group aims to coordinate collection of new data to produce an improved bathymetry and topography in critical locations around the Antarctic grounding line. NECKLACE is working to collate existing data and support further field measurements of basal melt to be used for testing of satellite data and for assimilation into models.
- Model intercomparison projects aim to test parameterization schemes and improve understanding of uncertainties in model projections, including MISOMIP2, ISMIP, and RISE.

JCIOI seeks to add value to existing initiatives, by enhancing connections between researchers, and working with the community to build new interactions. A key step in this process is the development of a framework for an ice-ocean observing system (FIOOS) – similar to the Greenland Ice Sheet-Ocean Observing System (Straneo et al., 2019) – which should identify the highest priority research advances needed in the field, and make suggestions to address the knowledge gaps through observing, parameterizing, and modeling ice-ocean interactions. As an initial step, in the appendix we propose some key research questions that need to be advanced to progress understanding in the field.

Appendix A: Priority Research Questions

Summarising the key research questions from each session

- How widely applicable are current parameterizations used to calculate melt, and what is the resulting uncertainty in large-scale melt volumes?
- How can we translate improvements in understanding of small-scale physics of the ISOBL to large-scale models?
- What is the role of subglacial discharge in driving melt at the ice-ocean boundary?
- How can we coordinate internationally to gather the critical data needed to advance the field, including bathymetry, basal melt rates, and sub-ice shelf ocean conditions?
- How can we create the long-term data records needed to distinguish short-term from long-term variability?
- How can we effectively integrate observational data into models to improve performance?
- How can early-career scientists be better enabled to innovate in field science, given the difficulty in accessing logistics?
- What research developments should be prioritized in the short term to provide more realistic sea level projections on the timescales needed by stakeholders for planning and mitigation?

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