Ocean Cryosphere Exchanges in Antarctica:

Impacts on Climate and the Earth System

IACS/IAPSO/OCEAN:ICE joint session at IUGG OCEAN:ICE interactions – Ice sheet impacts on ocean circulation and climate feedbacks JP03/JP04 Breakout Discussion Session

Milestone MS26

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Table of contents

Means of verification of the achievement of the milestone

As part of the International Union of Geodesy and Geophysics (IUGG) conference, the OCEAN:ICE team has organised a breakout session on 14 July 2023 from 08:30-10:00 am (CEST) on the following topic: OCEAN:ICE interactions – Ice sheet impacts on ocean circulation and climate feedbacks JP03/JP04 Breakout Discussion Session. The partner in charge of the delivery of the milestone is UKRI-BAS (PP13) together with DMI (PP1).

Work Performed

Building on the IUGG programme, the panel debate was co-ordinated in collaboration with the following the IACS/IAPSO/IASPEI inter-association symposia sessions:

- JP03 "Physical and Biogeochemical Ocean and Ice Processes in the Southern Ocean: Observations, State Estimation and Modelling" and
- JP04 "Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling"

These sessions represented a cross cutting examination of the Southern Ocean's interaction with the Antarctic Ice Sheet and associated processes.

A breakout session under the title **OCEAN:ICE interactions – Ice sheet impacts on ocean circulation and climate feedbacks JP03/JP04 Breakout Discussion Session** was organised by partner UKRI-BAS.

This was hosted and moderated by the convenors of these sessions, with the support of the OCEAN:ICE Horizon Europe project. The discussion session took place on Friday 14 July 2023, from 08:30-10:00 am; on the day between the two sessions JP03 and JP04, overlapping as little as possible with other relevant sessions. It followed the format of short scene-setting talks with a moderated panel and plenary discussion, arranged around the main themes emerging from the two sessions.

Additionally, the session was held as a hybrid meeting, with outside participation from people not attending IUGG welcome and encouraged.

Discussion themes and panellists included:

• Antarctic coastal circulation and heat/freshwater transport – Dr Wilma Huneke (Australian National University)

• Ice sheet-ocean processes: Prof. Sophie Nowicki (University of Buffalo)

• Modelling ice sheet ocean interaction: Dr Hélène Seroussi (Dartmouth College)

• The carbonate system response to Southern Ocean and ice sheet changes: Prof. Ric Williams (University of Liverpool)

• Large scale ocean-ice sheet interaction and climate impacts: Dr Ariaan Purich (Monash University)

Convenors: Dr Andrew Meijers (British Antarctic Survey), Dr Felicity McCormack (Monash University), Dr Ruth Mottram (Danish Meteorological Institute), Dr Adele Morrison (Australian National University), Dr Yoshihiro Nakayama (Hokkaido University), Prof. Tony Payne (University of Bristol), Prof. Joellen Russell (University of Arizona).

The discussion revolved around the following issues:

1) **Why the Southern Ocean matters in the global climate system?**
2) **What are the implications of Southern Ocean changes on ice sheet melt rates and potential instability?**
3) **What is the role of the Southern Ocean in the carbon cycle?**

4) What are the challenges for our community?

Where are we headed to?

•Are we able to make projections?

•Which processes need to be further considered?

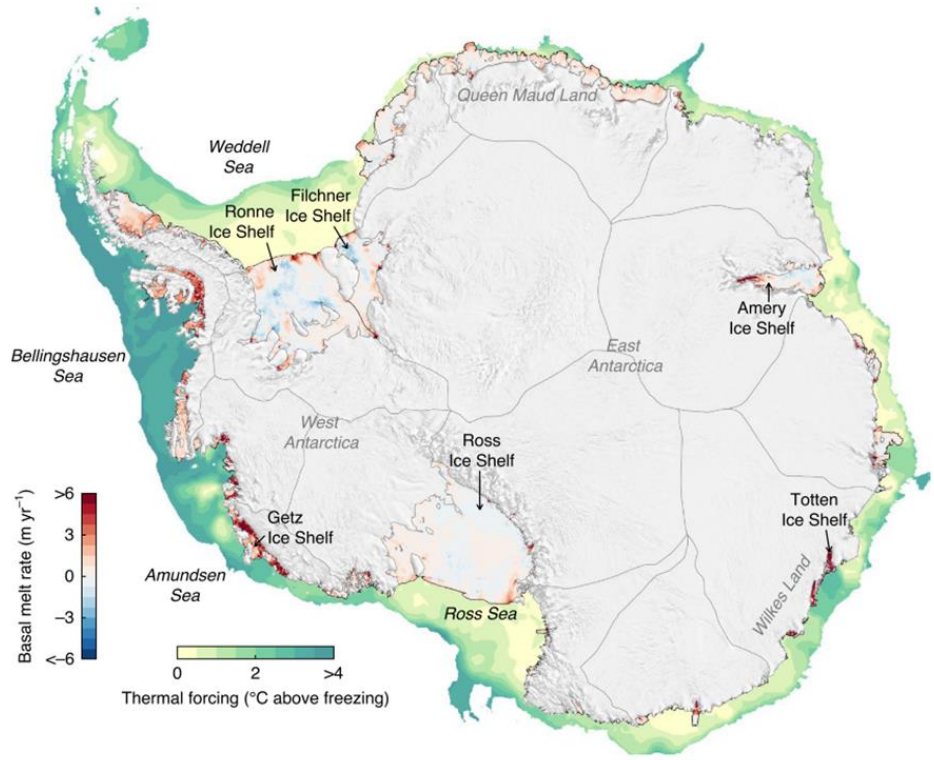

Fig.1: Antarctic coastal circulation and heat transport, Adusumilli et al. 2020.

Below we summarise the discussions and panel input in response to these questions.

Uncertainties in the Antarctic margin processes

As the ice sheets melt, they are and will continue to release freshwater into the Southern Ocean. A huge amount of focus is on sea level, but in this panel, we shift the focus to discuss how this release of freshwater will affect the rest of the climate system as well and how we can best understand this scientifically.

As a simple overview we have the Southern Ocean with cool and freshwater on the surface and warm and salty water below. Adding extra freshwater increases the stratification of the ocean reducing how much of this warm surface water comes to the surface, leading to a cooling at the surface but warming underneath. If we think of this across different scales, around the Antarctic, margins as shown in the schematic below, at first sight this subsurface warming caused by the melt water has the potential to lead to positive feedback, with ocean warming melting the ice shelves, but there is also the melt water coming in from the melting ice sheet causing more subsurface warming and changes in the ocean circulation, so there may also be changes in the currents that are reducing the transport of warm water and it is therefore possible to have negative feedbacks. These are the uncertainties in the Antarctic margin processes, and high-resolution models are required to capture them. We saw in the

JPO3 session that this meltwater can therefore change the deep ocean circulation, which affects the global circulation too. Talks in that session also showed observational evidence back this up.

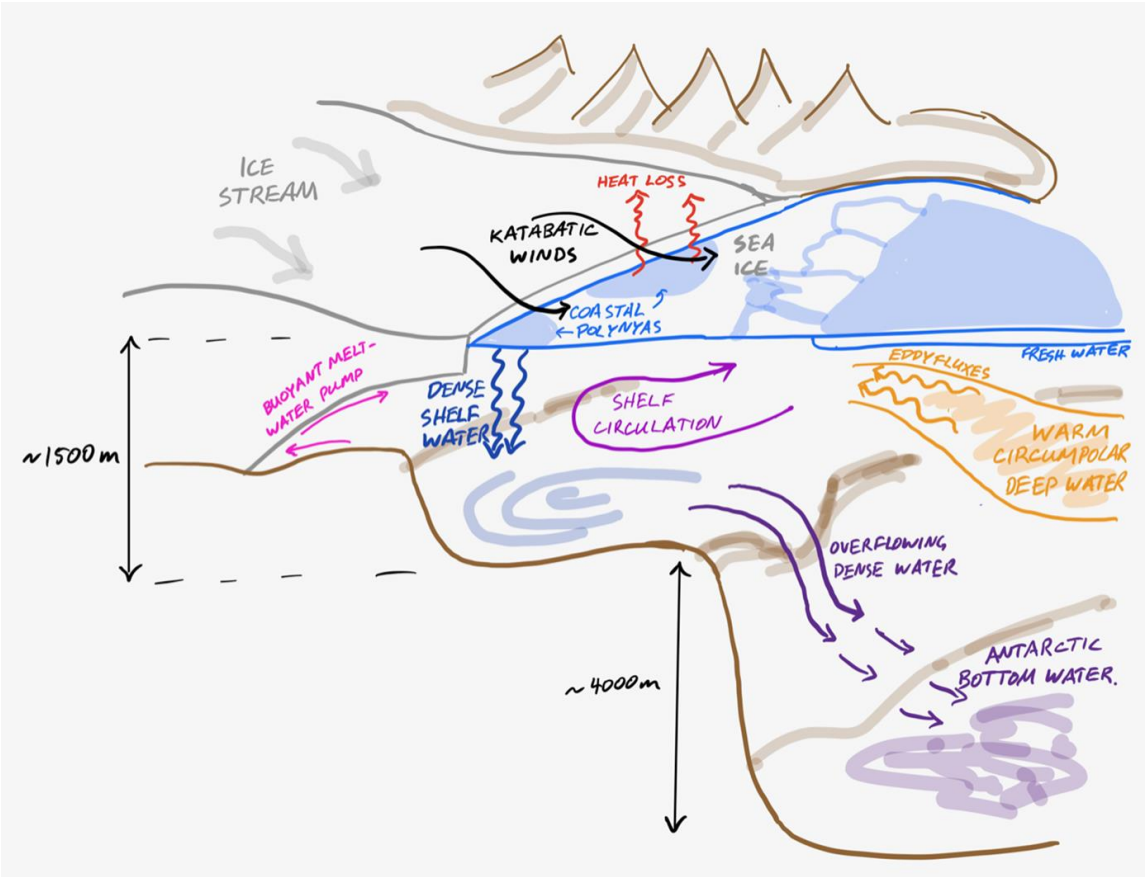

Fig. 2: Schematic diagram showing the important processes and linkages between the Antarctic ice sheet, the Southern Ocean and the global climate system, Andy Hogg, 2023.

Stepping back from the Antarctic margin, the meltwater entering the Southern Ocean can have a much wider influence. Surface cooling, will likely affect sea ice for example, causing sea ice concentration to increase or at least to be lost at lower rate. But currently we do not have a good grasp of how important this meltwater impact is and there is a vast range in modelling studies.

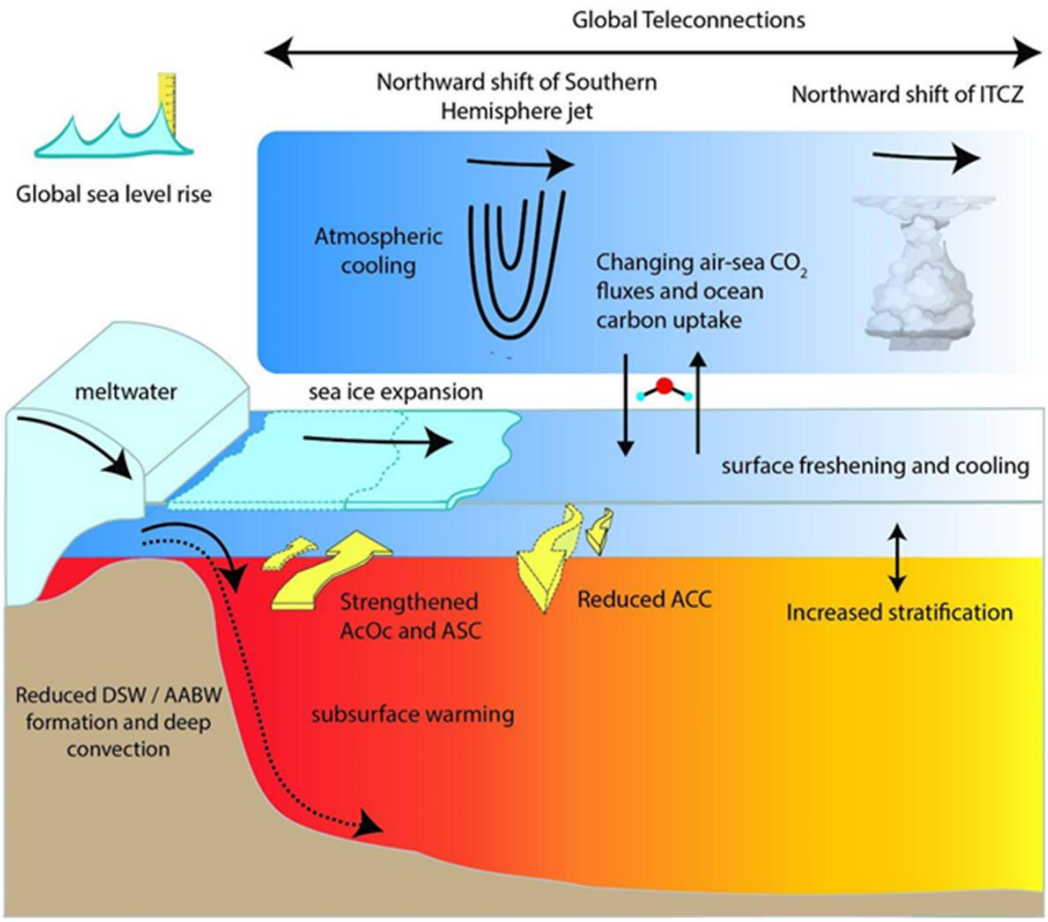

Fig. 3: A schematic showing the key impacts of Antarctic ice sheet meltwater forcing on the climate system. Relevant changes in ocean circulation are highlighted including changes in the Antarctic Slope Current (ASC), Antarctic Coastal Current (AcOc), Antarctic Circumpolar Current (ACC), Dense Shelf Water (DSW) and Antarctic Bottom Water (AABW) formation. Swart et al 2023. https://doi.org/10.5194/egusphere-2023-198

Warming the Southern Ocean at depth (due to climate change) changes the temperature gradient across the Southern hemisphere, but this also has an effect on the overlying atmosphere. It is plausible that ocean changes can affect the Southern hemisphere westerly jets and precipitation across the southern hemisphere, and even further into the tropics. There can also be a shift in the convergence zones. At the panel debate, it was emphasised that these are substantial changes. It's important that we know about how precipitation will change.

The panel also identified the problem that meltwater fluxes are not included systematically in the CMIP6 models. This means that and the models that inform the IPCC, inform policy, and are used for regional downscaling do not include what is likely a very key process. This may help to explain some of the biases in the Southern Ocean identified in the CMIP6 models, but it's also a problem as we are missing a process that can have important feedbacks both locally around the Antarctic margin but also on the wider global scale. To fill this gap, the audience and panel determined the need for both more observations but also focused modelling and the requirement to lobby the CMIP panel to ensure freshwater fluxes are properly represented in participating coupled models.

OCEAN:ICE is going to cover part of this gap through the work of WP1: WP1 will establish the role of Antarctic marginal seas in regulating heat delivery to the ice shelves (supporting WP2-4) and in the formation and export of dense water to the global ocean (supporting WP5-6). WP1 will deploy three

pairs of ice-capable floats in regions that are currently poorly observed and represent important links between regions of significant ice-ocean interaction. One pair will be deployed between the Amundsen and the Ross Sea, to connect upstream and downstream moored arrays and the other two pairs along the East Antarctic margin near the Denman Glacier, and Totten Ice Shelf.

Southern Ocean carbon sequestration

The discussion about carbon cycling in the Southern Ocean covered three points: carbon context, knowledge gaps and the wider global relevance.
There are three different processes:

- Drawdown by solubility of carbon that is largely temperature driven
- Biological drawdown of carbon
- Going the other way, carbon-rich, deep waters are brought back to the surface and outgas

And it's a subtle competition between those three processes in the Southern Ocean. Observations from Argo Floats show high latitude outgassing because of the carbon, rich, deep water being brought up to the surface, changing to a subtropical drawdown, linked to the subduction process.

All three of these processes act on the shelf under the ice, but we don't have an understanding of their imprint on the carbon cycle, and each will likely be modified by the environment. We simply don't know how much the carbon transfers are, which is a massive knowledge gap. nd a priority for future research. Session talks suggested that the balance between these processes will change due to climate warming. Currently the Southern Ocean is responsible for 42 to 43% of the global uptake of carbon, it's disproportionately important. Between global climate models there's a very tight spread that's plus or minus 3% for the individual Earth system models and so you can take a view from that always great consensus. But many of the processes that could be important are not in those models.

We've got three fundamental processes acting over this Southern Ocean ice sector and there's a fundamental knowledge gaps associated with each of those in terms of you what's going to happen over the next 50 years and sequestration of carbon. The panel and audience identified a number of key issues to be addressed: what's going on in this area with the delivery of freshwater, what are the changes of stratification out from the ice zone, and how these are affecting the open ocean processes.

In OCEAN:ICE WP6 will provide data for an assessment of the additional impacts of enhanced freshwater and iceberg calving on a range of global and regional climate indices, such as SLR, global mean surface temperature, ocean heat and carbon uptake, in partnership with the UKRI-BAS BIOPOLE project (A. Meijers, M. Meredith) https://biopole.ac.uk/

Challenges in Ice Sheet Modelling

The panel and audience identified a number of key issues related to ice sheet modelling. In particular, the ice-ocean boundary itself is a big problem. There are only a few models capable of resolving this. However, and in line with the other points raised here: We need to simulate ice shelf cavities, but there are only very few observations, the bathymetry is very poorly known, and ice shelf cavity geometry is lacking in many places. These are very basic and simple boundary conditions but almost completely missing over very large areas of Antarctica. Maybe even worse, every time we measure a new place, we find new things. This is also applicable to ocean salinity, the temperature etc, and the panel identified that we also need a time series, not just a snapshot for calibration and validation of models.

Another key point in this discussion space was the difference between model components. Ocean and atmosphere models are very different to ice models. The response of ice models takes decades, the ocean responds on months to days and the atmosphere from days to minutes. Reconciling these differences, especially within a coupled modelling framework is a challenge. Equally the spatial scales are very important for projections. Global Coupled Models run at ¼ degree, but this doesn't resolve ice shelf basal cavities, so ice sheets also need high-resolution ocean models. And in the grounding zone many of the tools used to study ice shelves break down, as do the assumptions in models, for example the hydrostatic assumption in the water column.

How to get to projections of high sea level rise? Are we missing processes? Or are there things we do not know? Are our sliding laws too static and not allowing rapid retreat. Paleo evidence (e.g., octopus DNA, see Figure 4) shows that we really need to get better at modelling the system.

A question to address for the Southern Ocean community is how to reconstruct surface boundary conditions on decadal timescales and extend the relevant surface boundary condition to multi centennial timescales. We really need to figure ways to make our models collapse together at the high sea level.

OCEAN:ICE is going to cover part of this gap through the work planned in its WP5: WP5 will provide global context for the impact of high latitude deep water formation on global ocean properties and circulation. It will use the interior distribution of water mass properties derived from existent global salinity and δ18O hydrography to make a novel application of an inverse approach. This will reconstruct surface boundary conditions on decadal timescales and, for older deep waters, extend the relevant surface boundary condition to (multi) centennial timescales. This study will include an analysis of δ18O decorrelation length and time scales and will provide information that can be used to inform (e.g., via SOOS) new high latitude δ18O sampling strategies. The inverse analysis itself will produce a unique observation-based historical time series of surface oxygen isotope ratios. This will inform WP2 isotope modelling and can be used to inform the magnitude and likely range of variability in boundary conditions, in addition to identifying historical variability and extreme events.

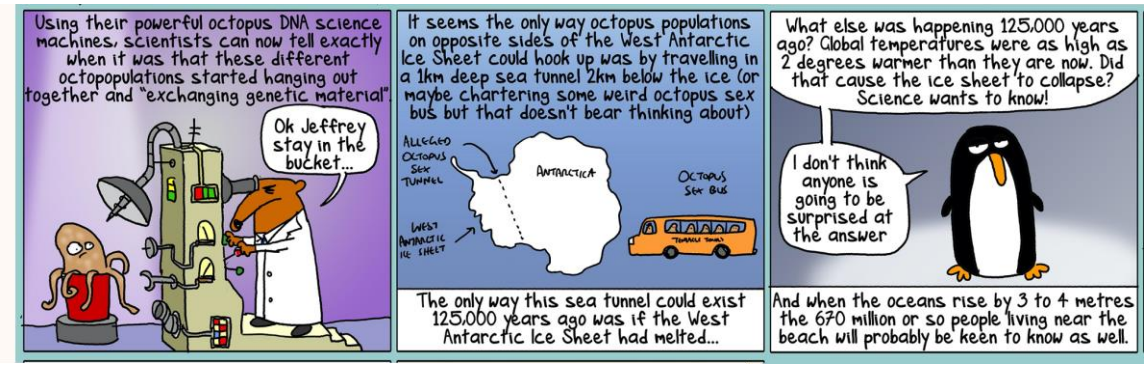

Fig.4: Cartoon by First Dog on the Moon https://www.theguardian.com/commentisfree/2023/feb/06/exclusive-the-octopus-sex-scandal-that-rocked-the-antarctic based on scientific article Lau et al., Genomic evidence for West Antarctic Ice Sheet collapse during the Last 2 Interglacial Period, https://doi.org/10.1101/2023.01.29.525778

Discussion Points

There was a lively discussion following the panel summaries, with input from scientists across the earth system spectrum and a few key points are summarised below.

- Geographically, there are two main areas with poor observations and poor representation in models: the continental shelf break and the ice shelf cavity out to the grounding line.
- Spatially, there are problems at the very small spatial scales that are not resolved in models and have to be parameterised and at the same time these are often not well observed to test and develop parameterisations.
- At the large scale there is large spatial and temporal variability, some of which is stochastic, some of which reflects poorly understood processes. Both of these make it hard to interpret and improve models with observational datasets.
- Models: There are large biases within both ocean models and coupled climate models that affect how the Southern Ocean and the Antarctic ice sheet react to climate change forcing.
- Missing observations, particularly in winter and in some key areas around Antarctica hamper even key process understanding e.g., outgassing of carbon driven by winter storms. It's likely that there is a systematic bias in observations.
- The SOFIA project, looking at realistic freshwater hosing experiments, will help. SOFIA stands for Southern Ocean Freshwater release model experiments Initiative and materials can be found on SOFIA Github: https://sofiamip.github.io/
- The relative role of the freshwater from ice sheet melt and intensification of the hydrological cycle needs to be further explored. It is not really clear what is more important – or if it matters.
- Monitoring over wider areas for basal melt of ice shelves, also with longer temporal coverage all the way to the grounding lines would be helpful. See also the OCEAN:ICE milestone MS6 report from the Earth Observation workshop.
- An agreement to take freshwater fluxes around Antarctica to the World Climate Research Programme for input as part of CMIP7. These are not currently in the scenario MIP/DECK experiments and the community needs to make the case that it's important to the panel. CMIP7 planning is already well advanced so this is an urgent need.

Conclusions

There is obvious need to collect more inputs from the scientific community around these three large areas of gaps identified at the session. OCEAN:ICE will be represented at the SOOS annual meeting which will further work on defining which observations should be prioritised and where.

The upcoming annual meeting in October 2023 (https://ocean-ice.eu/2023/06/12/save-the-dates-23-26-october-2023-project-annual-meeting-oceanice-paris/) , to be held in Paris, alongside the SO-CHIC annual meeting, provides a chance to review recent results of ongoing research activities and to provide inputs for recommendations for further research priorities to be addressed by the Southern Ocean community.

Appendix

As a reminder of the session themes, we attach here the description of the sessions **JP03 and JP04** for completeness.

JP03 Physical and Biogeochemical Ocean and Ice Processes in the Southern Ocean: Observations, State Estimation and Modelling (IAPSO, IACS)

Convener: Joellen L. Russel (USA, IAPSO)

Co-Conveners: Martin Vancoppenolle (France, IACS), Adele Morrison (Australia, IAPSO), Ilana Wainer (Brazil, IAPSO)

Description

Quantification and simulation of the physical and biogeochemical processes that determine the Southern Ocean and its ice cover's mean state, variability, and response to external forcing are critical to our understanding of the climate system as a whole, and for reducing uncertainties in climate projections. Advances in data collection, state estimation and modelling capabilities have finally established the necessary infrastructure to permit a deeper understanding of the Southern Ocean's processes that are relevant to climate. This session will present new results based on modelling and/or observational efforts that investigate ocean and ice processes in the Southern Ocean, in terms of physical and biogeochemical processes, as well as ocean-ice-atmosphere interactions.

JP04 Ice Sheet-Ocean Interactions: Challenges and Insights From Theory, Observations and Modelling (IAPSO, IACS, IASPEI)

Conveners: Felicity McCormack (Australia, IAPSO), Isabel Nias (UK, IACS)

Co-Conveners: Donald Slater (UK, IACS), Sue Cook (Australia, IACS), Yoshihiro Nakayama (Japan, IAPSO), Helene Seroussi (USA, IACS/IAPSO), Rick Aster (USA, IASPEI)

Description

Ocean-driven melting of the Greenland and Antarctic Ice Sheets is accelerating and is a key process contributing to the significant uncertainty associated with estimates of future sea level rise. Ice sheet-ocean interactions range across spatial scales: from the microscale processes governing melt at the ice-ocean boundary layer, through the buoyancy-driven circulation beneath ice shelves and at tidewater glaciers, to large-scale fjord and open ocean circulation patterns; and across a range of timescales: in response to seasonal fluctuations in warm water supply to the ice-ocean front to multi-decadal and centennial oscillations in response to intrinsic ice and ocean dynamic processes. This symposium brings together researchers working in the areas of interactions between ice sheets, ice shelves, tidewater glaciers, icebergs, and the ocean, and covering a range of spatial and temporal scales that are relevant to ocean-driven melting of ice. The session will cover theoretical, observational, and modelling disciplines. Studies that offer new insights and technologies to improve understanding of ice-ocean interactions are particularly welcomed.