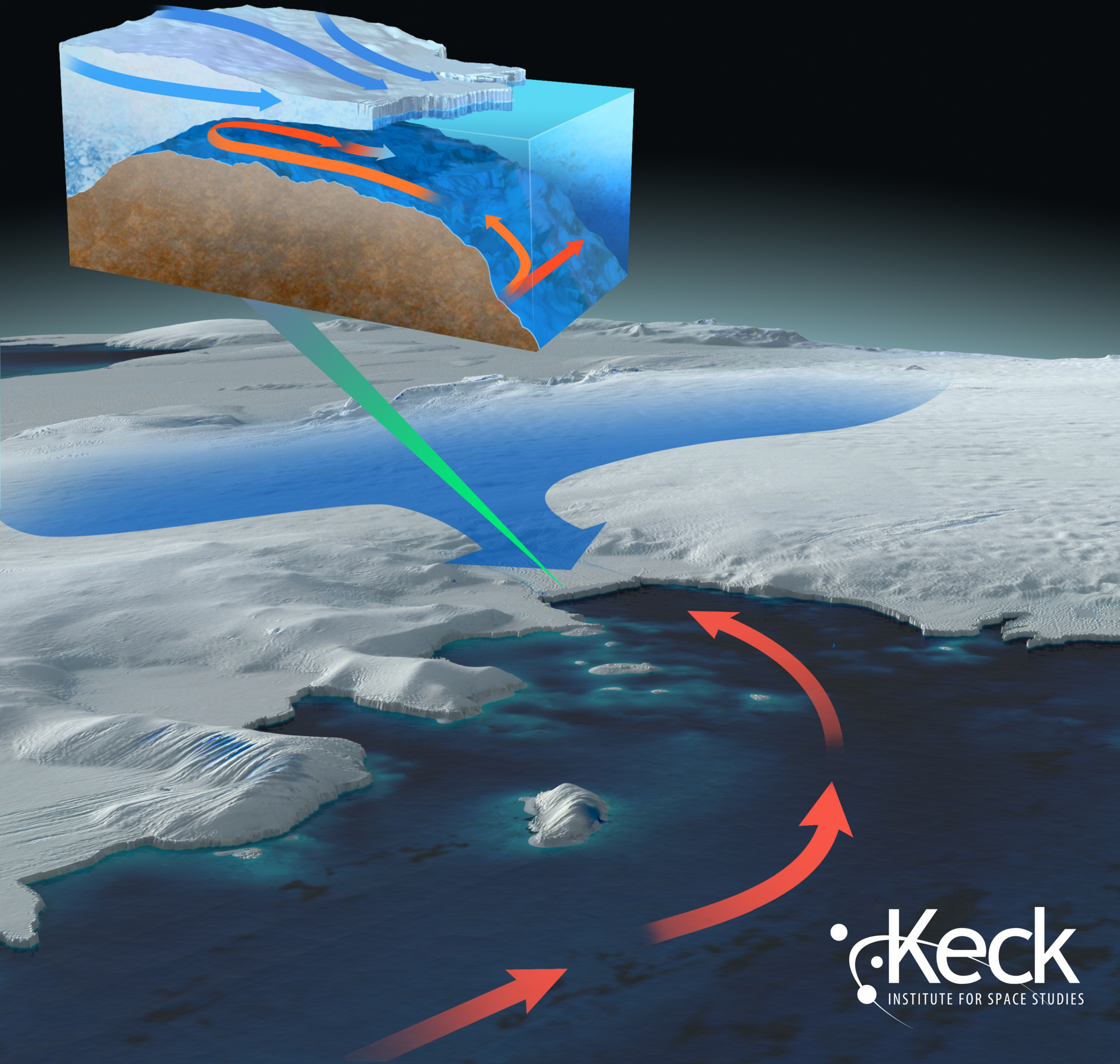
The Sleeping Giant

Measuring Ocean-Ice Interactions in Antarctica



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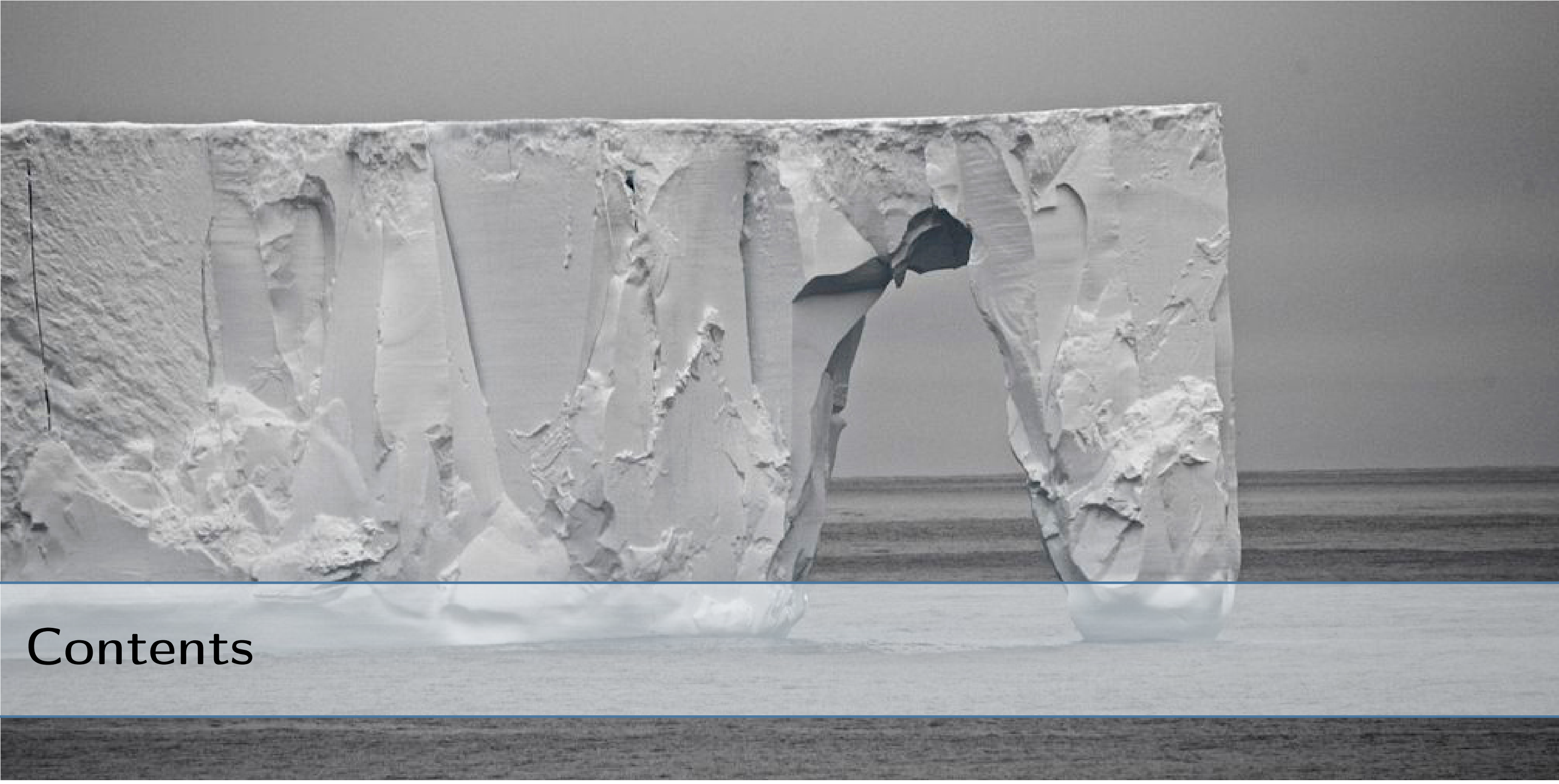

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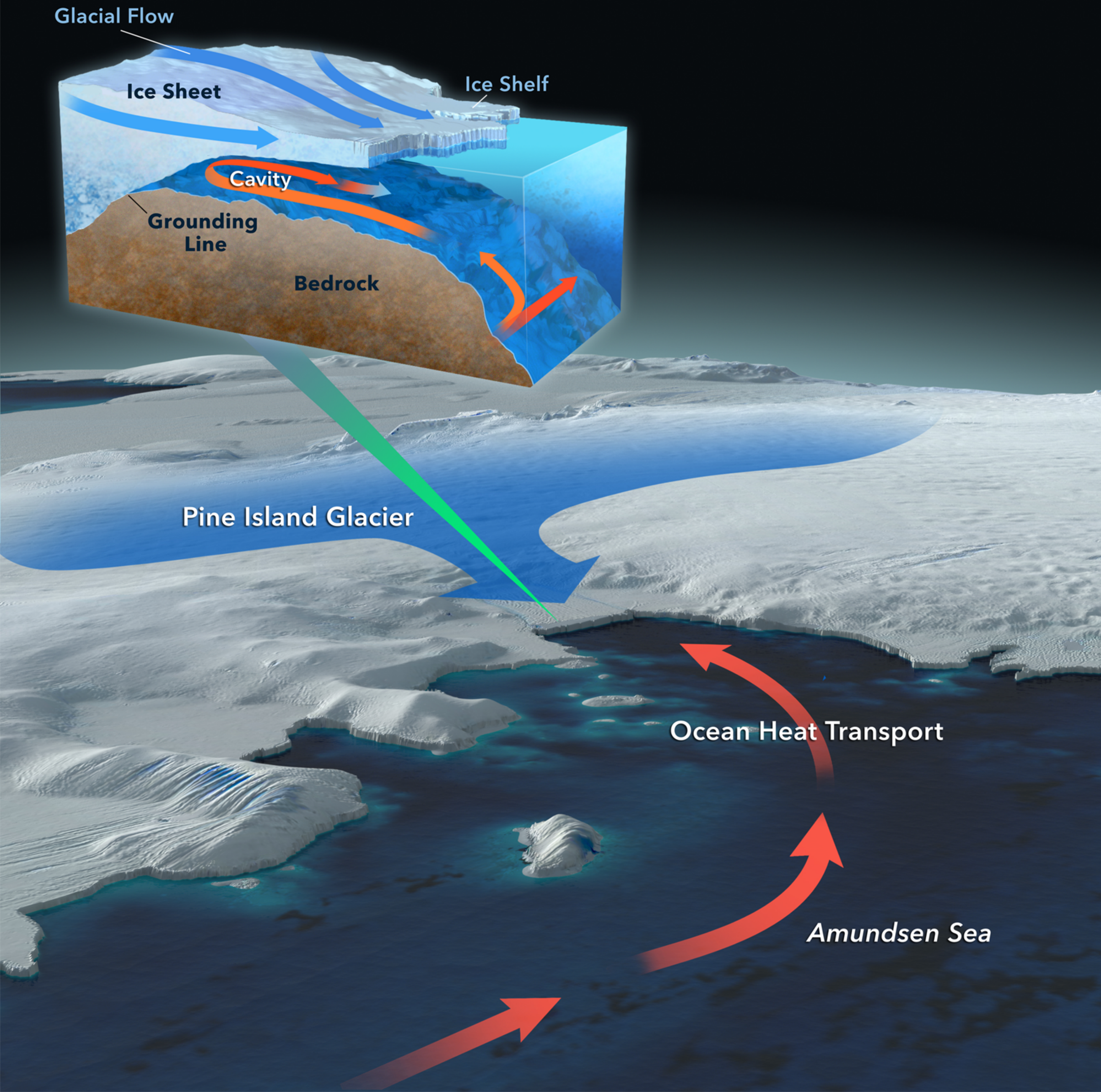
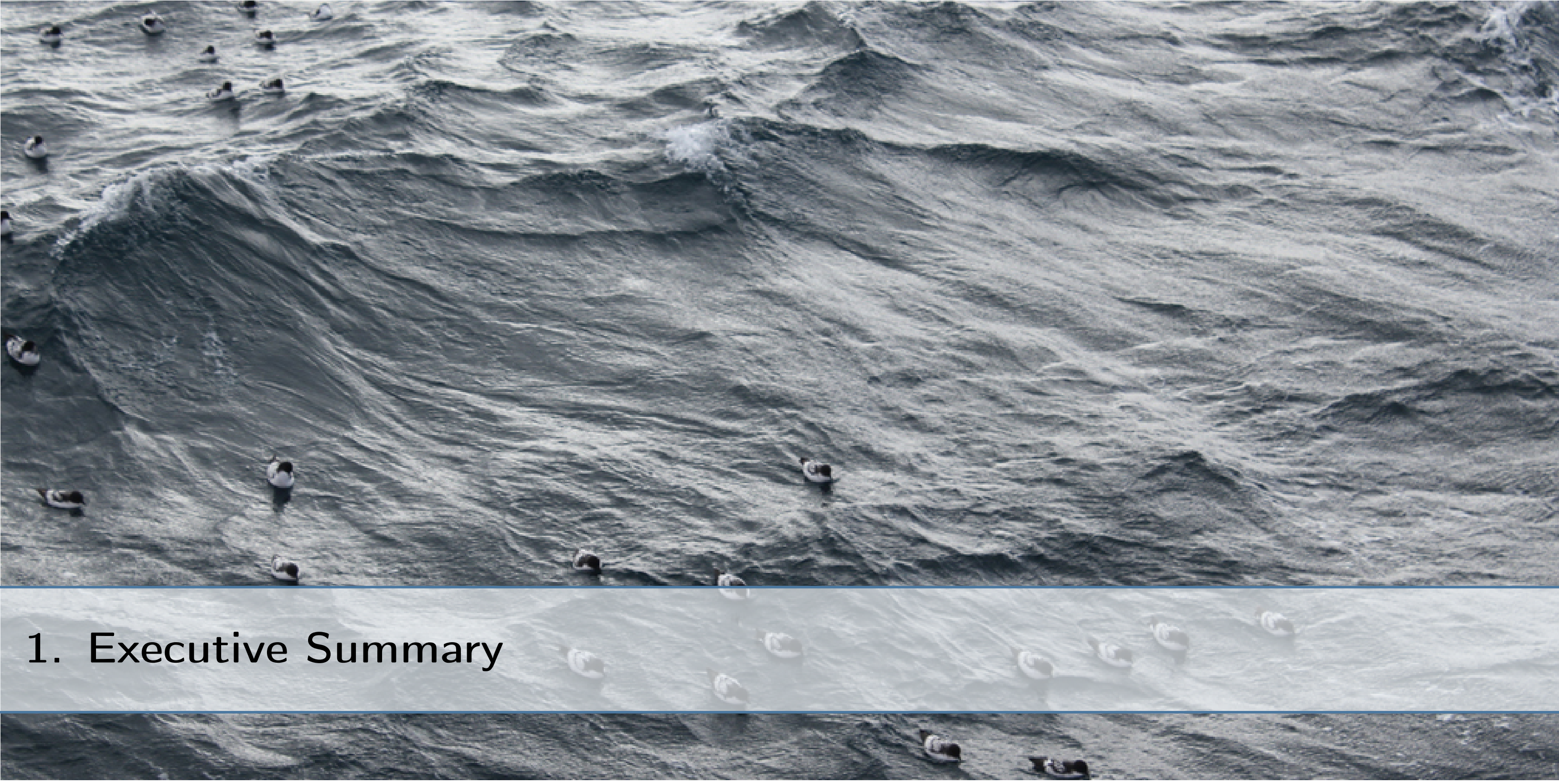
This image and the cover depict a cutaway of the Pine Island Glacier and the cavity that sits beneath its ice shelf. Ice flow and ocean currents are depicted by blue and red arrows. Warm water from offshore ocean currents that makes it into the cavity has the potential to cause rapid melting and increased ice loss. Cavities like this may hold the key to projecting sea level rise in the 21st Century.





1. Executive Summary

Global sea level rise threatens to be one of the most costly consequences of human-caused climate change. And yet, projections of sea level rise remain poorly understood and highly uncertain. The largest potential contribution to global sea level rise involves the loss of ice covering all or even a portion of Antarctica. As global atmospheric and ocean temperatures rise, physical processes related to the ocean's circulation: (i) carry this additional heat into the deep ocean, (ii) transport it poleward via the overturning circulation and (iii) ultimately deliver the heat to the underside of floating Antarctic ice shelves. Enhanced melting that occurs due to warm ocean waters plays an important role in the loss of ice from the continent. Our understanding of the first two steps that bring heat towards Antarctica has increased substantially over the past two decades through improved measurements of air-sea interactions and interior ocean properties (e.g., Argo). Yet, the constraints on the oceanic delivery of heat to Antarctic ice shelves and its impact on melt rates remains critically under-studied. Our inability to constrain the rate of retreat of Antarctic glaciers and how the Antarctic Ice Sheet will behave in a warming climate remains the single most significant reason for the large uncertainty in sea level projections over the 21st century. This problem is the focus of the KISS study, **"The Sleeping Giant: Measuring Ocean Ice Interactions in Antarctica,"** and stands as one of the grand challenges of climate science today.

An improved understanding of the controls on Antarctic melt rates must overcome both scientific and technical challenges. Antarctic ice shelves and their influence on Antarctic ice sheet stability represent one of the most challenging physical systems to both monitor and model. Processes that impact melt rates involve fluid dynamics and solid mechanics, including multi-phase flows, sediment laden flows and fracture mechanics. Additionally, the ocean circulation within the complex geometry of ice-shelf cavities is poorly understood, and bathymetry within most cavities is almost completely unknown. Finally, there is substantial evidence that key physical processes that influence melt rates are turbulent and thus subject to intermittency over a range of scales, suggesting the need for long-term, persistent measurements to resolve temporal and spatial variability. Based on this, our KISS group approached this study using the framework of a dynamic Antarctic coastline, with a distinct focus on the physical feedbacks between ice mechanics and ocean circulation.

Scientifically, the KISS study identified a number of physical processes that will impact the rate of Antarctic ice loss over the next century. These include teleconnections between regions of ocean heat uptake and transport towards the Southern Ocean and across the Antarctic Circumpolar Current; the effectiveness of mesoscale eddies and wind-driven transport in moving warm Circumpolar Deep Water onto the continental shelf and towards floating ice shelves as well as modifications to this transport in response to changing atmospheric patterns; and the efficiency of heat carried into sub-ice shelf cavities in melting the overlying ice.

Ultimately our KISS study identified the role of variability within the ice shelf cavity as our primary scientific focus. The near total lack of direct observations within the ice-shelf cavity, and specifically near the grounding line itself was determined to be a critical limitation on improving our understanding of grounding zone processes. The KISS study identified future technology areas that are needed to successfully advance our knowledge of this complex system. These include:

- Persistent monitoring of heat, freshwater, and other tracer fluxes across the face of an ice shelf over a full seasonal cycle. Sampling rates should be sufficiently high to resolve mesoscale variability ($\sim$1 week), while the spatial distribution should capture lateral structure associated with mesoscale variability and boundary currents ($\sim$2–3 km).

- Development of autonomous navigating capabilities that would enable ocean robots to explore an unmapped domain, such as an ice-shelf cavity, using machine learning to both observe its environment (e.g., cavity geometry) and update sampling strategies.

- Improvements in inexpensive, low maintenance or even autonomous drilling capabilities, with the recognition that the top surfaces of the Antarctic ice shelves provide a "stable" platform for the supply of power and communication, and possible command stations for navigating and collecting data from under-ice autonomous vehicles.

This vision builds on recent efforts to instrument a small number of Antarctic ice shelves, the limited use of autonomous vehicles sampling within ice shelf cavities (e.g., Autosub), as well as discussions at other meetings in recent years, such as the SOOS Seeing Below the Ice Workshop in October, 2012. This KISS study acknowledges the technical challenges and the need to engage both the scientific and technological communities to solve this problem. While autonomous navigation in extreme environments is germane to future space exploration missions, the potential for major changes in global sea level provides strong motivation for the development of these exploration techniques in the service of our understanding of Antarctic ice sheet stability.

2. Study Overview

The continent of Antarctica holds enough ice to raise global sea levels by about 200 feet, or roughly 60 meters. It has been well established that ice loss from Antarctica is already contributing to sea level rise [*Shepherd et al.*, 2012] and that certain Antarctic glaciers may already be in a state of unstable retreat [*Rignot et al.*, 2014; *Joughin et al.*, 2014]. As global warming continues, the loss of Antarctic land ice will continue as well. The key open question is: **How fast will Antarctic ice loss proceed?**

This question lies at the heart of our study and stands as one of the grand challenges of climate science today. Current projections of sea level rise between now and 2100 range from 1 to 7 feet (2 meters) [*Church et al.*, 2013], which would affect hundreds of millions of people worldwide. Lack of understanding about how the Antarctic Ice Sheet will behave in a warming climate remains the largest single reason for the huge range of sea level projections over the 21st Century. The potential societal impacts of such sea level rise create an underlying urgency for addressing this issue.

Constraining the evolution of the Antarctic Ice Sheet requires accurately representing or simulating various complicated physical processes. A major challenge in understanding these processes is that large portions of the ice sheet sit below sea level. Ice flows from the ice sheet interior toward the edges of the continent. In Antarctica, most of these marine-terminating glaciers also have large floating ice shelves, which can be hundreds of thousands of square kilometers in area. Between the base of the floating ice shelf and the sea floor lies a cavity that is flooded by ocean water with temperatures above the freezing point (see Figure 2.1). Ocean currents flush water through these cavities, and if the water is warm enough it leads to melting along parts of the base of the ice shelf, especially near the "grounding line" or "grounding zone" defined to be the zone where the ice, ocean and bedrock are all in contact. Sufficient melt can result in retreat of the grounding zone. Furthermore, instabilities related to the flux of ice through the grounding zone in the presence of a bed that gets deeper moving inland, or retrograde bed, can cause glaciers to retreat further even in the absence of continued melting [*Weertman*, 1974; *Schoof*, 2007]. Because much of the West Antarctic Ice Sheet sits in a depression below sea level, the bedrock beneath the ice often slopes downward away from the open ocean. This "reverse" slope is a condition that causes outlet glaciers to be susceptible to this marine ice sheet instability. Such rapid loss of ice from the Antarctic Continent would cause rapid sea level rise around the world. Furthermore, it remains unknown exactly how rapid such a collapse could occur. These cavities—where ice, ocean and land intersect—are the vulnerable underbelly of the West Antarctic Ice Sheet and their evolution will ultimately determine the fate of Antarctica in a warming world.

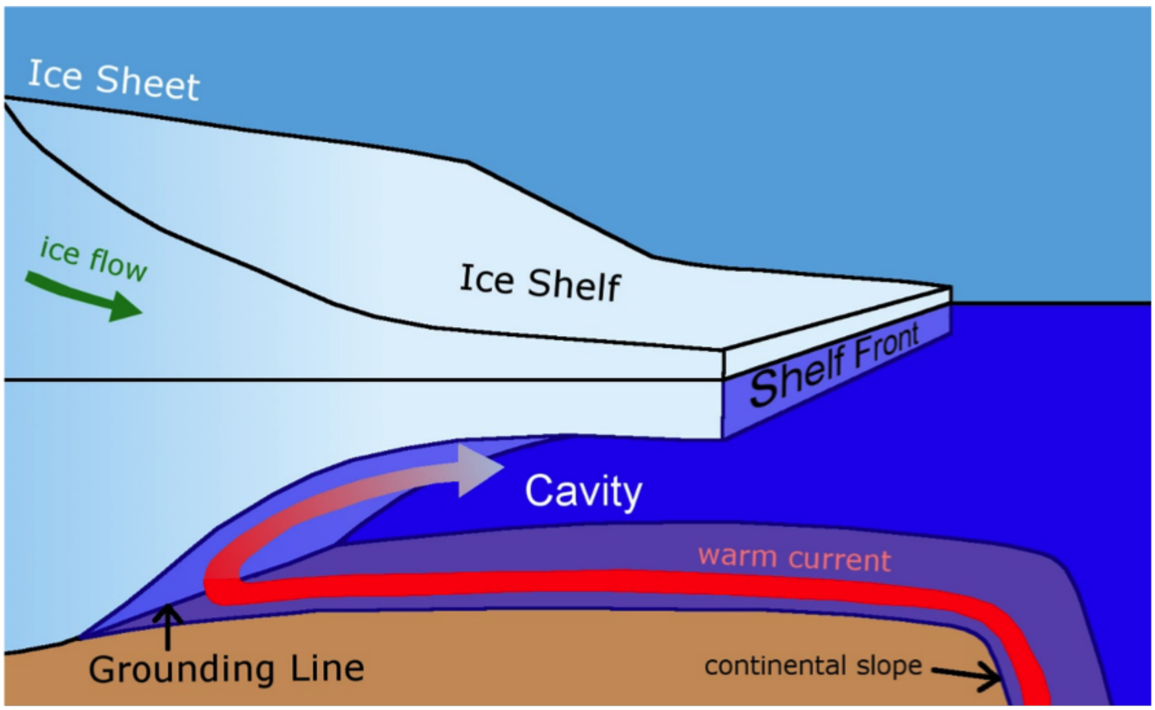


Figure 2.1: Schematic of the geometry of a typical Antarctic cavity sitting below a floating ice shelf in Antarctica. Warm waters enter the cavity at depth across the continental slope and shelf; the source of this water is relatively warm Circumpolar Deep Water (CDW) in the Antarctic Circumpolar Current. This warm water can enhance melting typically at the base of the ice shelf and cause retreat of the grounding line. In places where the bedrock slopes downward as you move inland, there is potential for runaway grounding line retreat and rapid ice loss. Contributions to changes in the mass of the ice shelf include melting, freezing of water back onto the base of the ice shelf, the outflow of the glacier, and calving.

During our KISS workshops, the importance of these ice shelf cavities emerged as a key research theme. Development of techniques to explore, understand, and ultimately monitor these important regions was identified as the highest research priority for improving our ability to project future ice loss from Antarctica. Of course, other aspects of the system demand attention as well, including changing atmospheric conditions, ocean circulation over the continental shelf and its delivery of heat to the cavity, improved understanding of ice sheet dynamics and improved numerical models of ice shelf and ice sheet dynamics, and observations of grounding zone variability. These topics are all discussed in the following report, but observations of the geometry, ocean properties, and currents in the cavity stand out as the highest priority for advancing sea level rise projections.

This report summarizes these findings, highlights the important research priorities, and identifies techniques for addressing them. It is organized as follows. Chapter 3 presents a concise description of the major technical advances identified during the KISS study. Chapter 4 provides both the scientific background and scientific justification to support the content in Chapter 3. Finally, we present a few targeted implementations of new observational techniques and report on their potential impact and feasibility in Chapter 5. We conclude in Chapter 6.

3. Major Technical Advances

3.1 Cavity instrumentation

Ice shelf cavities are notoriously difficult to observe. Remote sensing techniques can provide observations of the height and velocity of ice shelves at their top surfaces. Further offshore, satellite observations can also provide information about the ocean surface height and temperature. But observations of water properties and circulation within the cavity or near the ice shelf front can only be collected using in situ techniques. Because of their remote location and harsh conditions (especially during winter), these regions remain under-sampled.

The fidelity of how numerous processes that occur at the interface between the cryosphere and the ocean are represented in numerical models is not well understood, in large part due to a lack of long-term observations. The current scarcity of measurements makes any type of observation in the sub-ice-shelf cavity invaluable. However, ice-ocean interactions and their impact on sea level rise is fundamentally a time-variable problem that requires monitoring the system's behavior over at least several years. We describe current technologies and potential future developments to design such a system in sections 5.1 and 5.2.

Having developed the necessary technology, of central interest will be measurements of water and ice properties within the ice shelf cavity as well as the shape of the cavity, including the bottom bathymetry and the basal topography of the ice shelf. The cavity shape has a strong control over the circulation in the cavity along with the associated mass, heat, and freshwater transport across the cavity entrance. The roughness on the underside of the ice, including crevasses and channels, as well as the water and ice properties in the immediate vicinity of the ice-ocean interface (e.g., temperature and salinity of the water and ice rheology) provide insight into mechanisms of basal melting. The three-dimensional distribution of ocean temperature and salinity and density profiles within the cavity would allow estimates of ocean circulation. More generally, long-term in situ observations of the ice shelf cavity will provide a basis to relate variations inside the cavity to the states of the open ocean and ice shelf that are directly observable by remote sensing, thus establishing a means for longer-term monitoring and predictions.

The new technologies proposed below constitute a cost-effective approach to not only monitor changes in the cavity but also to provide a means to constrain coupled ice-ocean models at the various temporal and spatial scales involved in the interaction of ice shelves with the ocean (see Sections 4.1-4.3).

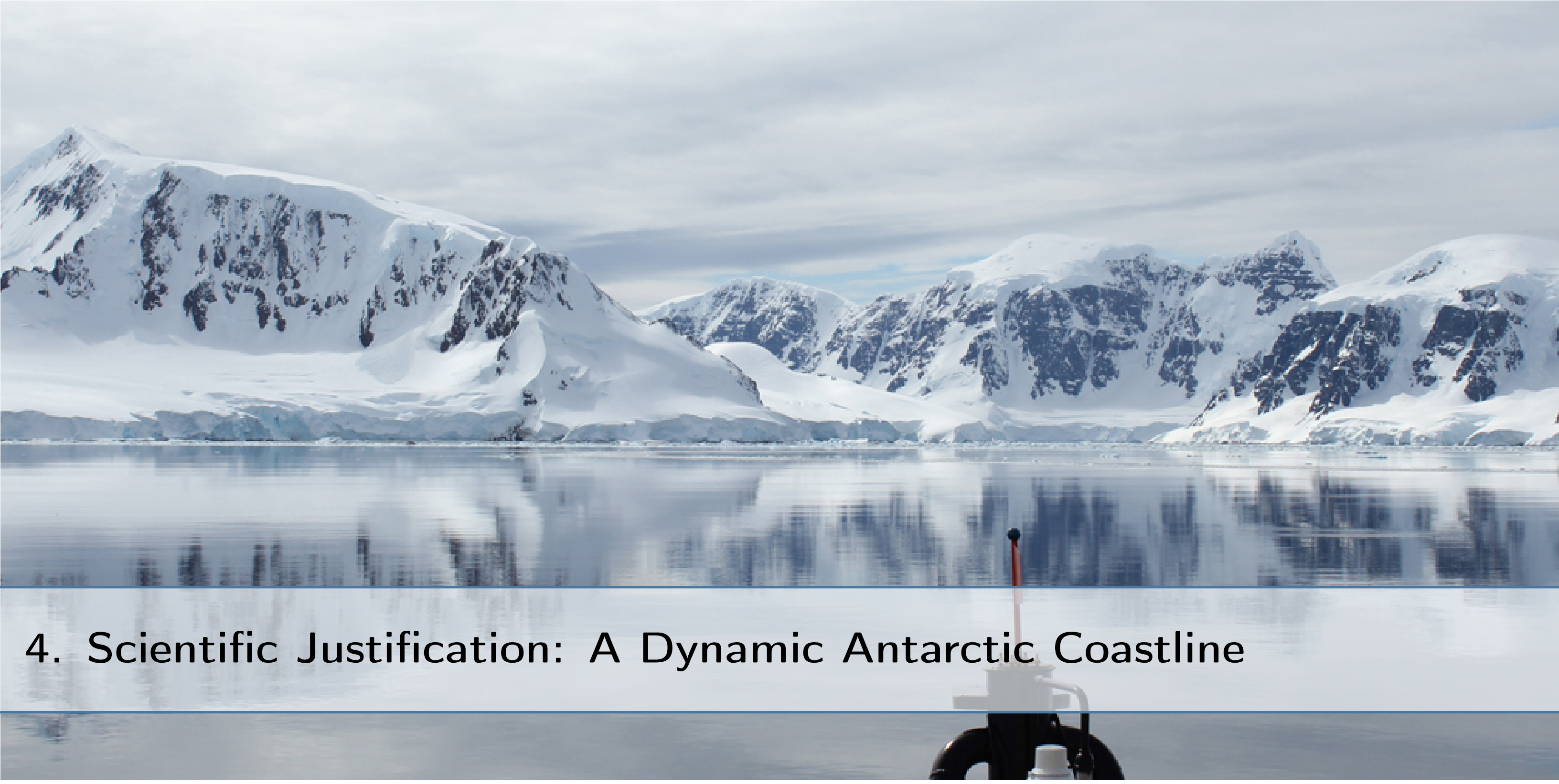
3.2 Monitoring Cavity-Shelf Exchange

The face of the ice shelf represents a natural boundary across which the exchange of heat and freshwater between the open ocean and the underside of the ice shelf can be measured. The primary goal of the proposed observational strategies is to accurately quantify the total heat and meltwater flux into and out of the cavity over several years. This would enable comparison with observations of the glacial evolution and shed light on the links between the two.

A key challenge is to maintain an observing system over the winter season in order to eliminate seasonal bias in the existing measurements. Therefore it is likely that the observational campaign will need to be predominantly autonomous, either comprising autonomous underwater vehicles (AUVs), or using static observational platforms such as moorings, cables or acoustic tomography. Keeping autonomous platforms operating in such an environment over such a long period will be a major logistical challenge regardless of the technology used. However, improvements in vehicle duration and instrument reliability suggest that these efforts will become increasingly feasible within the coming years. Indeed, the UK's iSTAR (Investigating the Stability of the West Antarctic Ice Sheet) project recovered moorings in early 2014 that had been operating and collecting measurements in front of Pine Island Glacier for roughly 5 years.

It is important that small-scale ocean currents that transport large amounts of heat are not missed. The inflow of warm water is typically dominated by a narrow boundary current, and the outflow of meltwater may be confined to a thin layer flowing just beneath the ice surface in the cavity. Measurements of temperature and salinity would ideally be taken on at least weekly time scales, with vertical resolution sufficient to resolve thin meltwater outflow (tens of meters), and a horizontal resolution sufficient to resolve boundary currents (likely 5 km wide). Direct velocity measurements would be needed to reference geostrophic velocities derived from temperature and salinity measurements. Taking direct velocity measurements from AUVs is likely to be a challenge, but would be possible if the AUVs had the capacity to use inertial navigation and acoustic location, or if they could utilize an Acoustic Doppler Current Profiler (ADCP) to derive absolute velocities. The alternative would be to use moored instruments for the purpose of referencing geostrophic current measurements from an AUV. The various advantages of these measurement technologies are discussed further in Section 5.1.

Maintaining measurements at this temporal and spatial resolution over a period of several years would provide unprecedented knowledge of the key processes important to ocean-ice interactions in Antarctica.



4. Scientific Justification: A Dynamic Antarctic Coastline

This section emphasizes the importance of temporal and spatial scales of variability at the ocean ice boundary. Consistent with our discussion during the two workshops, this chapter will be divided into subsections related to important dynamics impacting transport into the cavity (ice-shelf face), circulation and melting within the cavity, and grounding line evolution. There will be a particular emphasis on moving away from a grounding line definition, with a preference for describing a grounding zone that captures the complexity and variability of processes in this region.

4.1 Variability at the Ice Shelf Edge

It is vital to understand ocean variability at the ice shelf front since this is the primary forcing signal entering the cavity and influencing glacial retreat. The complexity and cost of carrying out these observations are less daunting than the in situ observations needed to provide monitoring of circulation and water properties in the cavity itself.

Oceanic variability at the ice shelf edge (and within the cavity) is forced by changes in the quantity of warm Circumpolar Deep Water (CDW) that enters onto the continental shelf. This inflow of warm water occurs preferentially within troughs at the shelf break, where topographic depressions allow deep warm water flowing in coastal currents to turn inland [*Walker et al.*, 2013]. The variability of this inflow is likely controlled by surface winds near the continental shelf break [*Wahlin et al.*, 2013, *Stewart and Thompson*, 2012; 2013], potentially linked to global-scale climatic variability [*Dutrieux et al.*, 2014]. However, uncertainty remains as to the relative importance of this wind-driven variability compared with the steady inflow driven by the ocean currents [*Arneborg et al.*, 2012]. It is known that the quantity of warm water on the shelf alters the depth of the thermocline and thus the volume of warm water reaching the ice base. In the case of Pine Island Glacier (PIG), it is the strength of the on-shelf circulation, rather than the temperature of the water itself, that is most important for determining melt rates [*Jacobs et al.*, 2011].

Analysis of high-resolution model output from a limited-area simulation using the MITgcm [*Schodlok et al.*, 2012] has been conducted for this study to further elucidate the variability of the heat flux into the PIG cavity. One conclusion of this work is that the mean heat flux is more than an order of magnitude larger than the eddy heat flux over the course of a single year (Figure 4.1). There is a distinct annual cycle in the mean component, although the mean heat flux is an order of magnitude larger than the eddy heat flux at any given time. The fact that the eddy heat flux is small, compared to the mean, is an encouraging result for observational campaign planning, since it implies that not all of the eddy heat flux must be resolved. Nevertheless, it does not remove the need to avoid aliasing high-frequency variability.

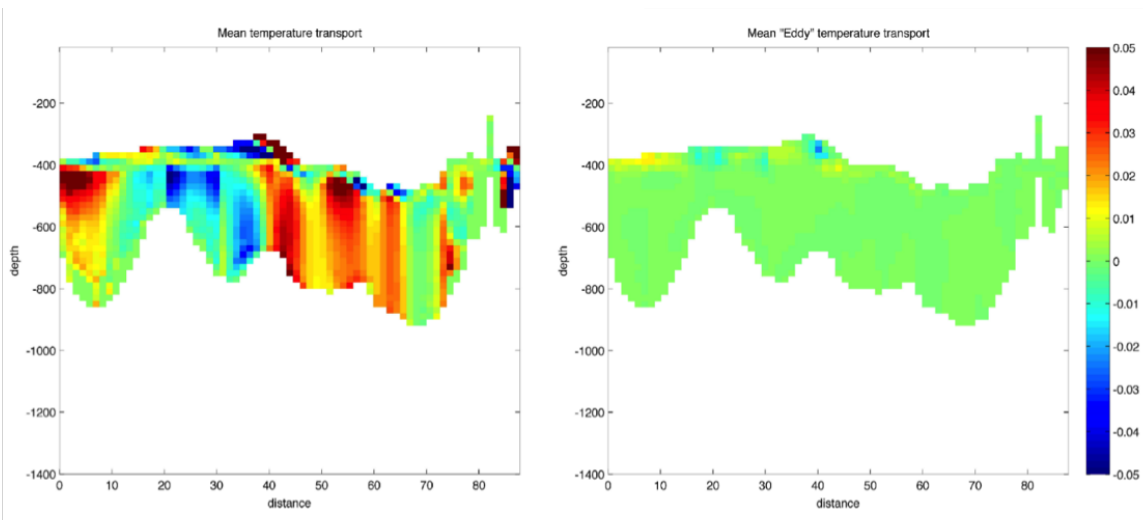


Figure 4.1: (Left) Mean temperature transport (°K m s^{-1}) and (Right) eddy temperature transport, into the PIG cavity, as derived from a numerical model simulation [Schodlok et al., 2012].

It is also important to measure the outflow of cold meltwater, since this is a direct measurement of the glacial response to ocean forcing. Comparison between the ocean heat flux entering the cavity and the meltwater leaving the cavity provides an indication of the efficiency with which heat is able to melt the glaciers from beneath [*Jenkins and Jacobs*, 2008]. Meltwater tends to form a buoyant plume that flows along the underside of the ice shelf and is tens of meters thick, although it may reach neutral buoyancy at a greater depth and thus separate from the ice base, depending on local stratification [*Hellmer and Olbers*, 1989]. This outflow may be localized to channels in the base of the ice shelf, with important implications for the distribution of melt within the cavity [*Vaughan et al.*, 2012]. It is therefore crucial that any observing system is able to capture this outflow, by taking measurements close to the base of the ice, ideally within 10 meters of the base of the ice shelf.

4.2 Cavity Properties, Circulation and Modeling

Ocean-ice interactions have been identified as one of the greatest sources of uncertainty in projections of future climate [*Church et al.*, 2013]. This has motivated substantial development of ocean models over the last decade to accommodate ice shelf cavities.

Inclusion of an ice shelf cavity requires a representation of the mass and property exchanges between the ocean, the ice shelf, and the oceanic boundary layer, and models typically employ the parametrizations of *Holland and Jenkins* [1999]. However, ocean models must also overcome the technical challenge of representing the abrupt change in water column thickness at the ice shelf front. Traditional z-coordinate models require only a straightforward modification of the surface pressure calculation in order to accommodate this boundary, traded for lower vertical resolution of the oceanic boundary layer [e.g., *Losch*, 2008]. Isopycnic models, in which density is used as a vertical coordinate, must impose a lateral discontinuity in the vertical position of the surface mixed layer [e.g., *Holland and Jenkins*, 2001]. Sigma-coordinate models, which use a terrain-following vertical coordinate, acquire an abrupt jump in the spacing of the numerical grid boxes [e.g., *Dinniman et al.*, 2003]. This may lead to large errors in the evaluation of the lateral pressure gradient [*Mellor et al.*, 1994].

As of yet, ice shelf cavity models do not satisfactorily represent the grounding line, where the thickness of the water column vanishes. This prevents models from resolving inflow to and outflow from the base of the ice shelf and melt rates close to the grounding line, where much of the melt is thought to take place [e.g., *Rignot and Jacobs*, 2002]. *Kimura et al.* [2013] have shown that the grounding line can be resolved using an unstructured finite element ocean model. Cavity models are also constrained to use very high horizontal resolution (~1 km) in order to resolve mesoscale eddies [*St. Laurent et al.*, 2012], which are known to dramatically alter the transfer of mass and properties in the open ocean [e.g., *Marshall and Speer*, 2012]. Most studies, even in recent years, have not employed sufficient horizontal resolution to resolve the mesoscale [e.g., *Dinniman et al.*, 2007, 2011; *Thoma et al.*, 2010; *Makinson et al.*, 2011].

Ocean cavity models have been used to estimate basal melt rates beneath Antarctic ice shelves in response to oceanic forcing, particularly the increased inflow of Circumpolar Deep Water (CDW) over the past few decades [*Jacobs et al.*, 2011]. Many of the recent modeling efforts have focused on the rapidly retreating West Antarctic Ice Sheet (WAIS). *Holland et al.* [2010] found that the CDW inflow and melt rate beneath the George IV ice shelf in the Bellingshausen Sea exhibit strong seasonal variability. However, at higher (~5 km) resolution the CDW is carried beneath the shelf by mesoscale eddies in submarine canyons [*Dinniman et al.*, 2011]. *Schodlok et al.*

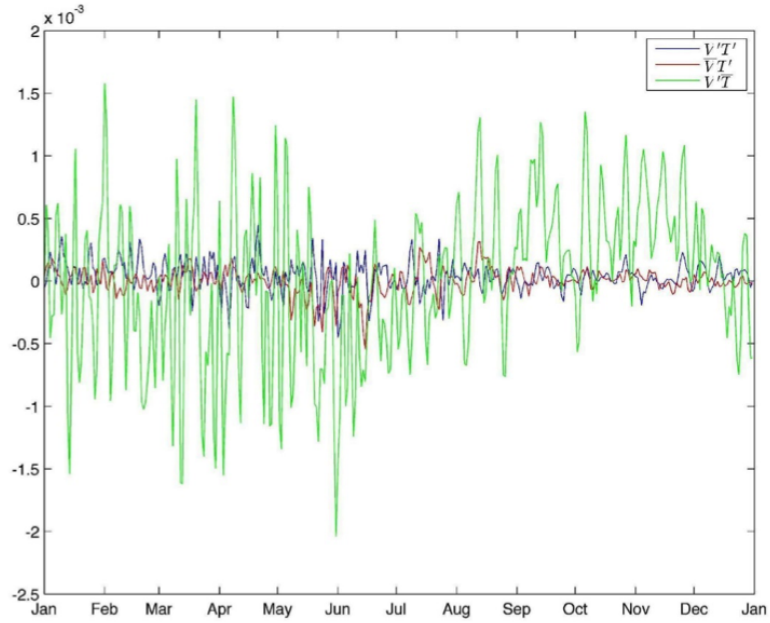


Figure 4.2: (Time series of eddy temperature transport components. Blue line: temperature transport associated with time-varying velocity and temperature. Red line: mean velocity and time-varying temperature. Green line: time-varying velocity and mean temperature.

[2012] demonstrated that the circulation and basal melt rates beneath Pine Island Glacier (PIG) are highly sensitive to the bathymetry, which remains poorly mapped beneath most Antarctic ice shelves. *Mueller et al.* [2012] showed that including tides substantially increases the basal melt rate close to the face of the Larsen C ice shelf, whilst *Robertson* [2013] found that tides increased the basal melting beneath Pine Island ice shelf by 25%.

Other studies have focused on the dense water formation sites in the Weddell and Ross Seas. For example, *Dinniman et al.* [2007, 2011] showed that CDW intrusions beneath the Ross Sea ice shelf are also due to mesoscale eddies in submarine canyons, but are somewhat suppressed by vertical mixing. *Thoma et al.* [2010] showed that melting beneath the Eastern Weddell Ice Shelves (EWIS) responds weakly to a warming of the CDW unless the water column warms below 1000 m. *Hellmer et al.* [2012] projected increased inflow of CDW beneath Filchner-Ronne in the coming decades due to an increase in the surface wind stress close to the ice shelf front, resulting from a reduction in the ice cover. *Makinson et al.* [2011] showed that including tidal forcing in a model of the Filchner-Ronne cavity approximately doubles the basal melt rate.

Cavity models have been applied to other regions of the Antarctic coastline, such as the Totten [*Khazendar et al.*, 2013; *Gwyther et al.*, 2014] and Amery [*Galton-Fenzi et al.*, 2012] ice shelves in East Antarctica. *Kusahara and Hasumi* [2013] applied a coarse-resolution ocean model to the entire Antarctic coastline, and found that the West Antarctic Peninsula (WAP) and East

Antarctic ice shelves display the largest increases in melt rate in response to an increase in the surface air temperature, whilst the Filchner-Ronne and Ross ice shelves are relatively unaffected. The increase in melt rates is due to increased inflow of CDW into the ice shelf cavities troughs in the continental shelf.

Regional modeling of Antarctic ice sheets is limited by computational constraints and a lack of data. Our understanding of the processes taking place under ice has been aided by a series of idealized and conceptual modeling studies. *Olbers and Hellmer* [2010] constructed a two-dimensional box model of the circulation and heat/salt fluxes in an idealized ice shelf cavern. For a 1°C increase in the inflow temperature they predicted that the Pine Island basal melt rate should increase by a factor of 1.4, while that of the Ronne should increase by a factor of 10. *Holland* [2008] constructed a two-dimensional conceptual model of the tidal front close to the grounding line. He showed that such a tidal mixing zone insulates the grounding line from the rest of the cavity, but that melting within the zone responds linearly to changes in the water temperature.

Several idealized studies have focused on the role of mesoscale eddies in transporting warm water and enhancing melt rates. *Nøst et al.* [2011] showed that an eddy-driven overturning circulation carries warm CDW beneath an EWIS-like ice shelf, and *St-Laurent et al.* [2012] showed that this transport is enhanced by the presence of a submarine canyon. *Arthun et al.* [2013] showed that High Salinity Shelf Water (HSSW) produced by a polynya at an ice shelf front is carried beneath the shelf by mesoscale eddies generated by an unstable boundary current. *Gladish et al.* [2012] and *Millgate et al.* [2013] have shown that an ice shelf's melt rate is strongly sensitive to the presence of basal channels.

4.3 Grounding Zone Dynamics

Our choice of focusing on cavity dynamics and, in particular, collecting observations as close to the ocean-ice-land interface as possible, comes from the recognition that the traditional labeling of a grounding line is inaccurate. A more appropriate description is a grounding zone. Tidal motion causes the landward extent of the grounding zone to migrate on hourly to seasonal timescales, thereby increasing the volume of the cavity near the grounding zone, potentially impacting melt rates within the grounding zone, influencing subglacial water pressure, and reducing the total area of ice that is in contact with the bed. Fluctuations at the grounding zone are likely to influence circulation and melting broadly within the cavity, but this remains a critically understudied aspect of this system.

As the areas where ice, ocean, and solid earth meet, grounding zones are influenced by ocean forces and ice stream dynamics on a variety of spatial and temporal scales. The dynamics of grounding zones are governed primarily by tidally-induced uplift of floating ice and the horizontal flow of ice across the grounding zone and are modulated by bedrock topography. The mechanical properties and gradient of the bed topography within the grounding zone have a significant influence on ice flux to the ocean [e.g., *Alley et al.*, 2007], while the gradient of the water column depth downstream of the grounding zone have important controls on tidal forcing and basal melt rates within the grounding zone [*Holland*, 2008].

Tidal motion causes the landward extent of the grounding zone, also called the flexure zone [*Fricker et al.*, 2009], to migrate on hourly to seasonal timescales [e.g., *Brunt et al.*, 2011; *Sayag and Worster*, 2013], thereby increasing the volume of the cavity near the grounding zone, potentially impacting melt rates within the grounding zone [*Holland*, 2008; *Jenkins*, 2011], influencing subglacial water pressure [e.g., *Walker et al.*, 2013; *Sayag and Worster*, 2013], and reducing the total area of ice that is in contact with the bed. The latter two effects, possibly along with other unresolved mechanisms, induce near-instantaneous changes in ice mass flux to the ocean through horizontal accelerations of ice stream flow [e.g., *Anandakrishnan et al.*, 2003; *Gudmundsson*, 2006; 2011].

Magnitudes of tidally-induced grounding zone migrations are not well known, owing to a dearth of repeat observations of the grounding zone on tidal frequencies, uncertainties in the proper representation of the mechanical properties of ice, and the coupling between ice and bedrock on short timescales. Many modeling studies of tidal influences on the grounding zone impose a static grounding line and apply viscoelastic and elastic rheologies for the ice and bed, respectively [e.g., *Walker et al.*, 2013]. These studies successfully reproduce the tidally-induced flexure properties of ice, thereby providing a mechanism for changing the subglacial water pressure, altering horizontal ice flow, and obfuscating grounding line position in ice-penetrating radar data [*Walker et al.*, 2013]. Regardless of their success in matching observations, the underlying assumptions of static grounding lines and viscoelasticity might not accurately represent the physics of the grounding zones [e.g., *Brunt et al.*, 2011; *Sayag and Worster*, 2011; 2013]. These fundamental model assumptions are self-consistent in that the assumption of a static grounding line appears to require a viscoelastic rheology in order to reconcile observations and models of tidal flexure across multiple ice streams.

Recent modeling efforts by *Sayag and Worster* [2011; 2013] relax the assumption of a static grounding line and apply a fully elastic ice/bedrock model to show that grounding lines can migrate several kilometers over a tidal cycle, consistent with ICESat observations of Filchner-Ronne Ice Shelf [*Brunt et al.*, 2011], where tidal amplitudes can be up to three meters [*Padman et al.*, 2002]. Ice flexure during the tidal cycle should change the basal water pressure and basal melt rates on the ice shelf near the grounding zone and facilitate horizontal acceleration [*Sayag and Worster*, 2013], though further investigation is warranted.

Modeling efforts to date employ 1D or 2D flow line models with simplified geometries and uniform mechanical properties that do not capture the true spatial complexity of grounding zones [e.g., *Fricker et al.*, 2009; *Brunt et al.*, 2010; *Rignot et al.*, 2011] nor varying ice and bed mechanical properties and topography [*Alley et al.*, 2007; *Anandakrishnan et al.*, 2007]. Critical questions remain regarding the influence of inhomogeneities in grounding zone positions, bedrock highs, "sticky spots" where bed stresses are much higher than surrounding areas, and non-uniform elastic or viscoelastic properties on ice flux and melt rates within the grounding zone.

5. Feasibility of Implementation & Future Technology Directions

Chapter 5 presents the three major advances that would significantly enhance our ability to predict the Antarctic contribution to future sea level rise. In this chapter, we provide further details about how these advances would be implemented. The focus is primarily on remote sensing products or field observations, but each avenue for future development will benefit from integration with modeling efforts being carried out at Caltech, JPL, and elsewhere. Each section identifies key measurement requirements that will improve our ability to model processes at the ocean-ice interface, including necessary or desired temporal and spatial resolutions, as well as a summary of current capabilities and suggestions for new techniques.

5.1 Exploration and Persistent Monitoring of Ice Shelf Cavities with AUVs

Persistent measurements within an ice shelf cavity would represent a major advance in our ability to observe ocean circulation and water mass properties as well as to measure cavity geometry and melt rates. An even more dramatic advance in our capabilities would be the potential for adaptive sampling, either through two-way communications with an AUV pilot or via machine learning and/or autonomy. **To achieve this goal, the necessary two key advances are a continuous source of power and communications.** The major ice shelves around Antarctica provide both a challenge and an opportunity in this respect. The obvious obstacle is penetrating the ice shelf, but sometimes there is a solid surface to provide a platform for an ice-shelf-based infrastructure to enable real-time data uplink and a long-term power source.

The challenge, then, is how to link a surface-based power system to assets deployed within the ice shelf cavity. A constraint on solutions to this problem is the size of an opening in the ice that can reasonably be created/sustained with existing drilling technologies, or through new technologies yet to be developed. Existing drilling capabilities suggest that a hole in the ice sheet could reasonably be drilled with a diameter of roughly 10 cm. It is easy to envision putting a small cable down through this hole to provide power and communications. It is more complicated to understand how an autonomous vehicle would connect to such a cable.

5.1.1 Measurement Requirements

Ice-ocean interactions are highly dependent on cavity shape, water mass properties, and circulation. In particular, local basal melt rates of ice shelves vary significantly with their bottom topography as well as with ocean bathymetry, which influences local circulation and heat transport to the ice-ocean interface. Temporally, studies have shown that ice shelf melt and calving rates at various locations around Antarctica are sensitive to variations on time scales between sub-daily (e.g., tides) to decadal (e.g., Circumpolar Deep Water (CDW); see Section 4.1). CDW—a source of melting for several ice shelves such as Pine Island Glacier—experiences advection and warming on various time scales, requiring long-term monitoring of these changes at the base of the ice shelf. Ocean cavities underneath ice shelves are not directly observable by remote sensing. Therefore, in situ observations provide a critical means to measure and to monitor these regions. !!!!Effective observations of sub-ice-shelf cavities will require sustained instrumentation that is mostly autonomous and able to communicate over long time spans. Such a task, however, remains challenging given current technologies and means of transportation. Traditional monitoring systems such as moorings, or even newer technologies such as gliders, require regular maintenance. Ship time needed to deploy and recover the instruments is expensive, as continuous observations require regular attendance. At the same time, the front of an ice shelf is often inaccessible given high sea ice concentrations along the ice shelf front. Autonomous vehicles that use satellite technology for communication are largely independent of ships but require an opportunity to surface, which is often hindered by the presence of sea ice that prevents devices from transmitting their data or receiving new instructions.

Hence, for long term monitoring of water mass properties and heat flux throughout the cavity we will need to design a stationary system that has independent power supply and means of communication. We describe current technologies and potential future developments to design such a system in section 5.1.3.

Having developed the necessary technology, of central interest will be measurements of water and ice properties within the ice shelf cavity and the shape of the cavity itself. The shape of the cavity, i.e. bathymetry and basal topography of the ice shelf, along with boundary forcing, dictate ocean circulation and its associated heat transport within the cavity region. The roughness on the underside of the ice, including crevasses and channels, and the water and ice properties in the immediate vicinity of the ice-ocean interface (e.g., temperature and salinity of the water and ice rheology) will provide insight into mechanisms of basal melting. The three-dimensional distribution of ocean temperature and salinity and density profiles within the cavity will allow estimates of ocean circulation to help identify pathways of heat and freshwater transport under the ice shelf, the divergence of which signify ice-ocean exchange. Isotopic ratios of oxygen and helium in the water column provide measures of glacial melt, including subglacial discharge. More generally, sufficiently long-term in situ observations of the ice shelf cavity will provide a basis to relate variations inside the cavity to the states of the open ocean and ice shelf that are directly observable by remote sensing, thus establishing a means for longer term monitoring. !!!!!

5.1.2 Direct Measurements at the Grounding Zone

The highest melting rates at the ice-ocean interface often occur at the grounding zone [*Schodlok et al.*, 2012] and its position has a direct bearing on the possible contribution of the ice sheet to sea level rise. Most grounding zones are temporally variable due to tides as well as to longer-term variations in ice sheet dynamics. Accessing the region uncovered by the moving grounding zone will allow direct observations of processes that contribute to grounding zone migration. Observations of the bedrock and sediment composition at the grounding zone would be valuable in estimating basal drag and how it influences glacier flow, especially in the case of grounding line retreat. Variation in water properties associated with grounding zone migration, including suspended sediment content and turbidity, in addition to temperature, salinity, and oxygen, would allow estimates of melt rates and the efficiency of ocean circulation in the transport of heat and freshwater into and out of this region.

Revealing the 3-D structure of the grounding zone would identify general cavity shape, ice-shelf bottom topography such as basal crevasses and channels, and ice surface roughness, all of which affect ice-ocean interactions. Each one of those measurements will moreover inform numerical simulations of melting at the ice-ocean interface and hence improve assessment of ice-shelf stability and projections of contributions to sea level change. The grounding line is also the site of subglacial freshwater discharge, if present. As one objective of the project is to measure net heat influx into the sub-ice-shelf cavity, it is necessary to quantify the contribution of the discharge at the grounding line, which can be done with analyses of the heavy isotopes of oxygen and helium.

5.1.3 Existing and Planned Resources; Perceived Limitations

5.1.3.1 Review of PIG study, WISSARD

Two recent American-led endeavors to drill through ice sheets and access subglacial environments have had limited success, yet still resulted in significant scientific advancement. The Pine Island Glacier project drilled through the ~500-meter-thick Pine Island ice shelf in three locations and accessed the sub-ice-ocean cavity [*Stanton et al.*, 2013]. At each site, a lightweight, hot-water drilling rig transported by light aircraft was used to drill a 20-cm-diameter hole through the ice shelf and a specialized suite of ocean instrumentation, including CTD profilers, acoustic altimeters to measure basal melt rate, and flux packages to measure ocean velocity, was lowered through the boreholes to sample the ocean cavity. Flux packages were left in place with telemetry stations on the ice-shelf surface and some instruments continued to function a year later. These measurements have shown that a buoyancy-driven boundary layer within a basal channel melts the channel apex by 0.06 m/d, with near-zero melt rates on the channel flanks [*Stanton et al.*, 2013].

The second project is the Whillans Ice Stream Subglacial Access Research Drilling program (WISSARD), which accessed Subglacial Lake Whillans (SLW) on Whillans Ice Stream, West Antarctica in January 2013. Here a hot-water drilling system transported by traverse and LC130 aircraft was used to create a 30-cm-diameter borehole through the ~800-meter-thick ice sheet, allowing for in situ measurements of the water column properties and direct collection of water and sediment samples in SLW. Drilling and lake entry procedures followed recommendations for environmental protection of subglacial aquatic environments [*Priscu et al.*, 2013]. Results reveal the presence of a viable microbial ecosystem in SLW, indicating that subglacial ecosystems contain possibly globally relevant pools of carbon and microbes that can mobilize elements from the lithosphere and contribute a significant nutrient flux to the Southern Ocean [*Christner et al.*, 2014]. In both cases, significant multi-year efforts involving multiple institutions and nations were required to deploy the drilling equipment. Even with the new technologies developed for these programs, subglacial access research drilling remains a significant logistical and technological challenge.

5.1.3.2 Drilling Capabilities

The main ice drilling organization in the U.S. is the Ice Drilling Program Office (IDPO[1]). IDPO was created by the NSF and gives priority to NSF-funded projects. IDPO can, however, support non-NSF funded project if certain conditions are satisfied. Part of IDPO is the Ice Drilling Design and Operations (IDDO), which provides engineering design support for new drilling systems. Ice drilling expertise can also be sought at JPL, in particular concerning the possibility of designing smaller docking stations.

5.1.3.3 Short-Term Challenges

Drilling holes through the ice shelf wide enough for instrument deployment (diameter ~50 cm) would permit observations in the cavity that are not readily possible by other means. The ice shelf surface can provide a relatively stable and easily accessible platform to accommodate power sources, computational and communication (satellite) equipment, i.e., an operational hub. Placing

[1]http://icedrill.org/index.shtml

these components at the surface frees measurement instruments from carrying these elements. The instruments would therefore be smaller and lighter, and have longer possible range and duration. Direct access through the ice shelf will also allow instruments to remain closer to such operational hubs compared to using ships or moorings in the open ocean as a base. Moreover, such holes will permit placing instruments directly in the proximity of the grounding zone, which is a key region of interest (acknowledging that these regions are typically heavily crevassed), facilitate placement of a network of acoustic transponders required for navigation within the cavity, and permit direct sampling of the water within the cavity and to measure the underside of the ice shelf.

Docking capabilities for ocean gliders have previously been discussed in an oceanographic context in terms of supporting cabled observatories such as the Canadian and the planned Endurance and Pioneer arrays on the western and eastern coasts, respectively, of the U.S. The docking capabilities of the Pioneer array are not presently available as a commercial product or demonstrated to be operational for long durations. Power for two AUV docking stations will be supplied by a multi-function node (MFN) at the base of the inshore and offshore EOM moorings. The use of docking stations will extend the duration of AUV deployments, allowing for multiple missions between deployment and recovery. The OOI (Ocean Observatories Initiative) AUV Requirements specify 25 missions over a deployment period of 120 days before the AUVs will be recovered for service and support, for up to 35 missions over 210 days before the docking stations will need service. There are limited diagrams of what these docks look like, but the few schematics available suggest these look like a hoop through which the AUV must navigate.

5.1.3.4 Potential Solutions

Drilling a hole through the ice shelf wide enough to lower a docking station can prove to be technically challenging and expensive. If building a smaller dock is not possible, two alternatives can be considered. The first is drilling a narrower hole (<10 cm) to lower only a cable that will provide power and communications to a docking station. The larger docking station itself would be lowered in the open ocean near the ice-shelf front and steered to dock with the cable. The advantages of this approach are that the technology to drill narrow holes already exists and is less expensive (see section 5.1.3.1); the same proposed technology that will be used to guide and dock AUVs to the docking station can be used to guide and connect the docking station to the power/communications cable; and at a later stage, developing technology to drill narrow holes autonomously can be presented to the Europa community as a feasible first-step on the road to more elaborate technology.

The other alternative is using rifts (fractures that span the entire thickness of the ice shelf) to access the sub-ice-shelf cavity [*Khazendar and Jenkins*, 2003]. The main advantage is the much reduced drilling needed (to get through a few meters of ice mélange that might exist in the rift). The main disadvantage is that logistical and safety consideration could render reaching rifts impractical in some locations.

5.2 Persistent Monitoring Across the Ice Shelf Front

The primary goal of the proposed observational strategies is to accurately quantify the total heat and meltwater flux into a glacial cavity over several years at least. This would enable comparison with concurrent observations of the glacial response and thus an understanding of the links between the two. It is important to note that these heat flux measurements should be kept in the context of far-field forcing of inflow onto the continental shelf. The proposed observing system would not directly observe these far-field processes, but it is anticipated that other research and monitoring projects would seek to monitor these regions; there is already a commitment to maintain persistent monitoring of the Amundsen Sea region.

5.2.1 Measurement Requirements

A key challenge is to maintain this observing system over the winter season, which is currently very poorly observed. Therefore it is likely that the observational campaign will need to be predominantly autonomous, either comprising autonomous underwater vehicles (AUVs), or using static observational platforms such as moorings, cables or acoustic tomography. Keeping autonomous platforms operating in such an environment over such a long period would be a major logistical challenge whatever the technology used, but is likely to be increasingly feasible within the coming years.

It is important that high frequency variability is not aliased by adopting a sampling regime that is too coarse in time. Any variability that is too rapidly varying to be sampled adequately over long periods would ideally be quantified during a short-term intensive observation period so that the potential for aliasing can be understood and mitigated.

In terms of spatial resolution, it is important that small-scale ocean currents that may transport a large amount of heat are not missed. This is important in both the horizontal, where the inflow of warm water is typically dominated by a narrow boundary current along the sides of the cavity, and in the vertical, where the outflow of meltwater may be confined to a thin layer flowing just beneath the ice surface in the cavity. Even if gross estimates of the total volume flux can be obtained with coarsely spaced hydrographic sections [*Jacobs et al.*, 1996; 2011], it is desirable that these currents are resolved in order to understand their dynamics and be able to better simulate their behavior.

The heat flux into the cavity is highly variable over spatial scales equal to the Rossby radius of deformation, approximately 5 km. Model simulations suggest that the variability in the heat flux is most energetic at timescales of 15 days, roughly consistent with eddy processes. There is also a large annual cycle in most model simulations [e.g., *Thoma et al.*, 2008], and properly representing this is likely to be of importance to the ice sheet response. Tidal cycles will lead to variability at even shorter time scales, but since the harmonic signature of these is known, they can be accounted for and removed in a relatively straightforward manner.

In order to achieve the goals outlined above, measurements of temperature and salinity would ideally be taken on at least weekly time scales, with vertical resolution sufficient to resolve thin meltwater outflow, and horizontal resolution sufficient to resolve boundary currents that are likely 5 km wide. It would also be advantageous to measure dissolved oxygen as a tracer for the meltwater. Measurements of diapycnal mixing would enable understanding of vertical heat fluxes and water mass modification. Direct velocity measurements of some kind would be needed to reference geostrophic velocities derived from temperature and salinity measurements. Combining these measurements at this degree of resolution with the length of record required would be unprecedented for such an inaccessible region.

Taking direct velocity measurements is likely to be a challenge from AUVs, but would be possible if the AUVs had the capacity to use inertial navigation and acoustic location, or if they could utilize an Acoustic Doppler Current Profiler (ADCP) to derive absolute velocities. The alternative would be to use moored instruments for the purpose of referencing geostrophic current measurements from an AUV. However, while these measurements are only required at a single level, the horizontal resolution required would be onerous. The various advantages of these measurement technologies are discussed further in section 5.2.3.3.

5.2.2 Pine Island Glacier as a Test-Case

The Pine Island Glacier (PIG) and its ice shelf in the eastern Amundsen Sea Embayment is an ideal example of an ice shelf where monitoring would be both feasible and valuable. Thinning of the ice shelf and glacier acceleration have been observed there throughout the past four decades [*Wingham et al.*, 2009; *Rignot*, 2008]. PIG drains a large portion of the West Antarctic Ice Sheet, and is located in a region where most of the ice shelves are losing mass. The ocean has been implicated in the ice mass loss at PIG, whereas in other regions, such as the Larsen Ice Shelf east of the Antarctic Peninsula, the primary stimulus for ice shelf break-up appears to be atmospheric warming and the Foehn effect. The ice front of PIG is sometimes inaccessible by icebreaker because of extensive sea ice in the eastern Amundsen Sea, but is accessible roughly 50% of the years on record. Instrumentation would therefore have to be designed to survive multiple years, or to transmit data back and be expendable.

Whether PIG is representative of other ice shelves in the region is not known. There is a suggestion that its rate of retreat may be uniquely large because it was grounded on a submarine ridge, but is now free of that ridge [*Jenkins et al.* 2010].

One advantage of PIG is that ship-based measurements have been made at the ice front in several summers since 1994, with moorings there in recent years. Thus in only a few years of additional measurements a sparsely-sampled but relatively long time series has been developed. The British Antarctic Survey (BAS) and Lamont-Doherty Earth Observatory (LDEO) have been deploying some moorings at the cavity mouth, recently enhanced as part of the UK multi-institutional program iSTAR. BAS intends to maintain the time series of at least one or two moorings for the foreseeable future. These will monitor current velocity, temperature and salinity below the iceberg keel depth of 400 m.

The cavity entrance of PIG is reasonably well mapped with swath bathymetry. NASA's Operation Icebridge measurements along with Autosub surveys beneath the ice shelf have improved our knowledge of the cavity geometry. Access to the cavity front is usually safe and straightforward if there is little sea ice; it has also been achieved using icebreakers in years with moderate amounts of sea ice. The water there is deep, facilitating mooring and AUV deployments beneath the depth at which calving icebergs present a hazard. Numerical models of the region are well advanced in comparison with other Antarctic ice shelves, and the number of simulations that have been undertaken of this region provides useful context for future observational campaigns. A further advantage of PIG is that the tidal velocities are smaller than those at some other ice shelves.

Alternative ice shelves to study would be Thwaites, Dotson, Crosson, and Getz, also in the Amundsen Sea. Dotson, Crosson, and Getz are usually freer of sea ice, and should thus be more accessible than the eastern Amundsen Sea ice shelves. However, they have been comparatively less well studied in the past.

5.2.3 Review of Existing and Feasible Measurements

Here we present a review of several technologies that could be readily employed in the task of making sustained measurements of heat and freshwater fluxes across the cavity entrance of an ice shelf such as Pine Island. Included in this is the Autosub AUV as an example of a technologically advanced but expensive large AUV system that could be deployed, in contrast to the relatively inexpensive ocean glider technology that is examined as an alternative. In addition, the potential benefits and disadvantages of using moorings and ship-based measurements are evaluated.

5.2.3.1 Large AUVs: Autosub

Autosub has been deployed underneath ice shelves in the past. Autosub 3 was deployed under PIG in 2009 [*Jenkins et al.*, 2010] and 2014 as well as having been deployed under Fimbul ice shelf in the Autosub Under Ice Programme. Autosub 3 has been specifically adapted for missions underneath ice shelves, but only has sufficient battery power to conduct missions lasting approximately 24 hours. The newly developed Autosub Long Range has battery capabilities to be deployed for one month, although this lifetime is expected to be increased to several months, with the additional capacity to be able to sleep on the sea bed to extend the endurance further. Autosub Long Range is currently unable to work underneath ice shelves, but development of this capacity would be feasible in the near future. There are many other such platforms that have been developed, with a wide range of features, but all tend to be highly capable platforms limited by cost and battery life. Such AUVs have the advantage of being able to carry a relatively heavy sensor payload and collect temperature, salinity, dissolved oxygen and microstructure measurements, as well as collecting water samples.

Cost is the main limiting factor on the utilization of such technology for a long-term and high-risk deployment. Such autonomous submarines cost several million dollars, thus imposing a limit on the number that could be deployed.

5.2.3.2 Ocean Gliders

Ocean gliders are cheaper than the Autosub-class of AUVs: the average fully-equipped price is $200,000. Ocean gliders are a type of AUV that is particularly well suited to remote deployments in rough seas. Recent Seaglider (a type of ocean glider) deployments have achieved four months continuous data collection of temperature, salinity, dissolved oxygen and chlorophyll-a fluorescence at high temporal and spatial resolution; this has been proven sufficient to resolve eddies in the Weddell Sea in 2012 during the GENTOO project [*Thompson et al.*, 2014]. Longer deployments have been achieved by reducing the sampling requirements; the longest achieved to date is 11 months. Seagliders also have the capacity to sleep to conserve battery, but this has not been routinely used for long deployments.

New sensors are currently being developed for Seagliders, including turbulence profilers. There is also scope to develop acoustic navigation and data communication systems as well as underwater recharging stations for Seagliders, since the current license holder, Kongsberg, has expertise with such technology for other AUVs. The University of Washington has had several successful deployments using acoustic navigation under ice in the Davis Strait, and have collaborated with AWI for acoustic navigation of Seagliders in Fram Strait, but this software is not yet commercially available for use by other institutions.

The major limitations with ocean gliders for this application are currently their requirement to surface to receive commands and send data, as well as lack of sophisticated ice avoidance software and a limited battery life. If these issues can be addressed through acoustic navigation, development of relations with University of Washington, and a system to upload/download data underwater (again—discussions with Kongsberg suggest this is possible), Seagliders are a feasible instrument to collect the data required.

The Ocean2ice project deployed and recovered two Seagliders in Pine Island Bay as a pilot experiment. This brief deployment demonstrated the feasibility of such a campaign, but highlighted challenges such as sea spray freezing on the glider's antenna.

5.2.3.3 Moorings

Moorings have been widely used as a common way to collect data throughout the annual cycle in Antarctica. They carry temperature and conductivity sensors, as well as ADCPs and biological sensors. They also collect water samples on a mooring using equipment such as the McLane Remote Access Sampler (RAS), which is currently being used under sea ice in Fram Strait, and was also used in the Weddell Sea. While moorings provide a high temporal resolution dataset, they are fixed in one point of space, so an array is required in order to close any budgets that are of interest. Moorings deployed in polar regions are unable to sample the top few hundred meters of the water column, in order to allow for the keel of any icebergs that may pass overhead. However, upward-looking ADCPs deployed on moorings could add information regarding the currents up to the surface. Gaining measurements under ice shelves with moorings would require either drilling through the ice shelf or the use of a large AUV to deploy and recover the instruments.

The main drawback is that moorings take a considerable amount of time to deploy and recover— both of which are entirely dependent on sea ice cover with no easily implementable solution in sight. There is therefore a relatively high risk that the moorings will not be recovered, and without a system of data communication in place (such as AUVs equipped with acoustic data communication technology), the data would then be lost.

Another type of mooring is a static column profiler, such as the ICYCLER from ODIM instruments. This detects the depth of the ice at the surface using an echosounder, and samples below that height. It currently only samples in the top ~50 meters, but the anchor wire could be modified to add on various instruments at different depths in the water column.

5.2.3.4 Ship-Based Measurements

Collecting ship-based measurements often means that many different instruments can be carried, including all of the instruments mentioned above. CTD casts can be collected, and surface measurements are constantly collected through underway instrumentation. The cost per day of running a ship is approximately $30,000, and for thorough investigation into the ice front, this cost soon becomes prohibitive. A further restriction is inaccessibility to the ice front during winter months.

In conclusion, an ideal survey would include all of these instruments and platforms, providing thorough investigations into the initial and final conditions at the ice front with ship-based measurements and Autosub missions. Throughout the winter months, Seagliders could be used to run between mooring positions, which could be equipped with acoustic data communication and navigation transponders and a column profiler at the surface allowing for samples higher up in the water column.

5.2.3.5 Planned Observational Campaign from SOOS

The Southern Ocean Observing System (SOOS) is a major international collaborative effort aimed at increasing understanding of physical, biological and chemical properties, variability, and trends in the southern ocean. A key theme is understanding the role of the ocean in the stability of the Antarctic Ice Sheet. The observational strategy proposed overlaps with that outlined in this report, so an overview is presented here.

The SOOS observational plan aims to understand ocean processes that influence the marine ice sheets around the whole of Antarctica, including physical observations of ocean-ice and ocean-atmosphere interactions, as well as using chemical tracers to track meltwater dispersion. Key observations relating to the ocean forcing are temperature, salinity, and dissolved oxygen over the continental shelves, in order to understand the water mass modification in these regions. These measurements are also needed at the ice front and within the cavity, although retrieving these measurements remains a challenge. The report notes that monitoring of cavity melt rates from surface radars is a recent development that has the potential to offer great insights. The report also highlights the need for more meteorological observations to constrain the atmospheric forcing, as well as better observations of sea ice.

SOOS highlights the need for understanding ice-ocean interactions of a number of ice shelves to represent the variability in conditions found around the continent. The need for process studies to better understand the mechanisms at work is also highlighted. In addition, it would be desirable to maintain such observations over a long period. One possible approach suggested in the SOOS report is the creation of WOCE-style standard transects that could be repeated on an opportunistic basis but would facilitate persistent and repeatable observations, in addition to maintaining moored observations at key locations.

The observational strategy proposed by SOOS would include satellite-based and airborne observations of the ice sheet and shelf, and the bathymetry underneath, as well as bathymetric sounding of the continental shelf where existing data are scarce. Knowledge of the geometry of the cavity is acknowledged as a key target. The "straw-man" observing system aimed at capturing the ocean circulation would comprise ship-based CTD casts and moorings over the continental shelf and at the ice front. There would also be moorings deployed under the ice shelf, including some deployed by AUVs and others drilled through the ice shelf. These moorings would house a sound source for acoustic navigation for AUVs as well as enabling data transfer between moorings, AUVs and potentially a communication link to the operating science team. This combination of AUVs, moorings and occasional ship-based surveys is similar in many ways to the observational strategy that we are proposing, although we do propose incorporating additional technologies and strategies to those suggested in the SOOS report, as outlined below.

5.2.4 Challenges, Goals, and Innovations

5.2.4.1 Ice-Front Gliders/AUVs, Hydrography and Acoustic Tomography

There are a number of challenges and technical innovations associated with deployment and data retrieval of an armada of submersible vehicles in front of an ice shelf. As ocean gliders are typically deployed over the side of a ship, deployments would be performed in summer in sea ice-free conditions. In recent years the sea ice cover in Pine Island Bay has been minimal and thus a minor issue for deployment and retrieval in front of Pine Island Glacier. However, access to the ice shelf front is hampered by year-round sea ice in the Amundsen Sea, blocking the passage in to Pine Island Bay. Ships with ice breaking capabilities, e.g., R/V Polarstern or Oden, would be essential to access Pine Island Bay on a regular basis. Gliders could alternatively be deployed from the air, although this has never been attempted, would preclude in situ testing of the gliders' buoyancy, and requires further assessment of other logistical challenges associated with the airdrop.

With the current data storage technique, gliders must be retrieved by ship, so any observing system must account for the possibility that a ship might not be able reach them in a given year. Thus data must be stored until retrieval is possible or transmitted, e.g., via satellite, as often as possible. Retrieving the collected data could be difficult in winter because Pine Island Bay is largely covered with sea ice. In typical use, the gliders surface after every few dives and attempt to broadcast their data via satellite. This may be possible in front of PIG because of polynyas that are either formed by offshore winds or heat through upwelling of warmer waters. Gliders can be equipped with sea ice-detecting algorithms and instructed to surface when no sea ice is present. Note that no given spot in the polynya is open every day of the year, and even "clear" spots identified by remote sensing may contain a few centimeters of ice that would prohibit the gliders from surfacing.

Having this in mind, a simple strategy could be to deploy and collect the gliders and all of their data by ship every year, and then redeploy them for the following year. The batteries in the current generation of gliders can operate for around 6 months, so using present technology, this system would require two sets of gliders per year (assuming no losses)—one set sleeping while the others are active. This functionality exists in the current gliders, but further research would be required to determine whether they could be safely placed at the ocean bed in front of PIG. If not carefully positioned, they could become stuck in soft sediments at the ocean bed, or be advected far from their intended sleeping position by ocean currents. The forthcoming generation of gliders may offer extended battery life, and the in-development LRAUVs may have a range of over 2,000 km, sufficient to take weekly sections of the PIG front for a year. However, given the possibility that ships may be unable to retrieve the gliders/AUVs, potentially for years at a time, the ability to sleep is essential.

A more advanced approach is to provide fixed base stations with which the gliders/AUVs could navigate via echolocation. These could be attached to the base of the ice shelf and connected to a transmitter at the surface, or entirely positioned atop the ice with only a cable connection through to the water below. The drilling, satellite communication, and echo-sounding technology required to construct such devices currently exists. If the AUVs are equipped with inertial navigation systems, then a single sound source is sufficient for navigation purposes. Alternatively, a network of transponders can be used for triangulation by echolocation, with the added benefit that this network can relay messages between transponders. It is not known how far acoustic signals will travel underneath ice shelves, and this would need to be measured before deployment. Commercially available Seagliders are not currently capable of navigation by echolocation, and development and testing are required before deployment would be possible. It is also expensive and time-consuming to drill a hole large enough to accommodate an echo-sounding station, though somewhat less expensive if only cable-sized holes are required. Furthermore, another complication exists due the northward movement of the ice shelf front by 3-4 km per year [*Rignot et al.*, 2011]. If ships are able to access the front of the PIG, then an AUV could be used to deploy the echo-sounding station on the ice shelf base. An additional consideration is that these stations would need to be installed hundreds of meters inland from the ice shelf edge to ensure stability of the shelf during drilling. In an ideal situation, the gliders/AUVs could also dock with the sub-ice base stations and recharge their batteries via induction. This technology has yet to be developed, but could in principle allow the gliders/AUVs to operate beneath the PIG for several years, with no requirement for annual ship-based maintenance/collection.

Moored hydrographic measurements present an alternative and/or complementary measuring system to ice-front traversals by gliders/AUVs. The technology exists to drill a series of holes through the Pine Island shelf and attach moorings, and—if anchored atop the ice shelf—the data could be broadcast via satellite periodically. The main obstruction to conducting such a project is the cost of drilling large holes through the ice shelf. Additionally, the moorings would move 3-4 km per year with the ice shelf, which might break them if they came into contact with topographic ridges below. Hence a thorough assessment of the bathymetry is necessary. Making the moorings shallow enough to avoid such ridges may result in the measurements missing important components of the heat flux into the cavity. An alternative would be to affix moorings to the ocean bed ahead of the PIG, but they would need to be retrieved by ship and moved periodically to avoid being covered by the advancing ice shelf.

Acoustic tomography has been used successfully to calculate the temperature structure across wide sections of the open ocean, and presents an alternative means of mapping the temperature structure of the Pine Island Ice Shelf cavity. Installing the sound sources presents similar difficulties as hydrographic moorings, though only two sources should be required to provide temperature sections across the front of the PIG. The weak temperature stratification in this region may increase the signal-to-noise ratio in the measurements, and some development is necessary to determine whether the rugged underside of the ice shelf will interfere with the transmission of sound between sources. Even with optimum performance, this technology can only measure temperature profiles, whereas the salinity is crucial obtain an accurate estimate of the geostrophic velocity in this part of the ocean.

5.2.4.2 AXCTDs from Aircraft; SSH measurements; Icebridge; Potential for Sustained Observations

Accurate time-varying sea surface height (SSH) measurements will allow the determination of the steric and non-steric contributions (these components are not separable without other in situ measurements) to changes in the water mass near the ice cavity. SSH measurements will add to the suite of measurements proposed here to provide a view of not only the local environment, but also a far-field view for understanding correlative changes in the large-scale SSH and circulation.

SSH measurements from satellites have great potential for sustained oceanographic observations, if the data can be processed in such a way as to provide accurate, precise and reliable measurements. Changes in the height of the ocean surface (apart from very fast phenomena like surface waves and tides) are determined primarily by the underlying oceanographic circulation. In particular, ocean currents tilt the ocean surface (in some cases by many tens of centimeters), and these signals can be observed using space-borne altimeters. Furthermore, changes in subsurface density due to the presence (or absence) of warm water (which may be several degrees warmer than the ambient water) just outside of the ice shelf cavity may change the height of the ocean surface by as much as 5 to 10 cm. In principle, many of the satellite altimeters (such as the Jason missions, CryoSat-2 and AltiKa) measure such changes and may eventually be used to monitor the presence of CDW near the ice shelf cavities.

Available Assets:

- Current spaceborne assets
  - CryoSat-2: radar altimeter with polar reach (launched in 2010). Spot size: 300m by 1 km in Synthetic Aperture Radar mode.
  - Jason-2: very high precision radar (accuracy ~1 cm), with low inclination: turning latitude is 66°
  - AltiKa: Ka band radar with high inclination (launched in 2013)

- Future spaceborne assets
  - ICESat-2: lidar (launch in 2017). Spot size: 10 m.
  - Sentinel-3: will have a dual-frequency (Ku and C band) SAR altimeter (launch in 2015) with approximate the same resolution as the CS-2 SAR mode.
  - Jason-3 (launch 2015), Jason-CS (launch 2019). Both high precision, but low latitude.

- SWOT (launch 2020) swath mapping altimeter with high precision.

- Operation IceBridge
  - Current Operation IceBridge flights have Lidars capable of fine resolution sampling but these will be limited in time.

- Unmanned Airborne Vehicles (UAVs)
  - A long-range UAV (e.g. global hawk) equipped with lidar or radar will be useful for providing the kind of sampling need. NASA is developing such capabilities.

There are a number of challenges involved in the utilization of this technology to observe ocean heat flux into the cavity of an Antarctic ice sheet. The capability to use satellite-derived SSH for this purpose has not been demonstrated in the polar oceans. Initially it would be necessary to determine whether airborne and space borne assets can provide adequate resolution, sampling and accuracy to measure the expected changes in SSH associated with a change in ocean heat and meltwater fluxes. This is likely to require theoretical modeling work in addition to observations. In addition, many repeat hydrographic observations are needed in order to establish a clear relationship between surface height changes and the corresponding changes in subsurface temperature and salinity. Ship based hydrography could potentially be supplemented by airborne AXCTD probes, which provide accurate profiles up to 1,000 m depth and can be dropped in large leads in the sea ice with some effort.

NASA's new airborne mission OMG will address ocean/ice interactions around Greenland using aircraft deployed AXCTDs to survey the continental shelves surrounding Greenland, as well as glacier heights and extents for nearly all marine terminating glaciers around the periphery of the Greenland Ice Sheet. Although the oceanographic measurements are not designed to measure ocean fluxes (or transports) because of their broad spacing and once-per-year sampling, they will make it possible to trace changes in the large-scale temperature and salinity fields on the shelf from one year to the next. Similar strategies might be possible in certain regions around Antarctica, and this is a potential avenue for future study. Finally, one of the ancillary goals of OMG is to relate subsurface movement and distribution of warm salty waters (much like the CDW in the Southern Ocean) to changes in sea surface height as measured by altimetry. OMG will therefore serve as a building block for using SSH to monitor oceanographic change near the ice sheets.

Measurements of the sea surface in the presence of floating ice and icebergs will require special processing. Residuals in modeled tides and the geoid will hinder detection of changes in SSH. Therefore, a focused effort would be needed to demonstrate the feasibility of using this technology. The potential benefits of doing so suggest that such an effort would be worthwhile, especially as it would enable the use of historical altimetry observations extending back to 1992. Current activity working to improve coastal altimetry applications may be directed towards the Antarctic continental shelf.

5.2.4.3 Longer-Term Goals: Data Recovery, Autonomous Access to the Cavity

In the future, two major technological challenges must be overcome to permit persistent, sustained monitoring of the variability of ocean hydrography, air-sea fluxes, and lateral heat and salt transports at and near the mouth of ice-shelf cavities. The first concerns the recovery or transmission of measurements made by autonomous data-collecting systems, while the second concerns autonomous access to the cavity by these systems. Autonomous data-collecting systems include moorings and AUVs. Traditionally, long-term (>1 year) automated oceanographic data collection at a fixed location has relied on the use of moorings—stationary tethered lines instrumented with various sensors to measure ocean temperature (thermistor), salinity (conductivity cell), pressure (transducer), velocity (hydroacoustic current meter), or to transmit (or receive) sound signals (acoustic sources and receivers). These subsurface sensors, which may be set at fixed depths or programmed to travel along the mooring cable at fixed intervals, typically store their data onboard. Most commonly, these data are recovered only when the entire mooring package is physically retrieved. In some applications, the mooring is attached to a surface buoy, which may be instrumented to collect meteorological data. Being at the surface, the buoy may be equipped with a transmitter (Argos, Iridium, ORBCOMM, GOES, or METEOSAT) to allow the mooring and buoy data to be sent via satellite to scientists in real or near real time. AUVs, which are commonly instrumented with similar oceanographic sensors, may also employ satellite transmitters thanks to their ability to reduce their buoyancy and rise to the surface.

Unfortunately, even though satellite transmission technologies are well developed and are an effective means of remote data recovery, the operating environment at or near ice-shelf cavities render traditional methods of data recovery impossible. Seas at or near the mouth of ice-shelf cavities may be rough, iceberg infested, and inaccessible due to thick sea ice in the surrounding environment. Icebergs and sea ice can easily destroy any surface (or surfacing) instruments or may entirely block AUV surface access. Since oceanographic cruises are very expensive and typically of short duration, recovery ships cannot afford to wait until hazards or blockages associated with sea ice and icebergs clear on their own. Therefore, a long-term goal is to identify a robust technology that will allow the recovery of mooring and AUV data in such hostile environments.

One very promising idea to solve the data recovery problem is to use a network of acoustic modems to relay information from moorings or AUV to separate receivers beneath the ice-shelf cavity that are connected via cable to satellite transmitters at the surface. Solar panels and batteries at the surface could provide continuous power for the transmitters and the subsurface acoustic modems. Going further, one can imagine a network of surface power/data transmission stations spaced along the edge of an ice-shelf (preferably sufficiently inshore of the active calving zone), each of which provide data connectivity for distant moorings (e.g., moorings at the ice-shelf cavity mouth) and power to sensor packages attached to moorings or cables deployed in the cavity below. Indeed, such a cabled observatory would eliminate the need to recover moorings and AUVs at the cavity mouth. Yet another benefit of a cabled system is that in the event that a mooring or AUV is lost, the valuable data it collected would be saved.

Interestingly, this data recovery solution may also solve the autonomous cavity access problem. AUVs can determine their location via triangulation of sound signals from a network of acoustic sources. The network of cabled subsurface stations could be equipped with sound sources in addition to acoustic modems. As such, these stations could provide a fleet of AUVs the information they require to navigate pre-defined or user-specified trajectories across the cavity mouth or even within the cavity. The range and accuracy of the AUV navigation would be related to the number and density of cabled subsurface stations but could, in theory, allow AUVs to collect data inside the entire cavity and transmit that data to operators in near real time. If the AUVs are themselves equipped with acoustic modems, distant operators could use these data to send new instructions to the AUVs.

5.3 Remote Sensing

5.3.1 Measurement Requirements

5.3.1.1 Three-Dimensional Grounding Zone Structure

Until recently, the structure of the grounding zone has been inferred from satellite studies or from seismic, sounding radar and bathymetric studies of areas glaciated in the past [e.g., *Rignot et al.*, 1998; *Horgan et al.*, 2006; *Anderson et al.*, 2002]. These studies have resulted in advances in the understanding of the tidal motion of the grounding zone, episodic nature of grounding zone migration, and possibly ice-sheet stabilization due to sedimentation occurring at the grounding zone [*Alley et al.*, 2007]. Direct studies of the basal structures and properties at grounding zones remain sparse, but they have revealed that the structure of sedimentary deposits at the grounding zone depends on accommodation space created via basal melt and thus are dependent on ice-ocean interactions at the grounding zone [*Anandakrishnan et al.*, 2007; *Horgan et al.*, 2013]. For example, despite the relative abundance of grounding zone wedges in circum-Antarctic bathymetry [*Anderson et al.*, 2002], they are not ubiquitous at present day grounding zones [*Horgan et al.*, 2013]. This indicates that another mechanism stabilizes grounding zones against retreat and creates the characteristic grounding-line surface slope ramp [*Horgan et al.*, 2006]. Initial modeling studies indicate that the interaction of ocean water, subglacial water, and sediment may provide (de)stabilization mechanisms [*Parizek et al.*, 2013], but the dominant processes are dependent on local grounding zone structure. Thus, detailed continent-wide mapping of grounding zones is necessary, where results from satellite studies are tested against in situ mapping of ice, sediment, and ocean properties at a few critical grounding zones.

5.3.1.2 Strategies for Observations of Time-Dependent Processes in Ice-Sheet Grounding Zones

Tidally-induced processes in the ice-sheet grounding zones make interaction of subglacial water, sediment, and ocean water possible or, in some cases, likely [*Horgan et al.*, 2013]. These interactions may have both stabilizing [*Christianson et al.*, 2013] and destabilizing effects on grounding-line position [*Parizek et al.*, 2013], and further observations are necessary to determine dominant processes at particularly key grounding zones and then extrapolate these observations to a continental scale. High-frequency repeat observations needed to understand tidally-induced processes are particularly lacking. Surface deformation is observable over a tidal cycle using interferometric synthetic aperture radar (InSAR) complemented by high-frequency (1 Hz or less) GPS data. The three-dimensional basal structure of the grounding zone can be mapped using radar, active-source seismic, and repeat kinematic GPS surveys [e.g., *Horgan et al.*, 2013]. In addition to these techniques, new technologies should be deployed. Measurements of basal melt in ice-sheet grounding zones using an array of phase sensitive radars [*Corr et al.*, 2002] would be highly revealing. A similar set of measurements could also be conceived from an airborne platform. Finally, observations of the evolution of the subglacial water system, using dense passive seismic arrays would allow assessment of ocean water infiltration in grounding-zones and its subsequent effects.

Interferometric synthetic aperture radar and satellite laser altimetry data show that grounding zones migrate over a several-kilometers-wide zone during a typical tidal cycle with strong coupling between tidal forcing and the sub-daily velocity changes of the grounded ice [*Rignot*, 1998; *Bindschadler et al.*, 2003]. Due to the tidal flexure of the ice across the ground zone, the ice-shelf/ice-stream system may act as a viscoelastic beam partially supported by an elastic foundation with significant uplift (~1 cm) of the first few kilometers of grounded ice at low tide. This tidal uplift and depression cycle leads to basal pressure variations significant enough (~50 kPa) to affect subglacial water flow direction, till strength, ice-sheet flow, and grounding-line stability [*Walker et al.*, 2013; *Christianson et al.*, 2013]. Although observations are sparse, comprehensive geophysical campaigns over grounding zones indicate that they are more akin to subglacial estuaries than subaerial waterfalls, where subglacial water, ocean water, and sediment interact, likely causing unforeseen processes in this system [*Horgan et al.*, 2013]. Introducing some of these processes, such as basal melt across the grounding zone, enhanced lubrication across the grounding zone, or till compaction just inland of grounding can have dramatic effects on grounding-line stability in ice-sheet models, leading to both enhanced stability or more dramatic retreat, depending on grounding-zone conditions, grounding-zone width and subglacial topography [*Christianson et al.*, 2013; *Parizek et al.*, 2013]. Further coincident studies of tidal motion across the grounding zone, the basal interface in grounding zones, ocean water properties in the sub-ice-ocean cavity, and targeted coupled ice-ocean grounding-zone modeling are necessary to fully assess the importance of time-dependent grounding-zone processes to ice-sheet stability.

5.3.1.3 Ice Sheet/Stream/Shelf Surface Topography

The flow of ice is governed, in large part, by its surface slope. In particular, ice flow is largely affected by variation in topography at wavelengths greater than about 1 to 4 ice thicknesses [*Cuffey and Paterson*, 2010]. Most ice-sheet-wide digital elevation models (DEMS) are derived from spaceborne altimeter observations, typically compiled from several years of relatively sparse elevation data (10s of km). Thus, although often posted at 1-km resolution, such DEMs typically have much poorer resolution, approaching 10-km or more. Thus, substantial improvements in ice-sheet modeling could be realized with finer-resolution ice-sheet DEMs. Such DEMs also would provide major improvements in estimates of ice shelf melt [e.g., *Rignot et al.*, 2013]. Resolutions of 1-km or better should be sufficient for most ice-sheet modeling and processes studies, with perhaps finer resolution for thinner (<1 km thick) coastal ice.

For slowly evolving areas such as the central Antarctica Plateau, DEMS compiled from data collected over multiple years are sufficient. But for rapidly changing areas (i.e., thinning by meters per year), it is important that DEMs be derived from data collected as closely in time as possible and that the results are appropriately time-tagged. Where changes are large (e.g., Pine Island Glacier), sequential DEMs that have temporal resolution of at least 1 year are required.

5.3.1.4 Ice Sheet/Stream Bed Topography

Subglacial topography is routinely inferred through labor intensive ice penetrating radar campaigns. Recent advances, however, have shown that the coupling of these measurements with ice velocity vector information from interferometric SAR provides high resolution reconstructions of the glacier bed using a mass conservation approach [*Morlighem et al.*, 2014; *Rignot et al.*, 2014].

5.3.1.5 Ice Sheet/Stream/Shelf dH/dt and dM/dt

Ice-sheet-wide measurements of elevation change are important for determining ice sheet contributions to sea level rise [*Shepherd et al.*, 2012]. Such measurements with fine (annual or better) temporal resolution, however, also are critical for understanding the processes related to ice ocean interaction. For example, ice shelf thinning can increase speeds near the grounding zone, causing further thinning that results in grounding zone retreat. The resulting loss of traction as the ice ungrounds produces speedup and thinning above the grounding zone, which can rapidly spread inland. In such cases, the near-grounding zone thinning rate can evolve rapidly with time and the evolution of these rates is critical to determining how quickly thinning will induce further grounding zone retreat [*Joughin et al.*, 2010]. Thus, elevation for areas near rapidly evolving grounding zones should be measured at least annually with 10-cm accuracy.

5.3.1.6 Space-Based and Airborne InSAR

Recent InSAR analyses challenge the traditional model of slow evolution of ice sheets, assumed to have dynamic response times of the order of centuries to millennia. Although only a small fraction of the world's ice streams and glaciers have been sampled interferometrically, examples of short-term (days to decades) change are abundant [see *Joughin et al.*, 2011, and references therein]. In coastal areas, Interferometric Synthetic Aperture Radar (InSAR) also has been used to detect the retreat of glacier grounding zones [*Rignot et al.*, 2011], a sensitive indicator of ice sheet instability. The unanticipated variability in ice flow, largely observed with InSAR, prompted the Intergovernmental Panel on Climate Change to conclude in its 2007 assessment report:

Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude.

Although some progress had been made with the 5th IPCC assessment report, many of the fundamental challenges to understanding rapid ice flow changes remain. While existing sensors have revealed major changes, these observations, cobbled together from a variety of sensors, are far from systematic. Further progress requires a sustained set of observations with regular spatio-temporal sampling. No existing sensor can provide such coverage. Although some progress has been made with coordinated efforts by the international constellation of SAR instruments (Polar Steering Group PSTG), large coverage gaps remain. Progress is being made with the development of the joint NASA-ISRO SAR mission, scheduled for launch in 2020. This mission will provide continuous 12-day repeat coverage of all regions of rapidly evolving ice flow. In the interim, sustained efforts are required to obtain coverage as dense as possible in time and space from the existing SAR missions.

5.3.1.7 Altimetry for H & dH/dt (LIDAR/RADAR/Optical)

Radar altimeters have provided an extensive set of ice sheet observations (e.g., ERS-1/2 and EnviSAT), though often are limited by their large footprint. Recent improvements have been made with the launch of CryoSAT-2, but measuring ice sheet topography in high-slope regions with radar altimetry remains a challenge.

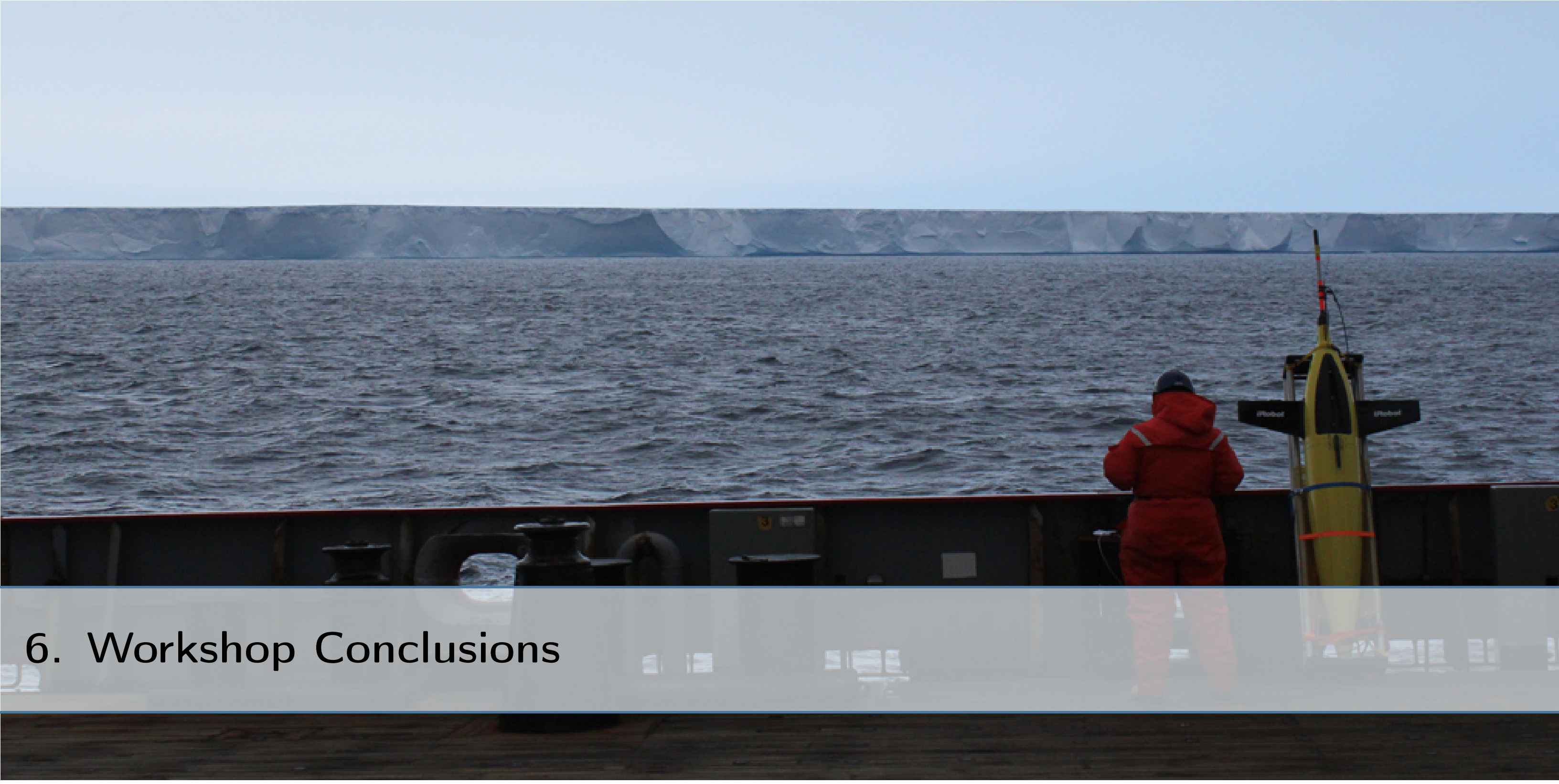
Many of the limitations of radar altimeters were overcome by the 70-m footprint of ICESAT-1, although clouds and other atmospheric phenomenon present additional challenges. Unfortunately, the limited life of the ICESat-1 lasers meant that the instrument could only acquire data for limited periods and only on every 3rd track of the original coverage plan. With three pairs of LIDAR beams operating without interruption, the launch ICESat-2 in 2017 will provide much improved measurements of ice-sheet elevation and elevation change.

Despite the improvements that ICESat-2 will provide, it will still not produce sufficient spatial resolution (~3 km at 71° latitude) for many studies ($\leq$1 km), particularly in ice-sheet modeling in coastal areas. Recent advances have been made with optical stereo from the WorldView satellites, which can provide meter-scale relative accuracy at horizontal resolutions of a few meters. Especially when combined with control from more accurate altimetry observations, these sensors can meet much of the need for fine spatio-temporal resolution elevation data over much of the rapidly changing areas of the ice sheet, provided that there is continued access to the data. While the applicability of these data is more limited for precise elevation change measurements, they can provide useful results where strong (>1 m/yr) thinning is underway.

DLR's TanDEM-X data probably provide the most significant source of high-quality, high-resolution topographic information in Antarctica, but access to these data remains limited due to the commercial character of the mission.

5.3.2 Short-Term Challenges

Recently, the InSAR-capable constellation allow for short repeat interval repeat observations (e.g., Cosmo-Skymed provides 4 repeats every 16 days with time intervals ranging from 1 to 8 days). In the near term, we need to develop algorithms that combine phase and speckle tracking observations from ascending and descending orbits to produce time series of 3D vector surface velocities. This approach should no longer assume constant secular velocities, but will rather allow one to find periodic (e.g., tidal) and other transient behavior. Of particular interest is looking at fortnightly tidal modulation of upstream velocities, rapid response during calving events, and crack evolution in ice shelves.



6. Workshop Conclusions

Over the course of the workshop, it became clear that there was a strong need for leadership in the scientific community on the topic of ocean-ice interactions in Antarctica. The potential for global catastrophe caused by rapid ice loss in Antarctica is very real. Although this report does not provide a complete roadmap for addressing this issue, we have attempted to prioritize research goals and have identified the ice-shelf cavities as a top research priority.

Identifying such a priority was not easy, given the varied interest, experience and expertise of our diverse participants. We discovered early on that it was necessary to identify a single overarching scientific question to guide our thinking and allow us to prioritize research activities. Because of the potential societal impacts, we formulated the following overarching science question to guide our decisions: ***How much will global sea level rise by 2050, and by 2100?***

Time and again we returned to this in our discussions. It became clear that such a narrowly worded question was critical in order to focus on the most important and effective research activities. An abundance of fascinating scientific questions remain to be answered about the interactions between the ice sheets and the ocean, land, and atmosphere. But society will demand that the scientific community focus their attention on priorities such as this.

In Section 5.1, we outline research activities and technology development that we feel will most effectively address the question: How much will global sea level rise by 2050, and by 2100? Study of the cavities between the floating ice shelves and the sea floor is critical to improve our ability to understand and predict how the Antarctic Ice Sheet will react to a warming world. But we also hope that the scientific agencies and broader scientific community will adopt a similar focus as the one that guided our workshop. Without such focus we may be forced to learn about ice sheet collapse the hard way—by watching it unfold before our eyes.

7. Appendices

7.1 Workshop Proposals

Workshop 1

Sea level rise remains one of the most poorly predicted and potentially costly impacts of human caused climate change. Projections for sea level rise between now and 2100 range from 1 to 7 feet, which could affect hundreds of millions of people worldwide. This dramatic range of uncertainty frustrates decision making at all levels, from government to industry to individuals. Global sea level depends on a complex, inter-connected system with many components. But the ice sheets of Greenland and Antarctica, which contain ice equivalent to 80 meters of sea level, are the most critical and most uncertain components of this system.

Recent work has suggested that interactions between the ocean and marine terminating glaciers may control the fate of some ice sheets. For example, in West Antarctica much of the ice rests below current sea level and is connected to the oceans through ice streams and outlet glaciers like Pine Island and Thwaites. It has been postulated that these two glaciers—both of which are thinning rapidly—are reacting to warm Circumpolar Deep Water that is intruding from the north, a process that could ultimately cause the collapse of the West Antarctic Ice Sheet and potentially result in 10 feet of global sea level rise.

We propose to study this potential "tipping point" of global sea level rise. In particular, we will develop scientific requirements for an observing system to monitor the ocean conditions near key outlet glaciers such as Pine Island and Thwaites, test hypotheses for relating ocean conditions to ice loss, and cultivate a new generation of sea level rise projections. Although many observational assets are already devoted to the Antarctic cryosphere, the ocean near Antarctica remains poorly sampled and long-term campaigns will be required in order to answer the fundamental questions that stymie present-day sea level projections. Given harsh conditions and remote locations, remote sensing techniques will likely play an important role along with more traditional in situ observing systems. Lessons learned from observational and numerical studies of particular outlet glaciers would be used to identify and better understand other regions of key ocean-ice interactions.

Workshop 2

This study will explore integrated field programs and numerical studies to describe high frequency variability at the ocean-ice interface in Antarctica, which includes dynamics impacting the ice sheet, ice shelf, and ocean circulation, both over the continental shelf and within the ice shelf cavity. We will bring together experts in the fields of oceanography, glaciology, solid mechanics, and technology to assess the current state of knowledge. A major goal will be to identify measurement requirements needed to capture pertinent physical processes that range from the long-term (decadal) evolution of the Antarctic ice sheets down to variability that occurs over a tidal cycle. These measurement goals will be developed into a set of modeling and field campaign priorities with an emphasis on persistent measurements, focused scientific requirements and a high likelihood of realization.

At the second workshop, we will synthesize the results of the sub-team studies on spatial and temporal measurement requirements. This will enable us to design two to three key instrument or experimental concepts for further development. Ultimately the goal is to identify key gaps in our ability to observe ocean-ice interactions, in particular those that are likely to feed back on the long-term evolution of the ice sheets and global sea level rise. This may include quantifying the oceanic mesoscale or "eddy" heat flux to the ice shelf-ice sheet system or temporal evolution of the grounding zone at sub-daily frequencies. The study participants are surveying the literature on this subject and compiling information on future field studies. This information will be detailed in the final report with an emphasis on new and innovative ways of integrating existing technologies.

7.2 List of Participants

Workshop 1

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