Position Analysis

THE ANTARCTIC ICE SHEET & SEA LEVEL

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Position Analysis: The Antarctic Ice Sheet and Sea Level

ISSN: 1835-7911

Tel: +61 3 6226 7888
Fax: +61 3 6226 2440
Email: enquiries@acecrc.org.au
www.acecrc.org.au

Cover image: Surface meltwater floods off the Sørsdal Glacier, East Antarctica. Credit: Sue Cook.

The Antarctic Climate & Ecosystems CRC is Australia's primary vehicle for understanding the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. Our purpose is to provide governments, industry and the public with accurate, timely and actionable information on climate change and its likely impacts.

Scientific Contributors

David Gwyther
Sue Cook
Ben Galton Fenzi
Alex Fraser
Felicity Graham
Kazuya Kusahara
Adam Treverrow
Lenneke Jong
Jason Roberts
Steve Rintoul
Anthony Worby
Tas van Ommen

Contents

Glossary

ApRES: An Automatic phase-sensitive Radio Echo Sounder is deployed on the surface of the ice, and uses radio wave interference to measure small changes in the thickness of the ice or the internal layers. Using this instrument, we can infer melting at the bottom of an ice shelf, thinning or thickening of the ice due to dynamical processes and the compaction of snow into ice.

Basal melting: Seawater can melt the bottom (base) of the ice shelf.

Bathymetry: The seabed topography is called the bathymetry.

Buttressing: Ice shelves provide a buttressing or backstress on their tributary glaciers. Removing or weakening the ice shelf can cause an acceleration of glacial flow into the ocean and an increase in global mean sea level.

Continental shelf processes & cross-shelf exchange: The continental shelf is the plateau of seabed that surrounds many of the Earth's continents. Ocean processes that transfer warm water from the open ocean to the continental shelf (cross-shelf exchange) can drive melt of Antarctic ice.

EAIS: East Antarctic Ice Sheet.

Glacier acceleration: If a glacier is accelerating in speed, it must be contributing more ice into the ocean, leading to sea level change. The acceleration of a glacier can result from thinning and loss of its restraining ice shelf.

Grounding zone: The region where an outflowing glacier is buoyed by seawater and begins to float is called the grounding zone. Monitoring the position of this is important for assessing whether a glacier is retreating or advancing.

Ice/ocean interaction: Processes that control how ice and seawater interact with each other.

Ice sheet & marine ice sheet: The Antarctic Ice Sheet has formed over millions of years through the slow accumulation and compaction of snow. In places, it is over 4 kilometres thick. Where this ice sheet rests on bedrock below sea level, it is called marine ice sheet, and is more susceptible to rapid loss, or discharge, into the sea.

Ice shelf and cavity: Ice shelves form where the ice sheet flows off the continental bedrock and begins to float on the surface of the ocean. An ocean-filled cavity exists beneath the ice shelf.

IPCC and AR5: Intergovernmental Panel on Climate Change and the fifth Assessment Report, published in 2013.

Mass budget: The ice sheet is sustained through the budget between mass loss processes (e.g. iceberg calving and basal melting) and mass gain processes (e.g. snow accumulation).

Modelling & coupled models: Computer models use algorithms, developed from theoretical and observational analyses, to simulate the approximate behaviour of a system. A coupled model combines distinct models to represent the interactions between parts of the Earth system.

Parameterisations: Some physical processes are difficult to explicitly include in model simulations and need to be represented, or parameterised, in a simpler form.

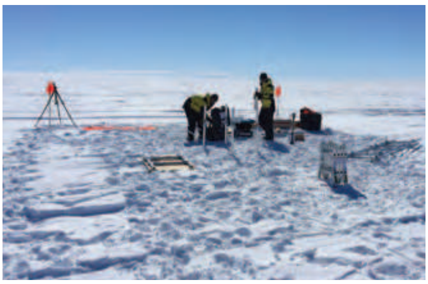
Paris Agreement: This agreement sets in place a framework for all countries to take climate action from 2020, including a global goal to hold average temperature increase to well below 2°C and pursue efforts to keep warming less than 1.5°C above pre-industrial levels.

RCP: Representative Concentration Pathways.

Sea ice: Ice that floats on the ocean, formed by freezing seawater and snowfall.

WAIS: West Antarctic Ice Sheet.

SUMMARY



Ben Galton-Fenzi

Installing an ApRES unit to monitor small changes in ice shelf thickness.

The rate at which ice discharges from the great ice sheets into the oceans is presently the greatest source of uncertainty in projections of global mean sea level rise. Reducing the uncertainty of ice sheet behaviour is important since the two great parts of Antarctica – the East and West Antarctic ice sheets – hold around 70 per cent of the world's fresh water and more than 90 per cent of its ice. If the ice sheet melted completely, global mean sea level would rise by about 60 metres, although the likelihood of this occurring over the next two centuries is low.

Key points from recent advances in research are as follows:

- Antarctica continues to lose ice at an accelerating rate, contributing about one quarter of a millimetre of global mean sea level rise per year over the period from 2000–2011.
- The ice loss from the Antarctic continent is from the coastal edge of the continent, particularly in areas where the ice sheet is termed "marine-based" meaning it rests on bedrock below sea level.
- Retreat of parts of the marine-based West Antarctic Ice Sheet (WAIS) that are underway are likely driven by changes in ocean heat supply to the fringing ice shelves.
- The East Antarctic Ice Sheet (EAIS) is likely to make a larger contribution to sea level rise than thought, as it contains about five times more potential to contribute to global mean sea level rise than WAIS.
- Recent discoveries of deep seabed channels and warm ocean waters near the EAIS may drive rapid melting of the Totten Glacier, verifying model predictions that relatively warm deep ocean water is present and causing variable melting and dynamic behaviour.
- Research on the Totten Glacier suggests the potential for enhanced ocean driven melting in the future with consequent retreat of the ice. Geological evidence suggests the Totten catchment has experienced large, rapid retreat in the past.
- New model simulations predict that the Antarctic contribution to global mean sea level rise will be larger and more rapid than has been estimated, with an additional 1 metre of sea level by 2100, under business-as-usual emissions scenarios. This new modelling, however, includes additional physical processes that are still relatively untested, highlighting the need for research focussed on both specific regions and physical processes.
- Research on past warm periods supports the view that sustained warming of around 2°C to 3°C above pre-industrial global mean atmospheric temperatures is associated with multi-metre sea level rise which must come from melting of Antarctica and Greenland ice sheets.

FIGURE 1: Map of Antarctic ice sheet with location labels

- Advances in our ability to observe and simulate the behaviour of ice sheets, ice shelves and their interaction with the ocean and atmosphere will deliver better assessments of the vulnerability of the Antarctic Ice Sheet to climate change and more reliable projections of global and regional sea level rise.

The ACE CRC and its partners are working to provide decision-makers with scientific information to guide policyon sea level rise mitigation and adaptation. Researchers are focussed on understanding how the Antarctic ice sheet is likely to respond to a warming ocean, and which regions face the greatest risk of increased ice discharge into the sea. Research efforts use a wide variety of methods, from field surveys of the Antarctic ice sheet and oceans to computer modelling of complex ocean-ice sheet interactions. Scientific insights gained through this research are helping to assess the vulnerability of the Antarctic Ice Sheet and provide more reliable projections of global mean sea level rise and its geographical distribution.

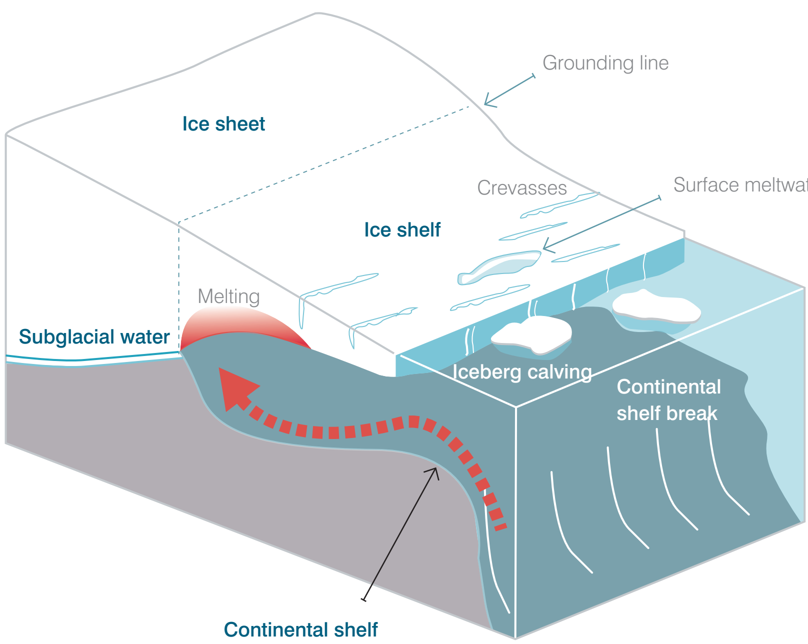
PART A
SCIENCE OVERVIEW

The Antarctic Ice Sheet is the single largest mass of ice on the Earth, with enough water to raise global mean sea level by nearly 60 metres [13]. This vast mass of ice has formed through the accumulation and compaction of snowfall over millions of years, and in some places is more than 4 kilometres thick. Under the influence of gravity, this ice is continually flowing towards the oceans in broad slow ice sheet flow (up to 10 metres a year) or fast-moving glaciers that can flow at a rate of several kilometres a year.

The ice sheet rests upon continental bedrock, but as the outlet glaciers reach the ocean they begin to float. These floating extensions of the Antarctic ice sheet are known as ice shelves. Ice shelves vary in size, from a few kilometres, to gigantic floating extensions of Antarctica, some 750 kilometres wide, such as the Ross Ice Shelf. Likewise, the thickness of ice where it starts to float can range from a few hundred metres, to over 2500 metres, for example beneath the Totten Glacier ice shelf. Ice shelves are also in a constant state of flux. They gain ice from glaciers flowing from the ice sheet and snowfall on the surface, and lose ice through calving of icebergs and melting by the ocean below.

The ocean cavity beneath the floating ice shelves is difficult to observe. Sea ice often prohibits access by ship to the ice shelf front, while drilling through ice shelves is expensive and logistically complicated given the thickness of the ice and by the crevassed and unsafe environment. Consequently, our

FIGURE 2: Schematic of ice sheet-ocean interaction. The ice sheet begins to float at the grounding line, forming an ice shelf. Warm water originating from off the continental shelf causes basal melting. Crevasses and meltwater on the ice shelf surface can causing iceberg calving and possible disintegration. Subglacial water and other bed processes control the flow of the grounded ice sheet.



R. Trebilco

A small tabular iceberg floats amongst sea ice.

knowledge of the ocean environment below the ice shelves is limited.

When ice shelves are melted by the ocean, this is referred to as basal melting. If the rate of basal melting increases faster than the input of new ice from the glacier upstream or snowfall on the upper surface, then the ice shelf will thin. As the ice shelf thins, it no longer provides as much force to hold back the flow of the glacier upstream, referred to as buttressing. The glacier will accelerate and release a greater volume of ice into the ice shelf. As this happens, the point at which the ice shelf begins to float, the grounding zone, will move inland. The acceleration in glacier flow and retreat of the grounding zone means more ice is added to the ocean and thus sea levels rise.

As a result, the evolution of the Antarctic ice sheet is strongly linked to changes in the ocean and atmosphere, and so understanding the sensitivities of the Antarctic continent to climate change is a current focus of intense research.

MELTING ICE SHEETS & RISING SEAS

Understanding how the ice sheets have responded to past climate change gives us insights into how sea level may change into the future. Ice cores and paleo-ice sheet models show that, during the last interglacial period (125,000 years ago), sea levels were 5 to 9 metres higher than present [10]. The partial or complete melting of the Greenland ice sheet and mountain glaciers, and ocean thermal expansion, contributed to this figure. However these factors alone are insufficient to account for sea level rise during that period, suggesting Antarctica must have contributed about 3 to 4 metres of sea level rise.

To understand Antarctica's current and future contribution to sea level rise, we must measure Antarctica's mass budget. The mass budget of the Antarctic ice sheet refers to the difference between mass gained from snowfall and mass lost by melt from the ice shelves and the calving of icebergs at the coast. Calculating the net mass budget is complex, because changes in snowfall, basal melting and iceberg discharge vary significantly by region. The best available methods for calculating mass (see box) show that Antarctica lost about 1500 to 2500 gigatonnes of ice between 1991 and the end of 2011 [35]. Noting that 360 gigatonnes of ice mass is equivalent to about 1 millimetre of global sea level rise, the total contribution to sea level rise from Antarctica over this 20-year period was about 4 to 7 millimetres (an average rate of 0.2 to 0.35 millimetres a year). Over roughly the same period, recent estimates of global mean sea level rise range from 2.6 to 2.9 millimetres per year, and show an increase in the rate of rise after small biases were corrected in the early part of the satellite altimeter record [42].

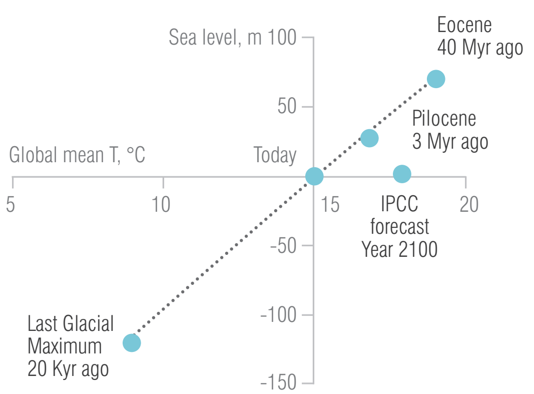


FIGURE 3: The IPCC forecast is less than 1 metre of sea level rise by 2100, while geological reconstructions suggest that a sustained 3°C warming would result in around 50 metres of sea level rise. Figure and caption adapted from Archer, D. (2012). *Global warming: understanding the forecast.* John Wiley & Sons.

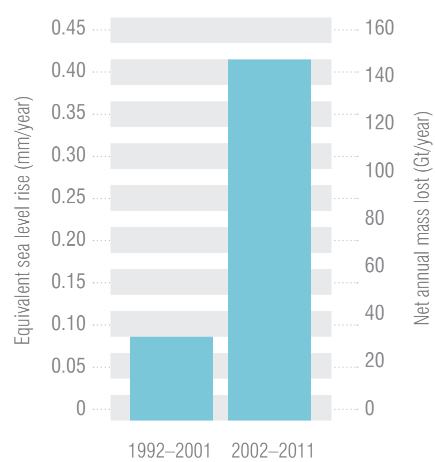


FIGURE 4: Average annual rate of Antarctic ice loss (1992–2011)

Large uncertainties remain regarding the potential contribution of the Antarctic ice sheet to global mean sea level rise. Projections of global mean sea level rise between now and 2100 vary widely depending on modelling methods and assumptions regarding future greenhouse gas emissions scenarios (Representative Concentration Pathways – RCPs). The projections in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) range between 0.26 and 0.82 metres by the end of the century under four separate emissions scenarios. The report finds that ocean warming and ice sheet losses are "very likely" to continue to drive the rate of sea level rise higher than the period between 1971 and 2010. The authors conclude that, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the likely range during the 21st century. However, there is medium confidence that this additional contribution would not exceed several tenths of a meter of sea level rise by 2100.

MASS BUDGET METHOD: SNOWFALL IN MINUS ICE OUT

Methods for measuring ice mass changes rely heavily on satellite observations, and fall into three main categories:

- The mass budget method uses measured snowfall (input), combined with losses across the margins (from measured velocity and thickness – output), to compute gains or losses over time.
- A second method monitors surface elevation changes to determine losses (lowering elevation) or gains (rising elevation) and infer mass changes.
- A third method uses satellite measurements of gravitational pull as the instruments pass over the ice to 'weigh' the ice sheet directly.

Christopher Michel

Iceberg, Cuverville Island.

There is no consensus on the ultimate thresholds for such large scale retreat of marine based ice, however two studies support the view that large losses are avoidable under the lowest emissions scenario (RCP2.6). One recent study [9] indicates that the RCP2.6 emissions pathway could restrict total Antarctic sea level contributions to just 0.20 metres by 2500, whereas the next highest emissions scenario used by the IPCC (RCP4.5) produces 0.32 metres this century rising to 5m contribution by 2500. Another study using a different ice sheet model finds similarly that substantial Antarctic loss can only be prevented by limiting greenhouse emissions to RCP2.6 levels, with losses of 0.6 to 3 metres by 2300 for higher emissions pathways [17].

New ice sheet modelling [9] raises the possibility of more rapid and early ice retreat. This work incorporates processes not typically modelled, such as hydro-fracturing, which happens when surface meltwater penetrates crevasses causing them to weaken, as well as the collapse of ice cliffs. This model achieves a better agreement with palaeo sea-level data from past warm periods, suggesting it may be more in line with future responses.

Notwithstanding prospects of multi-metre sea level rise it should be noted that even modest rises have severe consequences. Work by past ACE CRC and CSIRO researchers shows that for even a 0.50 metre rise in sea level, flooding recurrence intervals decrease by typically a factor of 300 [22]. In other words, a once-in-a-century flood event becomes a several-times-a-year event.

FIGURE 5: IPCC emission scenarios suggest up to 6.63 metres of sea level rise by 2500. New modelling[9] projections found 15.65 metres resulting from ice sheet processes, in addition to the IPCC projections.

FUTURE SCENARIO	2100	2500
Low emissions	0.26–0.53	0.50–1.02
High emissions	0.21–0.83	1.51–6.63
RCP2.6 + ice sheet dynamics [9]	0.11 ± 0.11	Additional 0.25 ± 0.23
RCP8.5 + ice sheet dynamics [9]	Additional 1.05 ± 0.3	Additional 15.65 ± 2.0

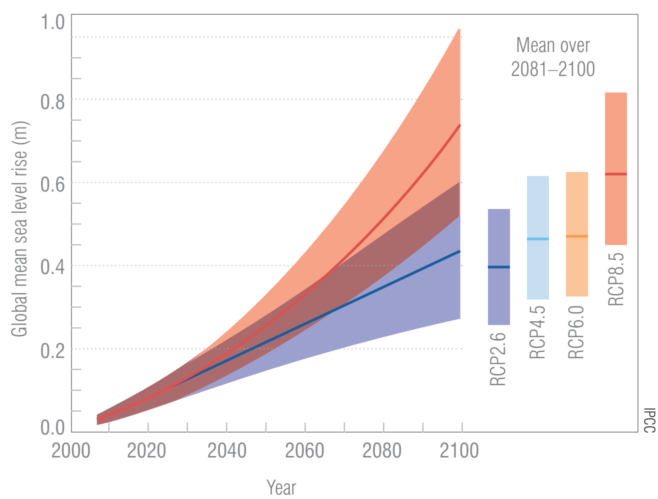
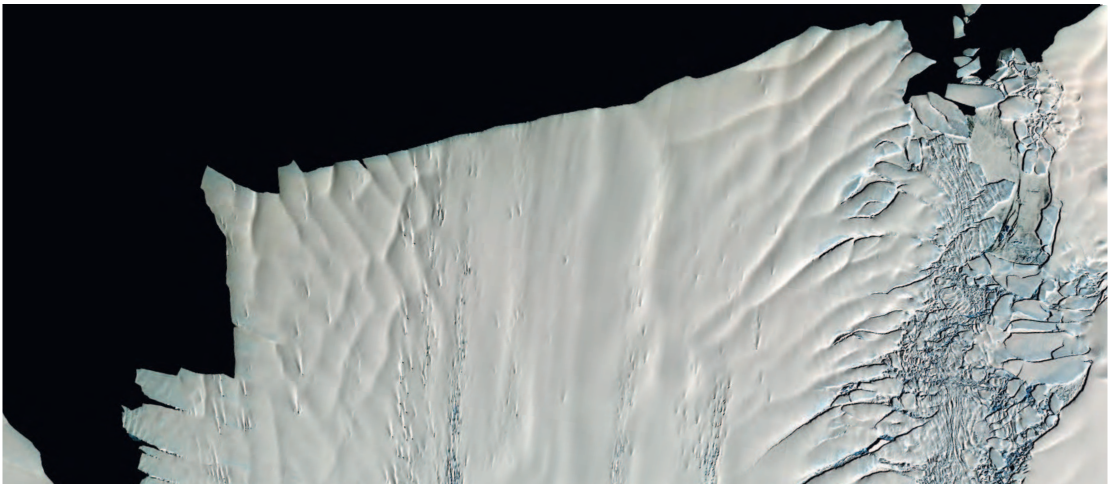


FIGURE 6: Range of IPCC sea level rise projections from different emission scenarios.

REGION OF CHANGE

AMUNDSEN BAY, WEST ANTARCTICA



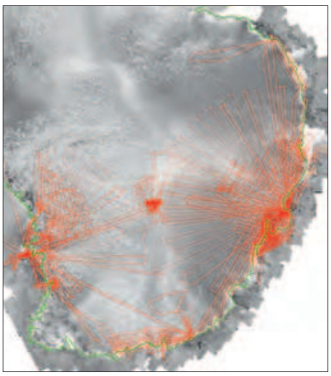
NASA

Pine island Glacier satellite image.

Several regions around Antarctica have been observed to be rapidly changing. The Amundsen Bay region of West Antarctica is today known for having the fastest retreating glaciers on the continent. One such glacier is Pine Island Glacier. Satellite and field observations have shown a consistent thinning of the ice shelf and acceleration of the glacier [23,41]. This has caused the glacier to retreat further inland. As the glacier retreats, it cannot find a stable position. As a consequence, studies have shown that it may irreversibly retreat inland [11]. It is thought that this retreat of the glacier began in the 1940s as the ocean responded to climate and drove higher basal melt rates [37].

Observations from ship and mini-submersibles found relatively warm seawater present, with temperatures around 2°C. Relative to the freezing point of deep ice in contact with seawater (~-3.5°C), the observed seawater is very warm and is causing rapid melting [24]. In the 1970s, continued melting thinned the ice shelf enough such that it retreated from a seabed ridge [37], allowing warm water to access newly exposed deep ice and drive rapid melting. Models suggest that this region of ice sheet has been irrevocably destabilised [25], and will eventually contribute possibly [3] metres to global sea levels over the coming centuries to millennia [12].

OCEAN INFLUENCES



Red lines show flight paths of aircraft used as part of the ICECAP collaboration.

Changes to Antarctic ice shelves are driven primarily by basal melting by the ocean. If the ocean warms, and warmer waters reach the ice shelf cavity then the ice shelf will melt more quickly. As ice shelves thin or weaken, they provide less buttressing with the consequence that more ice flows off the continent and into the ocean, raising sea level. We therefore need to understand how the ocean interacts with floating ice shelves to assess the Antarctic contribution to past, present and future sea level rise.

Marine ice sheets – ice sheets grounded on bedrock that is below sea level – are potentially less stable because their floating ice shelves are exposed to the ocean. Basal melting occurs when water below the ice shelf is warmer than the freezing point. The freezing point of seawater decreases with depth: it is about -1.9°C at the surface of the ocean, but about -4°C at a depth of 2500 metres. As a result, water that is relatively warm, e.g. -0.5°C, will produce strong melting at the base of an ice shelf.

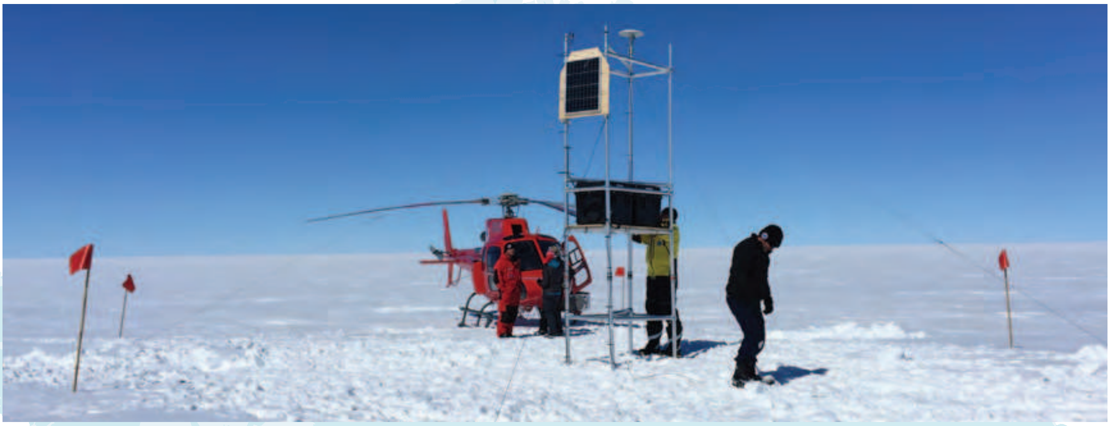
Melting of ice releases freshwater which is much lighter than the surrounding salty seawater. As the buoyant melt-water rises and exits the cavity underneath the ice shelf, water from outside the cavity is drawn in to replace it. The melt-water may also re-freeze to the base of the ice shelf if it becomes cooler than the local freezing point.

The rate of basal melt depends on how much heat is supplied by the ocean to the base of the ice shelf. The ocean heat supply, in turn, depends on both temperature and ocean currents. Where ocean currents transfer warm water from the open ocean across the continental shelf to the margin of Antarctica, basal melt rates are high. Where cold water fills the cavity below the ice shelf, basal melt rates are low. Tidal flows and small-scale processes like turbulent mixing and ice formation can also affect the rate of basal melt [20,16].

Warm water floods the continental shelf in parts of West Antarctica. In these regions, an increase in ocean heat flux has been linked to an increase in mass loss from both ice shelves and the ice sheet (see Amundsen box). Until recently, East Antarctic ice shelves were believed to be largely isolated from warm ocean waters and likely to experience low rates of basal melt. New evidence from satellite and ship observations, studies of past sea level, and numerical models show that the Totten region of East Antarctica is exposed to warm ocean waters that drive rapid basal melt (see Totten box).

REGION OF CHANGE

THE TOTTEN GLACIER, EAST ANTARCTICA



Ben Galton-Fenzi

Scientists install a GPS receiver on the Totten Glacier to measure its velocity.

Most attention to-date has focused on the rapidly changing glaciers in West Antarctica. East Antarctica, which holds most of Antarctica's ice, was thought to be more stable. However, new scientific evidence suggests that some parts of East Antarctica are also undergoing rapid change and may make a substantial contribution to future sea level.

The Totten Glacier, located roughly south of Perth in Western Australia, is the largest glacier in East Antarctica and contains a volume of ice equivalent to 3.5 metres of global sea level rise. Recent satellite observations have shown the Totten Glacier is thinning [5] and the grounding zone is retreating [28], like the rapidly melting glaciers in West Antarctica.

In West Antarctica, mass loss from glaciers has been linked to basal melt by warm ocean waters. East Antarctic glaciers were thought to be less exposed to warm ocean waters, so it was not clear what was driving the melting inferred from satellite measurements.

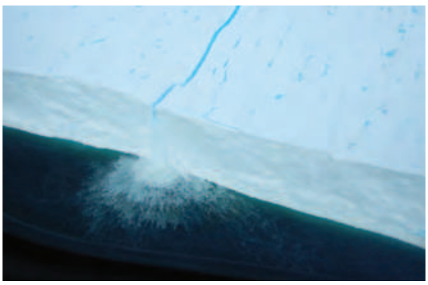
Exploratory modelling studies gave an early indication that warm water might reach the base of the ice shelf after all [19]. In 2015, Australian scientists aboard RV *Aurora Australis* made the first measurements at the front of the ice shelf and confirmed that warm water flowed under the ice shelf driving rapid rates of basal melt [31].

Field work is now being conducted on the ice shelf and glacier by scientists from the ACE CRC and partner organisations, using phase-sensitive radar and GPS equipment on top of the glacier to measure changes in velocity, thickness, basal melting, and other dynamics related to the glacier flow. Data from these studies will also be combined with oceanographic and airborne observations and models to assess the vulnerability of this part of East Antarctica to further warming.

Atmospheric processes are important to the mass budget of the Antarctic Ice Sheet. The ice sheet is constantly accumulating new mass as snow falls in the interior. In turn, this drives the flow of ice out towards the ocean. Atmospheric processes are also thought to be able to drive collapse of ice shelves and have important controls on the air-sea fluxes that can control the seawater that can drive basal melting.

ATMOSPHERIC INFLUENCES

Predictions of future snowfall around Antarctica are typically generated by regional atmosphere models, but these models must utilise the limited observations of Antarctic weather and climate for their evaluation and calibration. Satellite instruments, observing in the microwave bands, are able to penetrate the surface of the Antarctic Ice Sheet to a depth of several tens of metres [3]. With careful processing of this satellite data, in combination with ground measurements, scientists at the ACE CRC are able to make estimates of the distribution of Antarctic snowfall. As this data is completely independent from the estimates from atmospheric modelling, it provides crucial evaluation of the models used to estimate the mass inputs to the ice sheet.



Melting on the surface of the Sørsdal Glacier flows off the edge of the glacier and into the ocean. Surface melting can destabilise the glacier or ice shelf, making it more vulnerable to dramatic collapse.

The cold air temperatures around the continent suggest surface melting is perhaps a negligible contribution to mass loss from Antarctica. However, surface melting does occur in many coastal regions during the summer, and although it generally refreezes again during winter, it can affect the ice sheet in other ways. If surface meltwater ponds in regions where there are crevasses, the additional pressure created by the water can force crevasses to open further, in a process known as hydrofracture. By widening and deepening crevasses on a floating ice shelf, hydrofracture increases calving rates and is thought to be one of the causes of rapid ice shelf disintegration [34]. As the atmosphere warms, surface melting and hydrofracturing may increase and enhance the retreat of Antarctic ice shelves [9].

If hydrofracture occurs on the grounded portion of the ice sheet, it can provide a conduit for water to travel from the surface of the ice sheet to the bedrock below. The arrival of additional water at the base of the ice sheet changes the local water pressure, which can affect the ice sheet's sliding speed. This process has not yet been observed in Antarctica, but is known to occur in Greenland [8] and ACE CRC staff are now involved in a project monitoring surface lakes in East Antarctica hoping to observe the first directly-recorded lake drainage there.

REGION OF CHANGE

LARSEN C ICE SHELF, ANTARCTIC PENINSULA

The Larsen C ice shelf is the fourth largest ice shelf in Antarctica and is located in the Antarctic Peninsula. This region has experienced one of the highest regional atmospheric temperature increases on the planet (2.8°C in 50 years). Since 2014, a large and growing rift has been identified in the Larsen C ice shelf. In late 2016, this rifting accelerated and it is expected to result in calving of a large iceberg in the near future. This iceberg, with an area over 5000 square kilometres will remove about 10% of the ice shelf, and be one of the larger icebergs observed (the largest iceberg calved from the Ross Ice shelf in 2000 and was 11,000 square kilometres).

This iceberg calving does not directly lead to an increase in sea level as the ice is already floating. However the remaining ice shelf retards the flow of ice from the continent, and complete removal of the shelf would lead to increased discharge of this grounded ice and so to sea level rise. This was observed when the Larsen B ice shelf collapsed completely in 2002. Tributary glaciers increased their speed more than five-fold with a consequent impact on sea level. The impact here was small because the relevant tributary glaciers were not large. Larsen C is similar in this respect.

Current understanding suggests the Larsen C calving is not directly attributable to climate change, and it appears to be part of the pattern of growth, calving, retreat and regrowth seen in all ice shelves. Regional warming may have contributed, however, and the event may be unusual: the extent of the remaining ice shelf will be the smallest so far observed, and evidence from ocean sediments suggests that it is likely to be the smallest in tens of thousands of years.

A large rift in Larsen C ice shelf, photographed from a NASA research aircraft.

John Sonntag, NASA

Compared with the ocean and atmosphere, excluding fracturing processes, the response timescales of ice can be slow: in the interior of Antarctica, the flow of ice may be only a few centimetres per year, and even in the fastest flowing regions on the continental margins, outlet glaciers rarely flow faster than 10 kilometres a year.

INTERNAL ICE SHEET PROCESSES

Over recent decades, the availability of high-resolution satellite data has improved estimates of ice surface velocities. From these data, scientists are able to examine how ice flow has changed over time, and infer the processes or mechanisms that have governed this change. These include changes to the basic mechanisms of ice flow or dynamic feedbacks between the ice sheet and its surrounding environment.


Shutterstock

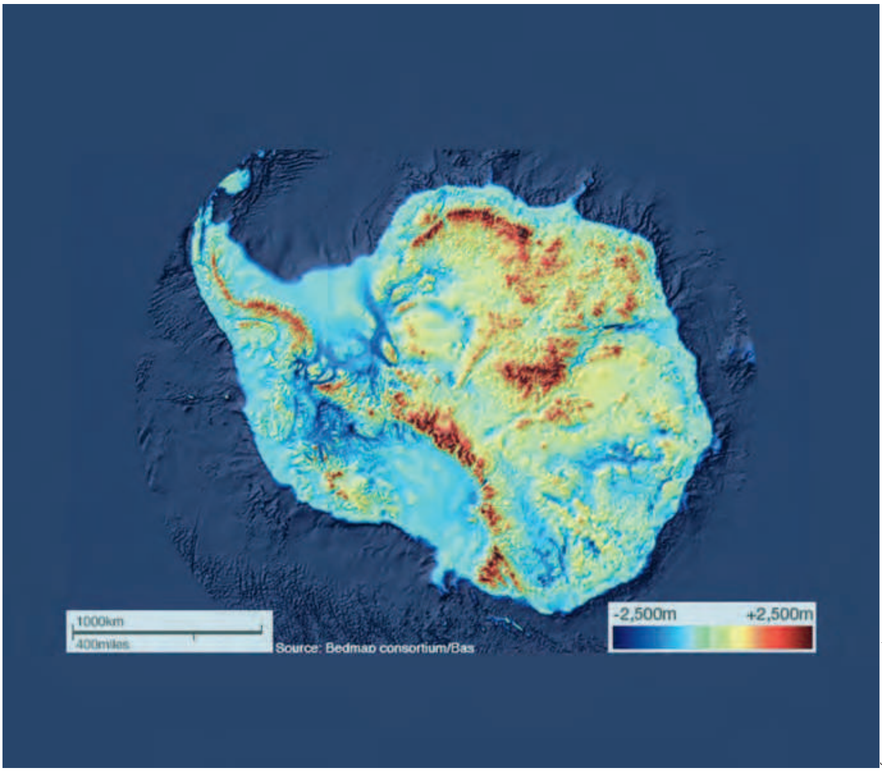
Ice shelves also lose mass through iceberg calving.

The presence of subglacial meltwater, generated at the interface between the ice sheet and the bedrock below, causes sliding of the basal ice – one of the dominant mechanisms of ice flow. The meltwater may be in the form of persistent or transient lakes and rivers, and may arise due to heating from the warmer bedrock below due to the presence of radioactive elements, indirectly as friction or directly by deformation as the ice flows across the bedrock. Localised acceleration of the ice sheet has been observed in satellite imagery when subglacial lakes suddenly drain, causing increased lubrication of the ice base as the water moves towards the ocean [36].

Another factor influencing ice flow is floating ice shelves acting to restrain glacier flow. This restraining effect is called *buttressing*: local topographic high points in the bed or side walls of a glacier effectively pin the ice shelves, increasing the friction that impedes increased flows. As ocean warming triggers ice shelf thinning, the buttressing effect of the ice shelves will decrease, and potentially open up more of the grounded ice to acceleration and retreat, with implications for sea level.

Recent studies have estimated that approximately 13% of shelf ice around Antarctica can be lost to ocean melting and iceberg calving without impacting their overall buttressing potential [15]. This shelf ice is denoted 'passive ice'. Loss of shelf ice beyond the passive sector has the potential to lead to irreversible retreat of many Antarctic glaciers. For example, in East Antarctica, only 4% of shelf ice on the Totten Glacier is estimated to be passive, suggesting it exerts a significant buttressing influence on the ice sheet.

International efforts over recent decades have been made to improve maps of the bed topography beneath the Antarctic ice sheet. An improved bed description is important not only for better estimates of the buttressing effect of ice shelves, but to provide insight into the susceptibility of Antarctic glaciers to rapid retreat as a result of an effect called the Marine Ice Sheet



BEDMAP Consortium/British Antarctic Survey

A topographic and bathymetric map of Antarctica without its ice sheets, showing areas grounded below sea level.

Instability (MISI) [43]. Improved bed topography mapping has revealed that much of the Antarctic continent bed topography is below sea level. In glaciers where the bed topography slopes downwards towards the interior, MISI can occur. This is where as the glacier begins to retreat, more ice is exposed, outflow increases, and the glacier retreats further.

To better characterise the state of the Antarctic ice sheet requires a multi-systems approach, combining the ice sheet, atmosphere and ocean systems. The ACE CRC is actively engaged in this area of research, from collecting data that characterises the subglacial environment, through to the development of numerical models of coupled ice sheet/ocean processes that provide insights into the sensitivity of the Antarctic ice sheet to climate change.

PART B

ACE CRC AND PARTNER RESEARCH

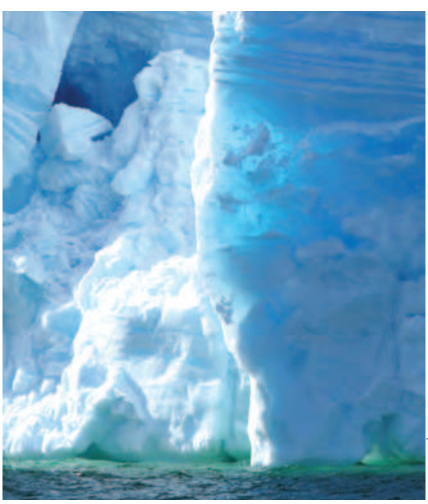
Scientists at the ACE CRC and partner organisations are conducting cutting-edge research into important elements of the cryosphere. This research covers a wide range of interactions, such as ocean melting of ice shelves, bedrock and internal ice flow dynamics, oceanography, ice shelf disintegration and glacial isostatic adjustment. To investigate these and other topics, scientists employ remote sensing observations from satellites and aircraft, as well as making direct measurements from ships and by travelling to remote locations in Antarctica. Computer models are a key tool for exploring cryosphere processes such as ocean-ice interaction and ice sheet flow and for combining ice sheets and oceans into coupled models to project future sea level rise. Ice shelf calving remains a poorly understood process, as is its role in overall ice shelf stability. Likewise, internal ice dynamics and the flow of the ice sheet over the bedrock are important, but the impact on the ice sheet is poorly understood. A better understanding of these mechanisms will lead to better simulations, calibrated by data being obtained by both remote sensing and field observations.

Research at the ACE CRC is guided by the following research questions:

- How is the Antarctic ice sheet responding to a warming ocean?
- What are the key regions of the ice sheet that are at risk of potential increase in ice discharge?
- How do models represent observed change and what is their reliability for informing future change?
- What are the limits on estimates of change with impacts on global sea level and climate?

The following section identifies how researchers at the ACE CRC are tackling these questions.

Left to right: an iceberg in West Antarctica; a Meltwater pool on the surface of the Sørsdal Glacier.



Christopher Michel

Sue Cook

RECENT OCEAN OBSERVATIONS

The Antarctic coastal ocean plays a major role in translating changes between the Antarctic Ice Sheet and the Southern Ocean. Basal melting of Antarctic ice shelves and dense water formation over the continental shelves are key physical processes.

In winter, persistent open water or thin sea-ice areas, called coastal polynyas, form in front of Antarctic ice shelves, icebergs, or the coastline. Strong winds flowing off the Antarctic continent cause heat loss from these open ocean polynyas, leading to the freezing of seawater and the formation of sea ice. The associated salt input to the ocean from sea ice formation results in the formation of cold and dense water over the continental shelves, a key contribution to global-scale deep ocean circulation.

From an ice sheet perspective, the active dense water formation becomes an effective cold barrier to separate ice shelves from relatively warm Southern Ocean water. Consequently, understanding the balance between cold and warm water on the continental shelf that drives basal melting of ice shelves is critical in understanding how the ice sheet will respond to warming climate.

In early 2015, the R/V *Aurora Australis* reached the edge of East Antarctica's fastest thinning glacier – the Totten Glacier. ACE CRC scientists were able to take the first direct measurements of the ocean alongside the front of the Totten Glacier. The expedition provided conclusive evidence that warm ocean water reaches the sub-ice shelf cavity, melting the ice shelf from below [31].

Paul Brown

The R/V *Aurora Australis* at the Totten Glacier, East Antarctica.

Observing how ice shelves and the ocean interact can be difficult in the field and logistically very expensive. Seasonal sea ice cover often prohibits ship access to these regions, and the thickness of ice shelves (sometimes more than 2000 metres) limits the observation technique to expensive platforms such as automated underwater vehicles or drilling holes through the ice shelf [7].

MODELLING ICE SHELF-OCEAN INTERACTION

Models are a key scientific tool for investigating ice shelf-ocean interaction. The equations that describe water circulation, and heat and freshwater exchange with the ice shelves, are solved on a three dimensional grid. Different regions and times can be simulated by modifying the information that is fed into the boundaries of the model domain. For example, numerical models were applied to the Totten region to predict the ocean state. Models were also used to develop a field research program to observe the ocean beneath the Amery Ice Shelf via boreholes that were drilled through the ice shelf (known as AMISOR).

Researchers at the ACE CRC and partner agencies are using ice shelf-ocean models to examine many different geographic regions and major ice shelves. A key outcome of this research has been to demonstrate the importance of atmospheric factors in controlling ice melting from the base of Antarctic ice shelves [6,19]. Strong winds that blow off the Antarctic continent cool the surface of the ocean, and as this cold water sinks, it can reduce melting beneath nearby ice shelves. Below ice shelves, scientists have examined other important mechanisms, such as the impact of tides. Another important mechanism is the formation of small ice crystals, which float up and freeze on to the base of the ice shelf [16].

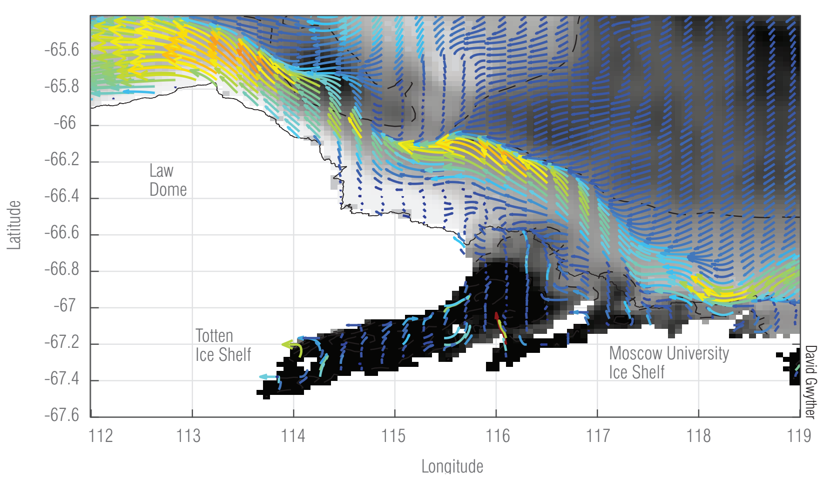


FIGURE 7: Map view of the Totten Glacier, showing simulated ocean currents flow westwards past the ice shelf cavity mouth.

The calving front of the Mertz Glacier Tongue, photographed from the R/V *Nathaniel B Palmer*.

David Gwyther

Ice shelf-ocean models are also used to explore the interaction between basal melting and dense water formation [26,27]. Numerical experiments showed that the balance of cold and warm water flowing underneath the ice shelves strongly depends on the location of coastal polynyas. The altered balance between cold and warm water in future warming scenarios strongly affects basal melting of Antarctic ice shelves. Numerical simulations have suggested that increased freshwater input from ice shelf basal melting has large impacts on dense water formation, which leads to a weakening of the Southern Ocean deep circulation, with implications for global climate [21]. These findings are examples demonstrating how ice shelves can respond to future changes in the atmosphere, sea ice, and the ocean.

ICE SHELF MASS LOSS OBSERVATIONS

The calving of icebergs accounts for about half of the ice lost each year from the Antarctic ice sheet. Ice can be lost in chunks as icebergs, with sizes from tens of metres to hundreds of kilometres across. Ice fracture is a fast and chaotic process and predicting precisely when an individual iceberg will form is almost impossible. However, estimating long-term average loss of ice as icebergs is becoming possible through the development of new numerical modelling and measurement techniques. To-date, robust estimates of iceberg calving rates remains one of the largest uncertainties in predictions of how the Antarctic Ice Sheet will change.

Work at ACE CRC tries to reduce this uncertainty in two main ways. Firstly, by using satellite imagery and field observations to monitor processes which can change the rate of iceberg production. Secondly, novel modelling techniques allow us to predict how those processes will change the fracturing of an ice shelf.

Melting of the underneath of a floating ice shelf by the ocean can thin the ice, thereby leading to it weakening and more liable to fracture. ACE CRC radar units (ApRES) and Global Positioning System (GPS) receivers have been deployed in the field to monitor melt rates underneath ice shelves in several locations around East Antarctica, including the Totten, Amery,

Mertz Glacier in 2014.

Sue Cook

A three-dimensional computer simulation of rifts and cracks forming as the Totten Glacier flows out to sea. These cracks can lead to large iceberg formation and destabilisation of the ice shelf.

and Sørsdal Glaciers. The ApRES units allow live monitoring of the basal melting and thinning of the ice shelf, and compaction of surface snow layers, with daily data transmitted via satellite. These deployments, together with the airborne deployments of expendable bathythermographs in the ocean near the Totten Glacier, will provide the first connection between observed ocean state, basal melt rates, and the flow speed of the Totten Glacier.

Melting at the surface of an ice shelf can also directly lead to increased iceberg calving, as the liquid water acts to widen existing crevasses and fractures. This process is thought to be behind the dramatic disintegration of Larsen A and B ice shelves in the Antarctic Peninsula. Instruments from an ACE CRC supported field project on the Sørsdal Glacier are monitoring the growth of lakes and surface melt water features. These dual field programs will allow us to determine if calving rates in East Antarctica are likely to increase in coming years.

David Gwyther

As well as observing present-day conditions in Antarctica, scientists are also using novel modelling methods to help understand the processes behind fracture on ice shelves. The fracture model, which simulates the growth of individual crevasses over very short timescales (seconds to minutes), has been applied for the first time to an Antarctic ice shelf, the Totten. The simulation allows us to test precisely how changing conditions will affect crevasse growth and iceberg production. As the model is developed, the results will improve the simulations of iceberg calving in ice sheet models, which are used to predict sea level rise contributions.

ICE SHEET BASAL CONDITIONS

Melted ice.

Antarctic bed topography plays a critical role in the dynamics of ice flow and is a key driver of where and how fast ice flows. While the advent of the satellite era has enabled new and profound insights into the ice sheet surface, the nature of the bedrock below has remained largely a mystery until only recently.

In the past, deriving high-resolution Antarctic bed topography maps has been hindered by technological constraints, given both the difficulties of fieldwork in the harsh environment, and that the bed topography is covered in ice that is up to 4 kilometres thick in some places. Knowledge of this bed topography is nonetheless essential to build up a picture of the glaciers most at risk of retreat under a warming climate.

In recent years, the ACE CRC has been closely involved in an international collaboration called ICECAP (for International Collaborative Exploration of the Cryosphere through Airborne Profiling) to measure Antarctic bed topography using a suite of geophysical instruments including radar, magnetometers, gravimeters, laser and GPS [32]. The key data stream is generated using an ice penetrating radar system mounted to a fixed wing aircraft, capable of building up a two dimensional picture of the internal layer structure of the ice and where it comes to contact with the bedrock. From this data, scientists can determine finescale structure of the bed topography, whether the ice is frozen to the bedrock below or whether there is meltwater (e.g., in the form of rivers and lakes) at the interface between the ice sheet and bedrock [46]. This collaboration also mapped the extensive Aurora Subglacial

Basin and showed the large potential sea level rise that may result from glacier acceleration in East Antarctica [45]. ACECRC scientists have shown that the ice drainage basins in the vicinity of Casey Research Station (south of Perth, WA) are grounded deep below sea level [32]. This ice has significant quantities of liquid water lubricating the ice flow [44], and has the potential to rapidly retreat inland with a large impact of global sea level [1]. Current work through the ICECAP collaboration is focussing on interactions between the ocean and ice-shelves, with the aim to identify pathways for warm water to enter beneath the ice shelves.

The bed topography data collected as part of ICECAP are being used in numerical ice sheet models of the Antarctic continent to understand how bedrock topography and subglacial conditions influence the dynamics of ice flow. The research focuses on determining the resolution of bed topography required to achieve stable and consistent predictions of ice sheet dynamics. Outputs from this research will help prioritise locations where we need improved bed topography information.

Among a large number of important research findings, this research has revealed that the bedrock of much of the Antarctic continent lies below sea level [13]. In marine-terminating glaciers where the bed topography is below sea level and slopes downwards towards the interior of the continent, the ice sheet is at risk of rapid retreat as warming ocean waters melt the ice shelves from below [43]. This phenomenon, the marine ice sheet instability, is an active area of research for scientists at the ACE CRC.

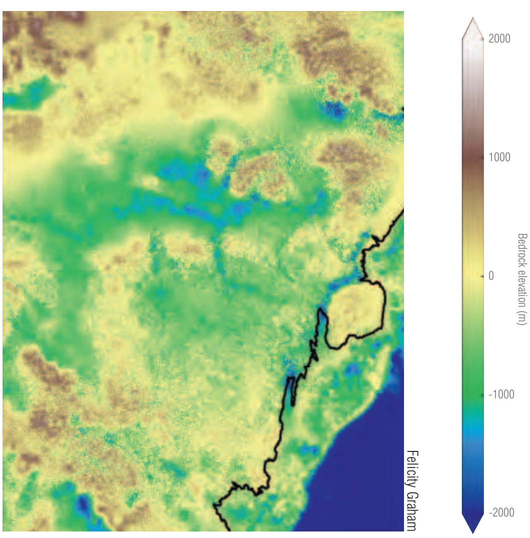


FIGURE 8: Bedrock elevation (m) in the Aurora Subglacial Basin from a high-resolution synthetic terrain (Graham *et al*., under review). The black curve illustrates the MODIS Mosaic of Antarctica 2008-2009 grounding line.

ICE FLOW DYNAMICS

The slow deformation of ice is one of the key processes contributing to the transport and discharge of ice from the Antarctic Ice Sheet into the surrounding ocean. The numerical relationship used to describe the flow properties of ice is one of the crucial components of the models used to simulate the long-term evolution of the ice sheet.

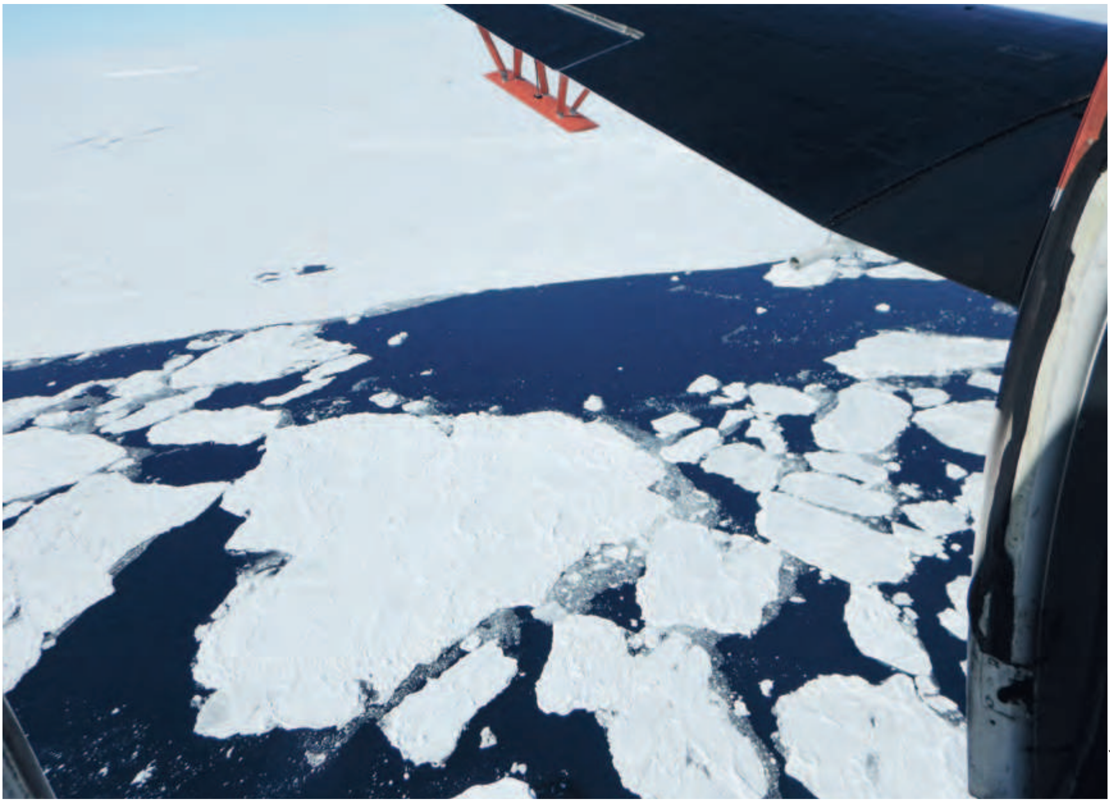
Despite being a solid material, ice is typically treated as a very slow flowing fluid in these models. This simplifying assumption contributes to the uncertainty in simulations of ice sheet evolution and consequently predictions of future sea level rise. The solid properties of ice – at the scale of individual crystals – determine the rate at which it deforms in response to the forces causing it to flow and play a role in governing the large-scale flow of the Antarctic Ice Sheet.

Scientists at the ACE CRC have been conducting laboratory ice deformation experiments to explore the links between its microstructure and flow rate under a range of conditions. These experiments demonstrate the sensitivity of ice flow to not only the magnitude of the forces causing it to flow, but also their orientation [39,4]. This work has allowed the development of a new flow relation for ice. A regional-scale study, using observed ice sheet flow rates, demonstrates that this description of ice flow properties provides a more physically accurate description of the complex flow characteristics of ice, in comparison to the relationship typically used in ice sheet models [40].

Recently, Antarctic Gateway Partnership and ACE CRC researchers have implemented this new description of ice flow physics into one of the leading continental-scale ice

Adam Treverrow

A sample of ice, about 10cm long, that has been deformed in a laboratory experiment to measure its flow rate. In this experiment the lower sample holder was held stationary while the upper holder was forced to the left. The sample was initially rectangular and stretching of the sample due to the very slow deformation of the ice is clearly visible. Experiments like this are important for understanding the physics describing the dynamics of ice flow, such as in the Antarctic Ice Sheet.

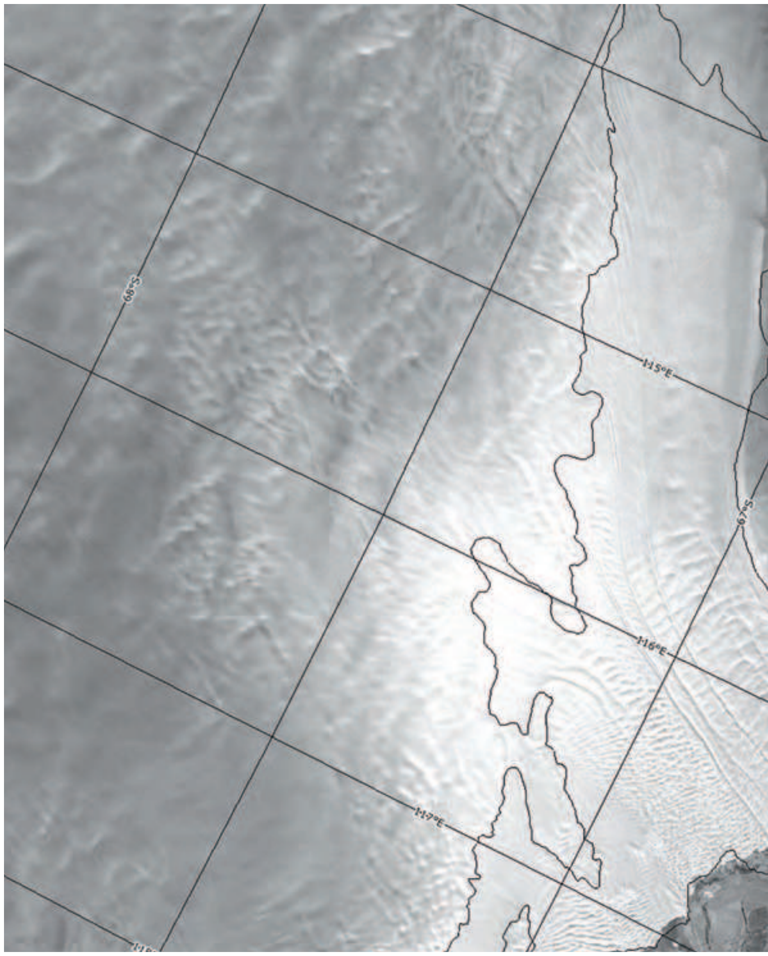


Felicity Graham

The Shackleton Ice Shelf, photographed from the Basler aircraft during ICECAP fieldwork.

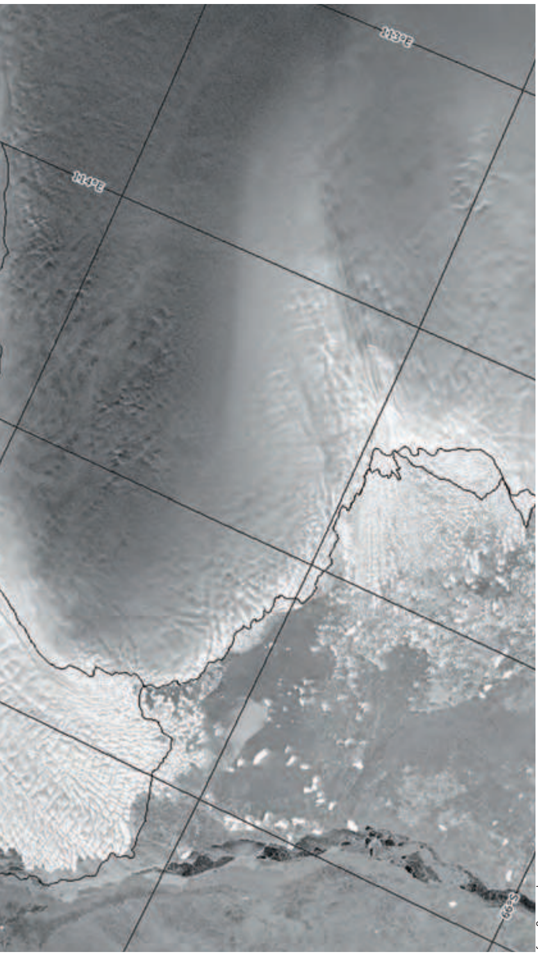
sheet models [18]. Importantly, these new, more complicated, algorithms are designed to be efficient so that simulations of the ice sheet make effective use of large supercomputing resources; an important consideration when simulating ice sheet evolution over millennial time scales [18]. Initial benefits of this new model indicate that the improved flow description predicts significantly different ice flow velocities in some of the most dynamically active regions of the ice sheet, with implications for predictions of the rate that the ice sheet will contribute to future sea level. To further investigate the implications of the new physics on the long-term evolution of the Antarctic ice sheet, ACE CRC efforts are being directed towards developing state-of-the-art models of actual Antarctic glaciers for testing against remote sensing and field observations.

ICE SHEET OBSERVATIONS FROM SPACE



Recent work has suggested that velocity fluctuations on the Totten Glacier may have been caused by changes in the rate of basal melting of the ice shelf, which in turn modulates the back stress the ice shelf provides to the grounded part of the glacier [33]. This hypothesis needs more data for verification and full understanding of the ice/ocean interaction in this region.

To address this data gap, the ACE CRC has initiated and funded an intensive campaign of satellite observations over the Totten Glacier. This satellite dataset will provide velocity maps over key parts of the Totten Glacier every two months for a period of two years. This high-frequency campaign of satellite measurements is designed to be synergistic with the ACE CRC-led deployment of Automatic Phase-sensitive Radio Echo Sounding (ApRES)and GPS instruments on the Totten Glacier in late 2016 (described below).



The Canadian Space Agency

Bryan Patterson

FIGURE 9: (left) RADARSAT Synthetic Aperture Radar (SAR) satellite image of the Totten Ice Shelf (outlined in black). SAR imagery is able to show much more structure than visible or infrared imagery in high snowfall regions, leading to more accurate glacier velocity determination.

Above right: Scientists install a GPS antenna on the Sørsdal glacier. The GPS station will track the flow of the glacier surface.

The on site GPS measurements installed as part of each ApRES package will be used to validate the satellite-derived velocity products. The satellite-derived velocity field will provide valuable spatial context for the interpretation of the point measurements of melt rate data obtained from the ApRES instruments.

This concentrated combination of satellite-derived and in-situ measurements presents the most intensive study of the Totten Glacier ever. This powerful fusion of datasets will enable a much more in-depth assessment of the state of the Totten Glacier system, including its sensitivity to ice shelf basal melt driven by warm water incursions.

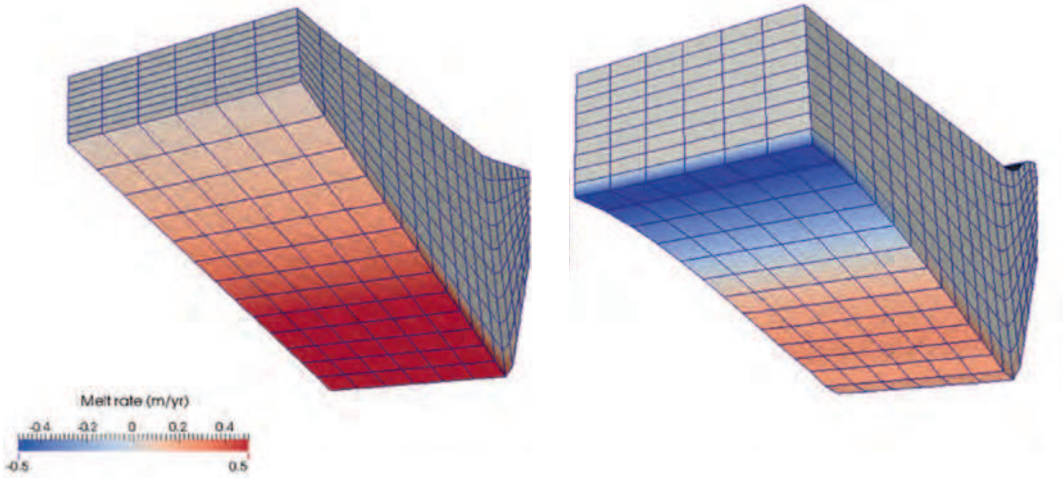
PREDICTING FUTURE CHANGE

Ben Galton-Fenzi

Above: Testing the snowpack on the Totten Glacier.

One way that we can examine how the ocean and the ice sheet influence each other is through coupled models. The latest IPCC report summarising international climate modelling efforts only included rudimentary understanding of the interactions with the Antarctic Ice Sheet. However, coupling models together can be a challenging problem. Models of different parts of the Earth's climate systems operate on different timescales. Typically, to accurately solve the fundamental equations, ice sheet models run over thousands of years in increments of months to years while ocean models may need to run at time intervals of hundreds of seconds. Model grids also differ, so sometimes it is necessary to interpolate data that must be exchanged between them.

Researchers at the ACE CRC are collaborating on building a state-of-the-art software framework to facilitate coupling a variety of ice sheet and ocean models, as a start towards developing fully integrated climate models that include interactions with the ice sheets. The software framework is being tested on idealised models with simplified domains with specified parameters, allowing us to be sure that we are passing information correctly. Researchers are participating in the Marine Ice Sheet-Ocean Model Intercomparison Project (MISOMIP), a World Climate and Research Programme Climate and Cryosphere targeted activity [2], which will compare a variety of models taking different coupling approaches. This software will be used for running a coupled model of the region around the Totten Glacier in East Antarctica that has the potential to be a significant contributor to sea level rise if it undergoes change driven by warming oceans.



Rupert Gladstone

FIGURE 10: A coupled ice sheet-ocean model allows the exploration of how the ice sheet changes due to flow dynamics and melting and freezing from the ocean. On the left, an ice shelf (shown from below) is melted strongly at the base, after two years (right), melting, freezing and the flow of ice have changed the geometry of the ice shelf.

iStock

The impacts of erosion at Collaroy Beach in Northern Sydney following an intense storm in June 2016. Many coastal areas will become more vulnerable to extreme events as sea levels rise.

PART C
FUTURE PRIORITIES

The key priority remains to quantify the past, present and future Antarctic Ice Sheet mass budget and its influence on sea level, especially for the East Antarctic Ice Sheet, which contains the largest mass of ice. Future research will continue to be guided by the following questions:

- What will be the magnitude of sea level rise from Antarctica and the rate of rise through time, particularly in the next one to two centuries?
- What are the points where abrupt or large changes become committed and what are the key regions susceptible to rapid change?
- How much is the relative influence between a warming atmosphere and warming oceans on the evolution of the ice sheet, and what are the feedbacks with other parts of the climate system with increased Antarctic Ice Sheet mass loss?

For each of these questions it is important to understand how climate warming scenarios influence Antarctica's response, with particular emphasis on 1) understanding what the Paris Agreement means for sea-level, and 2) quantifying thresholds for significant tipping points in ice sheet mass loss. Continued research efforts are required to quantify the processes controlling ice mass loss, using ground based and remote sensing observations, laboratory experiments, and numerical modelling, focussed on:

- Characterisation of key processes that influence the evolution of the ice sheet, such as: ice/ocean interactions; basal processes and knowledge of the subglacial environment and how they influence ice flow; bedrock uplift rates by glacial isostatic adjustment; grounding zone mechanisms; drivers of marine ice sheet instability; and, ice shelf disintegration.
- Sustained monitoring of ice flow discharge rates and dynamics and climate/atmosphere/ocean processes that transport heat to margins of the ice sheet.
- Understanding past changes in ice sheet and climate to better characterise sensitivity and constrain models.
- Quantifying the response of the ice sheet to ice shelf changes and projecting future change through the continued development and robust evaluation of coupled models that include ice sheet processes, including climate models.
- Identification of areas susceptible to rapid retreat, including extended surveys of unknown regions of the continental shelf bathymetry and Antarctic bedrock, and state estimates of the oceans and the ice sheet.

Opposite page from top: Sørsdal lake monitoring; sunrise over icebergs along the Sabrina Coast, East Antarctica.

Christian Schoof

David Gwyther

REFERENCES

Steve Rintoul

Deploying an ocean mooring in a polynya.

1 Aitken, A. R. A., Roberts, J. L., Van Ommen, T. D., Young, D. A., Golledge, N. R., et al. (2016). Repeated large-scale retreat and advance of Totten Glacier indicated by inland bed erosion. Nature, 533(7603), 385-389.
2 Asay-Davis, X. S., Cornford, S. L., Galton-Fenzi, B. K., Gladstone, R. M., Gudmundsson, G. H., Holland, D. M., et al. (2016). Experimental design for three interrelated marine ice sheet and ocean model intercomparison projects: MISMIP v. 3 (MISMIP+), ISOMIP v. 2 (ISOMIP+) and MISOMIP v. 1 (MISOMIP1). Geoscientific Model Development, 9(7), 2471.
3 Bingham, A. W., & Drinkwater, M. R. (2000). Recent changes in the microwave scattering properties of the Antarctic ice sheet. IEEE Transactions on Geoscience and Remote Sensing, 38(4), 1810-1820.
4 Budd, W. F., Warner, R. C., Jacka, T. H., Jun, L. I., & Treverrow, A. (2013). Ice flow relations for stress and strain-rate components from combined shear and compression laboratory experiments. Journal of Glaciology, 59(214), 374-392.
5 Chen, J. L., Wilson, C. R., Blankenship, D., & Tapley, B. D. (2009). Accelerated Antarctic ice loss from satellite gravity measurements. Nature Geoscience, 2(12), 859-862.
6 Cougnon, E. A., Galton-Fenzi, B. K., Meijers, A. J. S., & Legrésy, B. (2013). Modeling interannual dense shelf water export in the region of the Mertz Glacier Tongue (1992–2007). Journal of Geophysical Research: Oceans, 118(10), 5858-5872.
7 Craven, M., Allison, I., Fricker, H. A., & Warner, R. (2009). Properties of a marine ice layer under the Amery Ice Shelf, East Antarctica. Journal of Glaciology, 55(192), 717-728.
8 Das, S. B., Joughin, I., Behn, M. D., Howat, I. M., King, M. A., Lizarralde, D., & Bhatia, M. P. (2008). Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. Science, 320(5877), 778-781.
9 DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591-597.
10 Dutton, A., & Lambeck, K. (2012). Ice volume and sea level during the last interglacial. Science, 337(6091), 216-219.
11 Favier, L., Durand, G., Cornford, S. L., Gudmundsson, G. H., Gagliardini, O., Gillet-Chaulet, et al. (2014). Retreat of Pine Island Glacier controlled by marine ice-sheet instability. Nature Climate Change, 4(2), 117-121.
12 Feldmann, J., & Levermann, A. (2015). Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin. Proceedings of the National Academy of Sciences, 112(46), 14191-14196.
13 Fretwell, P. et al. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. Cryosphere 7, 1 (2013), 375–393.
14 Fricker, H. A., Siegfried, M. R., Carter, S. P., & Scambos, T. A. (2016). A decade of progress in observing and modelling Antarctic subglacial water systems. Phil. Trans. R. Soc. A, 374(2059), 20140294.
15 Fürst, J. J., Durand, G., Gillet-Chaulet, F., Tavard, L., Rankl, M., Braun, M., & Gagliardini, O. (2016). The safety band of Antarctic ice shelves. Nature Climate Change, 6(5), 479-482.
16 Galton-Fenzi, B. K., Hunter, J. R., Coleman, R., Marsland, S. J., & Warner, R. C. (2012). Modeling the basal melting and marine ice accretion of the Amery Ice Shelf. Journal of Geophysical Research: Oceans, 117(C9).
17 Golledge, N. R., Kowalewski, D. E., Naish, T. R., Levy, R. H., Fogwill, C. J., & Gasson, E. G. (2015). The multi-millennial Antarctic commitment to future sea-level rise. Nature, 526(7573), 421-425.
18 Graham, F. S., Morlighem, M., Warner, R. C., and Treverrow, A. (2017) Implementation and testing of an empirical scalar tertiary anisotropic rheology (ESTAR) in the Ice Sheet System Model (ISSM). In prep.
19 Gwyther, D. E., Galton-Fenzi, B. K., Hunter, J. R., & Roberts, J. L. (2014). Simulated melt rates for the Totten and Dalton ice shelves. Ocean Science, 10(3), 267.
20 Gwyther, D., Cougnon, E., Galton-Fenzi, B., Roberts, J., Hunter, J., & Dinniman, M. (2016). Modelling the response of ice shelf basal melting to different ocean cavity environmental regimes. Annals of Glaciology, 57(73), 131-141. doi:10.1017/aog.2016.31
21 Hellmer, H. H. (2004). Impact of Antarctic ice shelf basal melting on sea ice and deep ocean properties. Geophysical Research Letters, 31(10).
22 Hunter, J., (2010). Estimating Sea-Level Extremes Under Conditions of Uncertain Sea-Level Rise, Climatic Change, 99, 331-350, DOI:10.1007/s10584-009-9671-6.
23 Jacobs, S. S., Jenkins, A., Giulivi, C. F., & Dutrieux, P. (2011). Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. Nature Geoscience, 4(8), 519-523.
24 Jenkins, A., Dutrieux, P., Jacobs, S. S., McPhail, S. D., Perrett, J. R., Webb, A. T., & White, D. (2010). Observations beneath Pine Island Glacier in West Antarctica and implications for its retreat. Nature Geoscience, 3(7), 468-472.
25 Joughin, I., Smith, B. E., & Medley, B. (2014). Marine ice sheet collapse potentially under way

Paul Helleman

The Basler aircraft used by ICECAP scientists for airborne geophysical surveys.

for the Thwaites Glacier Basin, West Antarctica. Science, 344(6185), 735-738.

26 Kusahara, K., and Hasumi, H. (2013), Modeling Antarctic ice shelf responses to future climate changes and impacts on the ocean, Journal of Geophysical Research: Oceans 118 (5), 2454-2475

27 Kusahara, K., Hasumi, H., Fraser, A. D., Aoki, S., Shimada, K., Williams, G. D., Massom, R. and Tamura, T. (2017), Modeling Ocean-Cryosphere Interactions off Adélie and George V Land, East Antarctica, Journal of Climate 30 (1), 163-188

28 Li, X., Rignot, E., Morlighem, M., Mouginot, J., & Scheuchl, B. (2015). Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013. Geophysical Research Letters, 42(19), 8049-8056.

29 Paolo, F. S., Fricker, H. A., & Padman, L. (2015). Volume loss from Antarctic ice shelves is accelerating. Science, 348(6232), 327-331.

30 Pritchard, H., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., Van den Broeke, M. R., & Padman, L. (2012). Antarctic ice-sheet loss driven by basal melting of ice shelves. Nature, 484(7395), 502-505.

31 Rintoul, S. R., Silvano, A., Pena-Molino, B., van Wijk, E., Rosenberg, M., Greenbaum, J. S., & Blankenship, D. D. (2016). Ocean heat drives rapid basal melt of the Totten Ice Shelf. Science Advances, 2(12), e1601610.

32 Roberts, J. L., Warner, R. C., Young, D., Wright, A., van Ommen, T. D., et al. (2011). Refined broad-scale sub-glacial morphology of Aurora Subglacial Basin, East Antarctica derived by an ice-dynamics-based interpolation scheme. The Cryosphere, 5, 551-560.

33 Roberts, J. L., Galton-Fenzi, B. K., Paolo, F. S., Donnelly, C., Gwyther, D. E., Padman, L., Young, D., Warner, R. et al. (2017) Ocean forced variability of Totten Glacier mass loss. Geological Society, London, Special Publications, accepted.

34 Scambos, T., Fricker, H. A., Liu, C. C., Bohlander, J., Fastook, J., Sargent, A. et al. (2009). Ice shelf disintegration by plate bending and hydro-fracture: Satellite observations and model results of the 2008 Wilkins ice shelf break-ups. Earth and Planetary Science Letters, 280(1), 51-60.

35 Shepherd, A., Ivins, E. R., Geruo, A., Barletta, V. R., Bentley, M. J., Bettadpur, S. et al. (2012). A reconciled estimate of ice-sheet mass balance. Science, 338(6111), 1183-1189.

36 Siegfried, M. R., Fricker, H. A., Carter, S. P., & Tulaczyk, S. (2016). Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica. Geophysical Research Letters.

37 Smith, J. A., Andersen, T. J., Shortt, M., Gaffney, A. M., Truffer, M., Stanton, T. P. et al. (2017). Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier. Nature, 541(7635), 77-80.

38 Sun, S., Cornford, S. L., Gwyther, D. E., Gladstone, R. M., Galton-Fenzi, B. K., Zhao, L., & Moore, J. C. (2016). Impact of ocean forcing on the Aurora Basin in the 21st and 22nd centuries. Annals of Glaciology, 57(73), 79-86.

39 Treverrow, A., Budd, W. F., Jacka, T. H., & Warner, R. C. (2012). The tertiary creep of polycrystalline ice: experimental evidence for stress-dependent levels of strain-rate enhancement. Journal of Glaciology, 58(208), 301-314.

40 Treverrow, A., Warner, R. C., Budd, W. F., Jacka, T. H., & Roberts, J. L. (2015). Modelled stress distributions at the Dome Summit South borehole, Law Dome, East Antarctica: a comparison of anisotropic ice flow relations. Journal of Glaciology, 61(229), 987-1004.

41 Warner, R. C., & Roberts, J. L. (2013). Pine Island Glacier (Antarctica) velocities from Landsat7 images between 2001 and 2011: FFT-based image correlation for images with data gaps. Journal of Glaciology, 59(215), 571-582.

42 Watson, C. S., White, N. J., Church, J. A., King, M. A., Burgette, R. J., & Legresy, B. (2015). Unabated global mean sea-level rise over the satellite altimeter era. Nature Climate Change, 5(6), 565-568.

43 Weertman, J. (1974). Stability of the junction of an ice sheet and an ice shelf. Journal of Glaciology, 13(67), 3-11.

44 Wright, A. P., Young, D. A., Roberts, J. L., Schroeder, D. M., Bamber, J. L., Dowdeswell, J. A. et al. (2012). Evidence of a hydrological connection between the ice divide and ice sheet margin in the Aurora Subglacial Basin, East Antarctica. Journal of Geophysical Research: Earth Surface, 117(F1).

45 Young, D. A., Wright, A. P., Roberts, J. L., Warner, R. C., Young, N. W., Greenbaum, J. S. et al. (2011). A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes. Nature, 474(7349), 72-75.

46 Young, D. A., Schroeder, D. M., Blankenship, D. D., Kempf, S. D., & Quartini, E. (2016). The distribution of basal water between Antarctic subglacial lakes from radar sounding. Phil. Trans. R. Soc. A, 374(2059), 20140297.

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE