Symposium 2018

Antarctic Climate & Ecosystems Cooperative Research Centre

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry and Science

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FOREWORD

The past three decades have been a period of great advancement in Australian high-latitude science, with enormous improvements in our understanding of Antarctica and the Southern Ocean. Ambitious, wide-ranging and cross-disciplinary research projects have led to new discoveries that have fundamentally transformed our understanding of the region's role in the global climate system.

Through a long-running ocean sampling program, we now have a vastly improved understanding of the Southern Ocean's fundamental role in regulating the global climate and driving ocean circulation. We know that the Southern Ocean acts as a powerful handbrake on the rate of global climate change, but at the cost of increasing warming and acidification. We also know that the great Antarctic ice sheet, holding about 70% of the planet's fresh water, is melting at an accelerating rate under the effects of the changing ocean and atmosphere. Ecologists have shed new light on the impacts of these changes on fundamental ecological processes including krill reproduction and phytoplankton distribution, with major implications for fisheries and marine park management.

Often more sobering than comforting, these discoveries nevertheless represent major contributions to international scientific efforts to understand and address climate change. For nearly 30 years in Australia, the driving force behind these advances has been a multi-institutional collaboration that we know today as the Antarctic Climate and Ecosystems Cooperative Research Centre (ACE CRC). The ACE CRC is the largest research institution in the world focused on high-latitude climate and ecosystem processes and, critically, the links between the two. Launched in 1991 as the Antarctic CRC, its role has been to understand the changes happening in the Southern Ocean and Antarctica and to ensure that Australia has access to the best available information on this region and to prepare for climate change. During this time the research achievements under this partnership have been a cornerstone of our nation's efforts to understand, conserve and capture benefit from the Antarctic and Southern Ocean region.

After 28 years of continuous research, under a variety of names, the ACE CRC will officially wind up in 2019. One of the great legacies of this nearly three-decade journey will be to stand as a reminder, as if we needed one, of the great value of cooperative human effort. The unincorporated joint venture model has provided a low-friction mechanism to meaningfully connect people and ideas across the innovation system – building links between the key institutions in Hobart and with some of the best research organisations nationally and globally, and with the end users in government and industry. The CRC has drawn upon expertise and research infrastructure from all corners of the globe to develop project teams capable of tackling large, complex science questions. By partnering we drive efficiencies to ensure that research capability is used most effectively, and does not have to be duplicated across multiple institutions. Through its partnerships, the CRC will have leveraged approximately $700 million in co-investment between 1991 and 2019.

In the process, this enduring partnership has become an important driver of the Tasmanian economy and a major contributor in establishing the city of Hobart as a global centre for Antarctic research. Antarctic science is estimated as contributing in excess of $200 million annually to Gross State Product, bringing together diverse skills from around the world.

If collaboration has been the cornerstone of the ACE CRC's success, then the vision and commitment of its personnel is the driving force. The research leadership contributed to the CRC by all of the core partners, coupled with the investment in early career researchers, has delivered both excellent science outcomes and sustained capacity development in the sector. The CRC has supported close to 300 PhD students over its lifetime, many of whom have gone on to prominent appointments locally and around the world.

Perhaps one of the great, unsung achievements of these research efforts is the knowledge among Australians of the intimate connection we share with the Southern Ocean and Antarctica. Today, we have a much clearer understanding of how our own nation's fortunes depend on the vast and uninhabited region to our south. Our continent's weather systems, including the droughts and flooding rains that form part of our shared national story, emerge largely from powerful atmospheric processes over the Southern Ocean and Antarctica. Even small changes in this system can have far-reaching social and economic impacts, giving the quest for understanding this region an urgency that we cannot afford to ignore.

Today, Australia stands at the cusp of a new era of Antarctic engagement. New and improved research infrastructure is set to deliver stepped improvements in the capability of the Australian Antarctic Program to support Antarctic field research. Investments since 2016 include a new research and resupply Antarctic icebreaker RSV *Nuyina*, Antarctic overland traverse capability, new research station on Macquarie Island, commitment to develop a year-round Antarctic airlink, increased operating funding for the Australian Antarctic Division, Integrated Marine Observing System and CSIRO's Marine National Facility RV *Investigator*. Together these will ensure Australia remains at the technological forefront of ocean and cryosphere research. Underpinning these technological advances is a 10-year Commonwealth Government commitment to continue supporting Australian Antarctic science after funding for the ACE CRC expires in 2019.

Our past scientific achievements in Antarctica, and the character of those who led the way, have taught us the importance of cooperative effort, adventurous thinking and open minds. As we grapple with how to build on their success in the coming decades, the spirit of collaboration embodied by the ACE CRC will stand as a reminder of what's possible.

Katherine Woodthorpe,
Chair
Mark Kelleher,
CEO

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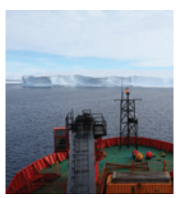
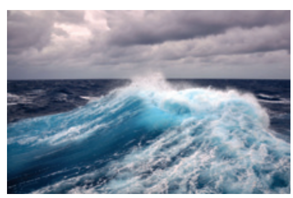

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ORIGINS

HISTORY OF THE ACE CRC

Australian Antarctic Division

Before the establishment of the original Antarctic CRC in 1991, Australian Antarctic research was fragmented. Research was conducted full-time by a relatively small number of government and university scientists. Many important scientific advances had been made in the period preceding, however those involved were aware of the need for greater focus in national research efforts. The small group of Hobart-based scientists who took those first steps toward establishing the Antarctic CRC knew that solving the big, challenging questions about Antarctica's role in the global climate system demanded a new approach.

In the late 1980s and early 1990s, the Antarctic and the Southern Ocean region was a research environment ripe for a more collaborative and inter-disciplinary approach. Australian involvement in major international projects like the World Ocean Circulation Experiment (WOCE) had clearly demonstrated the benefits of large-scale inter-agency collaborations on marine and Antarctic science. The University of Tasmania's growing interest in Antarctic collaborations was reflected in the establishment in 1989 of the Institute for Antarctic and Southern Ocean Studies (IASOS). This new centre, the precursor to today's Institute for Marine and Antarctic Studies (IMAS), became the springboard for some visionary thinking by senior researchers in Hobart that would help pave the way for a new era.

Around that time, there were a number of incentives for Australian researchers to take a more ambitious approach to Antarctic and Southern Ocean research. The availability of cutting-edge new facilities and technologies was opening up new frontiers for scientists. Australia's new icebreaking research vessel, *RSV Aurora Australis*, was commissioned for service in early 1990. It provided unprecedented opportunities for marine science with its fully equipped laboratories, facilities for ocean sampling, helicopter deck and a much greater ability than its predecessors to break through thick Antarctic pack ice. Added to this was access by Tasmanian-based research institutions to a new generation of environmental monitoring satellites that provided broad-scale data at unprecedented levels of detail.

Those same researchers knew that there were major gaps in our understanding of Antarctica and the Southern Ocean. They knew that this vast region, which covers close to a third of the Earth's surface, influenced the oceans and climates far beyond the Southern Hemisphere – but they had a somewhat rudimentary knowledge of the basic structures, processes and circulation that drove it, and how the system might be changing. They knew that most of the world's fresh water was locked up in the Antarctic ice sheet – but they did not know whether it was losing or gaining mass. They knew that the global climate was changing under the influence of anthropogenic carbon dioxide emissions – but they did not know how the ice sheet might respond to future changes in ocean temperatures and currents. They knew that the cold and turbulent waters of the Southern Ocean absorbed heat and atmospheric carbon dioxide – but they did not know how much or how important that role would be as a buffer against the changing climate. They knew that the Southern Ocean supported a rich and complex ecosystem – but they did not yet have a detailed understanding of the Antarctic foodweb, and how it too might respond to changes in ocean chemistry.

At the same time as the idea for a national Antarctic collaboration to tackle these questions was gathering pace, there was a growing awareness among policymakers of the need for a mechanism to encourage stronger research linkages across Australia's innovation system.

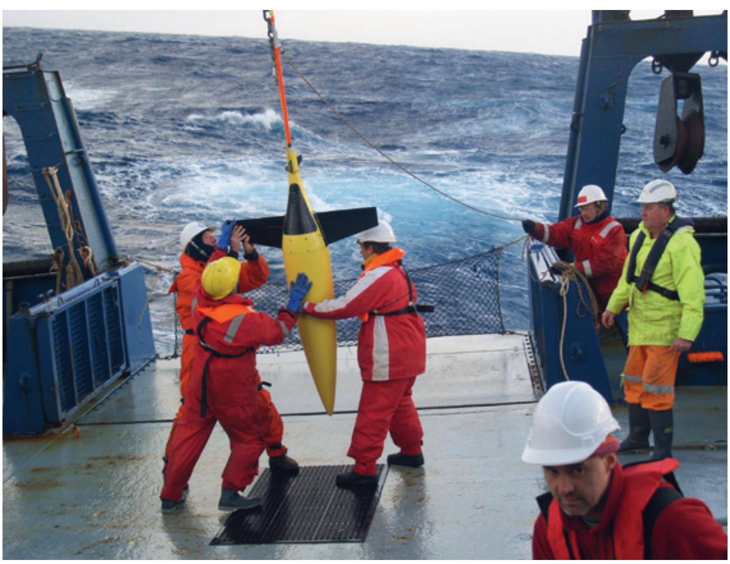
ACE CRC

When the Cooperative Research Centres Programme was introduced in 1990, one of its key aims was to integrate the differing approaches of industry, university and government-based science projects. The CRC guidelines also provided a much-needed mechanism for involving non-government and private sector players in shaping research priorities.

Among a small group of senior researchers based at IASOS in Hobart, the idea took root that the CRC Programme may provide the kick-start needed to establish a new national research partnership.

The city of Hobart, as the base of operations and science for the Australian Antarctic Division and CSIRO's marine science division, was the obvious location for such a centre. As support for the idea grew, the Bureau of Meteorology and Geoscience Australia both stepped forward to join the bid. The joint application of these five organisations bore fruit in early 1991 with the announcement that Antarctic and Southern Ocean research would have a place in the first funding round to establish an Australia-wide network of Cooperative Research Centres.

The Antarctic CRC began its life with the signing of contracts in September 1991 to set up an unincorporated joint venture of the five participating organisations. It was co-located with IASOS at the University of Tasmania's Centenary Building. Under the terms of the joint venture agreement, the University has been the centre agent responsible for administration of the CRC throughout its life.



CSIRO

This foundation partnership became the platform for a growing sequence of collaborations with a much larger extended family of Australian and foreign universities and agencies. Within just a few years, the CRC had established collaborative arrangements with 13 Australian government agencies and universities, many of which continue to the present day.

The benefits of partnership soon became clear, not just in Australia but world-wide, as this newly-focused Antarctic research effort made its impact. The research undertaken by this alliance has driven enormous improvements in our understanding of Antarctica and the Southern Ocean, and of this region's central role in the global climate system. Through the partnership, the ACE CRC will have leveraged approximately $700 million in co-investment over its 28-year life time, including for logistics support that has underpinned its research activities in Antarctica and the Southern Ocean. In the process, the city of Hobart has transformed into an international centre of research excellence in Antarctic and Southern Ocean science that rivals anywhere on Earth. The research presence in Hobart is a foundation element of the city's global status as a gateway city to the Antarctic, and has helped transform and diversify the Tasmanian economy by supporting activity across many different sectors.

The notion of 'the public good' has remained a core part of the CRC mission over its lifetime, perhaps best captured by the ACE CRC's simple tag line of *Climate Science for Australia's Future*. Direct commercial returns have been elusive, but it was clear from the beginning that there was a broader-scaled economic return from the CRC which in itself justified the funding of fundamental research. As the gathering momentum of the research effort drew together the


ACE CRC

complex strands of information about Antarctica and the Southern Ocean, it became clear that knowing more about the contribution of this vast southern region to planetary processes can be of enormous long-term economic and planning benefit to this country. This research has also provided an important input to Australia's participation and leadership in a broad range of international governance forums, especially the Antarctic Treaty System.

As the public good benefits of this research became clearer, so too did the need for a dedicated research facility that could bring together much of Tasmania's strengths in marine and Antarctic science under one roof. Recognising this opportunity, the University of Tasmania put forward a successful proposal to establish a state-of-the-art research and teaching facility on the Hobart waterfront. The award-winning Waterfront Building was completed in 2014, and today brings together scientists from a number of different agencies, including the University's Institute for Marine and Antarctic Studies (IMAS), the Integrated Marine Observing System (IMOS), the Southern Ocean Observing System (SOOS) and the ACE CRC.

Australia's leading role in Antarctic and Southern Ocean science today is, in large measure, a result of that original commitment and shared scientific vision of the CRC partners since its inception. As the current incarnation of the CRC winds up in 2019, it celebrates close to three decades of sustained research in the Antarctic and Southern Ocean. The pages of this booklet provide only a snapshot of the diverse research activities, fieldwork and scientific achievements during that period. This research has helped transform our understanding of the physical climate system and the impacts of climate change on the ecosystems of the Southern Ocean, while also informing government policy and delivering direct benefits to Australian industries and the broader community.

Climate change will continue to be a determining factor in the life of our nation for many years to come, influencing our prosperity to the tune of billions of dollars annually. The complex interactions of the oceans, ice sheets, atmosphere and ecosystems to our south represent some of the greatest uncertainties in our understanding of these changes. For the ACE CRC's successor, the most critical climate questions in Antarctica and the Southern Ocean will continue to demand high levels of collaboration across multiple disciplines and institutions.

BACK IN TIME

PAST CHANGES IN THE ANTARCTIC ICE SHEET

The Earth's climate system is constantly changing – from the familiar annual transition of the seasons to ice age cycles spanning a hundred thousand years. Throughout human history, climate variability has profoundly influenced the way human societies have organised themselves, both positively and negatively. Shifts in temperature and rainfall patterns can impact on food supply and create disease vectors, leading to famine, migration and other societal pressures. Today, the impacts of a particularly severe El Niño on the Australian economy can be measured in billions of dollars.

With a system as complex and variable as the global climate, scientists face a major challenge in the task of predicting future climate change. This is partly because we still don't sufficiently understand how the Earth's climate functioned in the period before modern scientific measurements began. Basic instrumental records provide, at most, about two centuries of global climate information, which is not enough to examine the full range of climatic variability, nor to reach conclusions about the forces that drive change. The modern era of widespread observing networks, with satellites and robotic floats in the ocean, provides an abundance of new information about critical climate processes, and modern-day changes, but our only long-term view of the Earth's past climate is via proxies. Proxy records can include historical data, such as the log books of sailing ships, or they can include information laid down by natural processes in things such as tree rings or ocean sediments.

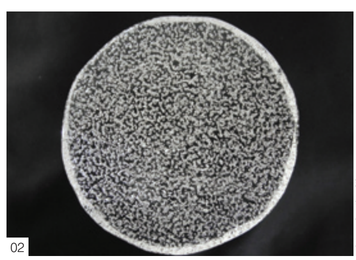
In the Antarctic, ice cores provide an immensely valuable archive of information about the Earth's climate over hundreds of thousands of years. As snow accumulates over the ice sheet and becomes compressed into layers, it traps a wide variety of gases, chemicals and impurities from the surrounding atmosphere. Once extracted from the ice sheet, ice cores can be analysed using instruments such as mass spectrometers, ion and gas chromatographs, and X-ray tomography machines. Variations in concentrations of particles, chemical compounds and isotopes present in the sample provide information on the prevailing environmental conditions at the time the snow layer was formed. Because the Antarctic and global climates are intricately linked, an ice core from a well-chosen site can be used to reconstruct an uninterrupted and detailed global climate record extending over hundreds of thousands of years.

AUSTRALIA-ANTARCTICA LINKS

One of the surprising discoveries of Antarctic ice core research has been the high-level of detail it can provide for Australian climate reconstructions. Australia is well-known for being a land of climate extremes, and flood and drought events in recent times have resulted in enormous economic, social and environmental costs. Unfortunately, we only have about 100 years of instrumental climate records, which provides a

01

Jill Brown (AAD)Vent



02

Tas Van Ommen

01: A scientist working in the ACE CRC's Hobart freezer laboratory holds up an Antarctic ice core.

02: A thin cross section of an Antarctic ice core containing trapped air bubbles.

limited understanding of the true range of climate variability in Australia.

One of the first major ACE CRC studies into the links between Australian and Antarctic climates using ice cores revealed a strong connection between snowfall rates at Law Dome and rainfall in the Western Australian wheat belt region. Meteorological records indicate average winter rainfall in south-west Western Australia has decreased significantly since the 1970s. This makes understanding the drivers of this change and the longer term variability issues of particular concern. Scientists from the ACE CRC partnership have demonstrated the annual snowfall record at Law Dome is inversely correlated with rainfall levels in south-west Western Australia. In other words, high snowfall at Law Dome tends to accompany dry conditions in south-west Western Australia. The work showed a large atmospheric circulation pattern linking the two regions which brings cold, drier air masses to south- west Western Australia while driving warm, moist air toward East Antarctica and Law Dome.

This connection allows the Law Dome snowfall record to be used as a proxy for rainfall in south-west Western Australia that has been used to extend records as far back as the ice core allows – currently 750 years. The work showed Law Dome snowfall since the 1970s was exceptionally high in this period, implying the drought may be similarly unusual. The work also suggested that the prevalence of this drought-connected atmospheric pattern may be linked to stratospheric ozone depletion.

The Law Dome ice core record has also been shown to have clear

THE LAW DOME ICE CORE

Australia has built a substantial record of achievement in the study of past climates, led by strong collaboration between scientists from the ACE CRC, through two of its major partners, the Australian Antarctic Division and CSIRO. Australia is one of just a handful of nations to have drilled an Antarctic ice core from surface to bedrock, at a location called Law Dome near Casey Station in 1993. Australia has also contributed to a network of shallow ice cores, including the 2013 Aurora Basin ice core from inland of Casey Station and the 2018 ice core from near Mount Brown near Davis Station.

Largely through its work on Law Dome ice cores, Australia has established a leading role as a specialist in high-resolution climate records. Law Dome is located about 120 kilometres from Casey Station, at the edge of the East Antarctic ice sheet, and rises 1,400 metres above sea level. The drilling operation recovered a 1,200 metre-long surface-to-bedrock ice core containing a climate record extending back 90,000 years. Due to its location close to the coastline and unique topography, the site offers significant benefits for the study of past climates. The Dome is exposed to the major storm systems from the Southern Ocean, which deliver very high snowfall for a polar location and preserve fine detail. The coastal location also provides records that have strong connections to lower-latitude climate processes such as the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). As a result, the Law Dome ice core has helped provide insights into Australia's climatic variability over thousands of years.

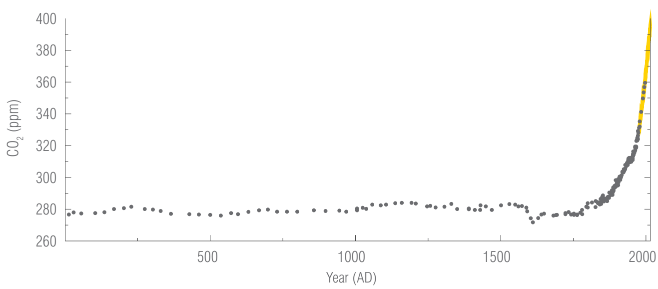


FIGURE 1: Law Dome's 2,000 Year CO_2 Record: The CO_2 data from Law Dome ice core provides the world's most accurate and detailed greenhouse gas records for the past 2,000 years. This work, done in collaboration between CSIRO, ACE CRC and AAD, is the cornerstone of modelling studies that require high resolution data to simulate past changes and is, in itself, a major highlight of Australia's Antarctic research. The graph shows the clear and sudden increase in CO_2 since the pre-industrial era, and also illustrates the fidelity of the ice core measurements (in black) and the more recent direct atmospheric measurements from Cape Grim, Tasmania (in yellow).

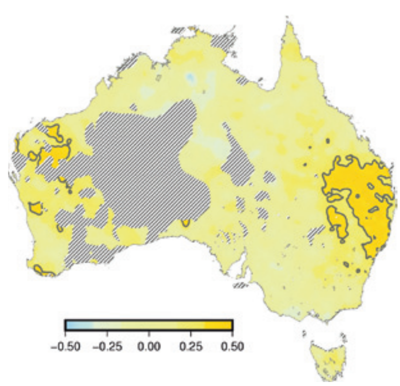
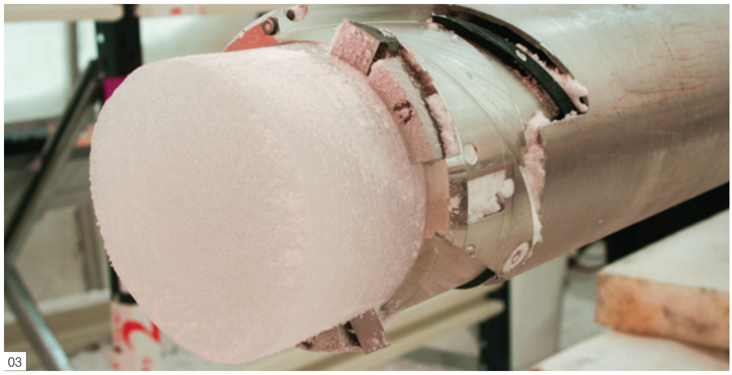


FIGURE 2: Map showing correlation between rainfall and the Law Dome sea salt proxy. Hatched areas indicate regions where the instrumental record is unreliable for the full length of comparison. The scale shows the correlation coefficient.

03: Close up view of an ice core drill head and freshly drilled ice core.



Mark Curran

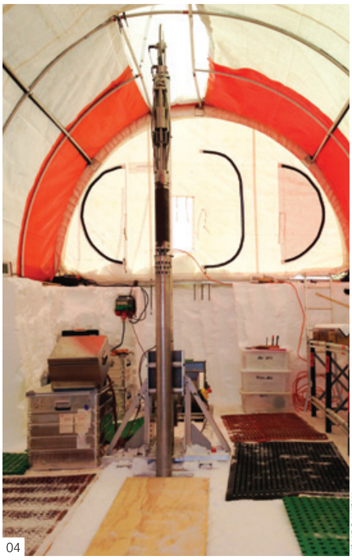
links to climate in large parts of Eastern Australia, a region which shows not only large inter-annual but also multi-decadal variability in rainfall. A key driver of this multi-decadal variability is the Interdecadal Pacific Oscillation (IPO) – a consistent pattern of Pacific Ocean sea surface temperature changes that vary on about a 25-year scale. Records from the past 100 years indicate changes in the IPO are strongly associated with food and drought risk across Eastern Australia and the broader Pacific Basin. Using this knowledge, scientists working with the ACE CRC have determined sea salt levels in the Law Dome ice core can provide a long-term record of the IPO's variability and therefore rainfall levels in eastern Australia. Among the key findings of this study is that the so-called 'Millennium Drought' between 1996 and 2009 was not an exceptional event for eastern Australia during the past 1000 years. In fact, Australia experienced several much longer droughts during this period, including one during the 12th century that lasted close to 40 years.

Surprisingly, Antarctic ice cores can even provide long-term rainfall reconstructions at the level of individual river catchments. In a world first, work by the ACE CRC and the University of Newcastle researchers suggests that catchment management plans used by many Australian water authorities, which rely on the short instrumental record, are underestimating the true risk of drought and flood. A thousand-year ice core record shows a consistent story of much wetter wets and drier dries. For example, the Williams River catchment, which provides water for the Newcastle region of New South Wales, the longest wet spell in the catchment since 1900 lasted about eight years. In contrast, a much longer ice core record shows a pattern of lengthy wet periods.

THE BIPOLAR SEESAW

Long-term records of climate offer valuable insights into the climate system and its response to large or abrupt changes in the past. Our ability to understand and model these past changes is important as we seek to understand the current rapidly changing climate and predict the future. Research led by ACE CRC scientists based with the Australian Antarctic Division has contributed to our understanding of changes during the period from 21,000 to 11,000 years ago, as the Earth was emerging from the last glacial period to the present warm and relatively stable Holocene period. This was the last time the climate system experienced a CO_2 increase comparable with recent increases over the industrial period, albeit much more slowly. It was also a time when large ice sheet losses led to rearrangements of ocean circulation and abrupt changes in climate of the two hemispheres. Understanding the linkages between the hemispheres is important for evaluating future global climate responses to ice sheet changes.

The key to the ACE CRC findings has been the very high time resolution of the Law Dome ice core through this deglacial period. This allows the records to be tightly synchronised with Northern Hemisphere records from Greenland by aligning rapid changes in atmospheric methane concentrations that are seen in all ice cores. Temperature changes in Greenland and Antarctica during the last glacial period and through the transition to the Holocene show dramatically different character. Antarctica shows warming when Greenland temperatures are cold, and steady (or even cooling) temperatures when Greenland is warm. The changes between cold and warm in Greenland appear to coincide with the warming and cooling changes in Antarctica – a pattern that has become known as the "bipolar see-saw" and which is connected to overturning circulation in the Atlantic Ocean. When this Atlantic circulation slows, the North Atlantic cools and heat accumulates in the Southern Hemisphere, leading to the warming trend seen in Antarctic ice cores. ACE CRC studies have been instrumental in establishing that these changes in the Northern and Southern Hemispheres coincide to within about 200 years. In fact, recent results from West Antarctica have narrowed this range somewhat and established that the Southern Hemisphere



04: Inside an ice core drilling tent at Aurora Basin North in 2014.

Mark Curran

changes likely follow the Northern Hemisphere by 200 years (at the edge of the range established from Law Dome).

The Law Dome long-term record has also been combined with other highly detailed Antarctic records over the deglacial period to compare the evolution of temperature and CO_2 at the end of the last glacial period. This relative timing was initially estimated from low resolution deep ice cores from the interior of Antarctica which appeared to suggest that warming preceded CO_2 increase by 700 years or more. Using the more accurately dated Law Dome record, ACE researchers showed that the CO_2 rise lagged temperature rise by less than 400 years, likely much less, and possibly in near-synchrony with temperature. Any lag of CO_2 rise might appear surprising when we consider the modern concern around CO_2 driving temperature, but it needs to be remembered that the initial warming at the end of the glacial period was triggered by other factors – in particular gradually changes in the seasons associated with the Earth's orbit.

This initial slight warming triggered release of CO_2 from the ocean which then acted as a feedback, driving further warming and the full end of the ice age. The Law Dome result and timing has profound implications for the rate at which CO_2 is absorbed/released from the Southern Ocean and is important for understanding CO_2 uptake in a warming climate.

RECENT FIELDWORK

An international project led by Australian scientists at the Australian Antarctic Division and the ACE CRC successfully extracted ice cores at Aurora Basin North, about 500 kilometres inland of Casey station in 2013-14. The international team extracted a 303 metre-long ice core, which provides annual climate records for the past 1,100 years, and extracted two shallow ice cores spanning the past 800 to 1,000 years. The ice cores are being analysed for a range of climate parameters including temperature, snowfall, volcanic forcing, solar forcing, greenhouse gas forcing, sea-ice extent, atmospheric variability, dust sources from Australia, and biomass burning events. This ice core provides a valuable link between the coastal Law Dome record and the interior of the continent.

More recently, in the summer of 2017-18, a team of Australian ice core researchers embarked on another deep field expedition to recover a 2,000-year-old ice core from Mount Brown, inland of Davis Station. The 300-metre core is expected to provide a record of the climate history of the Indian sector of the Southern Ocean, and hopefully a more robust picture of climate variability in Australia over the last one to two millennia. The region is known as a 'cyclone nursery' as it is where many storms are born before they head from west to east across the Southern Ocean and impact both Australia and East Antarctica.

FUTURE DIRECTIONS

One of Australia's new major commitments is funding to the Australian Antarctic Division to lead an international project to drill an ice core climate record reaching to beyond a million years. Presently the oldest ice core record of the climate is from the EPICA Dome C ice core, which enabled a reconstruction of the climate spanning some 800,000 years. Reaching beyond a million years will be significant because it spans a time in Earth's history when the standard period between ice age cycles suddenly shifted pace. Marine sediment proxy records extending back several million years clearly show a change in pacing of ice age cycles from 100,000 years most recently, to about 40,000 years before about 1.5 million years ago. The change came about progressively between 1.3 million years ago and 800,000 years ago, just where the ice core record ceases.

Our understanding of what caused the switch from shorter to longer interglacial cycles is incomplete. Both correspond to changes in solar forcing with the Earth's orbit, but we don't know why the climate system switched. Changes in background CO_2 levels are a potential cause, and understanding how this may have happened has clear relevance for understanding future CO_2-driven change. Glaciologists believe the Antarctic ice sheet likely holds "coreable" ice that is old enough to help address this. Starting around 2020–21, Australian and international science personnel plan to set up the drill and associated infrastructure in preparation for a three-to-four-year drilling program.

THE CHANGING EAST ANTARCTIC ICE SHEET

The East Antarctic ice sheet plays a central role in controlling the global climate and sea level. Understanding its sensitivity to climate changes and potential for retreat has been a key research objective of the ACE CRC partnership since its inception.

05: Surface meltwater floods off the Sørsdal Glacier, East Antarctica..

Almost five kilometres thick in places, the East Antarctic ice sheet is the largest ice sheet on the planet and contains enough water to raise global mean sea level by more than 50 metres. This vast mass of frozen fresh water has formed through the accumulation and compaction of snowfall over millennia. Snow deposited on to the ice sheet is compacted into ice that forms vast, slow moving glaciers flowing continuously towards the oceans under the influence of gravity. As they reach the oceans, the glaciers begin to float forming ice shelves that both melt from the bottom and calve icebergs. Understanding the complex physical forces that drive this ice loss is crucial to quantifying the East Antarctic ice sheet's future behaviour and response to global warming. The rate at which ice discharges from the Antarctic continent into the oceans is presently the greatest source of uncertainty in modelled projections of global 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. The projections agreed by 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 and that the collapse of marine-based sectors of the Antarctic ice sheet that will cause global mean sea level to rise substantially above the likely range during the 21st century. 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 half-metre rise in sea level, flooding recurrence intervals decrease by typically a factor of 300. In other words, a once-in-a-century flood event becomes a several-times-a-year event.

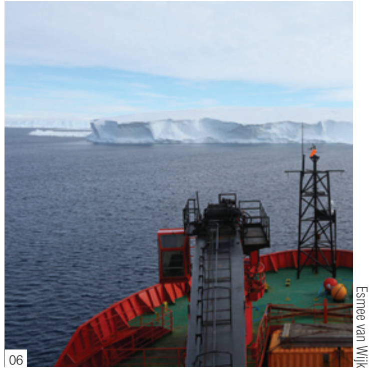
Researchers at ACE CRC have continued to focus on understanding how the Antarctic ice sheet is likely to respond to a warming climate, and which regions face the greatest risk of increased ice discharge into the sea. This research covers a wide range of interactions, such as ocean melting of ice shelves, bedrock and internal ice flow dynamics, oceanography, ice-shelf disintegration, and combines a range of different methods, including linking between field surveys of the Antarctic ice sheet and oceans and both laboratory and computer modelling of complex 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.

AIRBORNE SURVEYS

Until very recently, large swathes of the East Antarctic ice sheet were virtually unmapped, with no measurements of ice thickness. Today that has all changed thanks to the comprehensive airborne survey of East Antarctica carried out by the International Collaboration for Exploration of the Cryosphere through Aerogeophysical Profiling, known as ICECAP. The ICECAP project has involved researchers from the Australian Antarctic Division, the ACE CRC and the University of Tasmania working alongside American, British and French scientists. The project uses a fixed-wing aircraft, equipped with the latest ice mapping equipment such as ice-penetrating radar and laser altimeters, to produce detailed images of the ice sheet and bedrock. Over about a decade of operations, the ICECAP project has profoundly changed our understanding of the East Antarctic ice sheet. Knowing the shape and composition of the ice sheet in such detail has provided insights into how the ice flows and deforms over time. Among ICECAP's first surprises was the discovery of deep glacial canyons buried far beneath the ice, that extend hundreds kilometres inland from the edge of the ice sheet. The formations are geological relics of the growth of the Antarctic ice sheet, beginning some 34 million years ago, and reveal a past in which the shape of the ice sheet was very different.

TOTTEN GLACIER

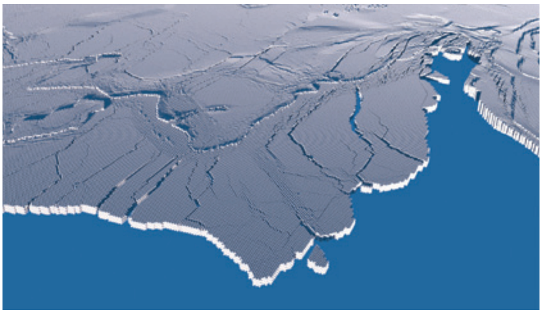
The East Antarctic ice sheet had, until the ICECAP surveys, been considered protected from the rapid glacial retreat observed in Greenland and West Antarctica because of a predominating view that the ice rests safely on ground above sea level. Data from ICECAP revealed that a large part of the catchment that feeds ice into the Totten Glacier rests on bedrock well below sea level. To give some idea of its size, there is enough ice in the Totten Glacier alone to raise global sea level by at least 3.5 metres, roughly equivalent to the projected contribution of the entire West Antarctic Ice Sheet.



06: A close up view of the Totten Glacier from the bridge of the Australian icebreaker *Aurora Australis* in 2015.

The first hint of the susceptibility of the East Antarctic Ice Sheet to change came when satellite imaging began to detect significant thinning of the region's largest glacier, the Totten. A critical insight came from the development of predictive numerical models developed by ACE CRC researchers which provided valuable early insights into the factors driving the Totten's melting. Using data from satellite and the ICECAP airborne surveys to constrain the models, researchers successfully simulated the interaction between ocean currents and the cavity under the Totten ice shelf in four dimensions. The simulations showed pathways for relatively warm ocean water from the deep ocean to flow up the continental shelf and under the ice shelf. However, the models needed to be evaluated using oceanographic observations to determine if ocean currents were, in fact, bringing warmer waters closer to the glacier.
A major impediment to measuring the ocean was the year-round presence of thick pack ice near the front of the glacier, which had previously blocked attempts by research ships to get in close. Until in early 2015, the model predictions were confirmed, when the *RV Aurora Australis* became the first ship to reach the edge of the Totten Glacier with modern oceanographic capabilities. Thanks to a lucky break in the sea-ice and some bold manoeuvring, the ship made a dash through a temporary crack in the ice for scientists to make the first direct measurements of the ocean alongside the ice shelf. The researchers used a suite of new instruments, such as autonomous floats designed to sample the ocean beneath sea-ice. Traditional oceanographic tools like conductivity, temperature and depth (CTD) profilers were also lowered from the ship to measure the ocean properties around the glacier front, and to look for chemical tracers of glacial melt. The team confirmed that warm water from the sea floor was reaching the sea bed in front of the glacier inside a one-kilometre deep channel that had not been clearly mapped by the aerogeophysical surveys of the region.

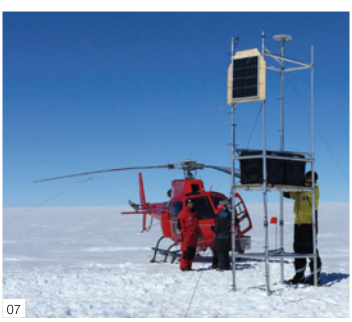
Scientists now believe that exposure to melting by the relatively warm waters makes the Totten much more like the glaciers of West Antarctica, where the rate of ice loss has been much greater in recent decades. The findings have also prompted a rethink of our understanding the East Antarctic ice sheet more generally, and work is underway at a number of other locations to determine whether similar ocean forces could be acting on other major glacial outlets. This includes



Sue Cook

FIGURE 3: 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.

ACE CRC fieldwork activities at a number of ice shelves, including the Totten, using a variety of sensitive instruments to measure changes in velocity, thickness, basal melting, and other factors related to the glacier flow. On-ice radar units and Global Positioning System receivers have been deployed in the field to monitor the connection between melt rates underneath the Totten, Amery, and Sørsdal Glaciers, and their connection with both the ocean and ice flow. These radar 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. Scientists have also begun deploying expendable probes from the air in regions hard to reach with ships, gathering information on both the ocean and seabed that, together with the computer modelling and on ice measurements enables them to measure changes that could affect glacier flow. This comprehensive suite of measurements and numerical modelling will provide the first connection between observed ocean state, basal melt rates, and the flow speed of the glaciers, enabling development of predictive models to more accurately assess the vulnerability of this part of East Antarctica to further warming.



07

Ben Galton-Fenzi

07: Scientists install a GPS receiver on the Totten Glaicer to measure its velocity.

FUTURE DIRECTIONS

This research is given urgency by indications that the rate of ice loss from Antarctic ice sheet is accelerating, having tripled to an estimated 241.4 billion tons per year since 2012. The key priority therefore remains to quantify both recent and future changes in the mass of the East Antarctic ice sheet, and its influence on sea level over the coming decades and centuries. Future research will continue to be guided by the following further 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?

Our ability to address these questions by modelling all of these processes is still in the early stages. New ice sheet modelling by the ACE CRC is beginning to consider complex processes such as iceberg calving and the development of rifts and fractures in more detail than previously possible. The calving of icebergs accounts for about half of the ice lost each year from the Antarctic ice sheet, but it is notoriously difficult to incorporate into estimates of future ice loss. More reliable methods for projecting long-term average loss of ice as icebergs, however, are becoming possible through the development of new numerical modelling and measurement techniques.

Much work remains to be done to isolate the climate change signal from the noise of natural glacial variability. To achieve this will require a more detailed understanding of the relative influence of a wide variety of factors that affect the rate of ice discharge over longer time scales; from the influence of ocean currents, to the subglacial bedrock environment, right down to the physics of the ice crystals. This in turn requires significant and continued efforts to observe and quantify the processes that control ice-mass loss in East Antarctica, using ground based and remote sensing observations, laboratory experiments and numerical modelling, aided by new technologies such as airborne and underwater robotics and super-computing.

CLIMATE HANDBRAKE

THE CHANGING SOUTHERN OCEAN

When the CRC began its life in 1991, the question of whether the Southern Ocean was changing was completely open. Today, scientists have much better understanding of why this wild and remote region, which occupies almost one third of the Earth's surface area, has such a profound influence on the world's climate and ecosystems. Observational analysis and modelling simulations developed through the partnership during the 1990s and through to this day have set the benchmarks against which our current understanding of change in the Southern Ocean is measured.

For example, the ACE CRC partnership has made major advances in understanding ocean circulation and the formation of Antarctic Bottom Water, which plays a key role in driving the global overturning circulation and regulating the climate. These achievements have sparked a surge in international scientific interest in this region, placing this once under-explored body of water at the centre of the global climate story and bringing new opportunities for collaboration.

We now know that the Southern Ocean is a major carbon and heat sink, storing more anthropogenic heat and carbon dioxide than any other latitude band on Earth and acting as a powerful handbrake on climate change. Research by the ACE CRC partnership has also provided data showing that the Southern Ocean is becoming fresher, more acidic and less oxygenated – and that all these processes are occurring more rapidly than in any other ocean.

THE OVERTURNING CIRCULATION

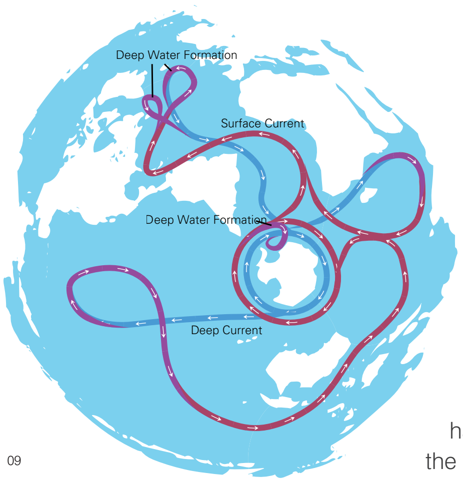
In the early days of the CRC, growing scientific interest in the ocean and its role in the global climate system provided Hobart-based oceanographers with the opportunity to collaborate in the World Ocean Circulation Experiment (WOCE). The WOCE field program, launched in 1990, was an opportunity for Australia to become a major player in a global research program. One of the key outcomes of the project was demonstrating that vertical circulation – the movement of water between the surface and the deep ocean – largely determines the amount of heat and atmospheric gas stored in the global oceans. Where water sinks from the sea surface, heat, carbon and oxygen absorbed from the atmosphere are carried into the ocean depth. Where water upwells, this heat and other gases tend to be released to the atmosphere. The CRC identified the Southern Ocean as a major contributor to the formation of the dense waters that fill the global ocean abyss – and drives the overturning circulation.

The global overturning circulation is a network of ocean currents that connects the deep and shallow layers of the ocean. The "lower limb" of the Southern Ocean overturning circulation is supplied by cold, dense Antarctic Bottom Water that sinks near Antarctica. Antarctic Bottom Water is formed where cold off-shore winds drive the sea-ice northward, creating narrow coastal regions of high sea-ice production known as polynyas. Salt ejected during sea-ice growth is added to the underlying water, making it saltier and more dense. During winter the density increases until the waters sink and flow down the continental slope to spread throughout the deep ocean. The


08

Steve Rintoul

08: The Southern Ocean's remoteness, combined with its extreme weather, create a unique set of challenges for oceanographers.



09

09: The simplified path of the thermohaline circulation. Blue paths represent deep-water currents, while red paths represent surface currents.

"upper limb" of the overturning circulation is formed from upwelling of deep water to the surface of the Southern Ocean, where it is driven northward by the wind and made more buoyant by warming and freshening. The surface waters sink into the ocean interior on the northern side of the Antarctic Circumpolar Current. In this way the Southern Ocean acts to link the deep and shallow limbs of the global overturning circulation.

A TECHNOLOGICAL REVOLUTION

Much of the progress made in recent years has depended on the establishment of innovative, long-term observational programs. A dedicated effort over several decades has turned the Australian sector of the Southern Ocean from one of the least observed to one of the best observed ocean regions. Supported by Australia's Integrated Marine Observing System (IMOS), an observing system based on ships, moorings, gliders and floats has been developed and continues to evolve as new technology and

new ideas open up new opportunities.

Undoubtedly the greatest revolution in ocean observing has come through the international Argo program. The Argo 'robots' are autonomous floats that drift with the ocean currents. Every ten days, the float changes buoyancy and rises through the water column, recording the temperature and salinity as a function of depth in the top 2,000 metres of water. Once the float reaches the sea surface, the information is relayed via satellite to researchers on land. The partnership has co-invested with other Australian and international partners in the Argo array, and this data has revolutionised our understanding of Southern Ocean climate processes.

The technology on board Argo floats is continually improving, and Australia has recently begun deploying new-generation, deep-diving Argo floats that can dive up to five kilometres below the surface of the Southern Ocean. By providing year-round measurements through the full ocean depth, the floats will fill a massive data gap for the climate research community.

10

ACE CRC

10: A crew member on board *RSV Aurora Australis* prepares to release an Argo float into the Southern Ocean.

THE WORLD'S LARGEST OCEAN CURRENT

The ocean circling Antarctica is dominated by the world's largest ocean current – the Antarctic Circumpolar Current (ACC). This current carries water from the Indian, Pacific and Atlantic Oceans and has a major influence on the southern hemisphere by insulating the Antarctic ice sheet from heat energy from the tropics. Despite its central role in the climate system, the dynamics of the Antarctic Circumpolar Current have remained poorly understood. In 2001, scientists from the ACE CRC developed new conceptual models of the Southern Ocean, showing how the ACC and overturning were dynamically connected through the action of winds, eddies and their interaction with the sea floor. The theory has been validated with field observations and is now included in ocean models used to simulate how the oceans could change in the future.

ANTARCTIC BOTTOM WATER

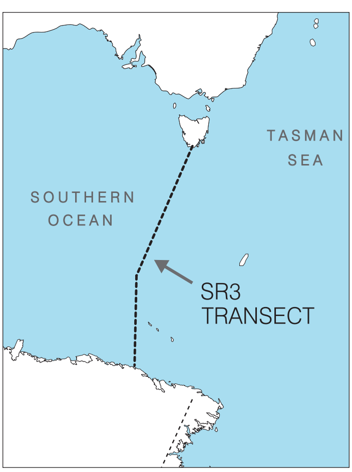
Prior to the work of the ACE CRC, it was widely believed that Antarctic Bottom Water was only formed in the Weddell and Ross Seas. Research has since shown that the Mertz Glacier polynya was another important source. On a rare winter voyage to the Antarctic coast in 1999, scientists quantified for the first time how much sea-ice was formed in the polynya "sea-ice factory" and its impact on the ocean. This voyage and subsequent long-term mooring observations have clearly demonstrated the importance of the region as a source of Antarctic Bottom Water.

More recent work led by ACE partners in Japan has used moorings and oceanographic observations collected by elephant seals to identify another source of bottom water at Cape Darnley in the Indian Ocean.

Researchers with the ACE CRC have also identified a significant reduction in the production of Antarctic bottom water in recent decades. A landmark study published in 2014 provided the most detailed assessment of changes in Antarctic Bottom Water to date. The paper showed that the volume of the dense bottom water layer has decreased by as much as 60% since the early 1970s. The authors concluded that the freshening of the source waters, was due to an increase in snowfall and increased melt of the Antarctic ice shelves. The impacts of these changes on the global climate system remains a key question for climate science.

INTERNATIONAL INFLUENCE

The IPCC's Fifth Assessment Report (AR5), published in 2013, included significant contributions from 18 ACE CRC scientists, including Dr Steve Rintoul, who was a Coordinating Lead Author for the Oceans chapter. The chapter assessed the observational evidence for change in the oceans, and showed that the oceans have stored about 93% of the extra heat energy accumulated by the planet over the past 50 years. Professor Nathan Bindoff was a Coordinating Lead Author for the Oceanic Climate Change and Sea Level Chapter of AR4 in 2007 – which confirmed for the first time that "warming of the climate system is unequivocal" – and also for the Detection and Attribution chapter of AR5, which provided the strongest evidence to date that human activities had made a substantial contribution to the warming of the Earth.



THE SR3 TRANSECT

Many of the major breakthroughs in Southern Ocean science, including our understanding of its role in carbon uptake, were made possible by data obtained during repeat observations along a line known as the Southern Ocean Repeat Section, or SR3 transect. The transect runs north-south between the south coast of Tasmania and the coast of Antarctica at approximately 140°E. Scientists involved in the partnership have conducted regular observations along this line since 1991, collecting samples at specific intervals to measure circulation, trace chemistry, pH, biology, temperature and salinity. This detailed and frequently repeated time series has proven to be an immensely valuable resource for climate science, providing researchers across many disciplines with a high-resolution dataset showing changes in ocean properties linked to the climate.

CARBON UPTAKE & CHEMICAL CHANGE

11

Pete Harmsen/MNF

11: Australian researchers deploy equipment for studying Southern Ocean chemistry.

In the past two decades, the ACE CRC partnership has played a central role in addressing some of the major uncertainties that once surrounded the role of the Southern Ocean in the global carbon cycle. A landmark study published in 2004, bringing together a large number of ocean datasets, gave clear insight into the remarkable capacity of the global oceans to absorb anthropogenic carbon dioxide. It showed that about one third of the additional carbon dioxide released into the atmosphere during the past 200 years from human activities has been absorbed by the oceans. The Southern Ocean has played a lead role in this process, accounting for a surprising 40% of this total anthropogenic carbon uptake.

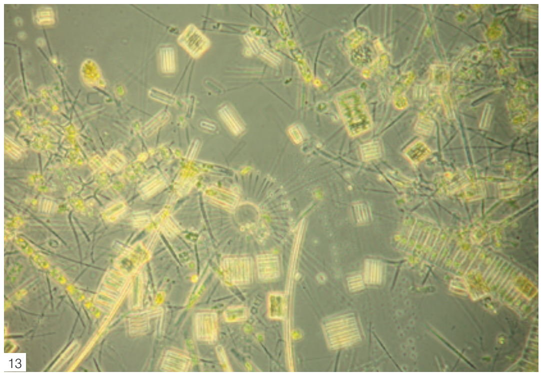
The cost is that the oceans are becoming more acidic. When carbon dioxide is absorbed by the oceans it reacts with seawater to form carbonic acid. Without the absorption of carbon dioxide by the ocean, the build-up of greenhouse gas in the atmosphere would be much more rapid and the impacts of climate change on land more sudden and severe. The Southern Ocean's ability to continue providing this 'service' at the current rate – and the full scope of the impacts of the ocean acidification – are both unknown.

In addition to measuring changes in the uptake of atmospheric carbon dioxide in the Southern Ocean over time, one of the key goals of ACE CRC research in this field has been to understand the physical, chemical, and biological processes that control the process of absorption, in order to improve predictions for future change.

When the first Antarctic CRC was formed, the extent to which the Southern Ocean contributed to the balance of atmospheric carbon dioxide was unclear.

It is chiefly through sustained sampling and observations by ACE CRC researchers over several decades that we now know that the Southern Ocean is likely to reach concerning levels of acidity sooner than any other ocean. Increased acidity has been shown to affect organisms in many ways, from their ability to build calcium carbonate shells or skeletons, to the success of their larval development, and is correspondingly expected to impact on fisheries and conservation management worldwide.

David Reilly



Patti Virtue

12: Studying ocean trace metals at low concentrations requires rigorous quarantine measures to prevent contamination.

13: Sea-ice algae

Two separate processes are responsible for transporting carbon from the atmosphere to the deep ocean. The so-called 'physical pump' refers to the dissolving of carbon dioxide from the atmosphere directly into seawater, and its transport to the deep ocean. The 'biological pump', on the other hand, refers to the transformation of carbon dioxide into carbon-based organic matter by phytoplankton during photosynthesis, which supports marine food webs, and transfers large quantities of carbon to the ocean interior when the organisms die and sink. These two carbon pumps operate continuously as part of natural ocean processes, and move much larger amounts of carbon dioxide in and out of the ocean than is emitted by industrial processes.

The ACE CRC has undertaken the longest-running repeat observations of anthropogenic carbon sequestered into the deep Southern Ocean by both the physical pump and the biological pump. The results of this work indicate that the Southern Ocean's ability to absorb carbon dioxide in fact varies considerably over decadal time scales. Work by the CRC has shown that the Southern Ocean's effectiveness as a carbon sink was in decline for several decades, up until roughly the turn of the century, when carbon uptake began to rebound. Studies have shown that between 2002 and 2012, the rate of uptake bounced back by about 0.6 billion tonnes of carbon per year – which is about six times Australia's annual emissions. The causes behind this high level of variability remain the focus of ongoing research, however researchers believe that shifting wind patterns and related changes in the overturning circulation are likely to be a major influence on the natural variability of the sink.

The other major process driving carbon uptake, the biological pump, has also been the focus of a long-running project using ocean moorings designed to measure the rate that biological particles sink into the deep ocean. Specially designed funnels capture particles sinking through the water column, which are collected and analysed by scientists in Hobart. In recent years, as part of Australia's Integrated Marine Observing System (IMOS), the moored observations have expanded to include quantification of ocean surface processes such as the air-sea transfer of both carbon dioxide and heat, and to collect biological samples to determine the organisms most important to photosynthetic carbon dioxide uptake. This work has begun revealing new insights into the complexity of the biological pump, including showing that sequestration to the deep ocean occurs more effectively in the Sub-Antarctic than Antarctic waters, and that silica and iron availability play important roles in determining which species are involved.

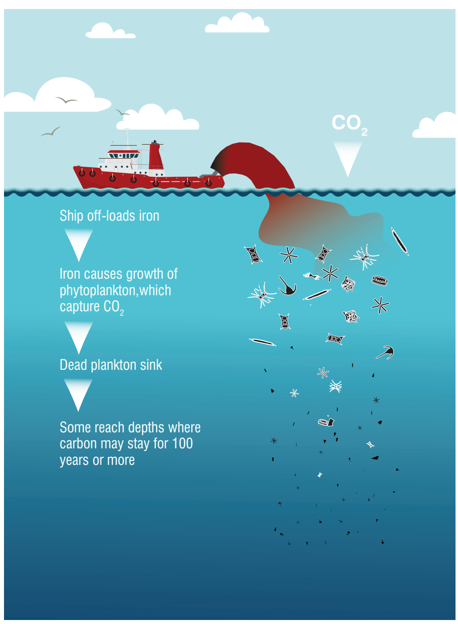
Changes in the Southern Ocean carbon pump have also been observed in response to changes in the cryosphere. Research published in 2014 described how the calving of the Mertz Glacier tongue in 2010 resulted in dramatic increases in biological CO_2 uptake, countering the ocean acidification from anthropogenic emissions. In contrast, work published in 2013 in Prydz Bay to the west, showed that ocean acidification proceeded there at twice the rate expected from anthropogenic emissions, owing to reduced biological pump activity. These results point to the importance of understanding the interaction between the ice shelf and ocean, and are a launching pad for the development of greater monitoring of coastal Antarctic biogeochemistry as a gauge for measuring ecosystem vulnerability.

OCEAN FERTILITY

Sequestration of carbon by the biological pump relies first and foremost on the abundant growth of marine organisms in surface waters. One of the great mysteries of the Southern Ocean has been its relatively low production of phytoplankton, despite the abundance of a large variety of key nutrients in the water. As early as the 1930s it was hypothesised that the Southern Ocean might be low in the trace micronutrient iron because of the ice capping the Antarctic continent, and the long distances from other continental sources of airborne dust particles. This was given a dramatic emphasis in the 1990 with the so-called 'Iron Hypothesis', which hypothesised that adding iron may remove enough CO_2 to cause an ice age. Yet at that time, measuring iron at the trace levels required was a Herculean task achievable by not even a handful of laboratories worldwide. Early work by the CRC took a two-step approach to test this hypothesis. Firstly, it organised an expedition involving 70 scientists from five countries to examine the current magnitude of carbon transport to the deep sea in the northern sub-Antarctic Southern Ocean and its relationship to iron availability, primary productivity, and ecosystem structure. Results showed a clear lack of iron, and yet a surprisingly high transfer of carbon to the deep sea that is similar to the global median.

Next, scientists from the CRC joined colleagues from New Zealand and the United Kingdom in the Southern Ocean Iron Release Experiment (SOIREE). This was the first scaled-up test of the idea that iron is limiting the growth of phytoplankton in the Southern Ocean. The experiment involved release of 10 tonnes of ferrous sulphate heptahydrate in a 55 square kilometre area south of Tasmania at a latitude 61 degrees south – an additional iron loading similar to annual natural input from the atmosphere downwind of continents. The additional iron brought a steep and sudden increase in phytoplankton growth in the vicinity, demonstrating that even cold, remote, deeply mixed ocean waters were sensitive to iron limitation. Based on these results, it appears that increased iron derived from continental dusts could explain about half of the lower atmospheric carbon dioxide which existed about 20,000 years ago, during the last glacial maximum period. Forward projection at that time suggested that a fully efficient ecosystem in the Southern Ocean promoted by iron fertilisation could delay the onset of dangerous atmospheric carbon dioxide levels for as much as 25 years, but this was later shown to be an upper limit. Subsequent work on naturally elevated iron inputs near Southern Ocean islands by ACE CRC and French collaborators have shown that the impact is likely to be much less – removing well under 10% of current CO_2 emissions.

Knowledge that the 'anaemic' state of the Southern Ocean might be restricting the rate of biological carbon sequestration has prompted proposals for larger scale experiments with deliberate ocean fertilisation. It was hypothesised that the process, known as marine geoengineering, could help offset anthropogenic carbon emissions and slow the rate of climate change. Experimental evidence for this hypothesis remains inconclusive, and the proposal remains highly controversial. The artificial iron enrichment experiments conducted to date have not shown clear evidence that iron fertilisation leads to significant removal of atmospheric carbon dioxide over longer timescales. There is expectation and some evidence, however, to suggest that iron fertilisation would result in a range of unintended and undesirable impacts, including toxic algal blooms, ocean oxygen depletion, and harmful impacts on marine foodwebs.



The Hope
Plankton poulations rebound to historic levels, reviving fisheries and sequestering vast amounts of carbon

The Fear
Iron leads to depletion of deep-water oxygen, alters food chain, and promotes toxic species; CO_2 soon resurfaces

FIGURE 4: Cartoon depicting potential outcomes of ocean iron fertilisation. It is not yet known whether fertilisation might generally enhance ecosystem production and drawdown of CO_2 ('the hope'), or whether this might lead to substantial and unwanted ecosystem changes that ultimately might do little or nothing to enhance CO_2 drawdown ('the fear').

Based on this evidence, the ACE CRC provided advice to the Australian Government in 2012 supporting a precautionary approach to deliberate iron fertilisation. This led to a successful Australian push for a global moratorium on marine geoengineering by the International Maritime Organisation. There remains, however much to be learnt through future scientific research on ocean fertilisation and scientists should be encouraged to improve our understanding of the ocean's natural response to nutrient addition. Research continues at the ACE CRC on understanding the potential scientific impacts of such actions, and how they compare to existing, natural iron fertilisation processes such as supply from sediments from island archipelagos, glacial and sea-ice release, hydrothermal vents, and even cetacean faecal discharges. A series of expeditions in recent years have set out to understand the processes involved in the natural iron fertilisation of waters around the Kerguelen Plateau, including Australia's only volcanically active islands of Heard and McDonald, which results in massive phytoplankton blooms each year.

AAP One

BALANCING THE CARBON BUDGET

One of the major stumbling blocks to the achievement of an international agreement on emission reduction during the 1990s was the high degree of uncertainty over the rate of carbon dioxide sequestration through natural processes. Scientists studying atmospheric carbon dioxide had been unable to account for the whereabouts of a large proportion of known anthropogenic carbon dioxide emissions – commonly referred to as the 'missing carbon'. Work by ACE CRC and CSIRO scientists as part the World Ocean Circulation Experiment (a globally agreed set of hydrographic sections) helped to close this gap by quantifying the Southern Ocean's role in anthropogenic carbon uptake. Together with scientific efforts demonstrating the importance of northern hemisphere forests in carbon sequestration, this global oceanographic collaboration helped clear the way for the first international agreement on emissions reduction in 1997, and for subsequent agreements under the United Nations Framework Convention on Climate Change. This foundational work remains one of Australia's most important contributions to climate science, and continues to guide important decisions on global emissions reduction.

FUTURE DIRECTIONS

Many uncertainties remain with regard to the response of the Southern Ocean to climate change and the consequences of Southern Ocean change. One key scientific uncertainty concerns the likelihood and magnitude of feedbacks to the climate system as a result of Southern Ocean changes. Feedbacks may occur due to changes in ocean circulation, the rate of carbon uptake by the ocean, the supply of iron, reduction in sea-ice extent and the potential for a warmer ocean to accelerate the loss of ice from the Antarctic ice sheet and therefore cause ocean freshening and sea-level rise. Warming and ocean acidification will also impact on marine ecosystems.

Southern Ocean processes are intimately linked to some of the most pressing challenges faced by society: climate change, sea-level rise, ocean acidification and the sustainable management of marine resources. To address these challenges, we need to continue to improve our understanding of the nature, causes and consequences of Southern Ocean change. New observing systems and sustained observations, which can only be maintained through international collaboration, plus advances in climate modelling that assimilate and integrate these observations, are improving our knowledge of Southern Ocean processes and changes. Sustained efforts in long-term Southern Ocean observations and modelling over the past three decades have clearly paid off, and will continue to bring significant dividends for society in understanding our changing climate.

CLIMATE ENGINE

CHANGE & VARIABILITY IN ANTARCTIC SEA-ICE

During autumn and winter, the surface of the Southern Ocean forms a vast floating blanket of ice that encircles the Antarctic continent. By the time this sea-ice reaches its annual maximum extent in September, it covers about 19-20 million square kilometres of ocean, or roughly three times the area of Australia. Most of this ice melts back by February, shrinking to an area covering only about three-to-four million square kilometres. This annual cycle of advance and retreat is one of the Earth's largest seasonal fluctuations, and a powerful physical driver of the global climate system. As the sea-ice forms over the ocean, it generates an enormous volume of cold, dense and salty water that sinks and drives deep ocean currents that flow northward from the Antarctic continent. This Antarctic Bottom Water circulates throughout the global oceans and helps drive its overturning circulation – a process that earns this region its nickname of the 'engine room' of the global climate system.

Sea-ice plays other crucially important climate roles. Its presence as an insulating blanket greatly modifies exchanges of heat, moisture, climate gases and wind energy between the atmosphere and ocean. The sea-ice is also crucially important to a myriad of organisms, ranging from microscopic algae through to krill, fish, penguins and great whales, which are adapted and intimately attuned to its presence and seasonal cycle. For human visitors, sea-ice also can have major implications for the safety of shipping, tourist and operational activities around the polar Southern Ocean.

Sea-ice also responds to changes in the environmental conditions in complex and often unpredictable ways. This makes the task of accurately predicting the future state and distribution of Antarctic sea-ice a major challenge for climate modellers and ocean navigators alike. The current generation of coupled climate models, although sophisticated in some respects, produce a wide range of simulations for Antarctic sea-ice, with few accurately reproducing the changes to sea-ice extent observed since the late 1970s. These factors unfortunately undermine the degree of confidence that can be placed in current predictions of likely sea-ice conditions over the coming decades. They also underline a critical need to carry out coordinated in-situ measurement programs to better understand sea-ice-atmosphere-ocean interactions.

Although the advent of the modern satellite era in the late 1970s revolutionised our ability to monitor and understand broad-scale sea-ice distribution and processes, there are still many fundamentally important questions that can only be answered through fieldwork. Australia is one of a handful of nations that has been able to conduct this important research around Antarctica, through dedicated, multi-disciplinary field campaigns from the research ice breaker *RSV Aurora Australis* operating deep within the East Antarctic pack-ice zone. In 1995, the HIHO-HIHO study resulted in much-improved understanding of how East Antarctic sea-ice forms and thickens, and its resulting effects on the ocean and atmosphere. The Mertz Glacier Polynya Experiment in 1999 quantified rapid ice formation rates in this coastal polynya, measured effects on the atmosphere and ocean, and confirmed the polynya's role as a globally-important site of bottom water formation. Four years later, the Antarctic Remote Ice Sensing Experiment (ARISE) carried out important work towards ground-truthing key

14

Jan Lieser

14: *RSV Aurora Australis* in the sea-ice during the SIPEX-II voyage in 2012-13

ACE CRC

15: Scientists at work on the sea-ice during SIPEX-II in 2012-13.

satellite data – improving remote sensing of sea-ice concentration, temperature and motion, and snow cover thickness. Building on these earlier voyages, the Sea-ice Physics and Ecosystem eXperiment (SIPEX) in 2007 and follow-on SIPEX-II voyage in 2012 together made a major contribution to our understanding of the role of sea-ice in the climate system and ecosystems. The aim of these cross-disciplinary voyages led by the ACE CRC has been to understand the interaction between the atmosphere, sea-ice and ocean and the relationships between the physical sea-ice environment, marine biogeochemistry and marine ecosystems.

During these and other voyages, scientists have conducted detailed experiments on ice floes to learn about the thickness, snow cover and other properties of the sea-ice, how it interacts with the ocean and atmosphere, the importance of the under-and intra-ice environment as a habitat for krill, and the potential effect of a changing sea-ice environment on Southern Ocean ecosystems. Dozens of unique experiments spanning from millimetres to kilometres have been carried out. These include micro-scale studies on the habitability of brine pockets within the sea-ice to airborne surveys of the sea-ice and snow cover thickness – extended in space and time by satellite data.

For their investigations, scientists have developed and used a range of novel instruments and techniques, including helicopter-borne radar and laser altimetry to measure the ice and snow thickness, drones for acquiring detailed images of sea-ice concentration and floe size, a remotely operated vehicle to observe and film krill and determine sea-ice algae distribution and biomass, and an autonomous underwater vehicle to study the under-ice topography and overall thickness. In parallel, modelling activities have played a key role in synthesising and interpreting the observations. The unifying goal of these investigations has been to improve our understanding of how sea-ice influences global climate, what factors are driving observed change and variability in the sea-ice environment, and how changing sea-ice conditions will affect the biogeochemical cycles and ecosystem dynamics in the Southern Ocean. Research carried out with the Antarctic CRC in the 1990s through the ACE CRC has steadily and incrementally improved our understanding of these important areas.

While major progress has been made, significant gaps remain in our understanding of fundamental sea-ice processes and phenomena. One issue at the centre of a lively public discussion in recent years is the surprising increase in the overall extent of sea-ice coverage around Antarctica in recent decades. In contrast to the spiralling downward trend observed in the Arctic, the average mean annual sea-ice extent around Antarctica has been increasing by between one and two percent per decade. This overall net trend, however, comprises more dramatic changes in both the regional and seasonal distribution of Antarctic sea-ice. Most notably, both sea-ice extent and annual duration have increased substantially in the Ross Sea sector, while major sea-ice loss has occurred in the Bellingshausen/Amundsen seas sector. Not only this, but the Antarctic sea-ice system has recently been prone to wild variations in sea-ice extent and distribution from one year to the next. After setting a record maximum in 2014, for instance, Antarctica's total sea-ice coverage reached its lowest recorded winter peak just three years later in 2017. Based upon ACE CRC and international research, a number of hypotheses have been proposed, all of which suggest that drivers of Antarctic sea-ice distribution are far from simple, and prone to substantial variability. Some studies suggest that wind-driven changes linked to ozone depletion have played a role, while others posit the input of fresh water from the melting ice sheet as a factor. Further research has highlighted the possibility of tropical to high-latitude atmospheric interactions playing a role.

Notwithstanding the recent attention paid to changes in

Antarctic sea-ice extent, there are a number of other critical sea-ice parameters such as thickness and volume that are of equal or greater significance, while being much more difficult to quantify at the large scale. Sea-ice thickness and volume are not only sensitive indicators of climate change but also a measure of total ice production and, hence, heat exchange between the ocean and atmosphere. Reducing this uncertainty is a crucial step to more accurately simulating the role of the coupled sea-ice-atmosphere-ocean system in climate models, and is a key focus for ACE CRC sea-ice and climate research.

Current methods for measuring and monitoring sea-ice thickness and volume over large-scales use satellite altimeters, but these systems require refining and ground-truthing using in-situ sea-ice observations. The ACE CRC has deployed a variety of airborne and underwater imaging systems aimed at bridging the gap between highly detailed in-situ and shipborne observations and large scale satellite remote sensing. These systems include airborne laser and radar altimetry for surface elevation (freeboard) mapping, and under-ice sonar measurements using an autonomous underwater vehicle for measuring ice draft. Another important variable in deriving sea-ice thickness from these data is the thickness of the snow cover on the ice. The ACE CRC and its partners have also recorded close to 25 years of ship-based sea-ice thickness measurements, including detailed observations from the ARISE and two SIPEX voyages. Together these data provide a valuable baseline for climate studies.

Recent studies using Autonomous Underwater Vehicles (AUV) have challenged much of what we thought we knew about sea-ice thickness, showing that the conventional picture of a relatively thin veneer of ice is only true in some places. In 2010 and 2012, scientists from the ACE CRC joined international partners to deploy an AUV equipped with an upward-looking multibeam sonar to record the structure of the under-ice surface. Operating at a depth of 20 to 30 metres beneath the ice, the AUV guided itself in a lawnmower pattern across a 400 by 400 metre grid, using sonar sensors to map the undersea topography of the ice. Observations using the UAV have increased the mean estimate for Antarctic sea-ice draft – the depth between the waterline and the bottom of the ice – from around 1 to around 3 metres. In addition, the previous recorded maximum sea-ice thickness at a single location has increased from 10 metres to 16 metres.

Previous estimates of the mean thickness of Antarctic sea-ice have been calculated using hourly ship-based observations and bore holes drilled by hand. The ability of the AUVs to roam further from the ship has revolutionised our ability to obtain accurate thickness data. The researchers are confident the technology will fill the gaps in ice-thickness data collected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Guy Williams

16: An ROV being deployed to survey the underside of Antarctic sea-ice.

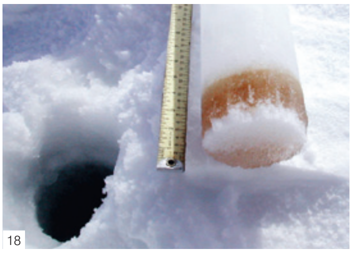
by other methods and improve our understanding of the role of ice deformation in controlling total sea-ice volume, to more accurately represent sea-ice in global climate system models.

INTERDISCIPLINARY SEA-ICE STUDIES

Early sea-ice studies at the Antarctic CRC were primarily investigations into the physical properties of sea-ice, but this focus has broadened significantly over time. For instance, work by the ACE CRC has brought a new understanding of the importance of algal communities that grow in, and on the underside of, Antarctic sea-ice. Sea-ice algae are an important food source for Antarctic krill, a key-stone species in Antarctic food webs. An important question relates to how sea-ice physical properties control the amount and timing of sea-ice algae growth, as well its release into the open water as the sea-ice melts. Researchers from the ACE CRC have developed new sampling and observing systems to address these questions, which included the use of remotely operated vehicles equipped with sonar, optical sensors and camera systems, to quantify ice algae and krill under sea-ice. The information on the physical and biological parameters of sea-ice, in combination with work on krill distribution, is enabling the development of methods for forecasting what might happen to krill populations given possible future changes in sea-ice extent and properties as the climate changes.

Sea-ice algae also provide a novel mechanism for scientists to reconstruct the history of Antarctic sea-ice extent and variability over much longer timescales than the four-decade satellite record. Up until recently, our knowledge of

Clive McMahon



ACE CRC

17: Researchers take a break from digging a snow pit during the SIPEX-II voyage in 2012-13.

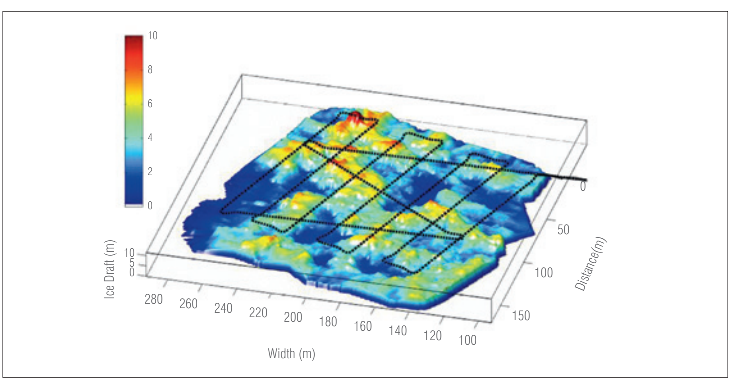
18: An Antarctic sea-ice core, showing the band of brown sea-ice algae colonising the underside.

the history of Antarctic sea-ice coverage and its variability prior to the satellite era has relied on observations recorded from whaling ships or on low-resolution ocean sediment core evidence. In a major advance, researchers from the ACE CRC's ice core team identified that a chemical marker in ice cores known as methane sulphonic acid (MSA) can provide a reliable proxy for past sea-ice extent. The mechanism for this link relies on the fact that sea-ice algae, which grow in the ice, produce a waste product known as dimethyl sulphide (DMS). This gas oxidises in the atmosphere to MSA, which is then transported on to the ice sheet in snowfall. The area of ocean covered by sea-ice from the spring maximum to the summer minimum controls the overall production of MSA. A larger maximum to minimum sea-ice excursion produces more DMS and MSA. By analysing annual levels of MSA in ice cores, scientists have reconstructed long-term changes in maximum sea-ice extent for large areas of Antarctica showing about a 20 percent sea-ice extent decline (around 1.5° latitude) from the mid to late 20th century, overlain by large decadal-scale cycles.

More recent ACE CRC research has shown sea-ice can indirectly influence the rate of glacial discharge. A study of recent ACE CRC-led research on the Mertz Glacier Tongue prior to its calving in 2010 and the catastrophic abrupt, rapid and large-scale disintegrations of ice shelves on the Antarctic Peninsula since 1995 has highlighted a previously under-estimated link – between coastal sea-ice (including stationary landfast sea-ice) and the stability of vulnerable floating ice sheet margins. This cross-disciplinary work combining observations with modelling has unearthed evidence that increased wave energy following regional sea-ice loss was a trigger mechanism that precipitated the collapse of ice shelves weakened by multiple factors – suggesting that sea-ice change can affect sea level rise (albeit indirectly). Further work is required to understand the nature of cross-cryosphere interactions involved, and the role of wave-ice interaction.

FUTURE DIRECTIONS

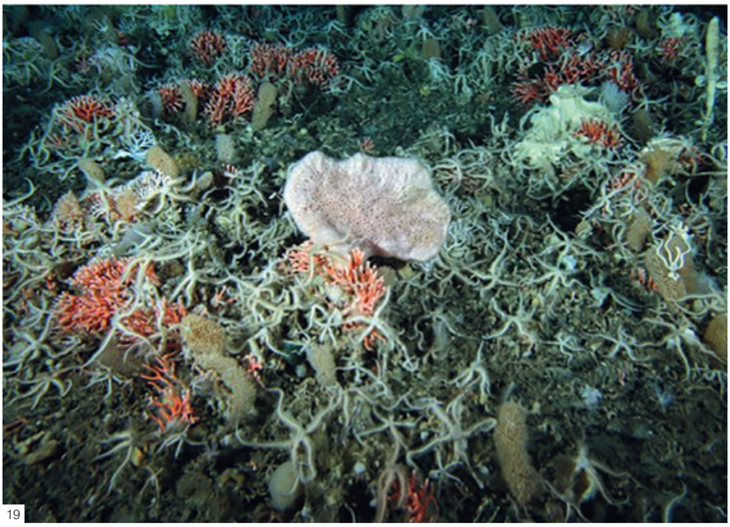
Improved knowledge of the precise interactions and feedbacks between sea-ice, the ocean, atmosphere and ice sheet is critical for modelling and understanding the current and future behaviour of Antarctic sea-ice. This again represents a considerable challenge, given the complex regional and seasonal sensitivities and possible feedbacks involved. Fortunately, we are on the cusp of an exciting new era in observational capability for monitoring the Antarctic sea-ice environment, using airborne and under-ice observing platforms in combination with the new Australian icebreaker *RSV Nuyina*. While satellites can measure sea-ice extent and concentration with considerable accuracy, it will be important to develop means of routinely monitoring and methods for predicting sea-ice and snow cover thickness over the entire sea-ice zone of the Antarctic. This new knowledge will support improvements to numerical models of the atmosphere-ocean-cryosphere system, and through this, the predictability of the global climate system itself.



AUV team

FIGURE 5: A 3-D map produced from multibeam sonar data collected by the AUV under an ice floe on 4 October 2012. The map shows a typical 'lawnmower' grid of about 150 x 150 m and the depth bar on the left shows thicker ice in red (up to about 10 m below the surface) and thinner ice in blue.

SOUTHERN OCEAN ECOSYSTEMS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Australian Antarctic Division

19: Southern Ocean seafloor ecosystem.

Despite the harsh and unforigiving climate, Antarctica and the Southern Ocean are home to an abundance of species that thrive in freezing conditions. A combination of the cold and isolation over millions of years has produced an ecosystem unlike any other, with many uniquely adapted species. The blood of the Antarctic icefish, for example, contains an anti-freeze compound that allows it to succeed in below-zero temperatures. Instead of blooming on the warm and sunlit surface of the ocean, like most phytoplankton, ice algae endure the long winter twilight by colonising the underside of the sea-ice. The sea-ice also provides a refuge for billions of Antarctic krill, which graze and grow on the algae during winter before the spring ice melt releases them into the open ocean in vast swarms. The sheer abundance of krill in the Southern Ocean provides enough food to sustain a great number and variety of foraging marine mammals and birds, including the growing population of baleen whales that return from the tropics every year.

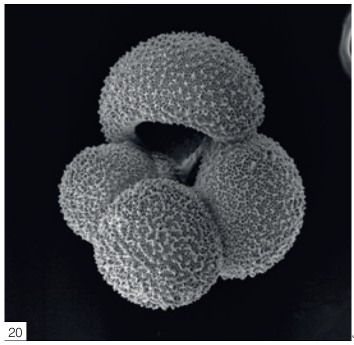
One cost of this highly specialised adaptation is vulnerability to change. Disturbances to ecosystems, such as warming, acidification, pollution and fishery depletion, have the potential to create major disruptions to Antarctic ecosystems. Research by the ACE CRC and other agencies has shown that the Southern Ocean, like many marine ecosystems world-wide, is encountering significant changes linked to climate change. The changes in pH, temperature, circulation and sea-ice – along with increased fishing pressure – are all likely to have far-reaching consequences for marine conservation. A key focus of ACE CRC efforts has been developing collaborative international projects designed to increase our understanding of both the distribution of key Southern Ocean species and the likely impacts of these pressures across the ecosystem. As a consequence, the ACE CRC has played a leading role in streamlining the delivery of science into policy forums. Its work is directly aiding policy makers to anticipate and address major conservation and management challenges in the Southern Ocean.

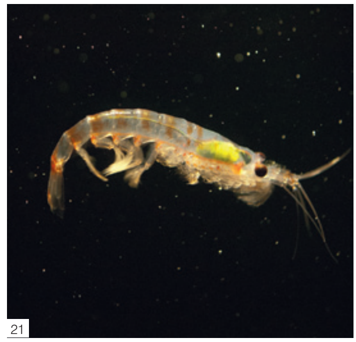
OCEAN PRODUCTIVITY

One of the fundamental questions for marine scientists in the Southern Ocean is how climate change will affect the growth of species at the microscopic level. Changes in sea-ice, ocean circulation, chemistry and temperature all influence which phytoplankton live and die in the ocean. The biological winners and losers of this process will ultimately be determined by the timing, rate and magnitude of change in each stressor, the order in which the changes occur, and the potential for consequences to be compounded when multiple stressors change at once. ACE CRC biogeochemists based at the University of Tasmania have developed new experimental methods for understanding the environmental conditions that influence the growth of phytoplankton, and how they might change during the coming decades. The team has

20: Studies show ocean acidification affects shell-forming species including *the planktonic foraminifera Globigerina.*

21: The Antarctic krill, *Euphausia superba*.





experimentally 'stress tested' a key diatom species under projected ocean conditions for the year 2100, measuring the organisms response to those changes. Where past experiments on phytoplankton have tended to focus on the effect of changes in individual properties such as pH or temperature, this study combined multiple drivers, including light, nutrients, carbon dioxide, temperature and iron, to gain an understanding of how these drivers interact and of their combined effects on phytoplankton.

The team has concluded that phytoplankton activity is likely to increase significantly, with phytoplankton in the sub-Antarctic Southern Ocean to grow at almost twice their current rate by 2100. While some species are likely to benefit significantly and others are likely to suffer declines in productivity, it is still too early to say how this will affect the broader structure of the ocean ecosystem. Whether these changes will tend to favour the larger diatoms preferred by krill, or the smaller, flagellate phytoplankton preferred by copepods is still unknown. The likely impacts on higher order species such as krill, fish and mammals is equally unknown. However, the techniques will enable development of more sophisticated models for predicting system-wide changes to marine ecosystems resulting from climate change.

There are many other types of marine microbes that could be significantly affected by changes in ocean chemistry. A key piece of ACE CRC research from 2009 observed that ocean acidification can negatively affect the ability of certain Southern Ocean microorganisms to form calcium carbonate shells. Researchers studied the shells of a protozoan called foraminifera in the Southern Ocean south of Tasmania. The team collected current-day foraminifera as they fell to the bottom of the ocean and compared them to foraminifera sampled from layers in the sea bed. The researchers found modern shells were 30% to 35% lighter than those formed prior to the industrial period, and that current-day shells are thinner than at any time in the last 200,000 years. Because a large proportion of foraminifera fall to the bottom of the deep ocean when they die, they act as a vehicle for removing carbon from the atmosphere. Any loss of shell-making efficiency might also reduce the efficiency of the ocean's capacity to sequester carbon.

KRILL

If phytoplankton are considered the foundation of the Southern Ocean foodweb, then Antarctic krill are the cornerstone. What will happen to the distribution of krill during this century is one of the most important questions for maintaining sustainable fisheries and ensuring long term conservation of the Antarctic ecosystem as we know it. Krill has the greatest crustacean biomass in the ocean and they form the staple diet of many animals including seals, whales, fish, squid, penguins and other seabirds. How much krill is in the Southern Ocean, and how the population fluctuates, are major questions to address in considering the protection of the Antarctic environment, particularly since the krill fishery is now expanding.

Krill are a cold-loving species, and the current hypothesis is that their northern boundary will contract southward as the ocean warms, limiting their range to a narrowing band of ocean around Antarctica. This may lead to the substitution of the krill-based foodweb with a fish-based foodweb in parts of the Southern Ocean, which is likely to impact a range of species at higher trophic levels, particularly those whose diets and feeding patterns are specially adapted to krill. Researchers from the ACE CRC, led by the Australian Antarctic Division, have undertaken a number of research voyages aimed at quantifying the abundance and distribution of the Southern Ocean krill population. Scientists have developed and deployed new systems for measuring krill distribution using scientific echosounders installed in the hull of the research vessel *RSV Aurora Australis*. This work has enabled the first scientifically-based estimates of the distribution and abundance of krill in the waters off East Antarctica covering a total area of 2.2 million square kilometres. The research formed the basis of advice to the international body that regulates the fisheries of the region – the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) – to set precautionary catch limits for the Antarctic krill fishery. The Kerguelen Axis program is investigating the factors that determine the northern limits to the distribution of Antarctic krill.

Research into the impact of ocean acidification on krill has shown that Antarctic krill reproduction is likely to be severely impacted if levels of carbon dioxide content in the Southern Ocean reach high levels consistent with what is expected with a 'business as usual' emissions scenario by the end of this century. Researchers based at the Australian Antarctic Division's krill laboratories in Kingston, Tasmania, exposed krill to a range of carbon dioxide concentrations in seawater to assess the possible impact of acidification on larval development. They discovered that while acidification at current levels (380 ppm) and moderate levels (1,000 ppm) did not adversely affect krill embryos, hatch rates beyond 1000 ppm rapidly declined and none of the embryos in the experimental tank survived when concentrations reached 2,000 ppm or about five times current levels.

FUTURE DIRECTIONS

Our ability to detect and understand ecological changes in the Southern Ocean requires a well-coordinated international program of observations, experiments, monitoring and modelling. Towards this end, researchers with the ACE CRC are playing key leadership roles in a number of important international initiatives including the Southern Ocean Observing System (SOOS), which has its international project office in Hobart. The program, which is funded by the Scientific Committees on Antarctic Research (SCAR) and on Oceanic Research (SCOR) is hosted by the University of Tasmania and aims to coordinate and enhance international research efforts to gather data from the Southern Ocean. These data include long-term observations of the physics, chemistry, and biology, which can be shared amongst the international scientific community. In 2018, the ACE CRC and the Australian Antarctic Division hosted the first Marine Ecosystem Assessment for the Southern Ocean (MEASO) in Hobart. The week-long conference, which brought together ecologists, fishing industry, policy and other expert stakeholders, is the first major attempt to produce a comprehensive circumpolar assessment of the current state of ecological knowledge on Southern Ocean ecosystems. The outcomes of the first MEASO will form a key contribution by the Antarctic and Southern Ocean marine science community to the 6th Assessment Review of the Intergovernmental Panel on Climate Change (IPCC) and to forums of the Antarctic Treaty System, including the Commission on the Conservation of Antarctic Marine Living Resources.

22: Emperor penguins.

These national and international collaborations will together provide an essential foundation for the development of new computational models for quantifying and assessing Southern Ocean habitats, species and foodwebs. The geographical focus of the ACE CRC's ecosystems modelling work is on the Indian and West Pacific Sectors of the Southern Ocean, where scientists are providing international leadership in the development of ecosystem models to simulate future changes to food webs, and help determine the major drivers of change. The so-called 'end to end' ecosystem models are bringing together information on physical ocean characteristics and the marine foodweb in East Antarctica. This work is part of the Integrating Climate and Ecosystem Dynamics (ICED) program, an international initiative aimed at developing a coordinated circumpolar approach to understanding climate interactions in the Southern Ocean, the implications for ecosystem dynamics, the impacts on biogeochemical cycles, and the development of sustainable management procedures. Over the longer term, the project aims to provide governments and management agencies with the best available forecasts when evaluating and adapting conservation and resource management strategies to future environmental change.

END USER APPLICATIONS

23

Rob Blakers

23: Remnants of fire intolerant alpine species, including cushion plants, in the Tasmanian World Heritage Area, after a large fire in 2016.

Recent changes in the climate have caused impacts on natural and human systems on every continent and in every ocean. In many regions, changing rain and snowfall patterns are affecting the quality and availability of fresh water. Many terrestrial, freshwater, and marine species have shifted their geographic ranges in response to ongoing changes in the climate and environment. Glaciers are in retreat at the poles, contributing to sea level rise and increased risks to infrastructure from storm surges. The impacts of these changes on human activities can be capricious; while some agricultural regions appear to benefiting from increased productivity, many more have been experiencing reduced yields and food security pressures.

Australia has not been immune from the impacts of these changes. A study published in 2018 led by ACE CRC research fellow, Dr Rebecca Harris, reveals that Australia's ecosystems are at a 'tipping point' due to the combined stresses of climate change and extreme weather events. Australia's average temperature has increased by one degree since 1910, but the superimposed effect of more extreme weather events such as fire, flood, heatwave and drought has driven catastrophic transformation of many natural systems. A constellation of catastrophic environmental events in recent years – from large-scale mangrove dieback to the disappearance of kelp forests and the loss of alpine forests to bushfires – suggest that many seemingly healthy and undisturbed ecosystems are likely to be at a tipping point.

As these impacts accumulate, so too has the need for expertise in planning and adapting to the impacts of extreme weather patterns, sea level rise and changing natural environments.

Without an in depth understanding of how global climate change will translate to impacts at a local level, it can be difficult to make mitigation and adaptation decisions – especially when it comes to justifying decisions with significant financial implications. Governments and industry at various levels have begun to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. The capability and expertise developed over three decades of Antarctic and Southern Ocean climate research in Hobart has made an important contribution, enabling the ACE CRC to put together a program of interdisciplinary research focusing on Australian climate impacts.

One of the challenges facing climate-exposed industries and government agencies in Australia has been the need for fine-scale climate information to inform local decisions. The ACE CRC's first major project in this area began in 2007, with the awarding of a contract to deliver the first comprehensive study of the Tasmania's exposure to future climate change. The *Climate Futures for Tasmania* project brief was to explore the potential impacts of climate change on Tasmania's weather, water catchments, agriculture and climate extremes, including floods and wind damage. In the process, the project broke new ground in the application of detailed climate projections at the local scale. *Climate Futures for Tasmania* provided the first fine-scale climate information for Tasmania by downscaling six global climate models with two emission scenarios to generate climate information from 1961 to 2100. The impacts of these scenarios were assessed against specific industry and environmental contexts such as dairy pasture growth, the oyster industry, ecosystems, hydropower generation, and infrastructure.

Climate Futures for Tasmania is arguably the highest-value piece of research in this field of research in Australia to date, providing products that have since been used in more than 100 other projects in Tasmania and across Australia. Today it remains the state government's most important source of climate change projections, and an essential part of Tasmania's climate change response.

A key element of the team's success has been the development of an end-user delivery model that successfully integrates the science of climate modelling with extensive stakeholder consultation and community engagement. This blend of hard and soft science approaches enables the creation of bespoke research outputs that meet the distinct needs of individual industry sectors or end users. Demand for this expertise from climate-exposed government and industry end users around Australia is also growing. Today the Climate Futures team works with a number of industry and government stakeholders, to produce targeted climate model projections for use in operational planning and decision making. The team's partners include water, energy and agricultural producers, emergency services, alpine ski-resort operators, forestry managers, the wine and aquaculture industries and government agencies.

RESEARCH OUTPUTS

In 2015, the group released a report assessing regional changes in fire danger in Tasmania through to 2100 under a high-emissions climate change scenario. The projections indicate a continued, steady increase in fire danger, as well as a longer and more intense fire season throughout most of the state. Most importantly for those who manage fire risk on the ground, the report provides detail on which geographical areas are likely to face the largest increases in fire risk. At its release, the study was the highest-resolution, long-term climate modelling study of future fire risk ever produced in Australia. The main findings of this scenario were the increased number of catastrophic fires days, the doubling of the area of Tasmania experiencing high fire danger days and the lengthening of the season and advance into spring season.

Ongoing research is investigating how changes to fire danger may affect the viability of prescribed burning as a tool to reduce fuel loads in the future. The results show that there may be a narrower window of suitable conditions for burning, as temperatures and fuel availability increase and fuels become drier across Tasmania in spring and autumn. This will affect the timing and resourcing of prescribed burning, and alternative methods to build resilience to bushfire risk may need to be considered. A very similar project around fire risk in

CLIMATE MODEL DOWNSCALING

The Climate Futures analyses draw on a computational methodology known as 'dynamical downscaling', a technique by which fine-scale projections are derived from large-scale global climate models. Dynamical downscaling introduces the influence of local features such as mountains, on atmospheric systems, rain shadow effects, or temperature changes on slopes with a particular aspect. The process turns a single grid cell into a grid of more than 3,000 useful locations at 5-10 kilometre resolution. In topographically varied regions like Tasmania or the Australian Alps, dynamical downscaling can add high levels of detail about climatic variability across space and time. The computing power required for such a task is considerable, with the current collections simulations at around ~500 terabytes of data.

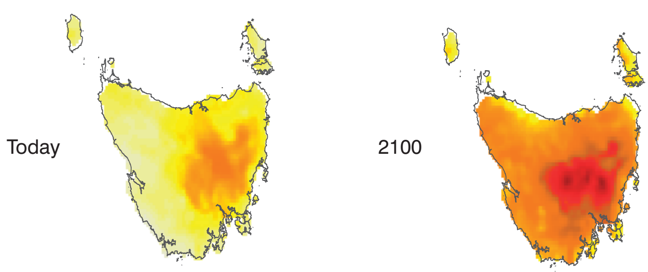


FIGURE 6: Simplified downscaled model output showing projected changes in rainfall projections for Tasmania during this century. Areas of darker red and orange indicate drier areas.

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24: World Heritage Area Fire, Lake McKenzie, Tasmania, 2016. The risk of catastrophic fires is projected to increase in many parts of Australia during this century.

the World Heritage Area was also undertaken after the disastrous fires that occurred in January-February 2016. The results from these two projects are being used by the Tasmanian Fire Service, State Emergency Service, Hydro Tasmania and the Tasmanian Wilderness World Heritage Area to inform long-term planning, resourcing and infrastructure decisions.

In 2015, the Victorian Alpine Resorts Co-ordinating Council commissioned a report aimed at supporting decisions about future investment in ski resort infrastructure, including snow making. A downscaled climate model for the Australian Alps region was used to develop year-by-year projections for mean temperature, precipitation, snow depth and season length at all of Victoria's popular ski destinations between now and the end of the century. These projections were used to assess changing conditions for making snow under warmer conditions. Detailed visitation data and snow observations gathered by the industry were also assessed to understand the likely impacts on the preferences of visitors. Commercial operators at Victoria's world-class ski fields are using this report to support long term investment, marketing and infrastructure decisions.

The group is currently working with Wine Australia to identify the main weather and climate risks to the industry, assess how these risks change with climate change and identify ways to manage the risks. An understanding of short-term climate variability, as well as trends in climate indices for the near and mid-term time scales will be provided in an accessible, usable form to grape growers and winemakers across Australia. Indices of heat accumulation, heatwave and frost will be tailored for particular grape varieties and regions, to provide better understanding of changing suitability in the near future and out to longer-term planning horizons.

To carry out this assessment, new high-resolution climate projections for southeastern Australia have been produced in partnership with CSIRO using their Conformal Cubic Atmospheric Model (CCAM) model. These projections represent a significant enhancement of the Climate Futures for Tasmania output, utilising Climate Model Intercomparison Project version 5 (CMIP5) as the global driving data and improvements to the representation of precipitation and other processes in CCAM. The research will provide industry with the fine-scaled climate information required to identify the most appropriate adaptation response within each wine region, to maintain grape yield, value and wine quality into the future.

FUTURE DIRECTIONS

Throughout human history, societies have adapted to climate variability and extremes with varying amounts of success. The impacts we have already observed in Australia during the early part of this century are projected to amplify, while the appearance of new and unforeseen effects is a virtual certainty. From infrastructure risks to the large-scale displacement of populations, it is anticipated that demand for adaptation expertise will continue to grow. In Australia, planning for sea-level rise and reduced water availability has already progressed considerably over the past two decades, while our response to the collapse of ecosystems has been relatively piecemeal.

Looking ahead, the Climate Futures group has identified biosecurity, invasive pests and water security as three core areas of additional focus for research in the coming years. Significant additional work is needed to continue to refine and improve the methodology, from improvements in modelling methods to the communication of climate risk to policy makers and end users. Some of these risks will be limited to a particular industry sector or region, while others will have cascading impacts beyond Australia. To some extent, climate change is also projected to have some potential and unexpected benefits. Whether Australia is nimble in our response – or whether we are defenceless in the face of change – will depend in large measure on our ability to understand and pre-empt what lies

SEA LEVEL RISE

Global sea levels have been rising slowly over the past 100 years and many coastal regions are currently experiencing the impacts of both erosion and inundation. These changes are expected to have a major impact on human societies because of the significant concentration of communities and infrastructure in coastal regions. Understanding the contributions to present sea level rise, and their causes, is crucial to projecting what might happen in the future. As sea levels rise, the severity and frequency of extreme events driven by atmospheric pressure, tides and storm surges is expected to increase. With 85% of Australia's population living in coastal areas, understanding the risks to infrastructure and private property is critically important. With some analyses projecting sea level rises of more than a metre by 2100, accurate sea level projections are, today, vital for planning in coastal areas.

The ACE CRC has helped Australia plan and prepare for future sea level changes by providing specialised technical consulting, specialised vocational training for governments and industry, and a sea level rise calculator tool called Canute. The web tool provides estimates of the necessary elevation for infrastructure on hard shorelines. In the case of soft shorelines, the platform estimates the distance infrastructure needs to be set back from the water to avoid shoreline recession. In developing the system, scientists looked at data from tide gauges and storm surge modelling at 12,000 points roughly every 2.5 kilometres around the Australian coast. Using this data, ACE CRC scientists created a suite of calculators that allow coastal planners to estimate a range of factors, such as waves and tropical cyclones, that can impact on the positioning of infrastructure.