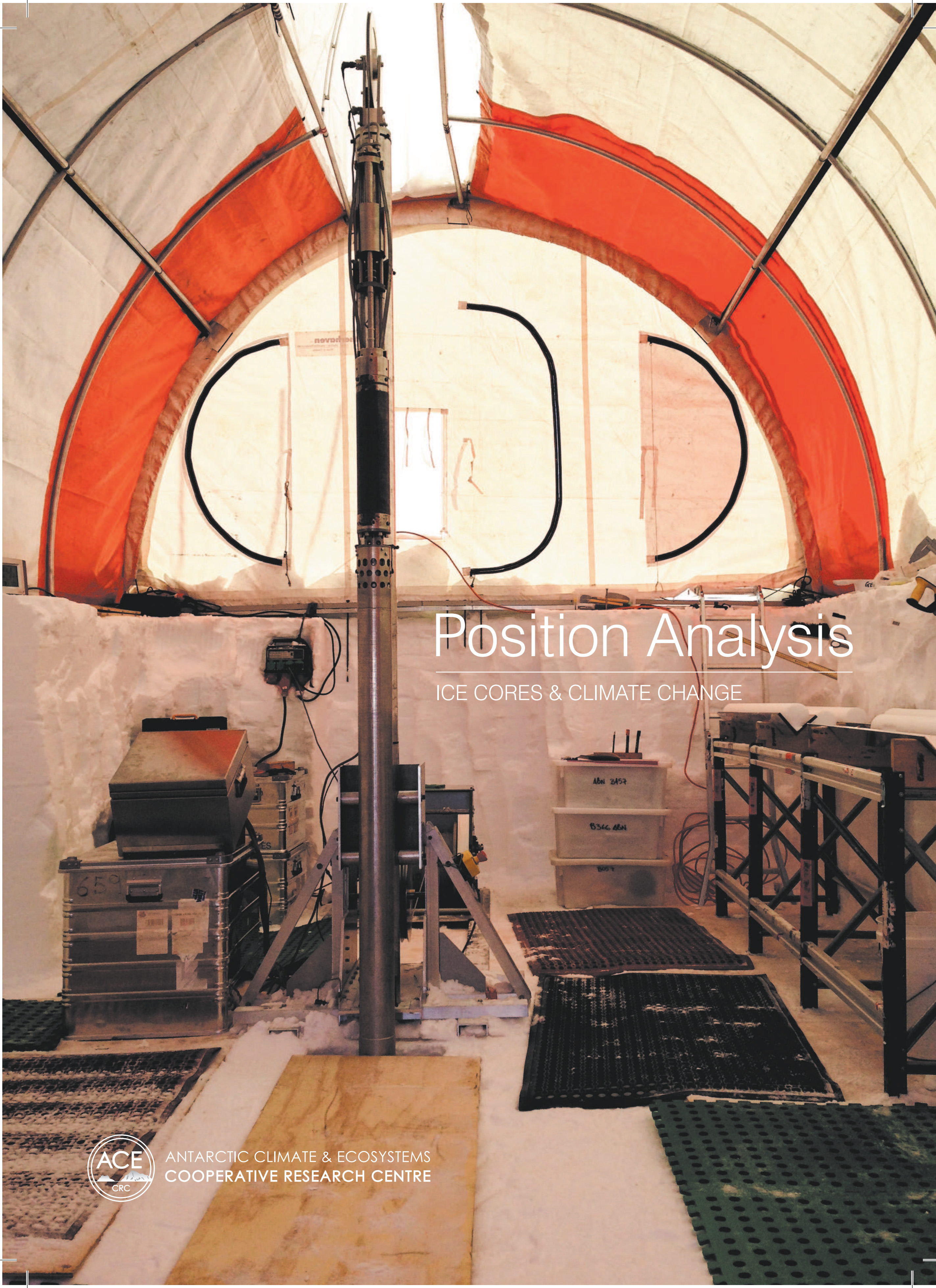

Position Analysis

ICE CORES & CLIMATE CHANGE

ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Australian Government
Department of Industry and Science

Business
Cooperative Research
Centres Programme

Position Analysis: Antarctic Ice Cores & Climate Change

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Cover image: Ice coring equipment inside a drill tent at Aurora Basin North in 2014. Photographer: Mark Curran.

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

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Australian Antarctic Division

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This document aims to:

1. Provide the context for ACE CRC ice core research within Australian and international initiatives;
2. Present research highlights from ACE CRC ice core science; and
3. Identify future directions and priorities, with emphasis on Australian and ACE CRC research.

Contents



INTRODUCTION

The Earth's climate system is constantly changing – from the familiar transition of the seasons to ice age cycles spanning a hundred thousand years, and beyond.

Throughout human history, climate variability has profoundly influenced the way societies have organised themselves. The rise and fall of some civilisations has been linked to environmental factors relating to climate. Shifts in temperature and rainfall patterns can exert pressures through impacts on food supply and disease vectors, leading to famine, migration and societal collapse.

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 significant challenge in predicting future climate change and the likely impacts on our society. This is partly because we still don't sufficiently understand how the Earth's climate functioned in the period before instrumental 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 and reach conclusions about the forces that drive change and the sensitivity of the system. In this context, building a more detailed knowledge of how the climate system operated in the past is critical. The modern era of widespread observing networks, with satellites and robotic floats in the ocean, provides a wealth 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 so-called "proxy" data – the fingerprints left behind in nature in tree rings, ocean sediments and in the skeletons of coral.

This publication focuses on one particular area of palaeoclimate research: the archive found within the Antarctic ice sheet, which is arguably the richest single source of information about the Earth's climate available to scientists today. This Position Analysis explores several recent discoveries in ice core climate science as well as future objectives, with a special focus on Australian-led palaeoclimate initiatives through the Antarctic Climate & Ecosystems Cooperative Research Centre.

Researchers from the ACE CRC and its partner institutions, particularly through the work undertaken at Law Dome in Antarctica, have been involved in landmark ice core research projects that have significantly increased our knowledge of pre-instrumental climate

"Our understanding of the Earth's climate, in particular, depends foremost on the Earth's history: how past climate changed."

Dr James Hansen, NASA

Why study past climate?

Climate science, like other fields of earth science and astronomy, is an observational science. It relies principally on understanding what we observe: nature conducts the experiments for us. Of course, the era of anthropogenic climate change brings with it an element of experimental science, where we are influencing the climate system but we do not have the luxury of controls or repeated experiments.

In this context, a detailed knowledge of how the climate system operates is critical. Ice cores provide an immensely valuable archive of information about the Earth's climate over the past several hundred thousand years. Importantly, the data from ice cores can tell us about both the drivers of climate change – including greenhouse gases, volcanic eruptions and solar variability – and how the climate responds to these drivers.

Remarkably, Antarctic ice cores tell us not only about the past climate of Antarctica, but also about climate on a global scale. One of the great surprises from this field of study has been the degree to which Antarctic climate variations match those of the planet as a whole, and how closely both of these match global atmospheric carbon dioxide. This is because the Antarctic and global climates are inextricably linked. Climate processes in the Antarctic and the Southern Ocean region – including the exchange of heat and carbon dioxide between atmosphere and ocean – have an enormous influence on the global system. Ice core science provides us with a direct means of understanding how this system has changed over time and how it is likely to change in future.

NATIONAL AND INTERNATIONAL CONTEXT

Australian science has a long and illustrious heritage in Antarctica, stretching back a century to the heroic era of Sir Douglas Mawson. Even in those early days, the importance of Antarctic climate science was recognised with clear statements from policy-makers and explorers about the potential for Antarctic meteorology to provide better understanding of our weather.

Australian ice core research in Antarctica dates from the late 1960s. This early work tended to focus on understanding the physical characteristics of the ice sheet itself by measuring properties such as temperature and ice crystal size and orientation. During the 1980s, with growing awareness of global climate change, Australian scientists became increasingly focused on the value of Antarctic ice cores for palaeoclimate information. Ice core science has grown to become a central component of Australia's scientific activity in the Antarctic and represents one of our most significant commitments to global climate science initiatives.

Australia is one of just a handful of nations to have drilled an ice core from surface to bedrock – at Law Dome near Casey Station. Australian scientists have delivered globally significant scientific results and contribute to a continuing research program guided by the Australian Antarctic Science Strategic Plan. This plan identifies a range of research goals that are guided by national capacity, regional and logistical interests, and internationally identified priorities.

As a major Southern Hemisphere nation and significant participant in Antarctic affairs, Australia has a clear and long-term interest in maintaining its scientific leadership in Antarctic climate science with ice coring continuing to be a key focus.

Andrew Moy

Mill Island Drill Camp

International cooperation

Ice core science is a logistically demanding, technically challenging and expensive undertaking that requires a high level of cooperation within and between nations. Developing this international collaboration is the role of a grouping known as the International Partnerships in Ice Core Sciences (IPICS), which is a planning group composed of ice core scientists, engineers and drillers from 23 nations. IPICS stands alone as a scientific coordinating body but receives sponsorship from recognised institutions within ICSU (SCAR, IACS and IGBP-PAGES). From its inception, IPICS has fostered close collaboration and information sharing in the context of an agreed set of priorities. As a result, they have developed a range of priority projects and developed white papers around these.

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i International Council for Science.

ii Scientific Committee on Antarctic Research, an interdisciplinary committee of ICSU.

iii International Association of Cryospheric Sciences, an association under the International Union of Geodesy and Geophysics, IUGG.

iv International Geosphere Biosphere Program – Past Global Changes; IGBP is sponsored by ICSU.

Tony Fleming/AAD

PRIORITY PROJECTS FOR THE INTERNATIONAL PARTNERSHIP IN ICE CORE SCIENCES

1 The oldest ice core

A collaborative international effort to locate and drill Antarctica's oldest ice core, with major potential significance for Australian ice core science (see The Million-Year Ice Core on page 26 for more details).

2 History and dynamics of the last interglacial period

This project seeks a better understanding of the period, about 120,000 years ago, before the last ice age. At that time, the planet was naturally a few degrees warmer and sea levels were six to nine metres higher than present. Better understanding of this time period would help to predict future change in a warming world.

3 The IPICS 40,000-year network

The IPICS 40kyr network is a project that explores the changes before and through the end of the last glacial (ice age) period. The period from about 20,000 to 10,000 years ago was the last time that climate underwent a significant global shift in CO_2 and temperature.

4 IPICS 2000-year array

Closely linked to the 40kyr network, this project is aimed at extracting a detailed record of climate of the past two millennia. This can be achieved by using shorter cores and lighter logistics to build a large enough array of records to capture the regional response of Antarctic climate to natural drivers, and then into the era of anthropogenic forcing. Australian work at Law Dome and with short (~1-2 century) cores from the coastal zone of East Antarctica has provided some of the most detailed records for this array.

5 Ice core drilling and technical challenges

The fifth item is a technical strand for the development of ice core drilling technology.

IPICS is reviewing future plans and is developing a further priority that will be focused on using ice cores to better understand the flow and behaviour of the ice sheet itself. Detailed white papers for these projects may be found on the IPICS website: http://www.pages-igbp.org/ipics/

ICE CORE SCIENCE EXPLAINED

As snow accumulates over the Antarctic ice sheet and becomes compressed into layers, it traps a wide variety of 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. The oldest continuous ice core records extend to about 128,000 years in Greenland and 800,000 years in Antarctica.

ICE CORE TIME HORIZONS

Present day

200 years ago
Approximate onset of industrial period

2,000 years ago
Target age for detailed reconstructions over pre-industrial period

11,500 years ago
Start of Holocene period (end of deglaciation)

21,000 years ago
Peak of last ice age (deglaciation begins after this)

115,000 years ago
Last interglacial period ends (onset of glacial period begins)

127,000 years ago
Last interglacial (warm) period begins

128,000 years ago
Oldest Greenland ice core

800,000 years ago
World's oldest ice core (EPICA Dome C)

There are three types of tracers found in glacial ice:

Air bubbles

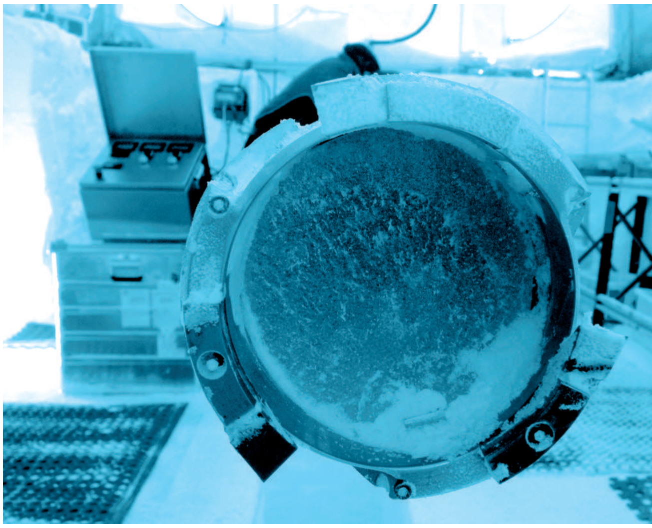
1 The air trapped in firn (porous compressed snow) and bubbles trapped within glacial ice provide the only direct record of the atmosphere before the modern era of atmospheric monitoring. The bubbles are formed as snow becomes compressed and the air in between the flakes is sealed off. The process of trapping only completes when the porous firn at the surface becomes completely sealed from the atmosphere above, which can depend upon the temperature and rate of snowfall. At warm, high snowfall places such as Law Dome in East Antarctica the process takes several decades, while at cold and low snowfall locations inland it can take more than a thousand years before bubbles seal off.

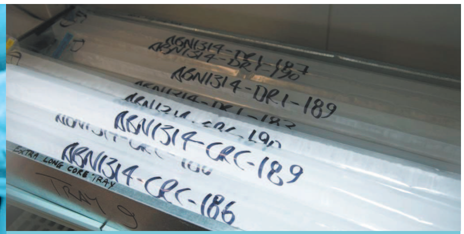
Impurities

2 While the snow that falls in Antarctica is relatively pure, it still contains a mix of particles and trace chemical compounds that reveal detailed information about past global climates. These impurities can include sea salts, volcanic acids, mineral dust, biological compounds, solar markers and human pollutants such as nitrate, sulphate, soot, lead, and even radioactive material from atmospheric bomb tests. Major disruptions such as volcanic activity on dates that are known to science can be identified in the ice core record to help calibrate the data and improve dating accuracy (see page 15).

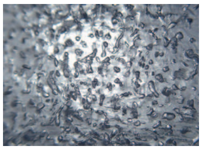
Water isotopes

3 The third type of information obtained from ice cores is contained in the ice itself. In ocean water, naturally occurring hydrogen and oxygen both come in rare, heavier forms called isotopes, which are present in ocean water in stable levels. When ocean water evaporates and is transported to polar regions, the ratio of the heavy isotopes changes due to the progressive loss of moisture as the air cools. By measuring the ratio of heavy water isotopes in an ice core sample, researchers can infer the temperature when the snow originally fell.





Because the ice cores contain only very low levels of impurities (down to a few parts per trillion in some cases) great care is taken to ensure the samples remain uncontaminated during transportation and processing. The cores are sealed in clean plastic and kept well below freezing point until they are ready for analysis under extremely clean laboratory conditions.



Mana Inou

The air bubbles trapped in ice cores are more than a proxy record. They provide an actual record of past atmospheric composition.

Physical and chemical tracers

A wide range of chemical tracers appear in an ice core. The number of these tracers available using modern analytical techniques has grown steadily. These chemical signals provide proxies for many environmental and climate-related parameters. Some of the most important climate-related parameters that can be tracked include:

Oxygen/hydrogen isotopes in water	→	Temperatures
Beryllium-10	→	Solar activity
Sulphate	→	Volcanic activity, biological activity
Methanesulphonic acid	→	Sea ice extent, biological activity
Sea salt and dust	→	Wind & atmospheric circulation
Trapped air bubbles	→	Atmospheric composition, including greenhouse gases

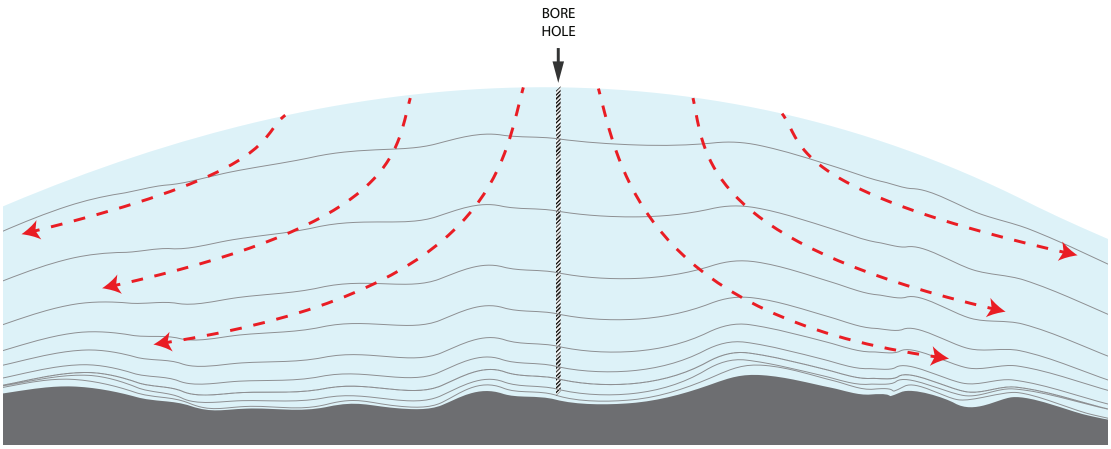


FIGURE 1: Ice domes (or ridges, sometimes called "divides") are local topographic high points, where ice flows down and outward. Compacted snow builds up over time in layers, with the ice mass being discharged from the edges. This means ice at any depth under the dome or ridge originated at that point. This simplifies interpretation of ice cores, especially deep ones, and is the reason why ice domes and divides tend to be chosen as locations for deep ice cores.

MAJOR ICE CORE SCIENCE FINDINGS

Two iconic climate science findings emerge from the field of Antarctic ice core studies.

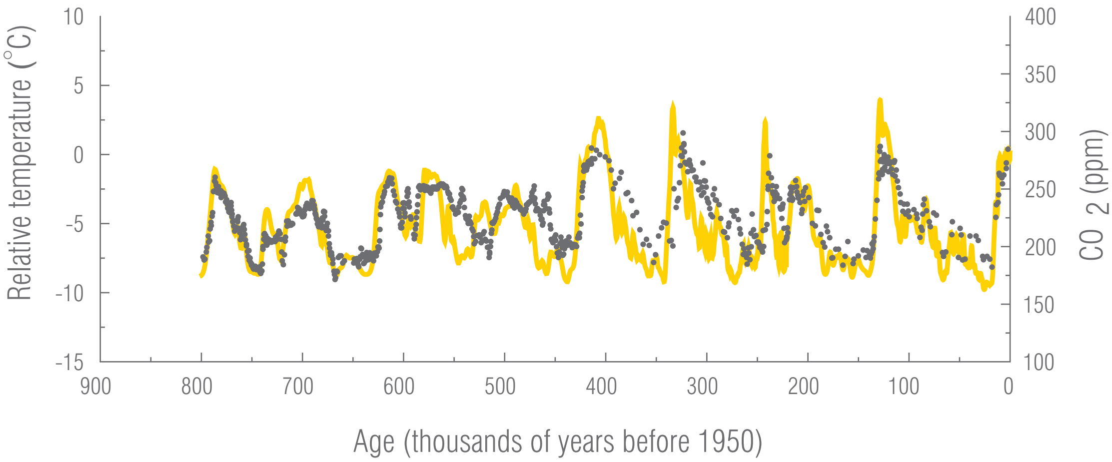
The first is the remarkably close coupling between Antarctic temperature and CO_2. Figure 2 depicts results obtained from the EPICA Dome C record[1,2] and clearly shows glacial ("ice age") cycles in temperature that recur at around 100,000-year intervals, and which were already seen (albeit in lesser detail) in ocean sediment records[3]. This temperature-CO_2 correspondence was first seen in the Vostok ice core, which covers about the past 400,000 years[4], and is also replicated in a core from Dome Fuji. Shorter records (EPICA Dronning Maud Land, Byrd, West Antarctic Ice Sheet, Law Dome and Talos Dome) also show the same changes over portions of the last glacial cycle.

Second, the Antarctic temperatures closely mirror global temperature data recorded in ocean sediment records, indicating that Antarctica registers a globally significant climate signal, not just a local one.

These observations together provide clear confirmation of both the importance of CO_2 in the climate system and of the key role that high latitude Southern Ocean and Antarctic processes must play, globally[5-7].

i The European Project for Ice Coring in Antarctica is a consortium of European countries and has drilled cores at Dome C and in Dronning Maud Land.

FIGURE 2: Ice core records of global CO_2 (dots) and Antarctic temperature (orange curve) for the past 800,000 years from the Dome C ice core[1,2]. The 800,000-year record shows major ice age cycles and the close correspondence between CO_2 and temperature.



Key international Antarctic drill sites

- Sites enabling climate reconstructions for at least the past 2,000 years.
- Sites where dating accuracy or resolution has so far prevented use in highest resolution reconstructions of the past 2,000 years.
- Sites where drilling or analysis is still under way.

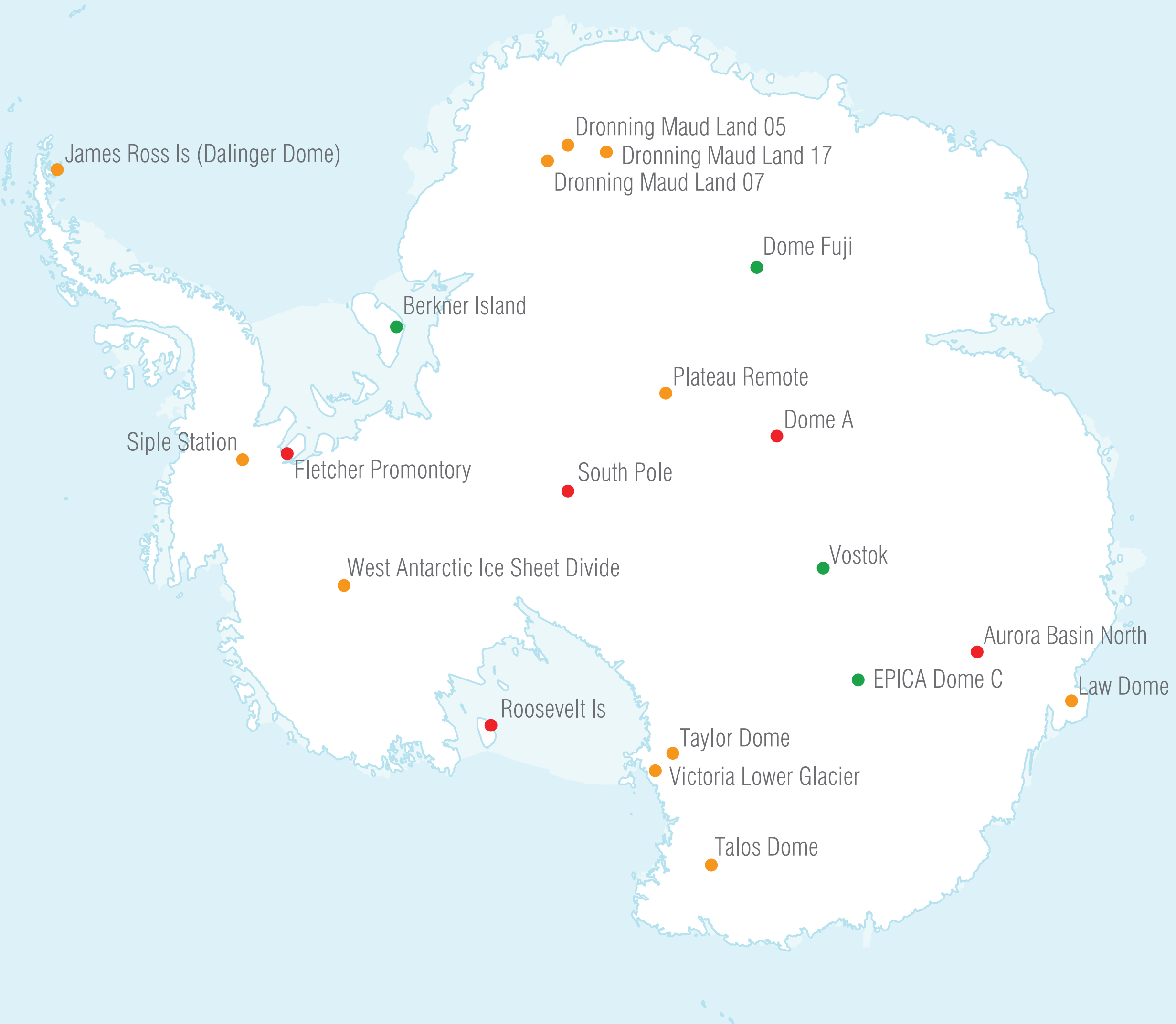


FIGURE 3: Map of international ice core sites in Antarctica with records of more than 500 years.

MAJOR ACE CRC HIGHLIGHTS

This section highlights a range of results to emerge from research conducted by The ACE CRC and its collaborative partners. The original Antarctic CRC (the first incarnation of The ACE CRC) was established in 1991, just as the ice core drilling initiated by the Australian Antarctic Division at Law Dome was in full swing. It was completed in February 1993.

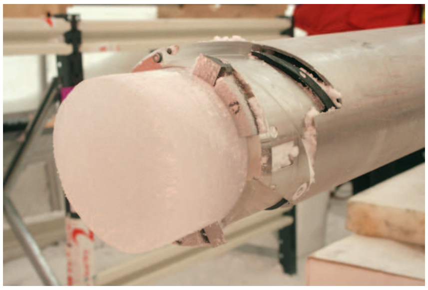
The major results fall into four categories that are discussed over the following pages.

1 Reconstructing climate drivers

2 Australian rainfall and drought

3 Past changes in Antarctic sea ice

4 Antarctic and global temperature reconstructions



Joel Pedro

Key drill locations

Law Dome: An unrivalled record of the recent era

Through its research on Law Dome ice cores Australia has established a leading role specialising in very high-resolution climate records. With few annually resolved records available from Antarctica, the Law Dome record provides an important resource for high-precision climate reconstructions.

Law Dome is located about 120 km from Casey Station near the edge of the East Antarctic ice sheet and rises 1400m above sea level (see Figure 3). The drilling operation recovered a 1200m-long surface-to-bedrock ice core from near the Dome's summit. The climate record contained in the core extends back 90,000 years.

Due to its location close to the coastline and unique topography, Law Dome offers several significant benefits for palaeoclimatology. The Dome is exposed to the major storm systems from the Southern Ocean, delivering very high snowfall for a polar location and preserving 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 climate patterns over thousands of years (detailed in the following pages).

Joel Pedro

Aurora Basin North: A new inland East Antarctic core
An international project led by Australian scientists at the Australian Antarctic Division and ACE CRC successfully drilled and extracted ice cores and snow pit samples at Aurora Basin North, 550km inland of Australia's Casey station in 2013-14. The international team extracted a 303m-long ice core, which will provide annual climate records for the past 2000 years, and extracted two shallow ice cores spanning the past 800 to 1000 years. The ice cores will be analysed for a range of climate parameters including temperature, snowfall, volcanic forcing, solar forcing, greenhouse gas forcing, sea ice extent, atmospheric variability (e.g. ENSO, SAM, IPO), dust sources from Australia, and biomass burning events.

Joel Pedro

ABOVE: Australian and international scientists hold the last core from Aurora Basin North in 2014.

RECONSTRUCTING CLIMATE DRIVERS

One of the principal benefits of analysing ice cores is that they record all three of the natural major climate drivers, or "forcings": greenhouse gas concentrations, solar variability and volcanic eruptions.

Understanding natural climate variability, and the mechanisms driving it, is important for improving climate predictability and attributing ongoing and future climate change to anthropogenic and natural factors.

The climate response to past natural forcing provides a unique means to assess sensitivity of the climate system over timescales from decades to millennia. This provides a way to predict future climate change under different forcing scenarios and over long time periods.

Our ability to model future change is, to a degree, benchmarked by our ability to reproduce past changes. This requires high-quality records of both climate forcing and climate itself over lengths of time that capture slower components of the earth system, such as oceans and ice sheets.

None of these tasks can be adequately addressed based on our knowledge of the instrumental period alone, so ice core records have become a unique and crucial source of information.

Greenhouse gases

The CO_2 data shown in Figure 4 come from Law Dome work[8,10-13] and are the most accurate and detailed greenhouse gas records for the period before direct atmospheric measurements. This work, done in collaboration between

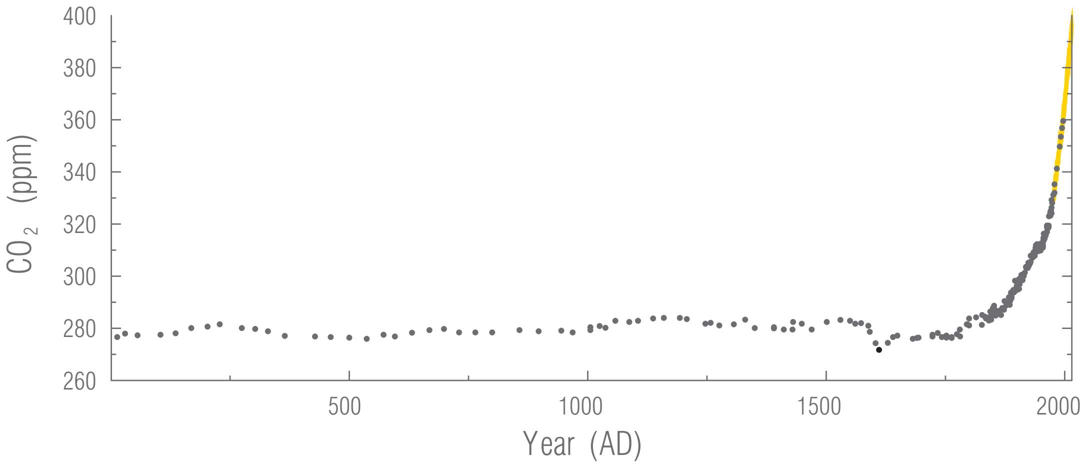
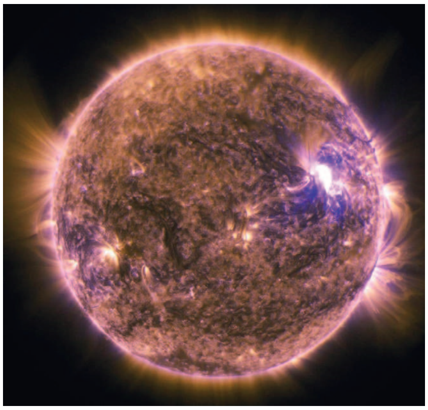


FIGURE 4: The above CO_2 record for the past 2,000 years uses ice core data from Australian (including ACE CRC) research[8] using Law Dome ice cores. This work, done in partnership between CSIRO, AAD and ACE CRC, provides the most detailed record available of atmospheric CO_2 before direct atmospheric measurements and is itself a major highlight of Australia's Antarctic research. The data also illustrates the fidelity of the ice core measurements, which can be seen in overlapping measurements from the ice (black) and atmospheric data (orange) from Cape Grim, Tasmania[9].

CSIRO, ACE CRC and AAD, is the cornerstone of modelling studies that require such data to simulate past changes. The work not only shows the clear increase in CO2 since the pre-industrial era, but also has sufficient detail to demonstrate overlap with the direct atmospheric measurements that follow. Other work includes studies of past variations in the key greenhouse gases methane and nitrous oxide, and on isotopes of CO_2 and methane. The isotope studies allow for exploration of the carbon-cycle, including sources of emission and uptake[14-16].


NASA

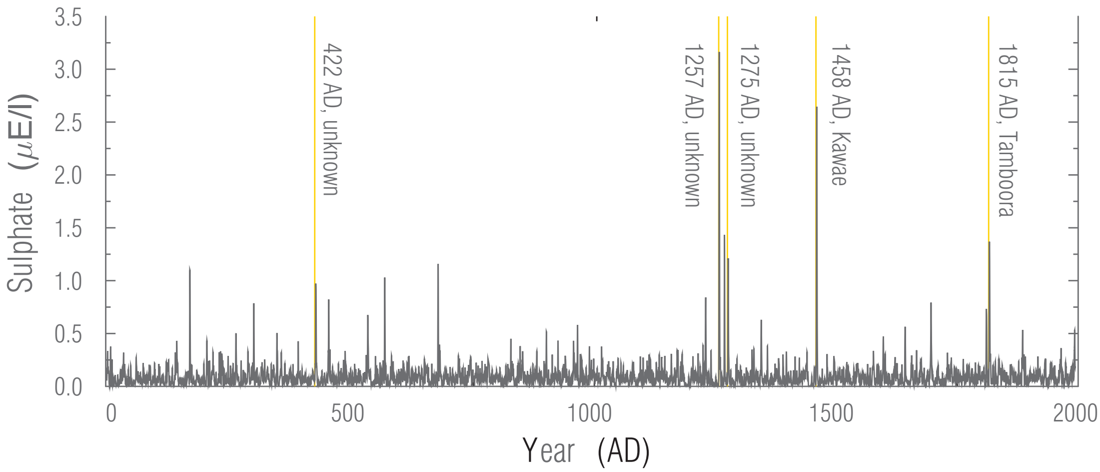
Solar variability

ACE CRC research has included studies of solar variability and forcing in collaboration with ANSTO (Australian Nuclear Science and Technology Organisation). The research on solar forcing focused on understanding the proxy that is used in ice core studies, which comes from cosmic ray production of beryllium-10 (analogous to carbon-14 production). The Law Dome work[17-19] allowed detailed comparison with instrumental records of solar activity and has shown that climate processes themselves also impact the $_{10}$Be signal. The net result is that this solar proxy must be interpreted with caution and that records from multiple sites are required to extract the highest-quality signal.

Volcanic forcing on climate

The high detail of the Law Dome ice core records allows annual layers to be detected and counted to give an extremely accurate chronology over the past 2000 years – the most accurate for Antarctica. This has been used to obtain an improved volcanic forcing record with refinement of the date of a major eruption and identification of likely confounding of multiple events[20]. This record is important for testing climate models with historical changes and gives information on both the size and timing of the eruptions. The new chronology also provides a basis for better synchronization of multiple ice core records, which has been used in developing a climate reconstruction for Antarctica[21].

FIGURE 5: Major volcanic activity evident in the Law Dome record over the past 2,000 years.



AUSTRALIAN RAINFALL AND DROUGHT

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 limited understanding of the true range of climate variability in Australia. ACE CRC ice core research has begun looking into pre-instrumental climate bounds using ice core records from East Antarctica. Due to the location of the Law Dome ice core on the coast of Antarctica, it records a signal that is directly linked to the climate of Australia. This archive from Law Dome can be exploited to produce long climate histories for Australia.

South-west Western Australian rainfall reconstruction

One of the first major studies into the links between Australian and Antarctic climates using ice cores revealed a strong connection between snowfall at Law Dome[22] 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

Tas van Ommen

Looking east from the Law Dome drill camp across a layer of fresh snow.

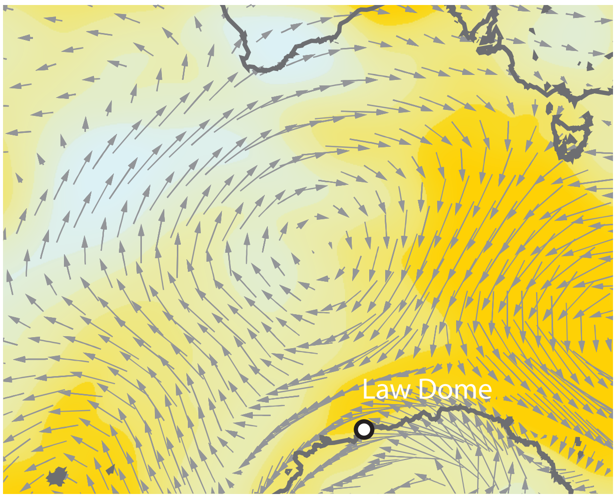


FIGURE 6: The atmospheric pattern associated with high snowfall at Law Dome and low rainfall in south-west Western Australia[22]. Arrows indicate wind direction, with darkest shading showing relatively moist air mass and light shading relatively dry air mass.

makes understanding the drivers of this change and the longer-term variability issues of particular concern.

Scientists from the ACE CRC demonstrated the annual snowfall record at Law Dome is inversely correlated with rainfall levels in south-west Western Australia, with high snowfall at Law Dome tending to accompany dry conditions in south-west Western Australia. The work showed an atmospheric pattern linking the two regions (Figure 6), 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 can be 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.

Eastern Australian Rainfall Reconstruction

The Law Dome ice core record has also been shown to have clear links to climate in eastern Australia (Figure 7), a region which shows not only large inter-annual but also multi-decadal variability in rainfall[23,24].

A key driver of this multi-decadal variability is the Interdecadal Pacific Oscillation (IPO) – a coherent pattern of Pacific Ocean sea surface temperature changes that vary on about a 25-year scale. The IPO is like a long-term counterpart of the more familiar El Niño/La Niña variations. Instrumental records indicate changes in the IPO are strongly linked to flood and drought risk across Eastern Australia and the broader Pacific Basin.

Scientists at the ACE CRC have determined the sea salt proxy at Law Dome provides a long-term record of this variability both in the Pacific and in rainfall levels in eastern Australia. Among the key findings of this study is that the so-called Millennium Drought between 1995 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.

This has implications for water resource infrastructure and suggests that water resource management plans need to account for decadal-scale droughts being a normal, if uncommon, feature of the hydrological cycle.

Wivenhoe Dam, Queensland

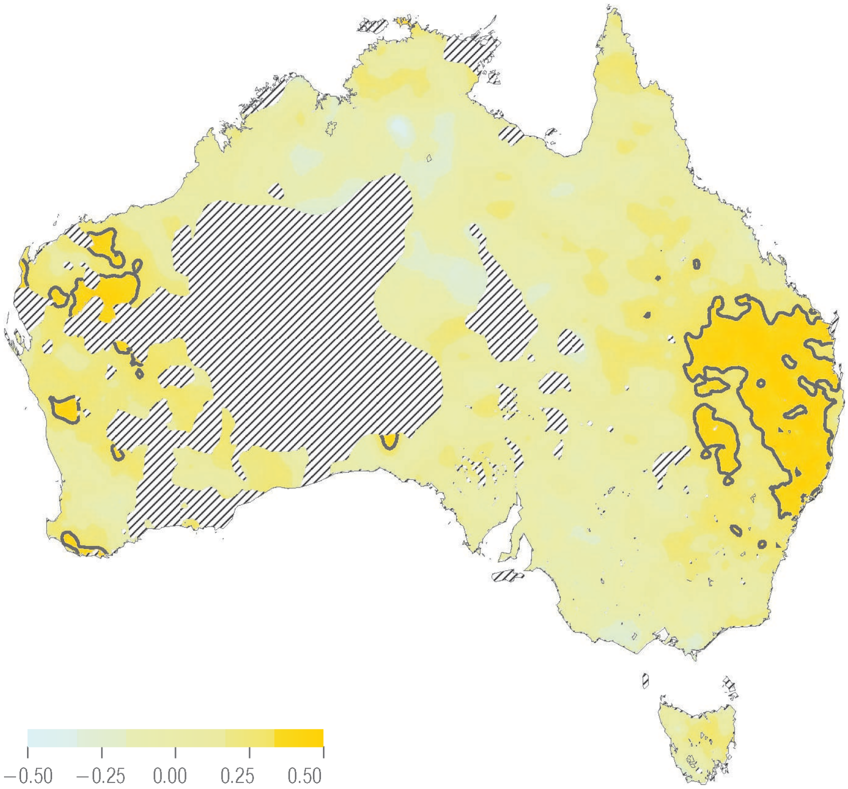
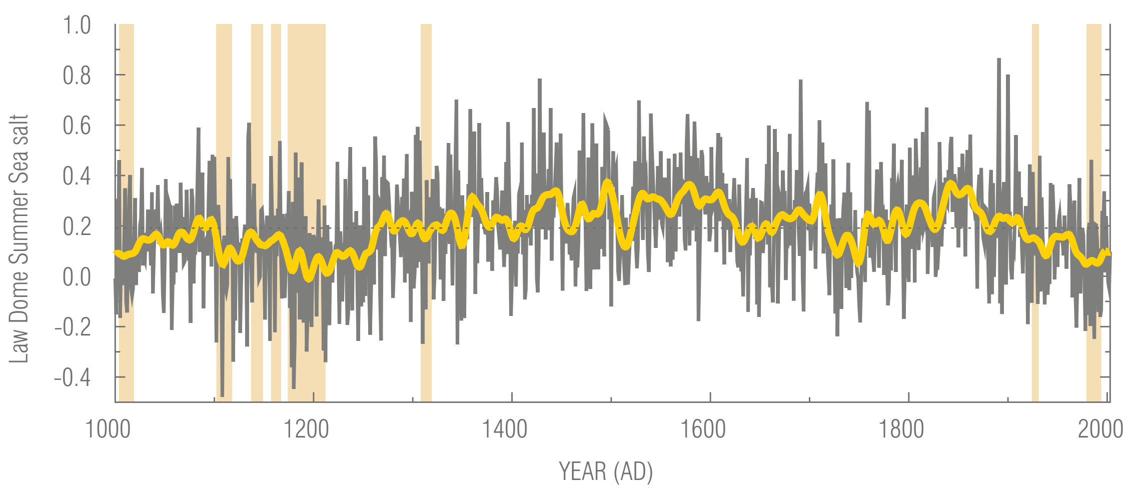


FIGURE 7: The lower panel shows the Law Dome summer sea salt record from 1000-2009 A.D., which is a proxy for rainfall in eastern Australia. The solid orange line is a 13-year smoothed record. The dotted line indicates the long-term average – for eastern Australia, periods below this correspond to potentially dry conditions and those above the average are potentially wet conditions. Vertical orange shading shows periods where the IPO is positive and the sea salt proxy is low, which corresponds to drought conditions. The upper panel shows the correlation map between rainfall and the Law Dome sea salt proxy[24]. Hatched areas indicate regions where the instrumental record is unreliable for the full length of comparison.



PAST CHANGES IN ANTARCTIC SEA ICE

Sea ice plays a key role in the climate system (see ACE CRC Sea Ice Position Analysis) but estimating changes in sea ice extent before the beginning of satellite records in 1979 has proven difficult. Sea ice reconstructions for Antarctica have tended to rely on observations recorded from whaling ships or on low-resolution ocean sediment core evidence. In a major advance, ACE CRC researchers identified that a chemical marker in ice cores known as methane sulphonic acid (MSA) can provide a reliable proxy for past sea ice extent[25] (Figure 8).

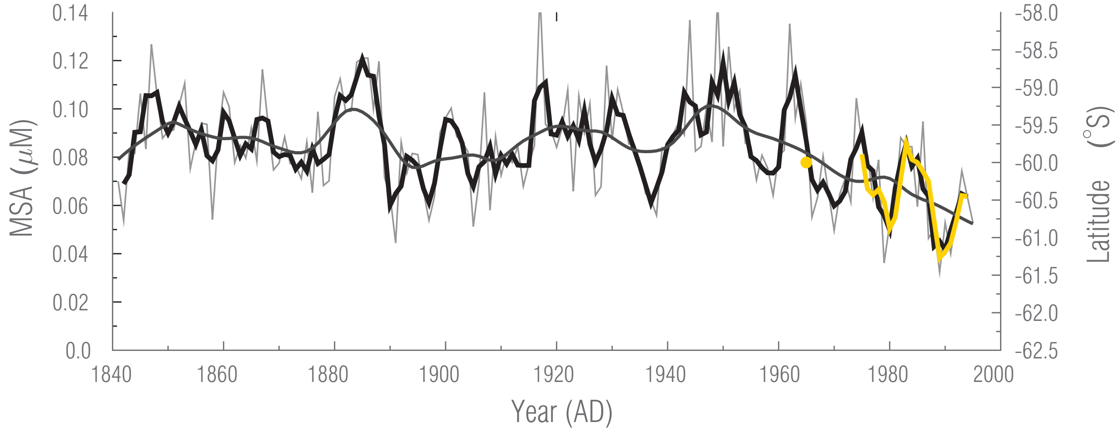
The mechanism for this link relies on the fact that sea ice algae, which grow on the underside of the ice, produce a waste product known as dimethyl sulphide (DMS). This gas oxidises in the atmosphere to MSA, which is transported on to the ice sheet in snowfall.

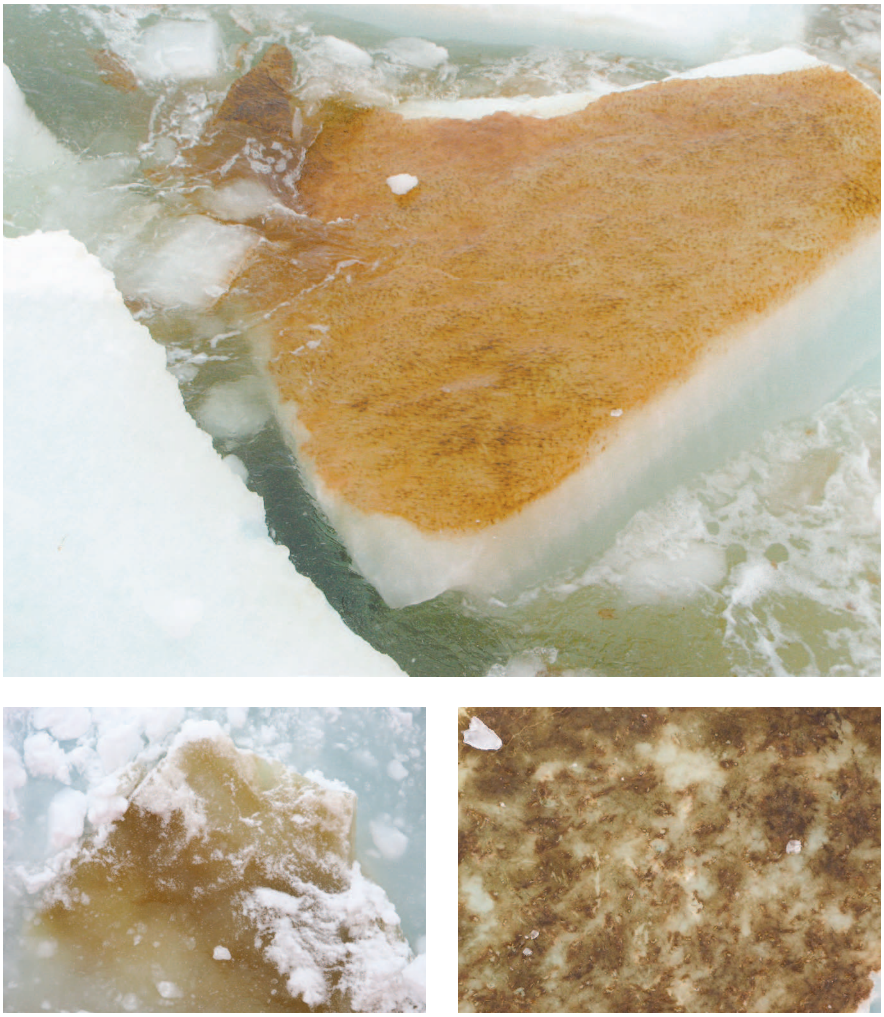
The area of ocean covered by sea ice from the spring maximum to the summer minimum controls the overall production of MSA. A larger maximum to minimum excursion produces more DMS and MSA. By analysing annual levels of MSA in ice cores, scientists have reconstructed long-term changes in maximum sea ice extent (at least in regions with a consistent minimum summer extent), such as east Antarctica (where very little sea ice remains through summer).

The results show about a 20 percent sea ice extent decline (around 1.5° latitude) from the mid to late 20th century that is overlain by large decadal-scale cycles. This also accords with data from whaling records, which show a similar decline over the period[26]. Newly available[27] imagery from NASA's Nimbus satellite from 1964 also agrees with the MSA-based sea ice reconstruction (Figure 8).

A new core from Aurora Basin North will provide a 2000-year annual record of MSA that will be used to investigate sea ice reconstructions. Additional MSA reconstructions from other

FIGURE 8: Sea ice proxy record from Law Dome MSA in ice[25]. Annual MSA (light grey), three-year moving average MSA (black), 20-year smooth (dark-grey) with satellite sea ice extent (orange line three-year moving average; orange circle, a single early Nimbus satellite datum).





Jan Lieser

Algae forming on the underside of sea ice produce a sulphurous waste product. After it oxidises in the atmosphere it is deposited onto the ice sheet in snow. This substance, known as MSA, provides a proxy record for Antarctic sea ice extent.

Antarctic regions show a general decrease in Antarctic sea ice extent in the 20th century[28]. Other proxies for reconstructing sea ice extent are being tested through ACE CRC linkages[29], with some showing considerable potential[30].

RECONSTRUCTING CLIMATE RESPONSES

Long-term change

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. The response to large changes in the past is also a key constraint on the sensitivity of the climate to CO_2 forcing that guides future projections.

ACE CRC and AAD research 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

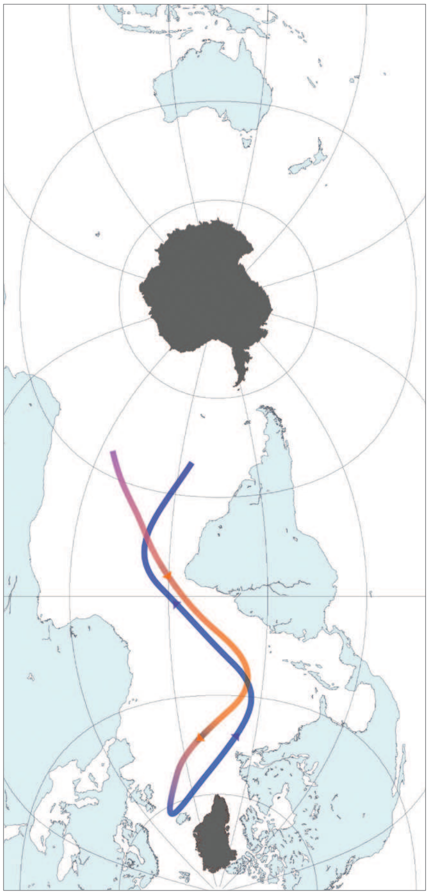


FIGURE 9: Simplified view of overturning circulation in the Atlantic Ocean. Surface waters flow from SH to NH, warming and carrying heat toward Greenland, returning as deep cold currents toward the SH. The speed and volume of this Atlantic overturning drives the bipolar see-saw between the hemispheres, warming one at the expense of the other.

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 ACE CRC findings has been the very high time resolution through the 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, as seen in Figure 10. 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 (Figure 9). 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[31,32] 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 changes likely follow the Northern Hemisphere[33] 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 (Figure 10). This relative timing has proved difficult to constrain and it was thought warming preceded the CO_2 increase by 700 years or more.

This work[34] has established that the CO_2 rise lags the temperature rise by no more than 400 years, likely much less, and is possibly essentially simultaneous with the temperature increase. The result has profound implications for the rate at which CO_2 is absorbed/released from the Southern Ocean and is vital for understanding CO_2 uptake in a warming climate.

Incidentally, the possibility of a delay between temperature increase and CO_2 is sometimes misunderstood outside the

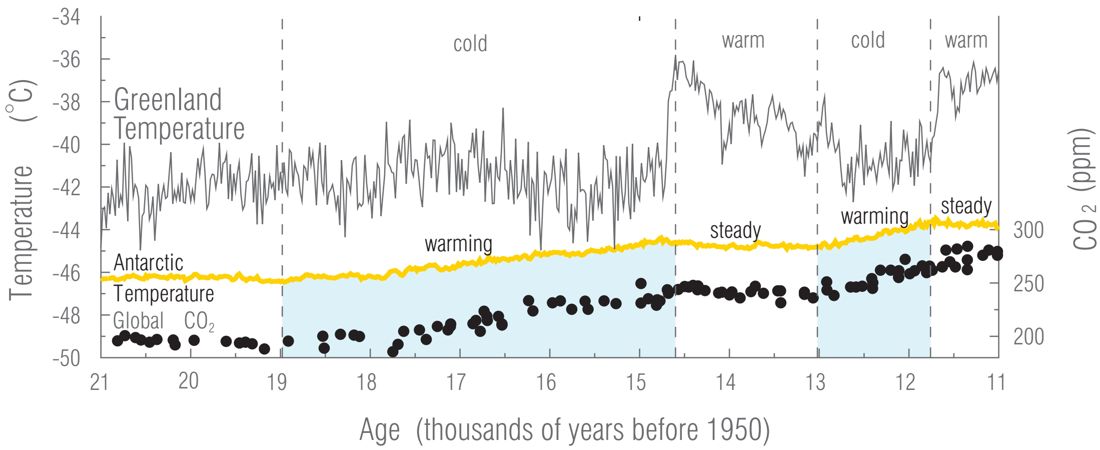


FIGURE 10: Temperature proxies for Greenland[35] (black) and Antarctica[31] (orange). It can be seen that when Greenland is in a cold state, Antarctica is warming and when Greenland warms up, Antarctic temperatures steady, or even decline slightly. The CO_2 record (black dots, from two Antarctic cores) shows a rise that is almost coincident with Antarctic temperature. ACE CRC research[34] established that the CO_2 rise follows temperature by 400 years or less.

science domain. The argument suggests temperature forces CO_2 but not vice versa. In fact, whatever the origin of a CO_2 increase, it will drive additional temperature rise. The two factors provide positive feedbacks for each other.

RECONSTRUCTING CLIMATE RESPONSES

The past 2000 years

With the development of a suite of records, improved dating and multiple cores, both in the Australian program and internationally, focus has increasingly moved towards the assembly of continental scale climate reconstructions, especially within the framework of the IPICS 2,000-year array and the IGBP-PAGES2k initiative. One recent publication of a global view with reconstructions from most continental regions[21] is the most advanced effort so far (Figure 11, top panel). This included the first 2000-year reconstruction for Antarctica that was led by ACE CRC scientists. This reconstruction, based on just nine ice cores, gives a first view of temperature evolution through recent millennia (Figure 11, lower panel).

Another recent study provides the most comprehensive Southern Hemisphere reconstruction (Figure 11, middle panel) of past climate and reveals the temperature history over the past 1000 years[36]. The study showed temperature variations over the past 1000 years have differed greatly between hemispheres, although both hemispheres show consistent warming over the past 40 years. This international coordinated effort utilised new Southern Hemisphere climate information from tree rings, lake sediments, corals, ice cores and climate models.

The Antarctic region stands out globally as the only region that doesn't show a strong warming signal in the late 20th century. This is also apparent in the shorter instrumental record, where overall warming has been modest, despite strong regional

warming in West Antarctica and the Antarctic Peninsula. Influences from ozone depletion, increased westerly winds and the sheer thermal mass of the surrounding ocean are all attributed with delaying and muting warming.

The reconstruction efforts will be broadened as researchers seek to build a more robust picture of snowfall changes[37,38] and other variables such as sea ice, ocean sea-surface temperature and even remote processes such as ENSO. These efforts will complement, but not displace, much-needed studies on single sites and proxies.

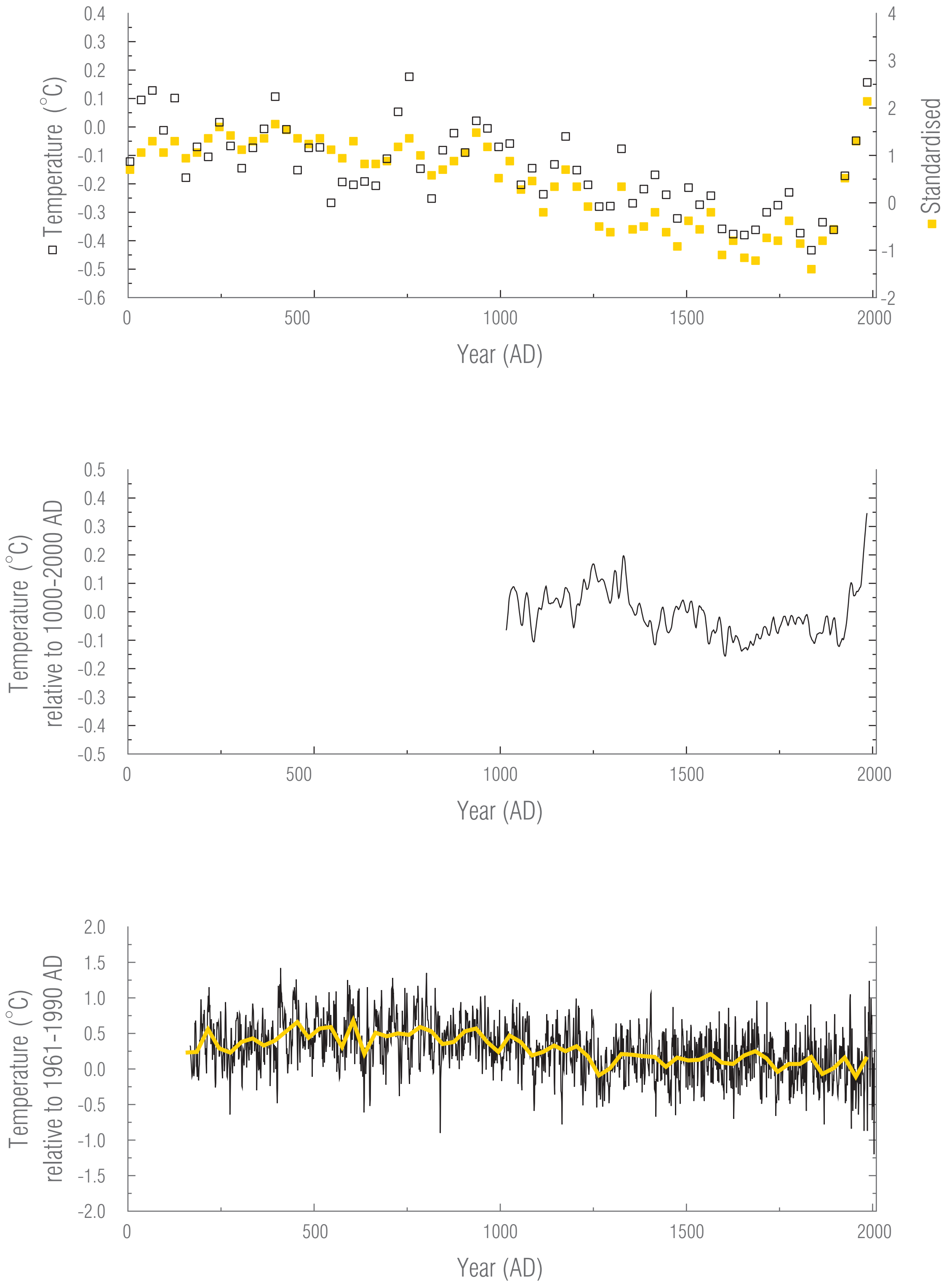


FIGURE 11: Temperature reconstructions including Antarctic ice cores: 2000-year reconstruction of global temperatures[21] (top), Southern Hemisphere[36] (middle), Antarctica[21] (bottom).

FUTURE OBJECTIVES

The future of ice core research is full of opportunity. The science coming from the very detailed Law Dome records continues to deliver valuable insights, particularly in applications to questions around Australian climate and mid-latitude climate processes. High-priority studies also involve extending the Law Dome record with short cores to allow longer and better comparisons to ongoing meteorological records. This is pivotal to underpinning interpretation of the ice core record as a whole.

Increasingly, however, the need is shifting to synthesis. Synthesis of multiple proxy indicators and multiple sites is required in order to improve sensitivity to the full range of climate processes and to develop an accurate spatial picture of past changes.

The need for additional ice core sites is critical, particularly in East Antarctica. The present ability to reconstruct Antarctic climate is severely limited, with just two detailed ice core records (Aurora Basin North and Law Dome) of more than 1000 years in the Australian Antarctic Territory (AAT). Developing this array is one of the key international priorities outlined by IPICS and is a major focus of the Australian Antarctic Science Strategic Plan.

Climate records from Aurora Basin and an expanded East Antarctic array will lead directly to improved Southern Hemisphere climate reconstructions and expand the capability to explore major linkages for Australian climate. This work is highly collaborative and will utilise international partners. The Aurora Basin project, for example, involved 17 organisations contributing from six nations: Australia, China, Denmark, France, Germany and the United States of America.

The million-year ice core

The climate record from ice cores presently extends back about 800,000 years and covers eight ice age cycles of about 100,000 years each. This is as far as we have direct measurements of past CO_2.

The past climate record from marine sediments extends back several million years and shows a change in pacing of ice age cycles from 100,000 years most recently, to about 41,000 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 41,000-year glacial cycles to 100,000-year cycles is incomplete. Both periodicities correspond to changes in solar forcing with the Earth's orbit, but why has 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 (more than a million years) to help address this[39].

International impetus to find and drill this ice is highly significant and is driving exploration, modelling and technology development.

Early results from Aurora Basin North are assisting in characterising regional variability and plans are underway to use this information with meteorological studies to guide selection of further ice core sites in the AAT so that the 'Antarctic 2k array' envisaged by IPICS and IGBP-PAGES achieves its aim to adequately characterise Antarctic climate. A further motivation aimed at better reconstruction of Australian climate is to find locations that complement Law Dome's linkages with lower-latitude climate.

Other IPICS priorities enter into Australian plans. Existing core material and ongoing interpretation of results from the Law Dome core will contribute to understanding the emergence from the last glacial period and contribute to the IPICS 40ky network results. Also, work from airborne radar surveys is useful for understanding deeper time changes to the ice sheet that help with exploring the last interglacial project. However, the big item on the horizon is the IPICS oldest ice project (see opposite). This work is already driving large-scale survey work in East Antarctica, and China is drilling at the highest point, Dome A, with oldest ice as a potential target.

This major multinational drive will eventually require two or more deep coring efforts, which will be signature projects for Antarctic cooperation. Coring will almost certainly take place in the Australian Antarctic Territory and Australian participation makes strong sense for a range of logistical, scientific and policy reasons. Research to underpin this has been underway for several years, with major Australian involvement in airborne surveys of the ice sheet.

AAD

Air-link opportunities

The recent introduction of an intercontinental air-link from Hobart to Antarctica has opened up new opportunities.

The ability to move science personnel more rapidly to and from the continent has enabled the involvement of more senior researchers.

In the ice coring field, two examples of such expanded opportunity exist. One is the expected benefit of encouraging senior international figures to join in fieldwork. Completed fieldwork at Aurora Basin in 2013-14 included the participation of drillers and scientists from the US, Europe and China, which strengthened the project and its collaborative outputs.

The second example, not anticipated, arises from the ability to rapidly return samples for analysis. One ice core project, studying the solar variability proxy based on beryllium-10, has been able to incorporate complementary study of beryllium-7. Beryllium-7 has a half-life of just 53 days and can only be measured with advanced accelerator mass-spectrometry.

For several seasons, this project has been able to collect samples and return them to ANSTO by air in just days, enabling new science opportunities to be realised.

A collaborating researcher from China processes an ice core at the ACE CRC's laboratory in Hobart.

Ice core science is, by definition, a deep field activity and this research will continue to rely on logistically complex and expensive capabilities. This is particularly so for major drilling operations. Recent Australian efforts have been enhanced by increased inter and intra-continental air links in Antarctica, especially via the hub provided by the Wilkins ice runway near Casey Station (see page 27). However, larger operations will still require traditional logistics and operations including over-snow traverses, albeit with great support from air operations. The capability to access remote areas reliably and insert teams is an ongoing need.

The Australian Antarctic Program, and within it ACE CRC, has developed a significant record of achievement, particularly in work at Law Dome. This achievement, as a national initiative, is important but along with the recent work at Aurora Basin it has been underscored by strong international collaboration. Such collaboration is a key to future progress. It provides opportunities to harness shared logistics and operations and further embeds the norms and values of the Antarctic Treaty System. In this way, collaborative ice core research directly addresses the first goal of the Australian Antarctic Program, which is "to maintain the Antarctic Treaty System and enhance Australian influence within it".

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