Exit Report
2010 - 2014

ACE CRC

ANTARCTIC CLIMATE & ECOSYSTEMS CRC

Image courtesy Australian Antarctic Division

Exit Report 2010-2014

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1. Summary of the ACE CRC

1.1 Overview

The ACE CRC is a strong, long-standing and productive collaboration between six core partners and 17 supporting partners. The core partners are the Australian Antarctic Division, CSIRO's Division of Marine and Atmospheric Research, the University of Tasmania, the Commonwealth Government's Department of Environment (under numerous formal names over the life time of the Centre), plus the Alfred Wegener Institute for Polar and Marine Research (Germany) and the National Institute of Water and Atmospheric Research (New Zealand).

The ACE CRC was funded through the Australian Government's Cooperative Research Centres Program under a Commonwealth Agreement covering the period from 1 January 2010 to 31 June 2014. The supporting partners include four commercial businesses plus research and academic institutions based in Australia and abroad.

1.2 World-leading science

The ACE CRC's science has been world leading. As a key driver of research and innovation, the ACE CRC has nurtured the scientific expertise, institutional links and industry innovation that has helped establish Australia's reputation for leadership and stewardship in the Antarctic.

During the funding period, ACE CRC researchers published 408 peer-reviewed scientific papers, including 15 in the prestigious family of *Nature* and *Science* journals. This body of knowledge constitutes a major contribution to global scientific understanding of climate change and its local, regional and global impacts.

The ACE CRC's scientists have led Australian contributions to major deliberations by international governance bodies including the Intergovernmental Panel on Climate Change (IPCC), the Commission for the Conservation of Marine Living Resources (CCAMLR) and the International Maritime Organisation (IMO).

1.3 Funding

Originally established in 1991, the ACE CRC has been successful in four selection rounds:

- 1991 CRC for the Antarctic and Southern Ocean Environment;
- 1996 CRC for Antarctica and the Southern Ocean;
- 2002 CRC for Antarctic Climate and Ecosystems; and
- 2009 CRC for Antarctic Climate and Ecosystems.

Following the introduction of new CRC program funding guidelines the ACE CRC was successful in seeking an extension in the 2009 (11th) selection round and was awarded a grant of $18.7 million over 4.5 years from 1 January 2010 to 30 June 2014.

The ACE CRC was able to attract significant levels of Australian and international funds in cash and in-kind support. This collaboration and in-kind support has been vital in enabling the ACE CRC to act as the primary mechanism by which Australia's Antarctic research sector can assemble multi-disciplinary teams of experts to address strategic science questions that cannot be tackled by one institution alone. These collaborations have enabled the ACE CRC

and its partners to define the agenda for Southern Ocean and Antarctic research globally, and helped in establishing Tasmania as a global centre for Antarctic innovation.

1.4 Third Year Review

An independent review of the ACE CRC in its third year chaired by Professor Alan Pettigrew found that the CRC was meeting the requirements of the *Commonwealth Agreement* and delivering on its proposed outcomes for end-users.

Among the findings of the review were:

- the ACE CRC was "*…highly focussed on public good end-user needs of national and international policy makers and climate change scientists;*"
- The CRC had "*…developed an effective and stable governance and management team that is strongly supported by the end-users and research providers;*"
- the CRC had delivered "*high quality outputs that serve the end-user needs of government and the private sector partners*"; and
- the outputs from the CRC's research "*…are being delivered and appear highly valued by the end-users and the broader 'community' (climate scientists, resource managers, city and infrastructure management planners, and policy makers).*"

2. Impacts

The ACE CRC has delivered significant impact by providing relevant, timely and actionable scientific advice to policy makers, industry stakeholders and the broader public. During the life of the ACE CRC, the Centre continuously sought new and innovative ways to communicate its research outcomes to maximise the uptake of its scientific work. The ACE CRC established a reputation for providing the clear and actionable scientific insights necessary to ensure Australia can successfully meet the challenges of a changing climate. The Centre's plain-English *Position Analysis* and *Report Card* publications summarised the latest developments in sea level rise, climate change, ocean acidification, sea ice distribution, ocean fertilisation and ocean ecology. To ensure uptake at the policy level, the Centre proactively engaged with relevant departmental offices and parliamentary offices on a regular basis. The Centre's scientists issued regular public statements and made numerous appearances in the media to provide an informed perspective on often-contentious issues relating to climate change. The Centre conducted regular reviews with end-users to understand their needs and continually improve outputs.

2.2. Publications

The following research summaries were produced during the 2010-2014 period.

Year	Technical Report/Position Analysis/Report Card
2010	Technical Report: The CSIRO Mk3L climate system model v1.2
2010	Technical Report: Shoreline Change at Roches Beach, South-Eastern Tasmania 1957-2010
2011	Position Analysis: Climate Change and the Southern Ocean
2011	Report Card: Southern Ocean Acidification
2011	Technical Report: Government Coastal Planning Responses to Rising Sea Levels
2012	Technical Report: Sea ice reports for the season 2011-2012
2012	Report Card: Sea-Level Rise 2012
2012	Technical Report: Estimating present day extreme total water level exceedance probabilities around the coastline of Australia
2012	Technical Report: Generic design coastal erosion volumes and setbacks for Australia part 1
2012	Technical Report: Generic design coastal erosion volumes and setbacks for Australia part 2
2013	Technical Report: Sea ice reports: for the season 2012-2013
2014	Position Analysis: Antarctic Sea Ice and Climate Change 2014
2014	Technical Report: Sea ice reports for the season 2013-2014

2.3 Impact Case Studies

2.3.1 Intergovernmental Panel on Climate Change Assessment Report 5

The Intergovernmental Panel on Climate Change (IPCC) is the international body responsible for providing governments with the largest and most comprehensive summary of the latest scientific information on climate change. The contributions of ACE CRC staff over several years to the release of the IPCC's *Fifth Assessment Report (AR5)* in 2013 represents a major commitment to end-users nationally and globally. Researchers from the ACE CRC played a leading role in preparing the report, with 18 staff contributing as lead authors, contributing authors, reviewers and editors. The report constituted the most comprehensive and definitive body of scientific evidence presented to date demonstrating anthropogenic factors driving climate change.

2.3.2 *Canute* sea level rise tool

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 almost 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* (www.sealevelrise.info).

The *Canute* webtool gives coastal planners detailed information on the height and positioning necessary for infrastructure to avoid inundation and erosion as sea levels rise. In developing *Canute*, scientists from the ACE CRC looked at data from tide gauges and storm surge modelling at 12,000 points roughly every 2.5 kilometres around the Australian coast.

The platform can provide estimates for probability of inundation for infrastructure at various elevations on hard shorelines. In the case of soft shorelines, it assists with estimating the distance infrastructure needs to be set back to avoid the impact of shoreline recession.

At the conclusion of the funding period there were approximately 416 active users and a further 412 users who have signed up to the website but have not yet completed the online training. Regular reviews held with key commercial participants have helped to significantly expand the tool's functionality.

The Sea-level Rise Impacts team has also worked closely with the Spatial Information CRC (CRCSI) to translate the output from the ACE CRC's sea-level rise calculator into high-resolution maps of predicted flood inundation. The CRCSI has built a subset of the ACE CRC's data into their new, web-based GIS, which is presently in testing mode. When their system is in production mode the ACE CRC will be able to link into their server to create flood maps on-the-fly from within the *Canute* website.

2.3.3 Climate Futures for Tasmania

In 2010 the Tasmanian Government launched Climate Futures for Tasmania, a project developed by the ACE CRC to model projected changes to Tasmania's climate during this century, and its impact on communities, industries and government agencies. The project provides 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 project interprets climate projections at a local scale, so that communities, industries and individuals can use information in their local planning and adaptation actions.

The project also looked at the impacts in the applied areas of water and catchments, assessing how water will flow through various Tasmanian water catchments and into storage reservoirs under different climate scenarios. The project also provided specific climate indicators relevant to productivity in key areas of Tasmanian agricultural production. Finally, working with emergency service agencies, the project identified the climate variables of greatest concern to emergency managers.

The Tasmanian Government describes the project as its "most important source of climate change projections at a local scale… [and] an essential part of Tasmania's climate change strategy." The project was made possible through the support of a consortium of government and private sector partners.

2.3.4 Oceanographic Data

In 2014, a team from the ACE CRC and IMAS provided the world's scientific community with a comprehensive new dataset for understanding the Southern Ocean's role in regulating the global climate. This new oceanographic data - gathered using electronic sensors attached to elephant seals – has filled a number of large gaps in our understanding of global ocean circulation and provided oceanographers with high-resolution observations to improve climate and ocean models.

Among a number of findings, the data led to the discovery of a new source of Antarctic Bottom Water – the cold, dense and salty water produced when sea ice forms on the surface of the ocean. Antarctic Bottom Water is one of the primary drivers of global ocean circulation, and is key to understanding the role of the oceans in heat storage and climate regulation.

The innovative technique of attaching the sensors to elephant seals allowed sampling in areas that had previously been impossible to reach. The seals can dive to depths of up to two kilometres and travel vast distances to forage, returning data from parts of the Southern Ocean that were previously inaccessible due to sea ice coverage.

The findings were published in the journal *Nature Geoscience* in 2013 (Williams et al., 2013) and the data was made publicly available via the website Nature Scientific Data.

2.4 Economic Impacts

As a public good CRC engaged in the fundamental science of climate change, the economic impacts of the Centre's research should be measured against likely future productivity losses resulting from climate change. A review was conducted in the ACE CRC's third year to determine the economic value of the ACE CRC collaboration to Australia. A method was developed with guidance from the Australian Government Treasury and Westpac Institutional Bank to estimate the impacts of climate change on Australian GDP growth rate. The method took into account both the benefits of early and effective action on climate change and the costs of those actions. Assuming that mitigation measures were effective, a net benefit of 4% GDP was assumed. A conservative estimate of the share of benefits that might be attributed to the ACE CRC investment was assumed of 0.15%. The premise was based on the basis that ACE CRC research assists policy makers to make more accurate assessments of the level and timing of mitigation and adaptation actions in response to climate change, avoiding the cost of either over or under response.

With a total investment of $91 million (NPV cash and in-kind over 4.5 years), a net present value benefit of $232 million was determined to be derived over 15 years. After costs of adoption were subtracted the benefit cost ratio was determined to be 2.6.

2.4.3 Economic Benefit: Planning for Sea-Level Rise

Sea-level rise is increasing the impact of inundation from extreme flooding events, resulting in damage to coastal assets. The ACE CRC, via its sea-level rise decision-support tool, *Canute,* (www.sealevelrise.info), assists coastal infrastructure owners to make more informed management and planning decisions to adapt to future sea-level rise and reduce damage costs from extreme storm tides.

As a basis for this assessment, a study conducted by CSIRO in Queensland (Wang et al., 2010) estimated a saving of $700 million from restrictions to planning in coastal hazard zones was used and extrapolated nationally. A benefit achieved by adaptation less the adaptation costs was calculated. An undiscounted benefit of $5.06 million per annum for fifteen years was identified which equates to a net present value of $53 million.

2.5 Economic Flow-On

Antarctic science is a major driver of the Tasmanian economy, contributing approximately $200M annually to Gross State Product and bringing together students, researchers and innovative businesses from around the world. As a key driver of research and innovation, the ACE CRC has nurtured the scientific expertise, institutional links and industry innovation that have helped establishing Hobart as a global Antarctic gateway.

A study by the Tasmanian Government (Blacklow Economic Consulting, 2012) found the sector directly employed close to 1,200 Tasmanians in research and supporting industries – plus a further 1,600 indirect jobs in Tasmania alone. The sector increasingly supports a highly diversified industry base that includes manufacturing, construction, earthmoving, electronics, freight, maritime services, air links, fuel supply, fire protection, conference hosting, catering and accommodation.

In summary, the study determined that the sector delivered $5.50 of total economic return for every dollar invested in 2012.

2.6 Spin off companies/Inventions

The ACE CRC has not created any spin-off companies.

3. Research

The following section contains a selection of key research highlights by the ACE CRC's four cross-disciplinary science programs: Oceans, Cryosphere, Carbon and Ecosystems.

3.1 Oceans: The Southern Ocean and Sea Level Rise (SLR)

'How is the southern ocean changing, and the implications that this will have for Australian and global climate now and in the future.'

The ACE CRC's Oceans program was successful in meeting and exceeding its goal of enhancing scientific understanding of the nature, causes and consequences of change in the Southern Ocean. The importance of scientific efforts to understand the Southern Ocean is now firmly established – thanks in part to the work of the ACE CRC and its partners.

Observational analysis and model simulations have transformed our understanding of the Southern Ocean, suggesting that this region, which occupies just 30% of the surface area, has a profound influence on the Earth's climate and ecosystems. The Centre's research has provided data showing that the Southern Ocean is becoming warmer, fresher, more acidic and less oxygenated – and that these processes are occurring more rapidly than in any other ocean. The ACE CRC made significant advances in understanding ocean circulation and the formation of Antarctic Bottom Water, which plays a key role regulating the global climate. Through these observations, it has become clear that any significant changes in the Southern Ocean region will have impacts throughout the Earth's climate systems.

3.1.1 International Influence

The ACE CRC's Oceans program has played a leading role in Australian contributions to international climate change deliberations. The Centre's contributions to the IPCC's *Fifth Assessment Report (AR5)* highlight the fundamental importance of its oceanographic observations for tracking the evolution of climate change. The IPCC's AR5 report was released in late 2004 and 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 *Detection and Attribution* chapter, which provided strong evidence that human activities had made a substantial contribution to the warming of the oceans. This finding was supported by earlier studies involving ACE CRC scientists examining changes in ocean temperatures (Gleckler et al., 2013) and oxygen concentrations (Andrews et al., 2012).

3.1.2 Antarctic Bottom Water

Observations by the ACE CRC and international partners have documented rapid warming and freshening of Antarctic Bottom Water – cold, salty and dense water produced in the process of sea ice formation. Antarctic Bottom Water circulates throughout the world's oceans and plays a key role in regulating the global climate. A paper published by ACE CRC researchers in *Geophysical Research Letters* (van Wijk and Rintoul, 2014) provided the most detailed assessment of changes in Antarctic Bottom Water (ABW) to date. The paper showed that the volume of the dense bottom water layer has decreased by 50% since the early 1970s but oxygen concentrations have remained high. The authors concluded that freshening of the source waters, due to a change in precipitation or melting of Antarctic ice shelves, is the primary cause of the changes in the bottom water layer.

Another important milestone in the study of Antarctic Bottom Water came in 2013, when ACE CRC scientists discovered a new source in the Prydz Bay region of Antarctica. Using sophisticated satellite data, oceanographic moorings and the data from tagged seals, ACE CRC scientists discovered that a stream of Antarctic Bottom Water was being produced from intense sea ice formation in the Cape Darnley Polynya north-west of the Amery Ice Shelf.

3.1.3 Mertz Glacier

In 2010-11, the ACE CRC Oceans Program leader Dr Steve Rintoul led a multidisciplinary team of 40 Australian and international scientists to the Mertz polynya in Antarctica to investigate changes from the sea surface to the sea floor following the calving of the Mertz glacier tongue in February 2010. This event allowed a great natural experiment to unfold, giving scientists an opportunity to study how the environment in this region would change following the loss of the 3,200 square kilometre tongue, and what implications this will have for regional

and global ocean circulation. The following year, a paper published in *Geophysical Research Letters* (Shadwick et al., 2013), and authored by scientists in the Oceans and Carbon programs, describes the oceanographic consequences of the event. Comparison of data collected before and after calving shows that the loss of the glacier tongue dramatically reduced the salinity of the dense shelf water that contributes to the formation of Antarctic Bottom Water, and also significantly enhanced ocean carbon sequestration through biological activity.

3.1.4 Other scientific highlights

The ACE CRC Oceans program has delivered a number of key research outputs including; producing the first continuous underway measurements of oxygen isotopes near Antarctica (Bass et al., 2014); a review paper assessing how changes in the physical environment affect the habitats of marine biota, with contributions from the Oceans and Ecosystems programs (Constable et al., 2014); evidence for widespread freshening in the sea ice zone (Aoki et al., 2013); a comprehensive review of Southern Ocean dynamics (Rintoul and Naveira Garabato, 2013); a study using the trajectory of Argo floats to quantify the westward flow south of Tasmania for the first time (Fieschi et al., 2013); a study using virtual particle trajectories in a numerical model to identify and quantify outflow pathways for ABW (van Sebille et al., 2013); a joint paper with the Carbon program explaining how physical and biological processes control oxygen and carbon dioxide concentrations in the Southern Ocean (Shadwick et al., 2014); and a metagenomic study published in *Nature Communications* showing how ocean currents shape the distribution and diversity of micro-organisms (Wilkins et al., 2013).

3.2 Cryosphere Program

> *'How will sea ice and the Antarctic ice sheet respond to changes in climate and what impact will changes in the cryosphere have on climate and sea level?'*

Antarctica's ice sheet affects the global climate system at a primary level, with far-reaching effects on surface temperatures, precipitation levels, wind and ocean circulation. It is estimated that if the Antarctic ice sheet melted, it would raise global sea level by nearly 60 metres. Recent observations suggest that the contribution to sea-level rise from the Antarctic ice sheet is increasing, and that this is due to increasing discharge of ice by glaciers, rather than simply more melting. However, the response of the Antarctic ice sheet to global warming remains one of the least understood questions in projecting future sea levels over the next 100–1000 years.

The ACE CRC's Cryosphere program is working to address these foundational questions through three key research projects: the dynamic role polar ice sheets play in determining future sea levels; the role of Antarctic sea ice in the climate system; and the records and dynamics of past and present climate changes.

3.2.1 Ice sheet Dyanamics

The Cryosphere Program's project to understand the dynamic role of polar ice sheets in future sea level delivered on a number of significant research milestones during the period. The Centre was involved in a major collaboration with international partners in the airborne geophysical survey of large unexplored sectors of East Antarctica. Project ICECAP, which continues today, uses a suite of airborne instruments to produce vital knowledge of bedrock

topography, basal rock, sediment and water conditions. This work has provided fundamental data which has been incorporated into BEDMAP2, a major project to map Antarctica's topography below the ice sheet.

The ice-ocean modelling resulting from ICECAP data has significantly advanced understanding of coastal ocean processes that control the melting of Antarctic ice shelves. This includes the first study showing the influence of coastal polynya activity on the basal melting of ice shelves, using the Mertz Glacier tongue (Cougnon et al., 2013). Another study examined basal melting under the Totten Glacier (Gwyther et al., 2014), which is a focus of East Antarctic ice mass balance studies (and ongoing ACE CRC research) due to its large regional rate of ice loss.

3.2.2 Sea Ice Project

The annual change in Antarctica from the maximum extent of sea ice in winter to the minimum in summer is one of the largest natural physical changes on the planet. A Cryosphere program project examining the role of Antarctic sea ice in the climate system, has made significant advances in understanding the role that sea ice plays in the earth's climate system. Over recent decades, satellite monitoring of Antarctic sea ice has detected a slight overall increase in extent of +1.5% per decade. In 2014, sea ice extent reached a maximum extent exceeding 20-million square kilometres for the first time since record keeping began in 1979. The ACE CRC sea ice team has added a significant and informed voice to public discussions over this phenomenon, publishing a detailed position analysis document and making a number of high-profile media appearances.

3.2.3 SIPEX II

In 2012, ACE CRC sea-ice scientists embarked on a major research voyage off east Antarctica dubbed SIPEX-II (Sea Ice Physics and Ecosystems Experiment II). This multi-disciplinary study, using RSV *Aurora Australis*, was specifically designed to address major gaps in the knowledge of sea-ice zone processes as identified by national and international end-users. Researchers measured the physical and biological properties of sea ice on small-to-regional scales using classical methods and state-of-the-art technology which included: ice coring surveys, remotely-operated and autonomous underwater vehicles, drifting buoys and instrumented helicopters. Accurately determining sea ice thickness remains one of the biggest challenges for sea ice scientists today, and the data gathered on this voyage will be used to calibrate and improve the accuracy of satellite-based sea ice monitoring systems, which are currently unreliable for measuring sea ice thickness.

3.2.4 Palaeoclimate Project

A key objective of the ACE CRC Cryosphere program has been to understand past and future climate change on a millennial time scale. Previous IPCC reports have underscored the need for more palaeoclimate records from the Southern Hemisphere. These records are needed to support climate reconstructions and process studies and to test models. The ACE CRC palaeclimate project is using ice core records to produce high-resolution climate records for the Antarctic, with emphasis on connections to Australian climate.

One of the Cryosphere program's key palaeoclimate outputs was the publication of a global region-by-region synthesis of temperature over the past two millennia, in *Nature Geoscience* in 2013. For the first time, ACE CRC scientists were able to recreate a high-resolution proxy record of the Southern Australia's climate dating back 2,000 years, by comparing Antarctic ice core records with instrumental records of Australia's climate. This discovery that

Antarctica and Australia's climates are fundamentally linked has helped us understand present changes in the context of long-term change. For example, this work has identified linked South-West Australian drought with snowfall changes in East Antarctica that are unprecedented in the last 750 years, implying that the drought could be similarly unusual – information which is critical for farmers and infrastructure planning in drought-affected areas.

3.3 Carbon: Southern Ocean Uptake

'Will the Southern Ocean continue to remove CO_2 from the atmosphere and how rapidly will this increase the acidity of the ocean?'

The ACE CRC has made major advances in understanding the role of the Southern Ocean in carbon sequestration. The Southern Ocean currently sequesters about 15 per cent of all carbon dioxide produced by human activities – roughly the same amount as all other oceans combined. The cost of this high carbon uptake is that the Southern Ocean is becoming more acidic more rapidly than any other ocean. A key question for the ACE CRC Carbon program has been the extent to which the Southern Ocean will continue to act as a buffer against climate change, or whether it could be approaching saturation point. Studies have shown that Southern Ocean's carbon sequestration ability has weakened in recent decades, highlighting the critical nature of this question.

ACE CRC researchers made major progress in measuring the uptake of atmospheric CO_2 by the ocean, including quantifying many of the biological and physical processes that control carbon uptake. The Centre's ecologists also shed new light on the impacts of these changes on fundamental ecological processes including krill reproduction and phytoplankton distribution – research that has had significant implications for fisheries and marine park management.

3.3.1 Ocean Carbon Uptake

In 2012, a significant breakthrough was made in understanding the relationship between past temperature and atmospheric carbon dioxide concentrations. In helping to resolve one of the most important questions in climate science, ACE CRC researchers demonstrated that the time lag between changes in temperature and changes in atmospheric CO_2 levels in the past were much shorter than previously thought – no longer than 400 years, and possibly a much shorter, near-synchronous response. All previous work had provided uncertainties on the time lag between temperature and CO_2 in the order of many hundreds to even thousands of years.

The Carbon program has also determined a reliable method for estimating net production of oxygen and consumption of CO_2 by an ecosystem at hourly resolution from moored sensors. Data gathered using this method has revealed unexpectedly high levels of production in deep, mixed layers in spring (Weeding and Trull, 2013, in review). This work is essential to advancing the understanding of seasonal productivity in the Subantarctic Southern Ocean and for properly including it in global carbon models.

Members of the ACE CRC carbon program had a lead role in the development of a new release of the Surface Ocean Carbon Atlas (SOCAT; Bakker et al 2014), including chairing the group responsible for all Southern Ocean waters south of 30°S. SOCAT is a major international effort to deliver a uniformly quality controlled data product of underway surface CO_2 observations for use by researchers in the detection of changes in ocean carbon uptake and for testing ocean carbon cycle models.

3.3.2 Ocean Acidification

Determining the extent of ocean acidification caused by the uptake of CO_2, and its biogeochemical ramifications was another key project for the Carbon program. Acidification is occurring most rapidly in polar seas, meaning that ecosystem responses in the Southern Ocean are a bellwether for probable impacts around Australia. The key challenge for the ACE CRC has been to understand both the uptake of anthropogenic CO_2, but also the resulting interaction with naturally varying processes that control the distributions of alkalinity, dissolved inorganic carbon, and nutrients.

A key piece of research published in 2014 offered an important insight into processes affecting CO_2 uptake and acidification in the Southern Ocean. Shadwick et al (2014) described how the calving of the Mertz Glacier tongue in 2010 resulted in dramatic changes in CO_2 uptake and ocean acidification. The study showed enhanced biological production and CO_2 uptake by surface waters since 2010 that counteracted the impact of human-induced acidification. The results pointed 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 vulnerability.

3.3.3 Ocean Fertilisation

The Carbon program delivered on a number of successful research milestones relating to the iron fertilisation in carbon uptake by the Southern Ocean. Research by the ACE CRC and its partners has demonstrated that carbon sequestration through biological activity is, in fact, restricted in large areas of the Southern Ocean by the limited availability of iron – a necessary ingredient for phytoplankton growth. Knowledge of this has prompted proposals for deliberate iron fertilisation as a potential strategy against climate change, a controversial practice known as 'geoengineering'. A key focus of the ACE CRC's research has been on understanding the potential impacts of such actions, and how they compare to existing, natural iron fertilisation processes such as glacial sediment release, hydrothermal vents and cetacean fecal emissions. A joint French-Australian research voyage in 2012, involving ACE CRC researchers, set out to understand processes involved in natural iron fertilisation of deep waters offshore from the Kerguelen Plateau. The research has significantly advanced our understanding of the role of iron in Southern Ocean biogeochemical cycles and ecosystem functioning. Based on research to date, the evidence supports a precautionary approach to deliberate iron fertilisation. In 2012, the Centre provided this advice to the Australian Government in support of a successful push for a moratorium on marine geoengineering in the International Maritime Organisation.

3.4 Ecosystems: Impacts of Climate Change on Antarctic Marine Life

'What will be the impact of Southern Ocean and sea ice changes on Antarctic ecosystems and fisheries?'

The Ecosystems program has contributed significantly to assessments of climate change impacts on Southern Ocean ecosystems during the term of the ACE CRC. Researchers applied a combination of field and analytical studies, along with qualitative and quantitative modelling methods, to determine what will happen to Antarctic marine ecosystems under a variety of climate change scenarios. This included identifying risks to key species from changes in temperature, acidity and sea ice properties.

3.4.1 Ecosystem Modelling

The program made a significant contribution toward the creation of an ambitious whole-of-

system Antarctic ecosystem model that brings together existing ocean, ice, atmosphere and food web models. This coupled modelling has not previously been attempted at a regional scale for the Southern Ocean, and is expected to be completed in the next term of the ACE CRC. Highly complex spatial and seasonal variations in Antarctic marine habitats such as the advance and retreat of sea-ice make the development of models of these dynamic processes challenging.

3.4.2 Sea Ice Ecosystems

The SIPEX-II voyage, led by the Ecosystems program's Dr Klaus Meiners, took place in September-October 2012. It revisited a study area off Wilkes Land to build on the information and observations collected in 2007. The voyage gathered data to help assess the impacts of climate change on the physical and biological elements of the East Antarctic sea ice zone. Results of the voyage and also the winter-spring voyage on the German AWI vessel *Polarstern* in the Weddell Sea and the South Atlantic have delivered important new insights on sea ice habitats and their importance as food for larval and juvenile krill. Importantly, a relationship has been established between sea-ice thickness and ice algal distribution, suggesting that the observed thickening of sea ice snow cover could negatively impact krill populations. These results and other work on the role of sea ice in Southern Ocean ecosystems was presented at an ACE CRC-led *International Symposium on Sea Ice in a Changing Environment* in Hobart in March 2014.

3.4.3 Other outputs

The Ecosystems program produced the *Report Card: Southern Ocean Acidification* in 2011, communicating recent developments in the potential impacts of ocean acidification on whole marine ecosystems. This Report Card received wide acclaim from the research and government communities, in particular for the accessibility of the information it contained.

During February 2011, the Ecosystems program participated in the Australia-Japan workshop 'Establishing a benchmark to assess climate change impact in the eastern Antarctic Marine System' which was held at the CCAMLR Headquarters in Hobart. This workshop consolidated collaboration on marine ecosystems change in eastern Antarctica. The Ecosystems program also worked with the IPCC AR5 committee to ensure that the Antarctic region would be adequately included in the deliberations of Working Group 2.

3.5 Publications

Since 2010 ACE CRC researchers have published well over 400 peer-reviewed scientific papers, including 15 in *Nature* and *Science* journals.

Table: ACE CRC scientific publications

Publications output	Jan-Jun 2010	10/11	11/12	12/13	13/14	TOTAL
Refereed papers	79	74	84	84	85	406
Books	0	3	1	0	0	4
Book chapters	13	10	19	5	23	70
Conference papers/abstracts	18	9	4	9	1	41
Publications/reports for end-users	6	8	24	25	15	78

4. Contributing to Australia's future research workforce

4.1 The impact of education and training programs in areas of skill shortages

The ACE CRC has been an impressive incubator of Australian science innovation, with approximately 160 PhD completions during its lifetime. One of the objectives of the ACE CRC's education program during the reporting period was to address the long-term unmet national demand for highly-trained personnel with quantitative skills in oceanography and marine ecology. Significant progress was made towards this objective during the life of the Centre, with many graduates progressing to high-profile professional careers with partner institutions, governments and industry world-wide.

4.1.1 Institute for Marine & Antarctic Studies

The ACE CRC education program continues to be supported by and provided through the Institute for Marine and Antarctic Studies (IMAS), which is part of the University of Tasmania. Students study a range of topics relevant to Antarctica and the Southern Ocean. ACE CRC and IMAS staff teach PhD, Masters by Research and Masters by Coursework students. They also teach Honours programs and units in undergraduate courses, mostly to students taking science degrees, although a few undergraduates from other backgrounds (e.g., Arts) do enrol in first-year Antarctic studies units taught by IMAS.

4.1.2 Quantitative Marine Science

Two of the main ACE CRC partners (CSIRO and the University of Tasmania) combined to create a specific postgraduate training program in Quantitative Marine Science. The ACE CRC is closely aligned with the QMS program, through co-funding and supervision of postgraduate students and in the creation and delivery of post-graduate course work. The ACE CRC Education program worked closely with the QMS program, with many of the

projects available to QMS students supported by ACE CRC scientists. The program involved the creation and delivery of formal courses in oceanography, fisheries science and mathematics. Funds were set aside to provide scholarships for research higher degree students wishing to enter the QMS program. The program has now operated for several years and is widely considered to be successful both in attracting and training students.

4.1.3 Massive Online Open Course

The Massive Online Open Course (MOOC) model of learning is a new style of open access, high-quality study that is revolutionising education worldwide. Through its partnership with IMAS, the ACE CRC has contributed its resources and expertise to the production of a highly popular online course entitled *Marine and Antarctic Science*.

Ecological Modeller Dr Jessica Melbourne-Thomas (ACE CRC & AAD) co-presents the course with Professor Craig Johnson (IMAS) through the Open2Study program of Open Universities Australia. The month-long course consists of 37 short videos across four modules, each with a range of quizzes and assessment tasks. Subject material includes how life evolved in the sea, the role of the ocean in climate and the impacts of climate change for ocean processes and marine biota. As of 18 September 2014, 3,673 students have taken the course; 15,125 videos have been watched; and 1,132 classroom posts have been made.

This innovative education and outreach tool is allowing the ACE CRC and its partners to share their considerable expertise with students worldwide, further enhancing Tasmania's profile as a global centre of excellence in Antarctic and marine studies.

4.2 Key educational outputs

4.2.1 PhDs completed

From 2010 to June 2014, 33 students were awarded PhD degrees.

4.2.2 Enrolments

Jan-Jun 2010: A total of 17 students were supervised by staff from the AAD; 17 by staff of CSIRO and 19 by staff funded directly by the ACE CRC.

2010-11: A total of 20 students were supervised by staff from the AAD, 13 by staff of CSIRO and 10 by staff funded directly by the ACE CRC.

2011-12: In total, 20 UTAS staff and 16 non-university staff were involved in PhD supervision.

2012-13: In total, 22 UTAS staff and 28 non-university staff were involved in PhD supervision.

2013-14: In total, 39 UTAS staff and 52 non-university staff were involved in PhD supervision.

Marine & Antarctic Science MOOC: As of 18 September 2014, 3,673 students had enrolled in the Massive Online Open Course (MOOC) course entitled *Marine and Antarctic Science,* co-presented by ACE CRC researcher Jess Melbourne-Thomas.

4.2.3. Postgraduate enrolments

The table below provides postgraduate information from 2010-2014 for the ACE CRC:

Year	Commenced	Awarded	Total Enrolled (FTE)
Jan-Jun 10	5	0	17
10/11	8	11	34
11/12	10	9	44
12/13	8	9	37
13/14	8	4	47.5

4.3 Graduate employment statistics

Jan-Jun 2010: Three students who submitted their thesis for examination in were successful in securing postdoctoral positions – one interstate and two overseas.

2010-11: Of the 11 students awarded PhD degrees, two are now employed at the ACE CRC, one at CSIRO Division of Marine and Atmospheric Research (CMAR), one at IMAS, four were successful in securing post-doctoral positions overseas, and three found employment in other areas. During the period, 12 PhD students submitted their theses for examination. Of these, 5 students were successful in securing postdoctoral positions: 1 at ACE, 1 at AAD, 1 at UTAS, 1 interstate and 1 overseas.

2011-12: Of the 9 completions, 1 is now employed at the ACE CRC, 1 found employment with CMAR, 1 is employed by IMAS, 1 is employed by Myriax, 1 is employed by the Western Australia State Government, 2 were successful in securing post-doctoral positions overseas, and 2 found employment in other areas.

2012-13: Graduates of the 2012-13 reporting period are now working at ACE CRC (1), AAD (1), AWI (1), industry (1), post-doctoral positions at Australian universities (2), started own business (1), and unknown (2).

2013-14: During the 2013-2014 reporting period, there were 4 completions and 1 withdrawal during the reporting period. The graduates are now working at post-doctoral positions overseas (3) and in fields other than science (1).

5. Collaborations

5.1 Overview

Collaboration is the driving force behind all of the ACE CRC's scientific projects, and the key to its success as a research organisation. The Centre is an unincorporated joint venture comprising 6 essential and 17 other participants. The six Essential Participants are bound by the Participants Agreement, and the Other Participants Agreements set out the duties and commitments of the remaining 17 parties.

At its commencement in 2010, the ACE CRC collaborated with 66 organisations; from Australia, New Zealand, Asia, North American and Europe. By 2014, the ACE CRC maintains 81 domestic and international collaborations. This equates to an 18% increase in collaborations.

During 2010-2014, two participants withdrew (MUN and GHD) due to logistical reasons, staffing, and other global economic factors. A table of the Essential and Other Participants is provided below.

Type of Participant	Participant
Essential	Alfred Wegener Institute of Polar and Marine Research (AWI), Germany
Essential	Australian Antarctic Division (AAD)
Essential	CSIRO Division of Marine and Atmospheric Research (CMAR)
Essential	Department of Climate Change
Essential	National Institute of Water and Atmospheric Research Ltd (NIWA), New Zealand
Essential	University of Tasmania (UTAS)
Other	Centre for Polar Oceanography and Modelling (CPOM), University College London, UK
Other	Chinese Academy of Meteorological Science (CAMS)
Other	Department of Sustainability, Environment, Water, Heritage and the Arts
Other	First Institute of Oceanography (FIO), China
Other	GHD Pty Ltd (withdrew)
Other	Institute of Low Temperature Science (ILTS), Hokkaido University, Japan
Other	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), France
Other	Memorial University of Newfoundland (MUN), Canada (withdrew)

Type of Participant	Participant
Other	Myriax Software Pty Ltd
Other	National Institute of Polar Research (NIPR), Japan
Other	pitt&sherry
Other	RPS MetOcean Pty Ltd
Other	SGS Economics and Planning Pty Ltd
Other	Tasmanian Government
Other	University of Texas at Austin, USA
Other	University of Texas at San Antonio, USA
Other	Vrije Universiteit Brussel, Belgium

5.2 ACE CRC Symposium

The bi-annual 2-day ACE CRC Symposium was launched in 2004 to promote a sense of community and common purpose among researchers associated with the ACE CRC, to strengthen staff and student commitment to the ACE CRC and to foster collaboration among participants. The symposia are also attended by ACE CRC end users from government and industry, and have been an outstanding success.

Table: Attendance at the bi-annual 2-day ACE CRC Symposium

Dates	2010	2012	2014
Number of attendees	100	110	130

5.3 The value participants place on being part of the CRC

The ACE CRC is a highly cost-effective mechanism for driving collaboration, leveraging 'in kind' contributions from our national and international partners in excess of five times the cash investment. The ACE CRC is the primary mechanism by which teams of experts are assembled from across our partners to address strategic, multi-disciplinary science questions that cannot be tackled by one institution alone.

5.4 Third year review

The ACE CRC third year review reflected the strong commitment of participants to the ACE CRC collaboration, concluding:

1. The ACE CRC collaboration is highly focussed on public good end-user needs of national and international policy makers and climate change scientists.

2. The ACE CRC also delivers targeted end-user value to public authorities and consultancy services in the planning sector.

3. The ACE CRC currently marshals the appropriate participants and other resources to achieve the proposed outputs; and the ACE CRC has developed an effective and stable governance and management team that is strongly supported by the end-users and research providers. This structure has been developed over some 20 years of collaboration between the participants.

4. The ACE CRC undertakes scientific research of high quality and the products are valued by end-users; and that these are also directly relevant to national and international interests.

5. The ACE CRC is achieving program delivery objectives, in particular the collaboration between researchers and end-users.

6. The ACE CRC provides an environment that is highly supportive of cooperative and collaborative research.

5.5 Case study: Impact through collaboration

The ACE CRC's participation in the international ICECAP project has enabled a major detailed airborne geophysical survey covering large areas of East Antarctica, filling in a vast blank on the map of Australia's Antarctic territory. Using airborne laser and ice penetrating radar instruments, magnetometers and gravimeters, huge areas of the East Antarctic have been surveyed in high resolution for the first time. The data will enable ACE CRC scientists to understand how ice flows from the continent into the ocean and, ultimately, how much this process might contribute to sea level rise.

The ICECAP collaboration involves the ACE CRC and partner institutions: the Australian Antarctic Division; the University of Texas at Austin; the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS); and non-partner Universities of Edinburgh, Bristol and Exeter. The project has been a highly successful mechanism for international collaboration, leveraging 'in-kind' contributions from national and international partners and funding from peak agencies such as NASA and UK's NERC, in excess of five times the ACE CRC's cash investment. The benefits of the partnership include access to scientific expertise, sharing of highly specialised sensing technology and logistics, and integration of Australian scientists into a world-class research team.

The data collected from hundreds of thousands of kilometres of flight-lines has enormously enhanced our understanding of the East Antarctic ice sheet, including revealing that much more of it rests on bedrock well below sea level than previously thought and therefore may be more vulnerable to a warming ocean and contribute more to future sea level rise than previously thought. In 2011, the collaboration led to a landmark scientific paper in the journal *Nature*. The paper illuminates a dynamic period of repeated growth and retreat of the East Antarctic ice sheet around 20 million years ago. The measurements of magnetic properties of the hidden bedrock have also provided recently published insights connecting the geology of East Antarctica and Australia associated with the break-up of past supercontinents.

As a component of NASA's Operation IceBridge, ICECAP flights along tracks previously surveyed by ICESat have extended and improved the precision mapping of the ice sheet elevation, demonstrating the power of advanced scanning laser systems, and gaining valuable insights into the current changes in East Antarctica.

By mapping bedrock beneath the ice, particularly across the largest data void in the Australian Antarctic Territory (a region about the size of New South Wales), ICECAP has dramatically improved the latest datasets (published in 2013 by the BEDMAP2 Consortium), providing essential data for realistic computer modelling of the evolution of the Antarctic ice sheet and future sea levels.

6.6 International engagement

The ACE CRC engages on the international stage in a number of different ways. Firstly, we have 23 institutional partners with whom we collaborate on significant scientific research projects. Antarctic and Southern Ocean research is complex and expensive, and takes many years to plan and undertake, so there is great benefit in collaborating across organisations, disciplines and national boundaries. ACE provides a unique mechanism by which we collaborate with international partners, giving Australian researchers an opportunity to engage internationally, and leveraging Australian Government investment in research many times over. An excellent example of this includes the ICECAP project, described in Section 3.2.1above where ACE CRC scientists leveraged the resources and infrastructure of the US program to survey large areas of East Antarctica. Similarly, the SIPEX II sea ice experiment, described at Section 3.2.3 above is an excellent example of Australia's ability to attract world-class international talent to participate in a multi-disciplinary voyage organised by ACE CRC using Australian research infrastructure.

ACE CRC scientists also engage directly, and at very senior levels, with major international research programs and coordinating bodies, such as the Scientific Committee on Antarctic Research (SCAR), Intergovernmental Panel on Climate Change (IPCC), Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), and the International Whaling Commission (IWC).

Collaboration is crucial in Australia's innovation system and CRCs are the primary mechanism by which Publicly Funded Research Agencies (such as CSIRO and AAD), Universities and industry can collaborate on strategic research projects.

Appendix 1– list of publications

Ohshima, K.I., Fukamachi, Y., et al. (2013). "Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya." Nature Geoscience **6**: 235–240.

van Wijk, E.M. and Rintoul, S.R. (2014). "Freshening drives contraction of Antarctic Bottom Water in the Australian Antarctic Basin." Geophysical Research Letters **41**(5): 1657–1664.

Shadwick, E.H., Rintoul, S.R., et al. (2013). "Glacier tongue calving reduced dense water formation and enhanced carbon uptake." Geophysical Research Letters **40**(5): 904-909.

Wilkins, D., van Sebille, E., et al. (2013). "Advection shapes Southern Ocean microbial assemblages independent of distance and environment effects." Nature Communications **4**: 1-7.

Shadwick, E.H., Tilbrook, B., et al. (2014). "Carbonate chemistry in the Mertz Polynya (East Antarctica): Biological and physical modification of dense water outflows and the export of anthropogenic CO2." Journal of Geophysical Research: Oceans **119**(1): 1-14.

Wang X., Stafford Smith M., McAllister R.R.J., Leitch A., McFallan S. and Meharg S. (2010) Coastal inundation under climate change: a case study in South East Queensland. CSIRO Climate Adaptation Flagship Working paper No. 6. http://www.csiro.au/resources/CAF-working-papers

Blacklow Economic Consulting (2012). "Tasmania's Antarctic, sub-Antarctic and Southern Ocean sector 2011-2012," Department of State Growth. http://stategrowth.tas.gov.au/__data/assets/pdf_file/0008/77894/ANTSCI13037_20130705_Antarctic_Economic_Report_July_2014.pdf