# Australian Climate Change Science Programme

ANNUAL REPORT 2013–14

1989-2014 25th ANNIVERSARY

Celebrating 25 years of climate change science

Australian Government
Department of the Environment

CSIRO

Australian Government
Bureau of Meteorology

The Australian Climate Change Science Programme – An Australian Government initiative

**Contact details**

CSIRO enquiries

1300 363 400

+61 3 9545 2176

enquiries@csiro.au

www.csiro.au

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Edited and produced by Karen Pearce, Bloom Communication. Additional editing by Paul Holper.

Artwork by the Bureau of Meteorology Communication Section.

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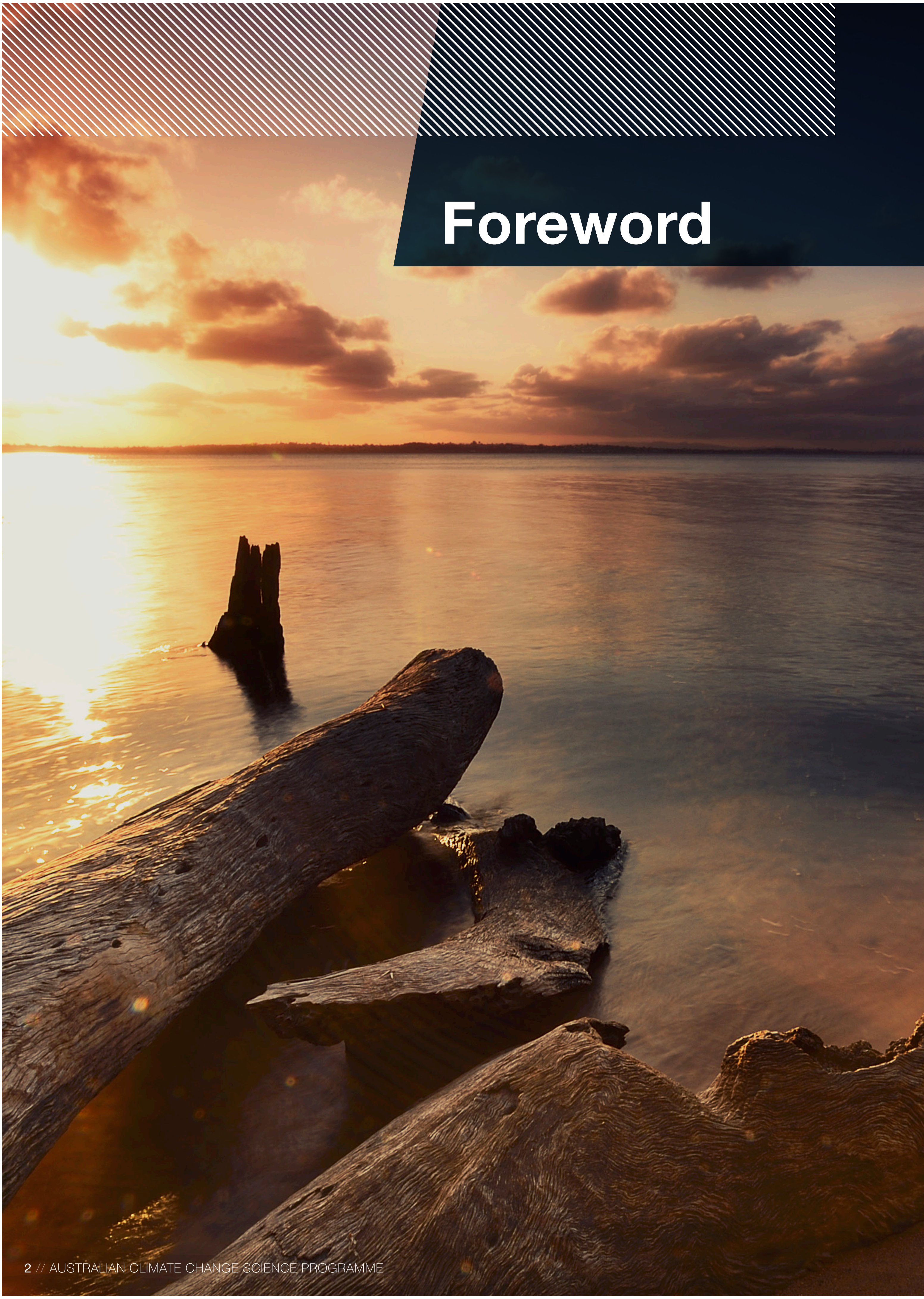
# Foreword



For 25 years, the world-class science undertaken through the Australian Climate Change Science Programme (ACCSP) has provided a comprehensive understanding of global and regional climate, and contributed to our understanding of the causes, nature, timing and consequences of climate change.

The ACCSP supports science that improves and analyses observations of the atmosphere, land and oceans; increases our understanding of climatic influences in the Australian region and how these are changing with global warming; augments our understanding of past and future climate change, climate variability and extreme events; and generates detailed national climate change projections. The science undertaken through the ACCSP is a cornerstone of climate research in this country, and is providing Australia with the foundations for the climate services of tomorrow. ACCSP research has also led to substantial improvements in short-term and seasonal forecasting.

In 2013–14 ACCSP researchers found that:

- Global carbon dioxide emissions continue to increase by 2.1% in 2012.
- Record-breaking rains turned semi-arid Australia into a carbon sink in 2011.
- The impact of declining northern hemisphere aerosols on sea-level pressure is larger in the southern hemisphere than the northern hemisphere.
- Deep ocean currents transmit high latitude climate variability to the Pacific.
- Sea levels continue to rise.
- The frequency of extreme El Niño events is set to double.
- Global warming alters the impact of El Niño on rainfall.

Researchers also:

- launched an online Global Carbon Atlas, and Carbon and Water Observatory
- developed a new woody vegetation dynamics model, a whole-of-reef biogeochemical model, and extended a wind-wave model
- expanded the observational programme at the Tumbarumba flux tower
- deployed 58 Argo profiling floats
- undertook the most complete assessment to date of changes in Antarctic bottom water
- commenced development of the next generation of the Australian Community Climate and Earth-System Simulator (ACCESS)
- provided underpinning science for the next national climate projections release.

While this report captures the science highlights of 2013–14, it is also a celebration of the ACCSP's 25 years of achievements and a thank you for the dedication of ACCSP researchers and staff from CSIRO, the Bureau of Meteorology and the Department of the Environment.

**Mr Paul Holper, Manager, CSIRO**
Australian Climate Change Science Programme

**Dr Helen Cleugh, CSIRO**
Co-chair, Australian Climate Change Science Programme

**Dr Robert Colman, Bureau of Meteorology**
Co-chair, Australian Climate Change Science Programme

# About

## Australia's changing climate

The biennial State of the Climate reports compiled by CSIRO and the Bureau of Meteorology provide a summary of long-term climate trends in Australia. The latest report, published in March 2014, noted:

- Australia's climate has warmed by 0.9 °C since 1910, and the frequency of extreme weather has changed, with more extreme heat and fewer cool extremes.
- Rainfall averaged across Australia has slightly increased since 1900, with the largest increases in the north-west since 1970.
- Rainfall has declined since 1970 in the south-west, dominated by reduced winter rainfall. Autumn and early winter rainfall has mostly been below average in the south-east since 1990.
- Extreme fire weather has increased, and the fire season has lengthened, across large parts of Australia since the 1970s.
- Global mean temperature has risen by 0.85 °C from 1880 to 2012.
- The amount of heat stored in the global oceans has increased, and global mean sea level has risen by 225 mm from 1880 to 2012.
- Annual average global atmospheric carbon dioxide concentrations reached 395 parts per million (ppm) in 2013 and concentrations of the other major greenhouse gases are at their highest levels for at least 800 000 years.
- Australian temperatures are projected to continue to increase, with more extremely hot days and fewer extremely cool days.
- Average rainfall in southern Australia is projected to decrease, and heavy rainfall is projected to increase over most parts of Australia.
- Sea-level rise and ocean acidification are projected to continue.

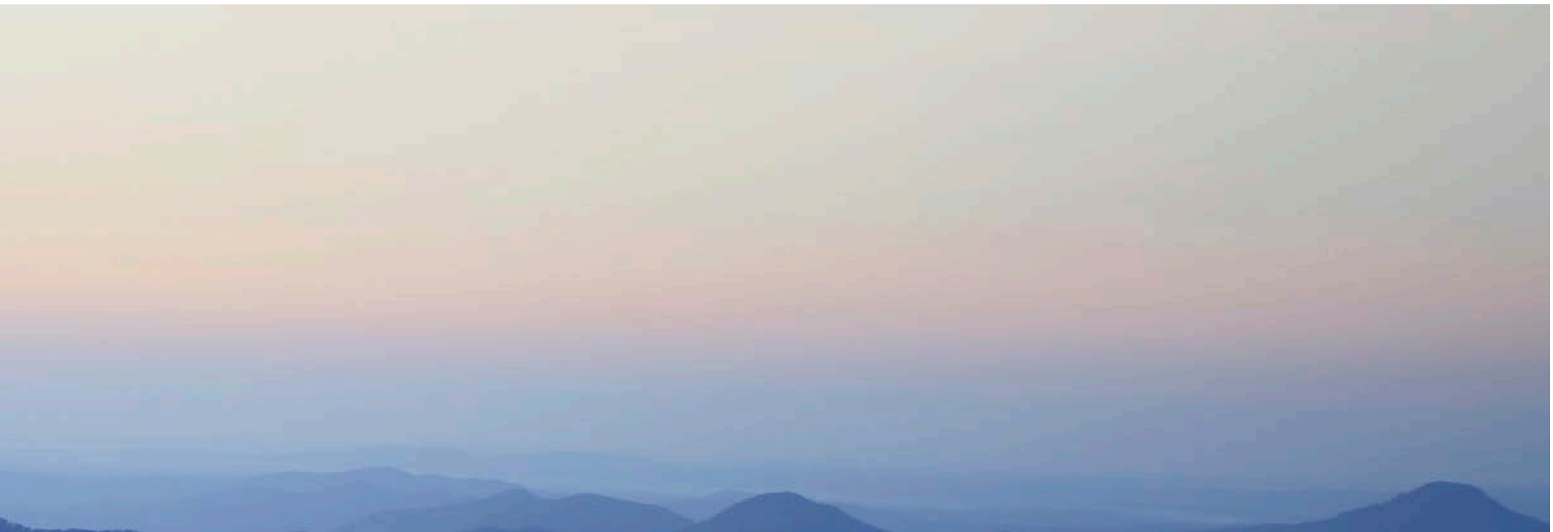
Science undertaken through the ACCSP improves our understanding of these trends. It helps Australia to determine what is happening to its climate, the causes of clearly observed changes, the extent to which the changes are long-term or cyclical and how our climate is likely to change in future.

The full *State of the Climate 2014* report is available at **www.csiro.au/Outcomes/Climate/Understanding/State-of-the-Climate-2014**

THE AMOUNT OF HEAT STORED IN THE **GLOBAL OCEANS** HAS INCREASED

**AVERAGE RAINFALL** IN SOUTHERN AUSTRALIA IS PROJECTED TO DECREASE

**SEA-LEVEL RISE** AND OCEAN ACIDIFICATION ARE PROJECTED TO CONTINUE



## The Programme

The ACCSP is the Australian Government's largest and longest-standing climate change science programme, having been running continuously since 1989. It is a key driver of Australia's climate change research effort, and provides climate research that underpins advances in shorter-term weather forecasting.

In 2013–14 the ACCSP received funding of $15 million through a collaboration between the Department of the Environment, CSIRO and the Bureau of Meteorology. More than 100 scientists throughout Australia were involved in the Programme, undertaking 25 projects across six key research areas (see Appendix 1 for a complete project list), and publishing 122 peer-reviewed papers or articles in Australian and international scientific publications. A further 34 papers were submitted for publishing and 16 others were accepted by the publisher and were 'in press' (see Appendix 3 for a complete publication list).

## National and international collaboration

The ACCSP is committed to sharing knowledge and improving research outcomes for the Australian community. Extensive collaboration and engagement with the Australian Government and Australian and international research agencies helps to ensure the research outcomes are robust.

Researchers collaborate extensively with university staff and students through joint research activities, lecturing and supervising students. There are strong links with the Australian Research Council Centre of Excellence for Climate System Science, including through the Australian Community Climate and Earth-System Simulator (ACCESS) and the National Computational Infrastructure facility.

ACCSP researchers have made profound contributions to the Intergovernmental Panel on Climate Change as authors of assessment reports and through dozens of cited publications.

ACCSP researchers play leading roles in international bodies such as the World Climate Research Programme, the International Geosphere-Biosphere Programme and the Global Carbon Project. The ACCSP also supports Australia's participation in global observation programs such as the International Argo Project and the global flux network and database (FluxNet).

See Appendix 2 for a complete list of ACCSP research partners.

MORE THAN **100 SCIENTISTS** WERE INVOLVED IN 25 PROJECTS

**122 PEER-REVIEWED PAPERS** OR ARTICLES WERE PUBLISHED IN SCIENTIFIC PUBLICATIONS

**RESEARCHERS COLLABORATED** EXTENSIVELY WITH UNIVERSITY STAFF AND STUDENTS

# 25 years of Australian climate science

2014 marks the 25th anniversary of the ACCSP. From humble beginnings, it has grown to become Australia's largest and longest standing programme studying the causes, nature, timing and consequences of climate change.

Over the past 25 years, ACCSP scientists have not only monitored the air, probed the oceans and explored the interaction between the landscape and climate throughout the country, but have developed world-class climate models and made internationally recognised scientific advances. ACCSP science has provided the foundation for Australia's climate change policy. It has also supported broader climate research including regional programmes and climate model development that provides national weather prediction, seasonal forecasting and extremes research. It has built strong and complementary links with other Australian and international research programmes.

## Programme origins

Since the inception in 1976 of the Cape Grim Baseline Air Pollution Station in north-western Tasmania, the measurements of pristine air here – unaffected by regional pollution sources – mirrored what US researchers had found atop Mauna Loa in Hawaii since the 1950s: each year the atmosphere contained more greenhouse gases. During the 1980s it became clear that atmospheric carbon dioxide concentrations were increasing globally. It was also becoming clear that the temperature of the planet was rising.

Although the relationship between increasing concentrations of greenhouse gases and rising temperatures was uncertain at this time, the need to improve our understanding of the climate system was widely recognised. It was also clear that the combined issues of rising greenhouse gas concentrations and increasing temperatures could have far-reaching implications beyond the atmospheric sciences.

In response to this major environmental challenge, CSIRO joined forces with the Commission for the Future to organise a multidisciplinary conference to draw attention to the matter. GREENHOUSE 87 spawned a seminal publication, *Greenhouse: Planning for Climate Change*, which contained dozens of papers examining the science and conceivable impacts of the ‘enhanced greenhouse effect’. Two years later, the Commonwealth Government granted CSIRO and the Bureau of Meteorology funds to undertake research into the phenomenon, and the Climate Change Research Programme was established.

Although its name has changed over the years (from the Climate Change Research Programme to the National Greenhouse Science Programme to the Australian Greenhouse Science Programme prior to its current title), the ACCSP has never wavered from identifying and focusing scientific activity on issues that are of the highest priority to inform policy and that advance our understanding of the climate system, in Australia, in the southern hemisphere and globally.

## Programme impact

The reach of the ACCSP has extended far beyond the corridors of CSIRO and the Bureau of Meteorology, with clear and considerable benefits for Australian and global scientific understanding.

### Informing policy and decision making

Since its inception, the ACCSP has served as an important focus of climate change science in Australia, concentrating resources on world-class science that meets government needs. The ACCSP and Australian Government have worked in partnership to ensure the research conducted is of the highest national benefit. Australian climate policy has been built on the robust evidence base provided by ACCSP research.

Climate science provides the foundations for policies that look to reduce our emissions, help us adapt to a variable and changing climate and ensure a cleaner environment for all Australians.

### The foundations for a broader national research agenda

The underpinning science capability within the ACCSP has allowed it to build strong and complementary connections with many other Australian research programmes. The ACCSP has worked to coordinate the delivery of climate science with the Centre of Excellence for Climate System Science, for example in developing Australia's climate modelling capability in support of research and climate and weather simulation across all timescales, and the Antarctic Climate and Ecosystems Cooperative Research Centre in delivering Antarctic and Southern Ocean science.

The science delivered through the ACCSP has also underpinned many programmes examining the likely effects of climate change on our environment, our economy and our society, as well as informing adaptation initiatives.

> "The ACCSP has produced an impressive body of work ... of the highest impact on climate change science, on a par with the best achievements obtained by the top research groups internationally."
>
> – DR SUSAN SOLOMON AND PROF. WILL STEFFEN, 2007 EXTERNAL REVIEW

### International reach

The ACCSP has made a major contribution to the international recognition of Australian climate change science. Through the relatively modest investment in the Programme, there has been extraordinary leverage of international scientific resources into our areas of interest. Our international memberships and collaborations with agencies such as the UK Met Office, NASA and the US National Oceanic and Atmospheric Administration (NOAA) give our scientists direct access to a wealth of international science beyond our own capability that may be tapped for Australia's benefit. The international standing of our research and scientists has also enabled Australia to influence the focus of global research.

As well as funding scientists to contribute to important bilateral and multilateral collaborations between Australia and other countries, the ACCSP supports Australia's participation in international research programs such as the World Climate

### SCIENCE INFORMING POLICY AND DECISION MAKING

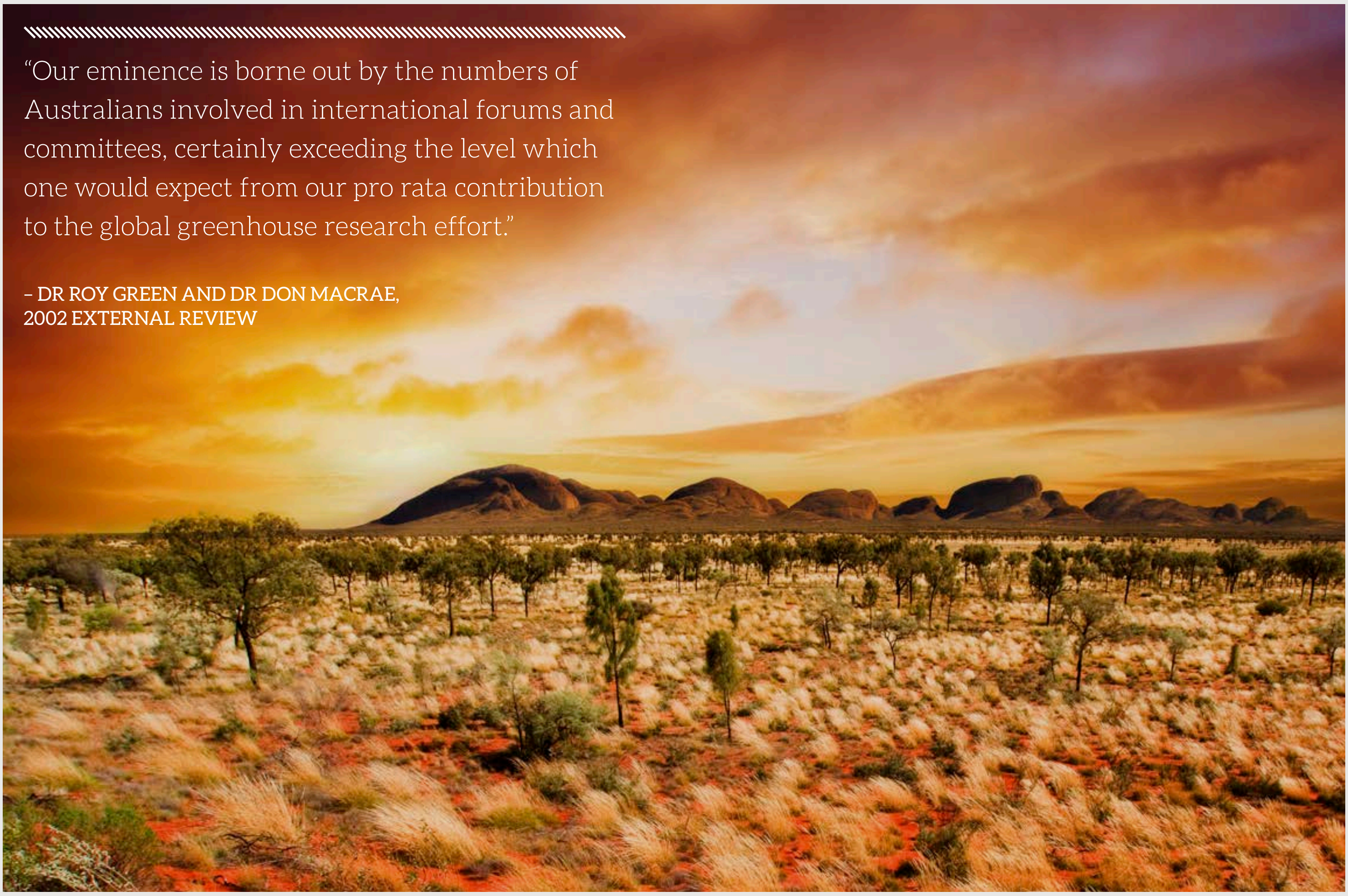
**Climate information is important for a wide range of decisions and sectors across Australia including infrastructure location and design, insurance for climate and weather events, agriculture and forestry, water supply, natural ecosystem management, land use planning and human health.**

**Research performed under the ACCSP has provided critical climate information and projections over the past 25 years to underpin planning and decision-making processes in these sectors.**

**For example, the impacts of climate extremes and changes in variability are significant for Australia, and can include:**

- **damage or loss of homes and infrastructure, disruptions to critical business operations and supply chains following extreme weather events**
- **health risks, particularly for disadvantaged groups**
- **risks to natural ecosystems such as the Great Barrier Reef.**

**ACCSP researchers have investigated the nature and cause of extreme weather events and the drivers of modes of variability that affect Australia, such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which play major roles in both wet and dry climate events. ACCSP researchers have provided projections of how the frequency and intensity of extreme events and key drivers of climate vulnerability, such as ENSO and the IOD, may change under a warming climate.**




Research Programme and the International Geosphere-Biosphere Programme. Our involvement ensures that the ACCSP science effort is both linked to, and an important component of, the global effort.

ACCSP work also contributes to the international science reviewed by the Intergovernmental Panel on Climate Change (IPCC). Dozens of our researchers have made significant contributions to the regular IPCC assessment reports that review the state of the science, including the recently released Fifth Assessment Report. ACCSP researchers contributed to the international scientific understanding on many topics including the attribution of observed changes to human-induced climate change, sea-level rise projections, climate variability, extreme weather events, climate projections and ocean acidification.

In addition, ACCSP scientists work closely with colleagues from many universities and research agencies around the world. As well as being invited to participate in and present at international meetings, our scientists have brought science leaders from around the world to Australia.

**The ACCSP paved the way for a host of regional programmes that have increased our understanding of climate change, including:**

- **South-Eastern Australian Climate Initiative (SEACI): investigated climate change and climate variability in the Murray-Darling Basin, Victoria and southern South Australia, paying particular attention to rainfall and run-off.**
- **Indian Ocean Climate Initiative (IOCI): examined the causes of the rainfall decline in Western Australia, and developed climate projections to inform policy.**
- **South-East Queensland Climate Adaptation Research Initiative (SEQ-CARI): the first comprehensive regional study of climate change adaptation in Australia, examining south-east Queensland's vulnerability to climate change and developing adaptation options.**
- **Goyder Institute for Water Research: providing scientific support for South Australian water management, including assessing changes in water availability as a result of climate change.**
- **Pacific Climate Change Science Program (PCCSP) and Pacific-Australia Climate Change Science and Adaptation Planning (PACCSAP): examining past climate trends and variability and providing regional and national climate projections for Pacific island countries and East Timor.**

# IPCC Fifth Assessment Report

In September 2013, the IPCC released the Working Group I contribution to its Fifth Assessment Report, reviewing the science of climate change. The Working Group II Report covering impacts, adaptation and vulnerability was published in March 2014, and the Working Group III report covering mitigation was published in April 2014. A report synthesising results from all three Working Groups will be released in late 2014.

ACCSP research is cited extensively in the Working Group I and II reports. Seven Programme researchers contributed as either coordinating lead authors or lead authors, and many other ACCSP researchers contributed to the report's content and review.

Working Group I lead authors were:

- Dr Steve Rintoul, coordinating lead author, Chapter 3 Observations: Oceans
- Dr Pep Canadell, lead author, Chapter 6 Carbon and Other Biogeochemical Cycles
- Dr Scott Power, coordinating lead author, Chapter 11 Near-term Climate Change: Projections and Predictability, co-editor of the Atlas of Global and Regional Projections, and contributing author of the Summary for Policymakers and Technical Summary
- Dr Julie Arblaster, lead author, Chapter 12 Long-term Climate Change: Projections, Commitments and Irreversibility
- Dr John Church, coordinating lead author, Chapter 13 Sea Level Change, and author of the Summary for Policymakers and Technical Summary.

Working Group II lead authors were:

- Dr Kathy McInnes, lead author, Chapter 5 Coastal and Low-lying Areas
- Dr Penny Whetton, lead author, Chapter 25 Australasia.

In addition, Dr John Church and Dr Scott Power are members of the core writing team for the overarching Synthesis Report.

ACCSP research contributing to the Working Group I report, included:

- the Global Carbon Project (GCP), which develops a comprehensive policy-relevant understanding of the global carbon cycle. In their 2012 Carbon Budget, the GCP reported that ocean and land carbon sinks respectively removed 28% and 23% of total (fossil fuel and land use change) carbon dioxide.
- leading ocean research involving analysis of data to track the changes in global and regional ocean heat and salinity patterns. These changes affect the rate of the sea-level rise and reflect changes to the global water cycle. More than 90% of the extra heat stored by the Earth over the past 50 years is found in the ocean, and changes in ocean salinity provide evidence that evaporation and rainfall patterns are changing as the Earth warms.
- Australia's world-leading global sea-level change research. Many of Australia's coastal communities are vulnerable to coastal inundation, erosion and infrastructure damage from sea-level rise and extreme weather events associated with increased greenhouse gases in the atmosphere. Projected changes are used to understand regional sea level, storm surge and wave changes on selected coastal locations.
- leading research on climate variability. The El Niño–Southern Oscillation, the Indian Ocean Dipole, and the Southern Annular Mode are major drivers of climate variability over Australia, influencing rainfall, floods, bushfires and drought.

The IPCC Fifth Assessment Report is available on the IPCC website at **www.ipcc.ch**.

(Left to right) John Church (CSIRO) and Scott Power (Bureau of Meteorology) with IPCC Working Group I Co-Chairs Dahe Qin and Thomas Stocker at the IPCC Working Group I Fourth Lead Author Meeting media briefing held at the Wrest Point Conference Centre, Hobart on 15 January 2013.

# The year in review

# Global and regional carbon budgets

The ACCSP investigates a range of topics that provide information on changes to greenhouse gas emissions and concentrations, nationally and internationally, and how these affect our environment.

25 YEARS OF CLIMATE SCIENCE

### Global and regional carbon budgets

Australian scientists have been monitoring greenhouse gases in the atmosphere since the early 1970s, but the advent of the ACCSP saw more funding directed to monitoring programmes and facilities, including monitoring at the Cape Grim Baseline Air Pollution Station in Tasmania and the establishment of CSIRO's world-class GASLAB/ICELAB facility in Melbourne. Using these facilities, ACCSP researchers continue to investigate a range of topics that provide information on changes to greenhouse gas concentrations and how these affect our environment.

In recent years, the ACCSP has also supported the Global Carbon Project to provide information on annual changes to global carbon release and uptake, and a complete carbon balance for the Australian continent.

Over the past 25 years the ACCSP has:

- improved our understanding of the role of the Southern Ocean in the uptake of carbon dioxide and its effect on the global carbon budget.
- taken high-precision measurements of both concentrations and isotopic ratios of atmospheric carbon dioxide over the Earth that have improved our understanding of atmospheric and oceanic transport processes.
- developed methods to calculate gas exchange at the Earth's surface that have provided a better understanding of how the atmosphere, land surface and oceans interact.

## SCIENCE HIGHLIGHTS

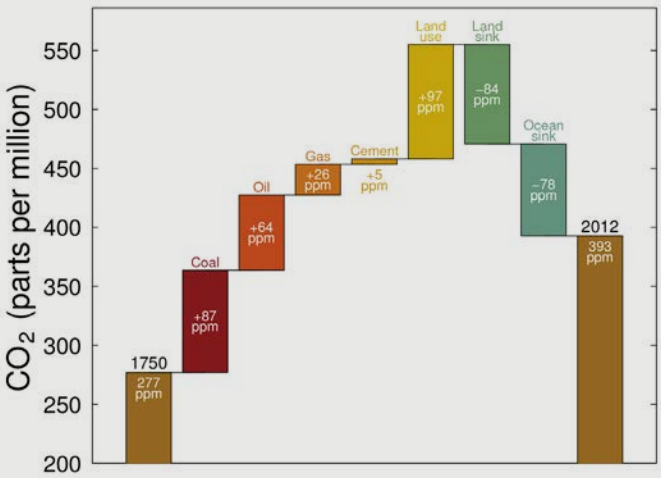
### GLOBAL CARBON BUDGETS, ANALYSES AND DELIVERY

Carbon dioxide and methane are the two most important greenhouse gases driving human-induced climate change. By annually assessing the emissions and removals of these gases to and from the atmosphere, and tracking their changes against IPCC emission scenarios, countries and international negotiators can estimate the mitigation effort required to achieve a given temperature stabilisation target.

#### Carbon dioxide emissions continue to increase

Carbon dioxide emissions from fossil fuel burning and cement production increased by 2.1% in 2012, with 9.7±0.5 GtC (billion tonnes of carbon) emitted to the atmosphere, 58% above 1990 emissions (the Kyoto Protocol reference year). Emissions are projected to have increased by a further 2.1% in 2013. The current trajectory is tracking along the IPCC's most carbon-intensive emissions scenario that takes the planet's average temperature to about 3.2 °C to 5.4 °C above pre-industrial times by 2100. In 2012, the ocean and land carbon sinks respectively removed 28% and 23% of total (fossil fuel and land use change) carbon dioxide.

The full global carbon budget is available at **www.globalcarbonproject.org/carbonbudget**



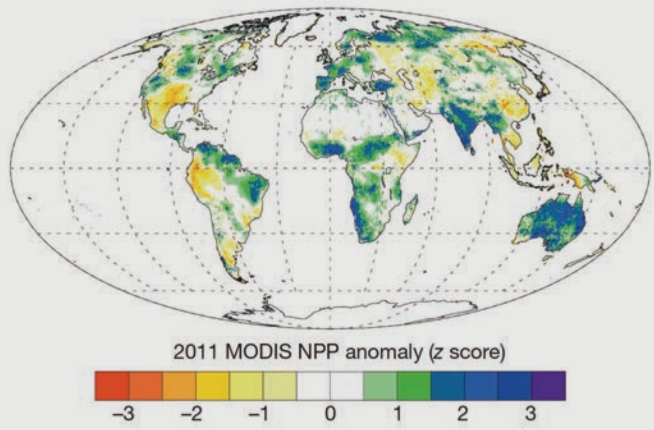



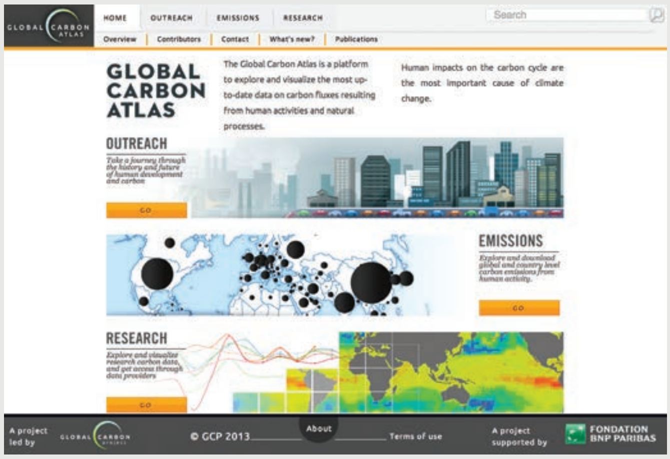

Figure 1: The cumulative contributions to the Global Carbon Budget from 1750 to 2012. Contributions are shown in parts per million (ppm).

Figure 2: Australia's greening response to increased rainfall in 2011 is apparent in the annual 2011 net primary production (NPP) anomaly estimated by the Moderate-resolution Imaging Spectroradiometer (MODIS).

## Record-breaking rains turned semi-arid Australia into a carbon sink in 2011

The land carbon sink (i.e. the carbon taken up by the land) in 2012 was much less than in 2011, a year of a strong La Niña weather pattern with increased precipitation. Further analysis of the anomalous year 2011 revealed that the size of the global land sink was unprecedented at least in the last 60 years, removing the equivalent of 40% of fossil fuel emissions that year. Surprisingly, the largest contribution to that sink anomaly was found in the semi-arid regions of the southern hemisphere with Australia showing the largest greening response. In fact, the 2011 Australian winter was the greenest that has ever been seen in the satellite period (since 1982).

Publication link: Poulter B, Frank D, Ciais P, Myneni R, Andela N, Bi J, Broquet G, Canadell JG, Chevallier F, Liu YY, Running SW, Sitch S, van der Werf GR, 2014, Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. *Nature*, 509, 600–603, DOI: 10.1038/nature13376.





## Online Global Carbon Atlas launched

A major deliverable this year has been the new Global Carbon Atlas, a key online tool to provide the most up-to-date carbon data and information for each of three types of audiences: public, policy makers/civil society engaged in climate change policy, and scientists. The Atlas was launched during the 2013 United Nations Framework Convention on Climate Change Conference of the Parties and received over 25 000 unique visits during the first week.

The Global Carbon Atlas can be accessed at **www.globalcarbonatlas.org**

25 YEARS OF CLIMATE SCIENCE

## Global Carbon Project

The Global Carbon Project (GCP) is an international collaboration to improve scientific understanding of the carbon cycle to support policy development and action on climate change.

The GCP is working towards building a complete picture of the global carbon cycle, including interactions and feedbacks between human, biological and physical dimensions. The ACCSP supports the GCP to provide information on annual changes to global carbon flows and stocks, and a complete carbon balance for the Australian continent.

## Cape Grim air archive

Behind an unremarkable door at CSIRO's Aspendale laboratory are racks of equally unremarkable looking stainless steel tanks. However, these tanks hold an invaluable collection of air samples that have been taken from Tasmania's Cape Grim every three months for more than 30 years. These samples offer an unprecedented history of the composition of the atmosphere in the southern hemisphere, and have enabled researchers to determine trends in the concentration of a range of atmospheric gases. For some of these gases, accurate and precise analytical methods have only recently evolved. The air archive is a unique resource that allows us to travel back in time to investigate past atmospheric changes.

# THE AUSTRALIAN TERRESTRIAL CARBON BUDGET: THE ROLE OF VEGETATION DYNAMICS

Integrated land surface analysis systems are essential to measure and report on critical flows of gases in and out of ecosystems, and how they might change in future. Carbon and water uptake and release are critical to Australia's sustainable future. Research seeks to better represent natural processes in computer models so that the flows can be better understood, monitored and simulated.

### New woody vegetation dynamics model developed

Current terrestrial carbon cycle models are limited by uncertain rates of biomass turnover. In order to overcome this limitation ACCSP researchers have developed a new terrestrial ecosystem modelling approach to predict woody vegetation dynamics and their effect on the terrestrial carbon cycle.

Called populations-order-physiology, the approach is suitable for continental to global applications and has been designed for coupling to the terrestrial ecosystem component of any Earth system model. Populations-order-physiology bridges the gap between first generation dynamic vegetation models with simple large-area parameterisations of woody biomass (typically used in current Earth system models) and complex second generation dynamic vegetation models, that explicitly simulate demographic processes and landscape heterogeneity of forests.

Populations-order-physiology is an ecologically plausible and efficient alternative to the large-area parameterisations of woody biomass turnover typically used in land surface models.

Publication link: Haverd V, Smith B, Cook G, Briggs PR, Nieradzik L, Roxburgh S, Liedloff A, Meyer C, Canadell JG, 2013, A stand-alone tree demography and landscape structure module for Earth system models, *Geophysical Research Letters* 40, 5234–5239.

### Carbon and water observatory available online

The BIOS2 modelling system is the key infrastructure for understanding the coupled carbon and water cycles in the Australian landscape. BIOS2 carbon/water model results for Australia at 5 × 5 km and monthly resolution are now publicly available in the newly developed online carbon and water observatory.

The observatory brings together the generation, operation, analysis and delivery of data. The observatory will provide stakeholders with background knowledge and ongoing information about the current status and historical patterns of the Australian carbon and water cycles since the beginning of the last century. The observatory will continue to be developed and updated to reflect current research outcomes.

The carbon and water observatory can be accessed at **carbonwaterobservatory.csiro.au**

## First steps taken in compiling methane budgets

ACCSP researchers conducted preliminary work on Australian regional methane fluxes in order to build datasets and capacity to deliver regional and national methane budgets in future.

Using both the Australian Community Climate and Earth-System Simulator (ACCESS) and the CSIRO Conformal-Cubic Atmospheric Model (CCAM), researchers conducted methane simulations for Cape Grim in Tasmania.

The forward model results of six different methane emission scenarios were broadly consistent with the observed methane record at Cape Grim. However, those scenarios with significant wetland methane emissions in winter overestimate methane concentrations at Cape Grim during that season, and all tested scenarios fail to represent a methane source in spring implied by the observations. Recent satellite measurements also point to a springtime maximum in south-eastern Australian wetland methane emissions, which is not present in the tested scenarios.

Overall, however, the work suggests that the anthropogenic inventory data for south-eastern Australian methane emissions are credible.

SCIENCE INFORMING POLICY AND DECISION MAKING

## Terrestrial carbon

**The ACCSP provides essential information for policy makers in establishing emission reduction policies that also improve the Australian landscape. Understanding how carbon interacts with the landscape is critical for informing emission reduction activities such as reforestation and revegetation, improving agricultural soils and managing fires in savannah grasslands. It allows for development of more effective sequestration methods, evaluation of sequestration options, implementation of effective actions and monitoring of progress.**

**The publication of Australia's first terrestrial carbon budget in 2013 was a significant milestone for Australian atmospheric science and for the management of carbon in the Australian landscape. The study quantified how much land carbon is lost or gained through plant and soil 'breathing' in response to a variable climate and rising carbon dioxide levels. The study found that in wet years vast amounts of carbon were absorbed while in dry years a nearly equal amount of carbon was released. This understanding is critical to implementing effective land sequestration policies and managing carbon in the landscape within a variable and changing climate.**

Publication link: Haverd V, Raupach MR, Briggs PR, Canadell JG, Davis SJ, Law RM, Meyer CP, Peters GP, Pickett-Heaps C, Sherman B, 2013, The Australian terrestrial carbon budget. *Biogeosciences*, 10(2), 851–869, DOI: 10.5194/bg-10-851-2013.


## THE OCEAN CARBON SINK AND ACIDIFICATION

Ocean acidification may have significant social and economic consequences for Australia, affecting tourism and fisheries and even the ability of reefs to help protect coastal regions. This project is providing leadership in research on the role of the Southern Ocean and Australian seas (including the Great Barrier Reef and Coral Sea) in the global carbon budget.

### Surface ocean carbon dioxide atlas for the high latitudes delivered

The surface ocean carbon dioxide atlas delivers a uniformly quality controlled surface carbon dioxide dataset, and is the major database for detecting changes in the ocean carbon sink and for testing ocean carbon cycle models.

ACCSP researchers led the international effort to deliver the atlas for all waters south of 30°S, including the Southern Ocean region.

Complementary research entails targeted efforts to determine carbon dioxide uptake and controls in critical regions of the ocean and in model-data assessments of air-sea carbon fluxes. High-latitude polar waters are important regions of change with marine ecosystems particularly vulnerable to acidification and where changing sea-ice distributions, stratification and winds are likely to alter carbon dioxide absorption in ways still not understood.

The surface ocean carbon dioxide atlas is available at **www.socat.info**

### Carbon dioxide uptake enhanced following removal of glacier tongue

Researchers investigated how the removal of the Mertz Glacier tongue in 2010 influenced carbon dioxide uptake and ocean acidification. The Mertz region is a major site of Antarctic bottom water, the cold, salty, dense water driving ocean currents and influencing the ocean carbon dioxide sink. The region also contains extensive reef ecosystems. In mid-February 2010 a massive iceberg collided with the glacier tongue, resulting in a calving event that removed about 80% of the tongue, leaving only a 20 km-long stub.

The study showed greatly enhanced biological production and carbon dioxide uptake by surface waters since 2010 that are opposite to expected ocean acidification changes. It also revealed a change in the potential for bottom water formation that could reduce long-term carbon dioxide uptake into the deep ocean. The changes in the Mertz region may be an indicator of future regime shifts for Antarctic coastal waters.

Publication link: Shadwick E, Tilbrook B, Williams G, 2014, Carbonate chemistry in the Mertz Polynya (East Antarctica): biological and physical modifications of dense water outflows and the export of anthropogenic CO2. *Journal of Geophysical Research–Oceans*, 119(1), 1-17, DOI: 10.1002/2013JC009286.

### Whole-of-reef biogeochemical model developed

Biogeochemical models of whole-of-reef systems help determine the way in which coral reefs might respond to acidification. A new model of a reef was published using Heron Island as a test bed. This model is the basis for scaling up from reef systems to the entire Great Barrier Reef and linking to global models such as ACCESS. The reef model is already being used in other studies of potential acidification mitigation options for reefs.

Publication link: Mongin M, Baird M, 2014, The interacting effects of photosynthesis, calcification and water circulation on carbon chemistry variability on a coral reef flat: A modelling study. *Ecological Modelling*, 284, 19–34. DOI: 10.1016/j.ecolmodel.2014.04.004.

## HISTORIC CHANGES TO THE CARBON CYCLE

One of the largest uncertainties in future climate is the behaviour of greenhouse gases, especially carbon dioxide, in a warmer world. The ability of coupled carbon-climate models such as ACCESS to project changes in the uptake of the gas by the land and oceans can be improved if the models are able to reproduce past changes. Work in this project is examining air samples in Antarctic ice cores to determine past changes in the composition of the atmosphere.

### Dust deposition derived from ice cores explains high variability in ocean carbon uptake

Using Antarctic ice core measurements of dust concentration, ACCSP researchers and US collaborators have derived the likely dust deposition across the global oceans over the past 1000 years. The iron associated with this dust stimulated biological carbon dioxide uptake, a process replicated by the ocean biogeochemistry component of ACCESS. There was a high degree of variability found in the carbon dioxide uptake, much of which explains the variations in atmospheric carbon dioxide modelled previously from the ice core record of carbon dioxide and its carbon-13 isotope. Especially evident is the increase in ocean uptake during a period of high dust in the early anthropogenic period, which could account for about 10% of the ocean sink since 1800 AD.

25 YEARS OF CLIMATE SCIENCE

## GASLAB/ICELAB

**With the establishment of the ACCSP in 1989, funding was available to set up CSIRO's world-class GASLAB/ ICELAB facility at Aspendale, south of Melbourne.**

**GASLAB (Global Atmosphere Sampling laboratory) contains sensitive, state-of-the-art equipment that detects oxygen, carbon dioxide, nitrous oxide, methane, carbon monoxide, hydrogen and chlorofluorocarbons in air samples collected at the Cape Grim Baseline Air Pollution Station in Tasmania, and from around the world.**

**Across the hall, in the ICELAB (Ice Core Extraction laboratory) air samples are recovered from polar ice cores, then analysed in GASLAB. Ice cores examined at GASLAB/ICELAB have offered up air samples dating back 30 000 years.**

### Little Ice Age carbon dioxide reduction due to land ecosystem

New ice core measurements of carbon dioxide and the carbon-13 isotope show for the first time that the land ecosystem was responsible for the carbon dioxide reduction during the Little Ice Age (a period of modest cooling – less than 1 °C relative to late 20th century levels – of the northern hemisphere from the 15th to 19th centuries). ACCSP researchers produced a simple model of carbonyl sulfide in the atmosphere to test the ability of this gas to act as a tracer of the carbon cycle. As expected, carbonyl sulfide concentrations increased during the Little Ice Age as a result of the reduction in soil respiration and photosynthesis. These results confirm and potentially quantify the temperature sensitivity of ecosystem carbon dioxide uptake and argue against the popular hypothesis that forest regrowth following human population declines was the cause of the Little Ice Age carbon dioxide decline.

The evolution of carbon monoxide, hydrocarbons and the perfluorocarbons over the past century was determined from measurements of firn air (air trapped in compacted snow) that was collected from Greenland and Antarctica during past ACCSP projects. Atmospheric modelling by CSIRO and collaborators inferred the emissions changes responsible for these trends, providing powerful top-down constraints that show significant differences from emissions inventory estimates.

# Land and air observations and processes

The ACCSP examines atmospheric behaviour and the way in which it is likely to change as concentrations of greenhouse gases rise.

Australian ecosystems absorb significant amounts of carbon from the atmosphere. However, the extent to which they can continue to act as a sink in the future is unclear.

Global emissions of human-generated aerosols are expected to decrease in coming decades. Such a decrease is likely to accelerate global warming, and alter aerosol-induced effects on weather patterns currently experienced.

## SCIENCE HIGHLIGHTS

### AEROSOL AND ITS IMPACT ON AUSTRALIAN CLIMATE

Aerosols are fine particles suspended in the atmosphere, which tend to exert a cooling effect on the climate. Australia lies in between Asia (the largest source of human-generated aerosols) and the pristine Southern Ocean. The resulting strong gradient in aerosol forcing may cause large effects on climate in our region. Australian regional aerosol may also affect our climate. Work in this project combines modelling and observations to understand the climatic impacts of aerosols in the Australian region and the broader southern hemisphere.

#### Impact of declining northern hemisphere aerosols on sea-level pressure is larger in the southern hemisphere than the northern hemisphere

Human-generated aerosols have substantially ‘masked’ the warming effects of greenhouse gases, though the extent of this effect is uncertain. Human-generated aerosol emissions from the northern hemisphere are projected to decline sharply in the next few decades, and this is likely to cause an acceleration of the warming effects of increasing greenhouse gases. Changes in wind and rainfall patterns due to declining aerosols may differ from the effects of increasing greenhouse gases, so it is important to assess the effects of declining aerosols on climate projections. This will ultimately lead to more robust climate projections for Australia.

Researchers have used four climate models to compare the effects of declining aerosols and increasing greenhouse gases in climate projections. The focus of this study was on atmospheric temperature structure, mid-latitude westerly winds and associated changes in sea-level pressure in mid- and high latitudes.

Changes in westerly winds and sea-level pressure caused by declining aerosols were larger in the southern hemisphere than in the northern hemisphere. This may seem surprising, given that aerosols are mostly concentrated in the northern hemisphere, but it is this very fact that causes the circulation response to be stronger in our hemisphere. Changes in mid-latitude westerly winds are known to be linked to changes in north-south temperature gradients, and for aerosol changes these temperature gradients are larger in the southern hemisphere (since aerosol effects are large near the equator, and vanish at the South Pole).

Figure 3 illustrates the results for projected changes in sea-level pressure, which are tightly coupled to changes in mid-latitude westerly winds. Changes in sea-level pressure are larger in the southern hemisphere than the northern hemisphere, and are of comparable magnitude for declining aerosols and increasing greenhouse gases. The changes in sea-level pressure have the character of a ‘positive’ change in the Southern Annular Mode, which entails positive changes in sea-level pressure at mid-latitudes and negative changes at high latitudes.

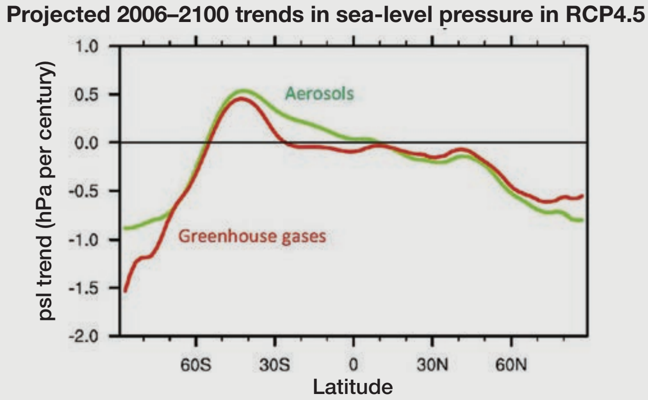



Figure 3: Projected 2006–2100 trends in sea-level pressure in projections driven by the medium-low Representative Concentration Pathway 4.5 (RCP4.5) for declining aerosols (green curve) and increasing greenhouse gases, including ozone (red curve).

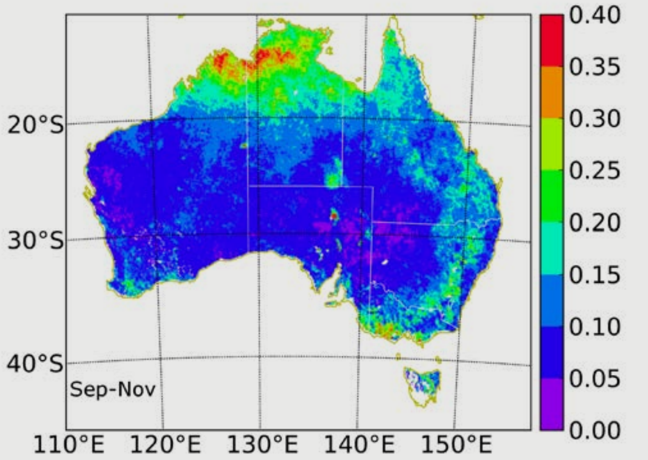



Figure 4: A plot showing mean aerosol optical depth for the savannah burning period September to November, averaged over 2002–08. It shows that aerosol optical depth is largest over the top end of Australia in this season.

## Australian tropical aerosol climatology derived

While aerosols from the northern hemisphere may decline, aerosols from biomass burning in the Australian tropics may continue to increase, and it is important to assess whether these aerosols exert significant climatic effects.

This aim is being addressed through model simulation of the climatic effects of different aerosol types and targeted observation of Australian aerosols. Generic assessment of Australian continental aerosols continues through operation of AeroSpan, a network of automated instruments located to characterise the primary sources of Australian continental aerosols. Global distribution of the Australian data through NASA AERONET (Aerosol Robotic Network) now underpins a wealth of international research projects aimed at accurate determination of planetary aerosol radiative forcing. Nationally, AeroSpan data were used to validate a new satellite algorithm giving unprecedented accuracy in aerosol retrieval (i.e. determination of aerosol loadings from satellite data) over Australia.

The climatology of Australian tropical aerosols was derived from amalgamated AeroSpan and Bureau of Meteorology sun photometer data. This provides the basis for aerosol transport model validation, which, for the first time, was undertaken in detail for the Global Model of Aerosol Processes (GLOMAP), the future ACCESS aerosol model. GLOMAP demonstrates that secondary organic aerosol processes can account for more than 30% of the aerosol optical depth. This is important because secondary organic aerosol formation is poorly treated in most global aerosol models.

Publication link: Mitchell RM, Forgan BW, Campbell SK, Qin Y, 2013, The climatology of Australian tropical aerosol: Evidence for regional correlation. *Geophysical Research Letters*, 40(10), 2384–2389.

25 YEARS OF CLIMATE SCIENCE

## Land and air observations and processes

**The ACCSP has been investigating the processes that govern the exchanges of gases and energy between the atmosphere and the biosphere and how they are likely to vary in a changing climate. Through the ACCSP, researchers have identified the importance of aerosols on the climate. As well as increasing our understanding of our atmosphere, this research has informed the development of climate models that can better simulate the real world.**

Highlights from this research include:

- establishing a link between increased rainfall in northern Australia and Asian-sourced atmospheric aerosols
- supporting the first multi-annual carbon dioxide flux measurements in Australian ecosystems
- quantifying for the first time the uptake and release of carbon dioxide, water and heat from a typical Australian ecosystem.

## Aerosol loading over Australia derived from satellite data

Derivation of aerosol loading from satellite data is notoriously difficult over Australia, largely due to the prevalence of bright (i.e. highly reflective) surfaces. Hence the method developed begins with a detailed and accurate model of the angular reflectance at the surface followed by an aerosol retrieval scheme that derives both aerosol loading and type. The results yield higher retrieval accuracy than hitherto achieved by existing international satellite products (MODIS, MISR), as judged by validation against AeroSpan and Bureau sun photometers. The results also provide the continental coverage needed for improved calculation of aerosol radiative forcing over Australia.

## REDUCING UNCERTAINTIES IN CLIMATE PROJECTIONS BY UNDERSTANDING, EVALUATING AND COMPARING CLIMATE CHANGE FEEDBACKS

Climate feedbacks are responsible for around half the uncertainty in climate change projections at global scales. A climate feedback is a change to a large-scale climate feature, such as the amount and distribution of water vapour, snow, sea ice or clouds, which increases or reduces the climate response to any changes in greenhouse gases generated by humans. A change that increases the climate response is termed a positive feedback. A negative feedback reduces the response. In this project research is focused on evaluating climate feedbacks in models with the purpose of identifying the critical physical processes, and thereby reducing the uncertainties in climate projections.

## Climate feedback leads to stronger projected Arctic sea ice retreat

A focus this year was on evaluating the water vapour, lapse rate and surface albedo (reflectivity) feedbacks in 35 models involved in the recent CMIP5 (Coupled Model Intercomparison Project 5). Figure 5 shows the average of the 35 models. Also shown are the average values from 23 CMIP3 models (i.e. models from the previous generation – around seven years ago). The feedbacks are mostly very similar between the two generations. For water vapour, the agreement is particularly strong. This is important as this is the strongest positive feedback in the climate system, so

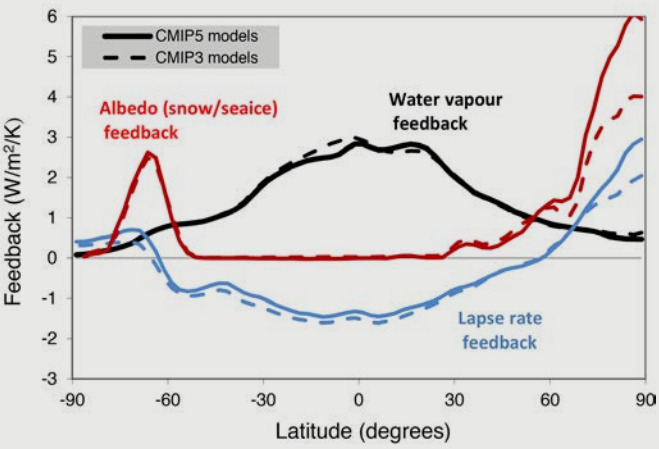



Figure 5: The distribution with latitude of three critical feedbacks in climate models for recent (CMIP5) and previous generation models (CMIP3). The feedbacks are: water vapour, lapse rate (vertical temperature gradient) and surface 'albedo' (reflectivity of sea ice and snow). Continuous lines show CMIP5 (35 models), dashed lines CMIP3 (23 models).

it indicates a robust model response. (There is some variability around this mean value – a spread across the individual models that is not shown).

The major disagreement between the generations of models is in the strength of the albedo (surface reflectivity) feedback at high latitudes in the northern hemisphere. Here there is a strengthening of feedback in recent models compared with the previous generation. This means models are suggesting stronger projected sea ice retreat in the Arctic. This is consistent with models being able to better capture the dramatic reductions in Arctic sea ice that have been observed in recent decades.

This work is revealing larger climate change at high northern latitudes, which has significant regional effects. It also affects temperature gradients, and therefore weather patterns across the hemisphere and globe.

Publication link: Colman RA, 2013. Surface albedo feedbacks from climate variability and change, *Journal of Geophysical Research*, 118, 1-8, DOI: 10.1002/jgrd.50230.

**SCIENCE** INFORMING POLICY AND DECISION MAKING

## Aerosols and climate

**Understanding how the climate will change and the rate at which it will change is essential for policy makers in determining emission reduction targets and adaptation strategies. Research under the ACCSP is helping policy makers to understand how aerosols are masking some of the climate change affects we would otherwise be experiencing.**

**Atmospheric aerosols are small particles suspended in the air that come from both natural sources (such as dust, bushfires and volcanoes) and human sources (such as industry and vehicles). Aerosols are masking some of the warming caused by greenhouse gases by reflecting incoming sunlight. They have also been found to influence wind, ocean and rainfall patterns including weakening of the subtropical jet, increasing rainfall over north-western Australia and changes to global ocean circulation.**

**Aerosols are short-lived in the atmosphere compared to greenhouse gases. It is predicted that aerosol concentrations will decrease significantly in the near term as global efforts are made to clean up industry and vehicle emissions. Distinguishing the climate effects of aerosols and greenhouse gases is therefore essential to developing accurate projections of future warming and rainfall patterns. ACCSP research is incorporating new understanding of aerosols into climate models to improve projections of Australia's future climate and enabling more informed decision making.**

Publication links:
Rotstayn LD, Jeffrey SJ, Collier MA, Dravitzki SM, Hirst AC, Syktus JI, Wong KK, 2012, Aerosol- and greenhouse gas-induced changes in summer rainfall and circulation in the Australasian region: a study using single-forcing climate simulations, *Atmospheric Chemistry and Physics*, 12, 6377–6404, DOI: 10.5194/acp-12-6377-2012.
Rotstayn LD, Collier MA, Chrastansky A, Jeffrey SJ, Luo J-J, 2013, Projected effects of declining aerosols in RCP4.5: Unmasking global warming? *Atmospheric Chemistry and Physics*, 13, 10883–10905, DOI: 10.5194/acp-13-10883-2013.
Rotstayn LD, Collier MA, Jeffrey SJ, Kidston J, Syktus JI, Wong KK, 2013, Anthropogenic effects on the subtropical jet in the Southern Hemisphere: aerosols versus long-lived greenhouse gases, *Environmental Research Letters*, 8, 014030, DOI: 10.1088/1748-9326/8/1/014030.
Cowan T, Cai W, 2013, The response of the large-scale ocean circulation to 20th century Asian and non-Asian aerosols, *Geophysical Research Letters*, 40, 2761–2767, DOI: 10.1002/grl.50587.

## ECOSYSTEM RESPONSE TO INCREASED CLIMATE VARIABILITY

The response of vegetation to climate variability is one of the largest uncertainties in projecting climate, carbon sequestration and water resources. This project is helping to quantify the carbon uptake and water use in Australian ecosystems by integrating flux data, remote sensing and modelling in time and space.

### Observational programme at Tumbarumba flux tower expanded

ACCSP researchers have continued leadership in OzFlux, and the Terrestrial Ecosystem Research Network (TERN) partnership, the Australian network of towers that continuously measures the exchanges (fluxes) of carbon dioxide, water vapour and energy between key terrestrial ecosystems and the atmosphere. The observational programme at the OzFlux flagship site at Tumbarumba, in south-east New South Wales, has been expanded, with tower-based remote sensing and relevant plant-specific spectral and biochemical data. Contributing the Australian data to the global network has allowed access to the global flux database (FluxNet) that contains data from over 650 sites.

### Terrestrial carbon uptake tracked

The ACCSP is part of a global effort to assess the skills of models in quantifying carbon uptake by the world's terrestrial ecosystems using remote sensing (MODIS data) and the FluxNet dataset as constraints. Results show that remotely sensed proxies and modelled gross primary productivity (carbon uptake) are able to capture significant spatial variation in mean annual productivity.

However, the ability of remotely sensed proxies and models to explain year-to-year variability in productivity was more limited. The models did reasonably well in moisture-limited biomes (including grasslands and shrublands) but failed to explain significant amounts of year-to-year variability in evergreen needleleaf forests, or deciduous broadleaf forests. Robust and repeatable characterisation of spatial and temporal variability in carbon budgets is critically important. The carbon cycle science community is increasingly relying on remotely sensing data. This analysis has highlighted the power of remote sensing-based models, but also provides bounds on the uncertainties associated with these models.

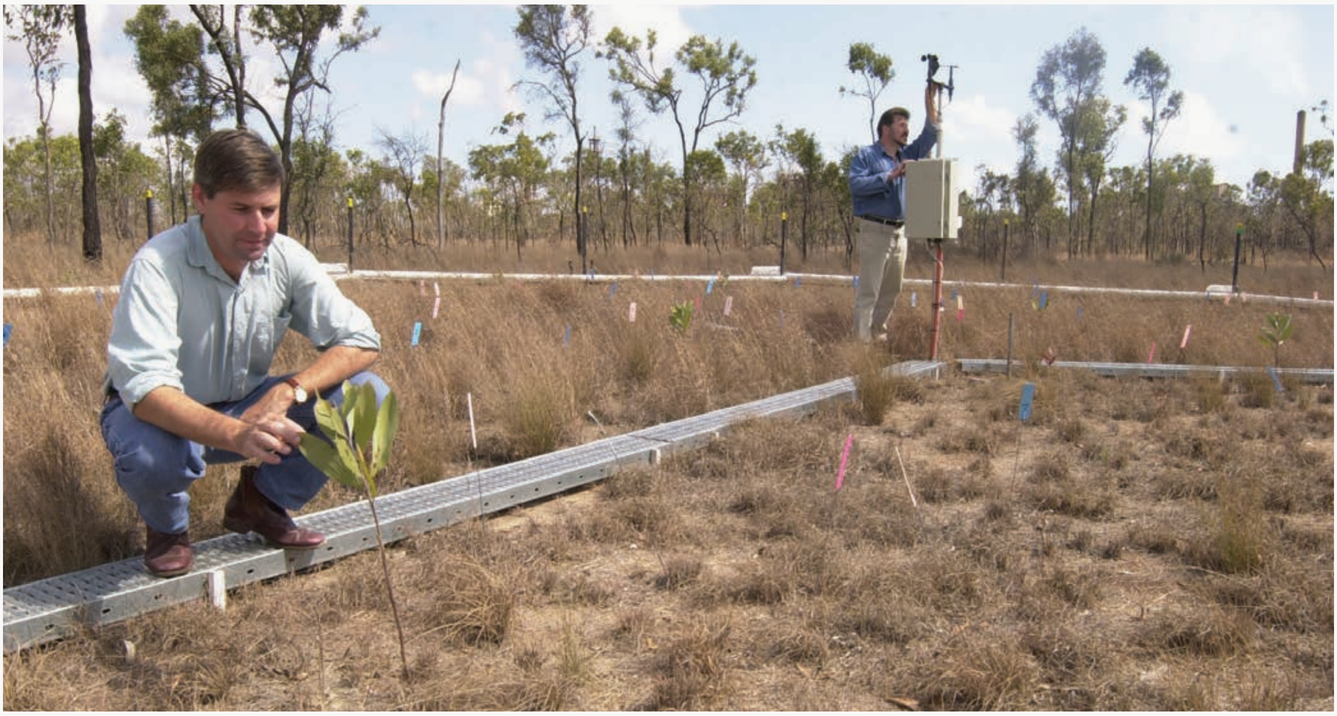
Greater model complexity and higher temporal resolution did not improve the ability of models to explain spatial or temporal variance in annual productivity.

The Tumbarumba flux station is part of a network of towers around Australia that continuously measures exchanges of carbon dioxide, water vapour and energy between the ecosystem and the atmosphere.

## OzFACE

The ACCSP supported research at the OzFACE facility in north-eastern Queensland, which was established to examine the impacts of carbon dioxide and climate change on tropical savannahs. This was the world's first field carbon dioxide experiment in the tropics.

A free-air carbon dioxide enrichment (FACE) system was set up to allow researchers to manipulate carbon dioxide levels over unenclosed plots of savannah. The system consisted of a series of rings that allowed researchers to deliver different concentrations of carbon dioxide to the plants growing within them. Monitoring the growth of vegetation under different treatments, researchers concluded that rising carbon dioxide levels are likely to favour the establishment and growth of woody plants, at the expense of grass production, in Australian savannahs.



# Oceans and coasts observations, processes and projections

The oceans have absorbed more than 90% of the extra heat stored by the Earth over the past 50 years. Sea level is rising and oceans are getting warmer and more acidic.

Changes in ocean salinity provide evidence that evaporation and rainfall patterns are changing as the Earth warms, including changes due to the intensification of the global water cycle.

25 YEARS OF CLIMATE SCIENCE

### Oceans and coasts observations, processes and projections

Prior to the ACCSP Australia did not carry out any research on the role of oceans in the climate. There were no consistent observation programmes in place, and there were no measurements south of Australia with sufficient resolution to determine how much water, heat and salt are carried from the Indian Ocean to the Pacific by the Antarctic Circumpolar Current.

Researchers have made substantial progress in understanding the behaviour of the oceans surrounding our continent and their role in the climate system. These advances have come from extensive observations from ships, moorings, drifting robotic floats and satellites, and from our ability to simulate the interactions between the atmosphere, ocean, sea ice and biogeochemistry.

Australia has also been a leader in international efforts to rigorously assess the extent to which sea level will change as the Earth warms.

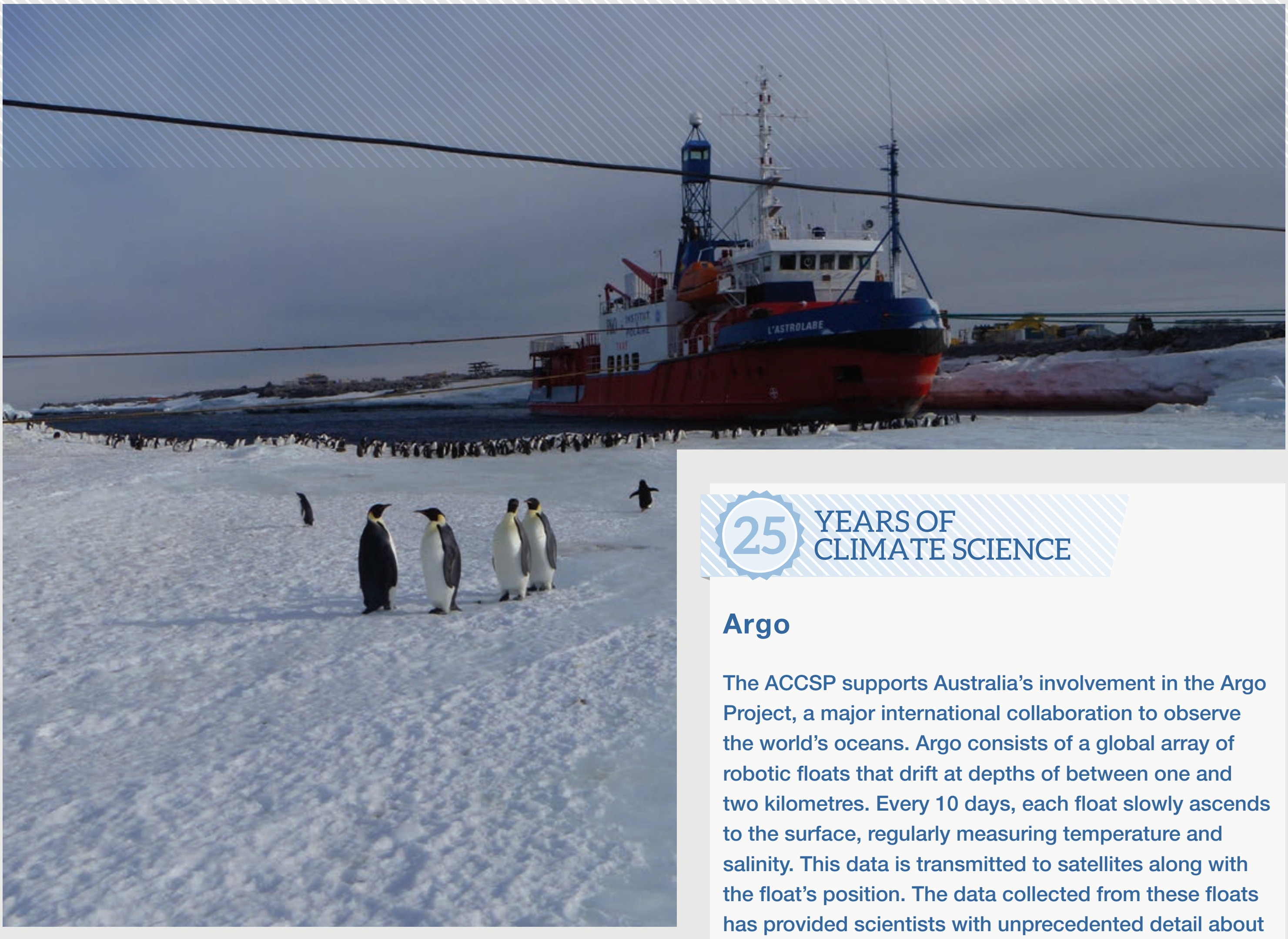
## SCIENCE HIGHLIGHTS

### OCEAN MONITORING TO UNDERSTAND OCEAN CONTROL OF THE GLOBAL AND AUSTRALIAN CLIMATE

The continued collection of climate-quality ocean data is fundamental to the detection, attribution and real-time tracking of the global climate system response to atmospheric greenhouse gas increases and sea-level rise. The ocean data are essential to validating and improving climate models. Through engagement and leadership in Global Climate Observing System (GCOS) international programs such as Argo, GOSHIP (repeat hydrography) and OceanSITEs, this project is delivering essential climate-quality ocean data streams across a range of scales from global to regional, from Antarctica to the equator.

#### Argo profiling floats deployed

Through the Integrated Marine Observing System (IMOS) partnerships, Australia has maintained its component of the global Argo array via the deployment of another 58 profiling floats. This deployment targets regions where other parts of the Global Ocean Observing System have been affected by piracy or poor deployment opportunities.



*L'Astrolabe*, docked near the Durmont Durville base in Antarctica.

By collaborating with the Royal Australian Navy, researchers deployed floats into the north-western Indian Ocean. Deployment in the far south Southern Ocean entailed partnering with French colleagues' Antarctic resupply vessel, *L'Astrolabe*. Argo data continue to be the primary tool for tracking ocean heat content globally, as well as underpinning seasonal and decadal climate forecasting efforts. Argo data have been central to documenting and relating the recent 'hiatus' in rising surface temperatures and the accompanying changes in the total heat content of the planet (which is dominated by the ocean). This total planetary heat content continues to rise.

Argo data can be accessed at **www.argo.net** or **www.imos.org.au**

### East Australia Current dataset compiled

The project also delivered the most definitive dataset describing Australia's major boundary current, the East Australia Current. This unprecedented 18-month record will be continued in future with renewed IMOS investment.

25 YEARS OF CLIMATE SCIENCE

## Argo

**The ACCSP supports Australia's involvement in the Argo Project, a major international collaboration to observe the world's oceans. Argo consists of a global array of robotic floats that drift at depths of between one and two kilometres. Every 10 days, each float slowly ascends to the surface, regularly measuring temperature and salinity. This data is transmitted to satellites along with the float's position. The data collected from these floats has provided scientists with unprecedented detail about temperature and salinity in the world's oceans, and also improves our ability to forecast climate and ocean conditions.**

**The first 10 Argo floats launched in 1999 were Australian. By July 2003, when the first Earth Observations summit was held, there were 815 floats delivering data. Today there are over 3600 floats in the global network. Australia is the second largest contributor to the global array (in terms of instrument numbers) after the United States. Argo has now collected over a million profiles of ocean temperature and salinity.**

**The International Argo Project home page is at www.argo.net**

## SCIENCE INFORMING POLICY AND DECISION MAKING

### Antarctic bottom water

**Polar regions are major drivers of global ocean circulation, which stores and distributes heat, oxygen, carbon and nutrients around the world.**

**Antarctica and the Southern Ocean are of great importance to Australia's national heritage. Due to our geography, Australia has a unique interest in Antarctic science. We are global leaders in this field and collaborate extensively with international partners to undertake research beyond our own capacity.**

**In Antarctica, cold, salty and dense water forms in distinct locations and sinks to the bottom of the ocean. This water is called Antarctic bottom water (AABW). While the importance of AABW to policy makers may not be immediately obvious, ACCSP research is helping us to understand just how critical it is to Australia's and the global climate.**

**Research under the ACCSP by Australian and US scientists has found significant changes to AABW. Measurements in 2012 found up to a 50% decrease in AABW compared to observations from the 1970s. Research has found that the decrease in AABW is largely driven by freshening of source waters related to changing rainfall patterns, ice melt and formation and ocean warming. This research provides evidence that oceans are responding rapidly to changes in the climate of polar regions. Changes to ocean currents will have significant ramifications on the climate system and could result in abrupt changes. Understanding the drivers of global ocean circulation is crucial to successfully modelling and projecting future changes in the global climate.**

Publication links:
Shimada K, Aoki S, Oshima KI, Rintoul SR, 2012, Influence of Ross Sea Bottom Water changes on the warming and freshening of the Antarctic Bottom Water in the Australian-Antarctic Basin, *Ocean Science*, 8, 419–432, DOI: 10.5194/os-8-419-2012.
Sloyan BM, Wijffels SE, Tilbrook B, Katsumata K, Murata A, Mcdonald A, 2013, Deep Ocean changes near the western boundary of the South Pacific Ocean. *Journal of Physical Oceanography*, 43, 2132–2141, DOI: 10.1175/JPO-D-12-0182.1.
Van Wijk EM, Rintoul SR, 2014, Freshening drives contraction of Antarctic Bottom Water in the Australian Antarctic Basin, *Geophysical Research Letters*, 41, DOI: 10.1002/2013GL058921.

## UNDERSTANDING OCEAN DRIVERS OF REGIONAL AND GLOBAL CLIMATE VARIABILITY AND CHANGE

Oceans store and transport vast amounts of heat and carbon dioxide, driving regional and global climate. They also act as a rain gauge: basin-scale changes in ocean salinity provide the strongest evidence to support the hypothesis that greenhouse warming leads to an enhancement of the global water cycle, with more precipitation in rainfall-dominated areas, and more evaporation in areas where evaporation dominates precipitation. Work in this project aims to observe and understand the circulation of Australia's oceans, from the equator to Antarctica, with a focus on the phenomena of greatest relevance to regional and global climate. A particular interest is the Southern Ocean, as changes in processes here affect climate, sea level, biological productivity and biogeochemical cycles on global scales.

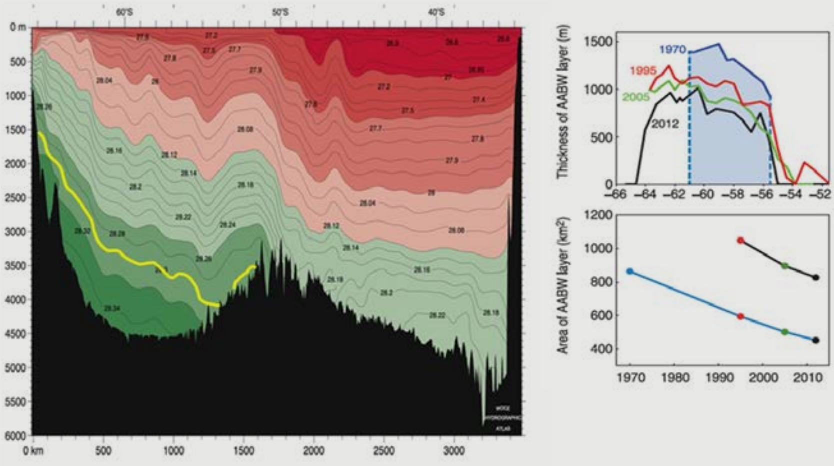
### Most complete assessment to date of changes in Antarctic bottom water undertaken

Dense Antarctic bottom water is formed around the margin of Antarctica and sinks to supply water and oxygen to the deepest layers of the ocean. Observations by the ACCSP and international colleagues had documented rapid warming and freshening of this dense water. However, the cause of the changes was not clear. The new study extended the record to 40 years and considered changes in oxygen as well as temperature and salinity. The research shows the volume of the dense bottom water layer has decreased by 50% since the early 1970s, but that oxygen concentrations have remained high. 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.

Publication link: Van Wijk EM, Rintoul SR, 2014, Freshening drives contraction of Antarctic bottom water in the Australian Antarctic Basin, *Geophysical Research Letters*, 41, DOI: 10.1002/2013GL058921.

### Deep ocean currents transmit high latitude climate variability to the Pacific

ACCSP researchers used repeated occupations (measurements) of two hydrographic sections in the south-west Pacific Basin from the 1990s to 2000s to track changes in Antarctic bottom water. The largest ocean property changes – warming, freshening, increase in total carbon, and decrease in oxygen – are found adjacent to the Basin's deep western boundary between 50°S and 20°S. Near the western boundary, the deep ocean warming and freshening has resulted in a decrease in the bottom density and thinning of the Antarctic bottom water layer. The overlying circumpolar deep water, incorporating the remnant salinity maximum of North Atlantic deep water, shows decadal freshening, increased total inorganic carbon, and decreased oxygen. Carbon and oxygen changes



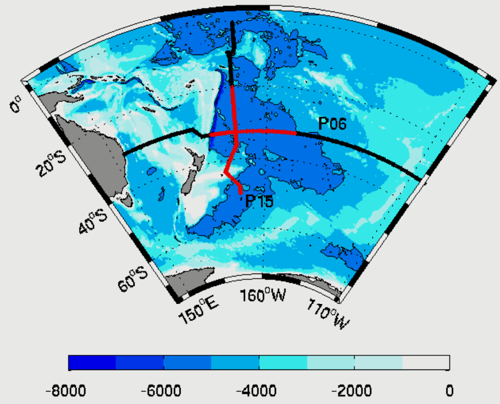




Figure 6: Changes in the properties of Antarctic bottom water at 115°E. The left panel shows the distribution of density on a transect between Australia (on the right) and Antarctica (on the left). The densest water is found in the deep ocean and closer to Antarctica. The yellow line highlights a density surface that marks the upper boundary of the Antarctic bottom water layer in 1995. Changes in thickness (top) and area (bottom) of the layer between 1970 and 2012 as a function of time are shown in the right hand panels. The bottom water layer has contracted in area by about 50% since 1970.

Figure 7: Location of repeat hydrographic sections (P6 and P15) occupied in the western Pacific Ocean between 1990 and 2009. Hydrographic stations used in this study are shown as red lines. The 5000 m depth contour (black curve) shows the region of the south-west Pacific Basin considered in this study. Bathymetry (shading) at 1000 m intervals.

cannot be solely explained by biological processes. The carbon and oxygen changes may be driven by physical processes such as circulation, interior mixing, and air-sea fluxes at the bottom water formation regions. The property changes are consistent with an increase in Pacific deep-water influence in the deep basin and a decrease in northward flow of Antarctic bottom water into the Pacific Basin.

The large property changes suggest that the deep western boundary provides a mechanism to rapidly transmit high latitude variability into the global deep ocean. While the south-west Pacific Basin is remote from Antarctic bottom water formation in the Ross Sea and Adélie Land, this study dispels the notion that the deep ocean is quiescent. High latitude climate variability is being directly transmitted into the deep south-west Pacific Basin and the global deep ocean through dynamic deep western boundary currents.

Publication link: Sloyan BM, Wijffels SE, Tilbrook B, Katsumata K, Murata A, Mcdonald A, 2013, Deep Ocean changes near the western boundary of the South Pacific Ocean. *Journal of Physical Oceanography*, 43, 2132–2141, DOI: 10.1175/JPO-D-12-0182.1.

## High latitude and tropical oceanic behaviour linked through ocean 'storms'

ACCSP researchers have developed a theory to explain the observed large-scale wavelike variability in the eddy-rich regions of the subtropical oceans.

Ocean 'storms' (i.e. within the ocean itself) serve as a mechanism to link high latitude oceanic behaviour to the tropics by providing an internal ocean pathway that communicates the wind-driven Southern Ocean decadal variability to the tropical oceans.

Much like atmospheric storms, vertical velocity gradients in the oceans generate eddies up to 100 km in diameter. Akin to mid-latitude atmospheric storm tracks, ocean 'storms' occur in regions where the trade winds and westerlies meet and at depths associated with subtropical mode water formation. These ocean 'storms' are evident in satellite observations and can be tracked in the South Pacific Ocean from the southern tip of Chile to Brisbane.

Understanding the nature of this linkage has far-reaching implications for understanding the oceans' control on internal climate variability.

## SCIENCE INFORMING POLICY AND DECISION MAKING

### Rainfall and water

**Understanding how rainfall and water availability may change in the future is critical to ensuring a reliable water supply for agriculture, industry and the environment.**

**Groundbreaking research carried out under the ACCSP found that the patterns of rainfall across the globe are already changing. In addition, these changes are happening faster than scientists expected. Scientists analysed thousands of ocean salinity measurements collected over the past 50 years to reveal shifts in the global rainfall and evaporation cycle. This research shows that on average, drier regions have become even drier, while wetter regions have become even wetter in response to global warming. The research also suggests that this pattern will continue as the climate warms further.**

**For Australia, this means that the northern parts may become wetter while southern parts are expected to become drier on average. Measurements of rainfall across the country support this finding. A change in fresh water availability in a warming climate poses risks to communities, industry, agriculture and ecosystems. Changes to the amount and location of rainfall will also have consequences for the frequency of extreme rainfall, flooding and drought – with corresponding impacts on infrastructure, water availability and food production. Managing Australia's fresh water in a changing climate is a key priority for adaptation policy.**

Publication link: Durack PJ, Wijffels SE, Matear RJ, 2012, Ocean salinities reveal strong global water cycle intensification during 1950 to 2000, *Science*, 336(6080), 455–458, DOI: 10.1126/science.1212222.

## ADDRESSING KEY UNCERTAINTIES IN REGIONAL AND GLOBAL SEA-LEVEL CHANGE, STORM SURGES AND WAVES

Many coastal communities in Australia and around the world are vulnerable to coastal inundation, erosion and infrastructure damage from sea-level rise and extreme weather events (storm surges and surface waves). Natural and managed systems are also highly vulnerable to increases in the frequency and scale of climate-driven extreme events such as storms and coastal inundation. Work in this project aims to update estimates of historical and projected sea-level change, extreme sea-level events and surface waves.

### Sea levels continue to rise

Sea levels continue to rise, both globally and around Australia. Comparison of sea levels measured by satellite altimeter data and tide gauges has revealed small time-dependent differences in the satellite observations. Correcting the satellite data for these time dependent differences results in an almost linear increase in sea level since 1993 (rather than the rate decreasing) and a reduction in the average rate from 1993 to 2013 by about 20% compared with earlier estimates. Analysis of models and their comparison with observations indicates the larger rate of sea-level rise since 1993 is largely a result of changes in natural forcing of climate and ongoing anthropogenic greenhouse gas emissions.

## Wind changes exacerbate extreme sea levels and coastal currents

Changes to extreme sea levels and coastal currents are likely to be greatest where large changes in wind speed and direction are projected to occur. Potential future impacts have been investigated in two locations where such changes are projected. Nearshore currents along the Ninety Mile Beach in south-eastern Australia are influenced by both wave and wind climate and have been shown to be influenced by the El Niño–Southern Oscillation such that El Niño conditions lead to more eastward currents, and La Niña to more westward currents. Future climate conditions will induce more westward currents in summer with possible implications for sediment transport. In the Gulf of Carpentaria, relatively large increases in extreme sea levels are projected in climate models that show an eastward movement of the monsoon shear line during summer.

Observations from tide gauges and satellites show that the rate of sea-level rise since 1993 is substantially higher than the average over the past century.

## Wind-wave climate model extended

The CSIRO global dynamical CMIP5-derived wind-wave climate model ensemble was increased to eight members. This now provides a minimum ensemble size to investigate uncertainty in wave climate studies associated with the physical response from alternative model formulations. The CSIRO ensemble is a primary contributor to the next, second, phase of the international coordinated ocean wave climate project. A project review meeting, held in November 2013, facilitated community collaboration, and clarified objectives, for the next inter-comparison project. The international project seeks to quantify the dominant sources of variance in international wave climate projections.

# Modes of climate variability and change

## The ACCSP seeks to determine the influence of natural climate variability and the influence of climate change on the Australian climate.

Oceans surrounding the Australian continent play an important role in influencing rainfall variability. The El Niño–Southern Oscillation, the Indian Ocean Dipole, and the Southern Annular Mode are major drivers of climate variability over Australia. El Niño conditions typically lead to droughts and bushfires in eastern Australia, whereas La Niña conditions often result in floods in eastern Australia.

Indian Ocean and Southern Ocean temperatures, as indicated by the Indian Ocean Dipole and the Southern Annular Mode, also play a role in determining the severity of droughts and floods.

ACCSP research helps explain these drivers of climate in the Australian region. This knowledge is fundamental for understanding their impact, assessing how they will respond to changing greenhouse gas concentrations, and determining likely rainfall in a changing climate.

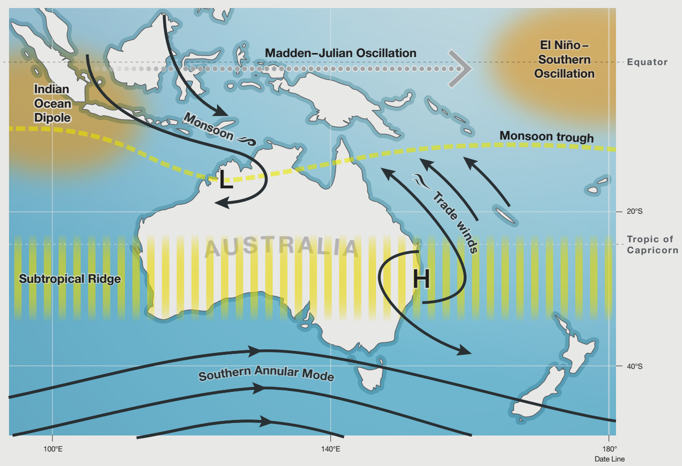



Figure 8: Drivers of climate variability in Australia include the Indian Ocean Dipole, El Niño–Southern Oscillation, and the Southern Annular Mode. Other drivers depicted are the Madden-Julian Oscillation, the monsoon, the Subtropical Ridge and the trade winds (Source: BoM)

## SCIENCE HIGHLIGHTS

### THE EL NIÑO–SOUTHERN OSCILLATION AND ITS IMPACTS ON AUSTRALASIA IN THE 21ST CENTURY

The El Niño–Southern Oscillation and fluctuations in the Walker circulation cause large changes in rainfall, severe weather, streamflow and crop production. This project examines the El Niño–Southern Oscillation and the way in which its impacts will change in response to global warming.

#### Global warming alters the impact of El Niño on rainfall

Using new analysis techniques and numerous global climate models, ACCSP researchers have found that the impact of El Niño on tropical rainfall variability is likely to intensify in response to global warming.

By the mid- to late 21st century, the projected changes include an intensification of both El-Niño-driven drying in the western Pacific Ocean (with associated impact on Australia) and rainfall increases in the central and eastern equatorial Pacific.

The discovery of robust changes in El Niño-driven rainfall anomalies was surprising because there is little agreement among the latest climate models on projected changes in El Niño-driven sea-surface temperature changes. Prior to this study climate scientists assumed that the future of the El Niño–Southern Oscillation could be understood only by first understanding what will happen to sea-surface temperature variability. This discovery shows that this is not the case, opening up an important avenue for future research.

Publication link: Power SB, Delage F, Chung C, Kociuba G, Keay K, 2013, Robust 21st century projections of El Niño and associated precipitation variability, *Nature*, 502, 541–545, DOI: 10.1038/nature12580.


The impact of global warming on El Niño–Southern Oscillation rainfall anomalies depends crucially on the phase. The impact of global warming is different for La Niña and El Niño events, and it is different for small and weak El Niño events.

Publication links:
Chung CTY, Power SB, 2014, Precipitation response to La Niña and global warming in the Indo-Pacific. *Climate Dynamics*, DOI: 10.1007/s00382-014-2105-9.
Chung CTY, Power SB, Arblaster JM, Rashid HA, Roff GL, 2013, Nonlinear precipitation response to El Niño and global warming in the Indo-Pacific, *Climate Dynamics*, 42, 1837-1856, DOI: 10.1007/s00382-013-1892-8.

The Walker circulation is one of the world's largest and most important wind systems centred in the tropical Pacific. It comprises the equatorial easterly trade winds near the surface of the ocean, rising air in the west to the north of Australia, westerly winds in the upper atmosphere, and subsiding air in the east.

Researchers discovered that the Walker circulation will move eastwards in response to global warming, which may alter the impact that El Niño has on some countries.

Publication link: Bayr T, Dommenget D, Martin T, Power SB, 2014, The eastward shift of the Walker Circulation in response to global warming and its relationship with ENSO, *Climate Dynamics*, 10.1007/s00382-014-2091-y.

25 YEARS OF CLIMATE SCIENCE

## Modes of climate variability and change

**Research undertaken through the ACCSP has improved our understanding of natural climate variability, and how this might change in the future. An important aspect of this continuing work is determining how the global water cycle will change, and the impact of these changes on Australian rainfall. Researchers are also unravelling how much of the change in our climate can be attributed to natural variability and how much is due to greenhouse gases.**

**Australian scientists have played major roles in understanding the nature of the El Niño–Southern Oscillation, quantifying its impact on the climate, and estimating how its impact on rainfall will change in the future.**

**At the outset of the ACCSP we did not know about the Indian Ocean Dipole; now we know in its positive phase it brings drier conditions to south-eastern Australia from winter through to spring.**

## RESPONSE OF INDO-PACIFIC CLIMATE VARIABILITY TO GREENHOUSE WARMING AND THE IMPACT ON AUSTRALIA CLIMATE

Australia's climate is strongly influenced by modes of variability in the Indo-Pacific region, particularly, El Niño–Southern Oscillation and the Indian Ocean Dipole. Intense El Niño events in 1982–83 and 1997–98 led to extreme tropical cyclones, drought, floods and other extreme weather events worldwide. This project aims to project changes in the frequency of such extreme events.

### Frequency of extreme El Niño events to double

Extreme El Niño events are characterised by a pronounced eastward extension of the west Pacific warm pool and development of an atmospheric convective zone, and hence a huge rainfall increase in the usually cold and dry equatorial eastern Pacific. Such events severely disrupt global weather patterns, affecting ecosystems and agriculture and causing tropical cyclones, drought, bushfires, floods and other extreme weather events worldwide.

Modelling studies reveal a future doubling in the occurrence of extreme El Niño episodes caused by increased surface warming of the eastern equatorial Pacific Ocean. This area of the ocean warms faster than the surrounding waters, reducing sea-surface temperature gradients. This results in the atmospheric convection zone shifts associated with these extreme episodes. The findings are in contrast to previous studies that found no consensus on El Niño change. Unfortunately, the increased occurrence of these episodes is likely to lead to more frequent extreme weather events.

Publication link: Cai W, Borlace S, Lengaigne M, van Rensch P, Collins M, Vecchi G, Timmermann A, Santoso A, McPhaden MJ, Wu L, England MH, Wang G, Guilyardi E, Jin FF, 2013, Increasing frequency of extreme El Niño events due to greenhouse warming, *Nature Climate Change*, 4, 111–116, DOI: 10.1038/nclimate2100.

### Frequency of extreme Indian Ocean Dipole events to increase

The frequency of extreme climate and weather events, such as flooding and drought around the Indian Ocean, is expected to also increase over the 21st century in response to high greenhouse gas emissions.

Researchers have assessed the effects of future 'business-as-usual' increases in greenhouse emissions on the frequency of extreme positive Indian Ocean Dipole events. The Indian Ocean Dipole is a cycle in which the region of peak sea-surface temperature swings back and forth between the eastern and western Indian Ocean. During the positive phase of this cycle, rainfall increases in the west due to warmer waters and decreases in the east where the water is cooler.

The research shows that global warming can alter the state of this cycle and may triple the frequency of extreme positive Indian Ocean Dipole events during this century. Extreme positive events have large impacts on the weather around the edge of the Indian Ocean. During an extreme positive event in 1997, for example, extensive flooding occurred in East Africa while Indonesia suffered severe droughts and wildfires.

Publication links:
Cai W, Santoso A, Wang G, Weller E, Wu L, Ashok K, Masumoto Y, Yamagata T, 2014, Increased frequency of extreme Indian Ocean Dipole events due to greenhouse warming, *Nature*, 510, 254–258. DOI: 10.1038/nature13327.
Cai W,.Zheng XT, Weller E, Collins M, Cowan T, Lengaigne M, Yu W, Yamagata T, 2013, The impact of greenhouse warming on the Indian Ocean Dipole. *Nature Geoscience*, 6, 999–1007. DOI: 10.1038/ngeo2009.

## ATTRIBUTION AND PROJECTION OF CLIMATIC EXTREMES AND CHANGE

Separating the climate change signal from natural variations (the climate noise) allows for the attribution of changes in Australian regional climate variations and extremes. This project uses observations to investigate interactions in the current climate, and climate model simulations to analyse changes in future climates.

### Human activity is changing the weather

A new method that separates the climate 'signal' from the climate 'noise' (i.e. variability) in the observed relationship between Australian rainfall and large-scale general circulation drivers has been formulated. The analysis provides a unified framework within which to understand the important relationships between the rainfall and circulation drivers. The method has been applied to a multi-model ensemble of 11 models that best simulate the observed large-scale circulation drivers. The research finds that the prolonged trends in rainfall over south-west Western Australia in winter and the monsoonal north-west region of Australia in summer are likely the result of external influences such as changes in greenhouse gases, ozone and aerosols. The trends are consistent with observations of the expansion of the tropics. Similar trends, due to external influences, are projected to continue and intensify under projected climate change scenarios. The robustness of these findings is under active investigation.

An innovative analysis method has been used to find the climate change signal in the year-to-year variations of the southern hemisphere circulation. An ensemble of climate models has been used to separate the climate change signal, attributable to changes in anthropogenic greenhouse gases, from the climate noise, due to natural variability. The climate change signal in the 20th century closely resembles the observed changes in the southern hemisphere circulation. In the 21st century, projected changes in the year-to-year variations of atmospheric circulation were found to be dominated by the climate change signal, and the magnitude of these changes increases with increasing greenhouse gas scenarios.

A new methodology has been formulated that separates the 'noise' and 'signal' components in decadal variations. The method will allow scientists to determine the upper limit on decadal predictability in important climate fields and thereby assess the prospect for decadal prediction.

New analysis has examined the interaction between weather systems and the extreme rainfall events in south-east Queensland, New South Wales and Victoria in January 2011. Observational analysis of the conditions during the extreme flooding near Brisbane on 11 January 2011 showed that enhanced convection over northern Australia was caused by the confluence of rapidly developing tropical disturbances (Kelvin waves) with slower moving regions of enhanced convective activity (the Madden-Julian Oscillation). This analysis is supported by theoretical analysis showing the rapid growth of Kelvin wave and monsoonal modes in January 2011 were suitable for the development of such tropical disturbances. The theoretical analysis also shows the conditions were similar during the last La Niña flooding events of similar proportions in January 1974.

New simulations have shown how changes in the tropical circulation have affected southern hemisphere extra-tropical regions. A climate model driven by observed values of sea-surface temperature and historical time-evolving carbon dioxide concentrations has reproduced the important interdecadal changes in jet streams, temperature, Hadley circulation, sea-surface temperature and precipitation. These simulations reproduce the reduction in zonal wind near 30°S and corresponding warming south of 30°S, leading to a reduced north-south temperature gradient in the atmosphere in the eastern hemisphere. This is driven by a weakening in the north-south tropical circulation (the Hadley Cell), and as a consequence high pressure systems develop further to the south. This in turn affects rainfall, most notably the reduction in winter rainfall over south-west Western Australia.

## VARIABILITY AND DRIVERS OF AUSTRALIAN CLIMATE OVER THE LAST 1000 YEARS IN COUPLED MODEL SIMULATIONS

Observations of Australian climate variability are limited to around 100 years of direct measurements – not a long enough time period to capture fully the range of natural variability, including decadal and longer changes. This project uses climate models and palaeoclimatic reconstructions to examine rainfall variability over the last 1000 years, permitting identification of the range of natural conditions that have occurred in the past, including the frequency of extended droughts and floods related to El Niño and La Niña.

### The Australian impacts of El Niño/La Niña events vary over time

The variability of east Australian spring rainfall is influenced by the occurrence of El Niño and La Niña events. However, the relationship is not always the same through time. For example, during the 1930s, there was a breakdown in the link between east Australian rainfall and the presence of an El Niño or La Niña event. Climate records are not long enough to determine whether the situation in the 1930s was an anomaly or a regular occurrence.

A 1000-year simulation with a well-performing climate model showed that while most of the time the relationship is strong, it weakens about once every century and at times becomes negligible, with correlations close to zero.

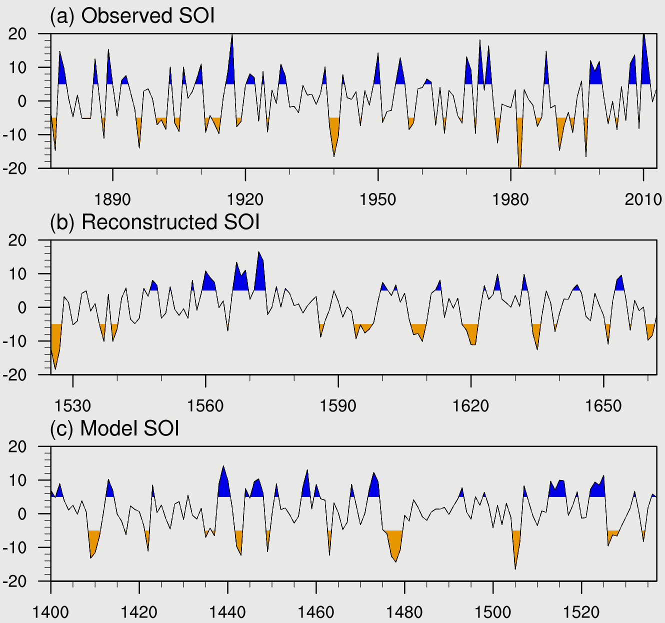



Figure 9: Time series of El Niño–Southern Oscillation for (a) observations, (b) palaeoclimate reconstruction and (c) MPI model. El Niños are in orange, La Niñas in blue.

The timing of the occurrence of each El Niño and La Niña event reveals a great deal about how the phenomena varies. Figure 9 (a) shows the observed record, with La Niña events shaded blue and El Niño events shaded orange. Researchers considered extreme climate events during the observed record and found only a few extensive eastern Australian flooding events. All of these were associated with extended La Niña events (1970s and 2010s). A 138-year analysis from a multi-proxy El Niño–Southern Oscillation reconstruction using corals and tree-rings shows an extensive period of persistent La Niña conditions, while simulations of the same length from a climate model reveal epochs with up to five of these sorts of events, and others with no major La Niña events.

There are mathematical tools (spectral analysis) that can help summarise the timescale on which the El Niño–Southern Oscillation varies. The El Niño–Southern Oscillation usually occurs on a timescale of three to eight years. In recent years, longer timescales have also become important, associated with a trend towards La Niña conditions. The palaeo-proxy reconstructions suggest that similar La Niña conditions have occurred in the past. Climate models also show epochs when the dominant timescale of the El Niño–Southern Oscillation shifts away from the usual three to eight years and becomes much longer, with one phase persisting for a number of years.

## VARIABILITY AND DYNAMICS OF THE NINGALOO NIÑO

In early 2011, ocean temperatures along the west coast of Australia were the highest ever recorded. This resulted in the first recorded coral-bleaching event in the pristine World Heritage Ningaloo Reef and massive die-off of economically important fish species off the west coast. This unprecedented marine heat wave has been termed the Ningaloo Niño. This project is providing historical context of this extreme event from both instrumental and palaeoclimate records, and identifying key seasonal mechanisms for initiating and strengthening the Ningaloo Niño, so that similar events in the future can be better predicted.

### Most Ningaloo Niño events occur in strong La Niña years

ACCSP researchers used the Bureau of Meteorology reanalysis product* to understand the role of air-sea coupling in the south-east Indian Ocean in initiating and amplifying the Ningaloo Niño event over the past 40 years. They found that the most extreme Ningaloo Niño marine heat wave events occur during strong La Niña years. However, most of the Ningaloo Niño events have their precursors in the south-east Indian Ocean, due to air sea interaction associated with a wind-evaporation-sea-surface-temperature feedback mechanism prior to the Australian summer monsoon. This feedback mechanism can drive clockwise wind anomaly patterns that accelerate the Leeuwin Current and its associated heat transport, causing the extreme

Collecting corals for palaeoclimate studies

warm temperature anomalies. The feedback operates until December when the mean winds reverse at the onset to the Australian monsoon and the growth of the positive sea-surface temperature anomalies is no longer supported. This research is an important contribution to understanding Indian Ocean climate variability.

Climate models are still unable to capture this important air-sea coupling mechanism in the south-east Indian Ocean, which is demonstrated in the poor skills of the climate models in simulating and predicting the extreme Ningaloo Niño event. This project has highlighted the importance of capturing this mechanism in order for models to be useful for coastal ecosystems management planning.

*POAMA (Predictive Ocean Atmosphere Model for Australia) Ensemble Ocean Data Assimilation System (PEODAS) for the period 1960–2011

## 2011 Ningaloo Niño unprecedented in 200 years

Researchers investigating the decadal variations of the Leeuwin Current strength from 1795 to 2010, based on coral proxy records at Abrolhos and paleo-reconstruction of El Niño–Southern Oscillation indices, found that the 2011 Ningaloo Niño marine heat wave event was unprecedented in the past 200 years. The interplay between Pacific La Niña induced zonal wind anomalies in the western Pacific and the meridional (north-south) wind anomalies off the west coast of Australia have driven the ubiquitous year-to-year and decadal variations of the Leeuwin Current over the past 200 years. The Ningaloo Niño appears to be rather sensitive to the zonal sea-surface temperature gradient in the Western Pacific, which had strong decadal variations in the early to mid-1800s, and in recent decades.

Publication link: Zinke J, Rountrey A, Feng M, Xie SP, Dissard D, Rankenburg K, Lough J, McCulloch MT, 2014, Corals record long-term Leeuwin Current variability including Ningaloo Niño/Niña since 1795, *Nature Communications*, 5, 3607, DOI: 10.1038/ncomms4607.

# Earth systems modelling and data integration

**Climate models are based on established laws of physics and use mathematical equations to represent physical processes of the climate system and their interactions. Validated against observations, they have demonstrated an ability to reproduce the observed climate. Earth system models encompass modelling of the atmosphere, land and ocean and include representation of the cryosphere, the hydrosphere and carbon flows. They are essential tools for studying climate.**

The Australian Community Climate Earth-System Simulator (ACCESS) is a sophisticated Earth system model that operates on the nation's most powerful supercomputers. A major collaborative undertaking, ACCESS brings together the climate observations, research and modelling capability of the Bureau of Meteorology, CSIRO, Australian universities and international researchers. The result is a climate model designed for Australian needs.

## SCIENCE HIGHLIGHTS

### ACCESS COUPLED CLIMATE MODEL DEVELOPMENT

The next generation of ACCESS, ACCESS-CM2, will feature a new atmospheric code that allows improved representation of surface and troposphere-stratosphere exchanges of wind, heat, moisture and other variables. Improved surface exchanges (with the ocean) will allow improved simulation of the El Niño–Southern Oscillation, the Indian Ocean Dipole and Pacific multi-decadal variability. Improved troposphere-stratosphere exchanges will allow improved simulation of trends in the subtropical high-pressure belt and the Southern Annular Mode. These improvements will allow the model to be used with greater confidence for applications in climate variability and climate change. In this project researchers are working on these improvements to develop ACCESS as a world-class coupled climate model, use it in international benchmarking and in support of IPCC assessments, and facilitate its broader use for climate applications.

#### Development of the next generation ACCESS underway

The initial ACCESS-CM2 coupled model has been successfully configured and several decadal-length test simulations performed. This first version of the ACCESS-CM2 includes atmospheric, land surface, oceanic and sea ice components. The atmospheric component is substantially upgraded from that in previous versions of the model, and includes significant improvements to representation of physical processes and much higher vertical resolution (85 levels compared with 38 in previous versions). Decadal-length test simulations show good technical functionality.

A 30-year simulation with the new atmospheric model to be used in ACCESS-CM2 has been conducted, and the results examined to assess model skill in representation of the simulated mean climate and climate variability.

#### New model evaluation methodology implemented

A powerful new methodology aiding model evaluation and development has been implemented. This methodology involves running climate models in weather forecasting mode, according to an international experimental protocol known as transpose-AMIP (T-AMIP). This method has benefit because many model biases (differences between model and observed climate features) affecting lengthy climate model simulations appear quite quickly (within days) after the start of the simulation. By starting the model from a realistic initial state, biases directly resulting from limitations in parameterisations (physical representations) of quickly adjusting processes such as clouds may be ascertained, while the more slowly adjusting circulation remains fairly realistic. Such precise analysis is not possible in a long climate simulation, where cloud biases are complicated by the presence of circulation biases. Further, the shortness of the simulations makes testing multiple model parameter values much more efficient.

25 YEARS OF CLIMATE SCIENCE

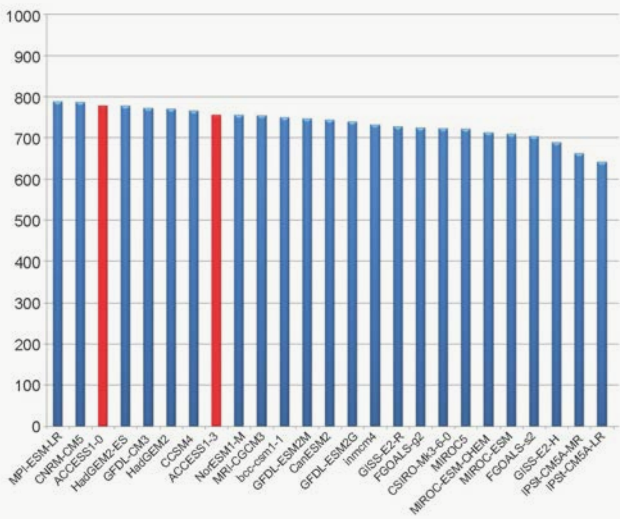
## Earth systems modelling and data integration

**From its very beginning, the ACCSP has supported the collection of climate data, investigation of climate processes and the development of improved climate models for Australia.**

**Prior to the ACCSP, Australia had only an elementary global climate change modelling capacity. The ACCSP has enabled Australian climate models to reach international standards.**

**The culmination of the years of model improvement supported by the ACCSP has been development of the Australian Community Climate Earth-System Simulator (ACCESS), our national climate model.**

**ACCESS delivers climate change simulations to the Australian and international science community. International model comparisons rate ACCESS highly, particularly for its capacity to simulate Australian climate. The contributions made via ACCESS to international engagement are recouped many times over through the wealth of tools, data and knowledge obtained for the national benefit.**




Average skill scores for a range of climate models over Australia, simulating the pattern and seasonal variation of surface air temperature, precipitation and sea-level pressure. A higher score means better performance. ACCESS simulations (red bars) rank in the upper level of models internationally.

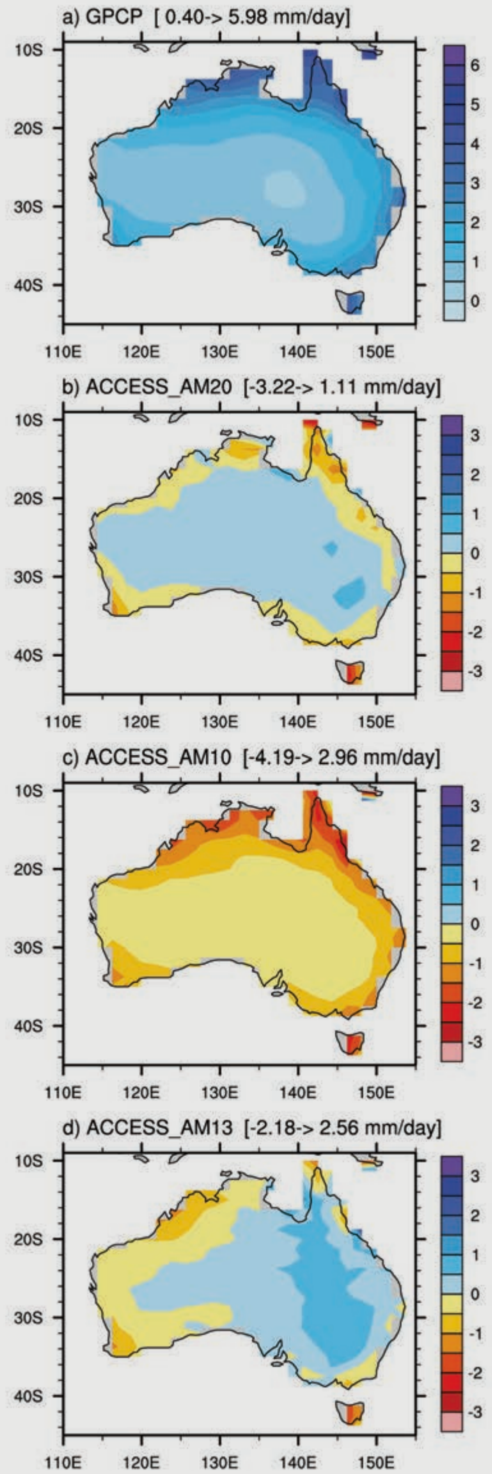



Figure 10: (a) Annual mean of the Australian rainfall from observations (dataset: GPCP) over the period 1982–2008, and the departures from this mean simulated by atmospheric components of (b) ACCESS-CM2, (c) ACCESS-1.0 and (d) ACCESS-1.3. Note the change in colour bar between the mean field (a) and the departures (b-d). Overall, the new atmospheric model shows smaller simulation errors in Australian rainfall than the existing atmospheric model versions. In particular, the large dry biases in northern Australia in ACCESS-1.0 and the widespread wet bias in inland eastern Australia in ACCESS-1.3 are reduced.

### Warm biases over the Southern Ocean addressed

Warm biases over the Southern Ocean are a concern for most climate models. To address this, modellers have evaluated cloud properties over the Southern Ocean from ACCESS simulations using satellite observations. This evaluation demonstrates that the simulated clouds allow too much solar radiation to reach the surface, because they have too little liquid water in the clouds. Improved treatments of the associated model parameterisation schemes have improved the liquid water partitioning and reduced the radiative warming bias at the surface.

### New ACCESS user interface developed

Enhanced and integrated ACCESS modelling infrastructure is being developed in conjunction with the National eResearch Collaboration Tools and Resources (NeCTAR) project. This work is improving ease of use of the ACCESS model, with improved user interfaces, support for easier sharing of code, data and experiments, and improved reproducibility of experiments. A new user interface for the coupled model has been completed. The ACCSP has conducted a training course on the use of the new ACCESS infrastructure including the coupled model user interface.

### ACCESS prepared to serve as the basis of an Earth system model

A revision of the CMIP5 ACCESS-1.3 coupled model, ACCESS-1.4, has been prepared to serve as the basis for the first ACCESS Earth system model, ACCESS-ESM1. It features an updated version of the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model, which has been developed over the decades by ACCSP researchers, and a more computationally efficient ocean-atmosphere flux coupler. The use of the new coupler and other technical changes have led to a major improvement in the computational efficiency of the coupled model, which now runs more than twice as fast. The improved speed facilitates a broader range of model applications.

## ACCESS CARBON CYCLE MODELLING

The land and oceans absorb more than half the anthropogenic carbon emissions, so the land and ocean carbon cycles have the potential to significantly influence future atmospheric carbon dioxide concentrations and climate. Further, the land and ocean carbon cycles provide critical insight into biological processes that sustain people and marine and terrestrial ecosystems. Including the carbon cycle in ACCESS provides an important avenue for investigating the future response of land and ocean ecosystems to climate change and ocean acidification. This project entails incorporating the land and ocean carbon cycles into ACCESS to render it an Earth system model.

### Carbon cycle changes modelled with ACCESS

Land and ocean carbon cycle modules have been incorporated into ACCESS and simulations performed of the past and future. Simulated past ocean uptake and storage of carbon was consistent with observations.

Researchers have investigated the impact of carbon-climate feedbacks on future atmospheric carbon dioxide concentrations using the land and ocean carbon modules incorporated into a simple climate model.

The model simulates higher atmospheric carbon dioxide concentrations and greater ocean acidification impacts than estimates based solely on prescribed concentrations associated with representative concentration pathways (RCPs). Hence, projections of the impact of ocean acidification need to consider how changes in the land carbon uptake could modify the rate of ocean acidification.

Figure 11 illustrates how rising atmospheric carbon dioxide impacts the carbon chemistry of the surface ocean. The white line (enclosing the blue area) denotes where aragonite (a form of calcium carbonate) becomes chemically unstable and starts to dissolve. The purple lines (aragonite saturation state of 3) enclose regions suitable for coral reefs. As one goes to higher future atmospheric carbon dioxide concentrations (through the different scenarios on each row), the white lines move towards the equator and the regions corrosive to aragonite expand. Suitable regions for coral reefs shrink, and in some cases (RCP6 and RCP8.5) disappear by 2100. Using the emissions (ECPs, in the right column) instead of concentrations (RCPs, in the left column) causes an expansion of aragonite dissolution areas and shrinks the area suitable for coral reefs.

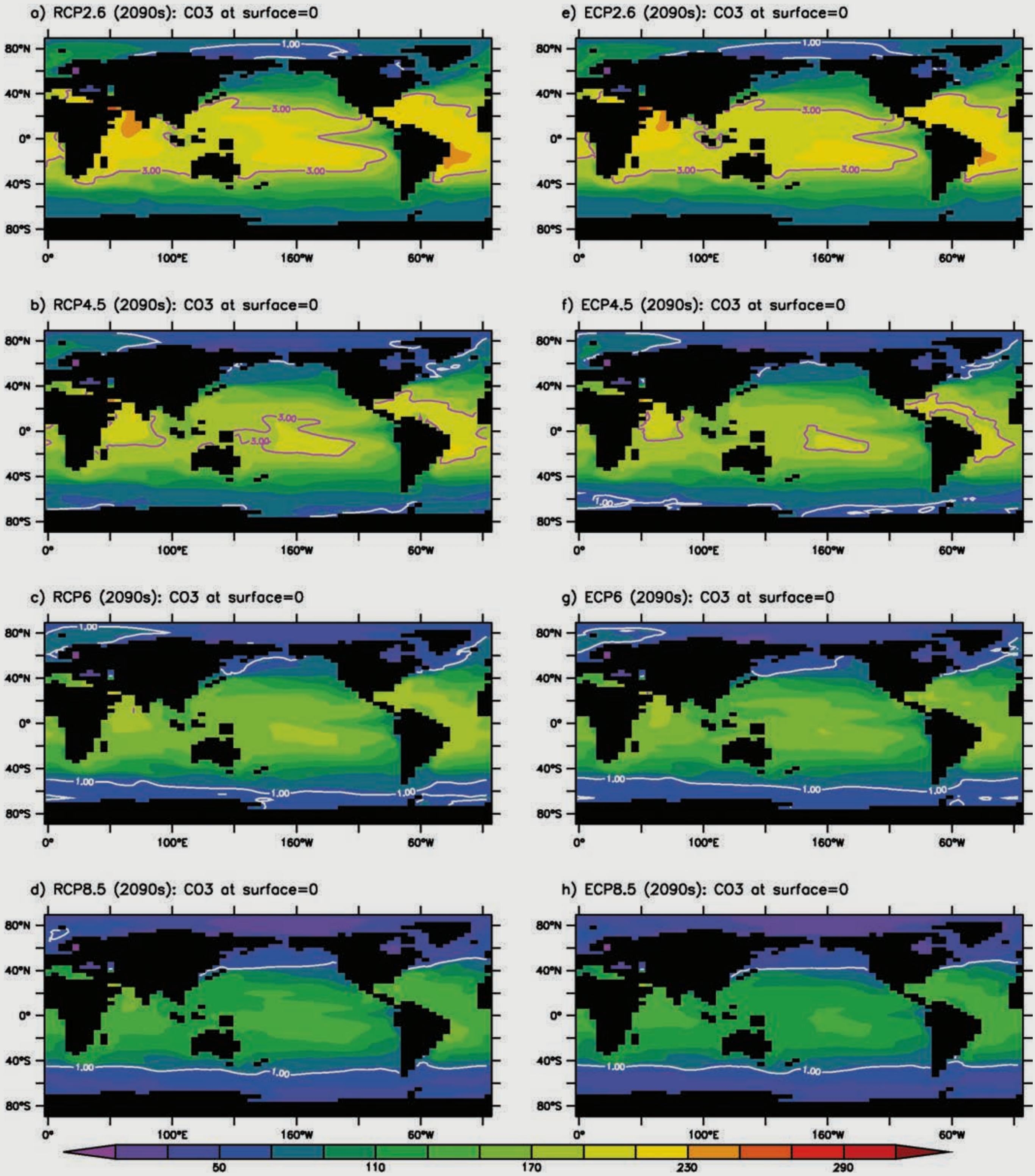



Figure 11: Surface ocean carbon ion concentration for the decade of the 2090s for prescribed representative concentration pathways (RCPs): (a) RCP2.6, (b) RCP4.5, (c) RCP6, and (d) RCP8.5; the same scenarios but where we prescribe the emissions and let our carbon modules determine the atmospheric carbon dioxide concentrations (ECPs): (e) ECP2.6, (f) ECP4.5, (g) ECP6 and (h) ECP8.5. The white line shows where the aragonite saturation state is 1; the blue area enclosed by these lines would be corrosive to aragonite. The purple line shows an aragonite saturation state of 3; the regions enclosed by these lines would be suitable for coral reefs.

## DEVELOPMENT OF ACCESS FOR AEROSOL AND CHEMISTRY

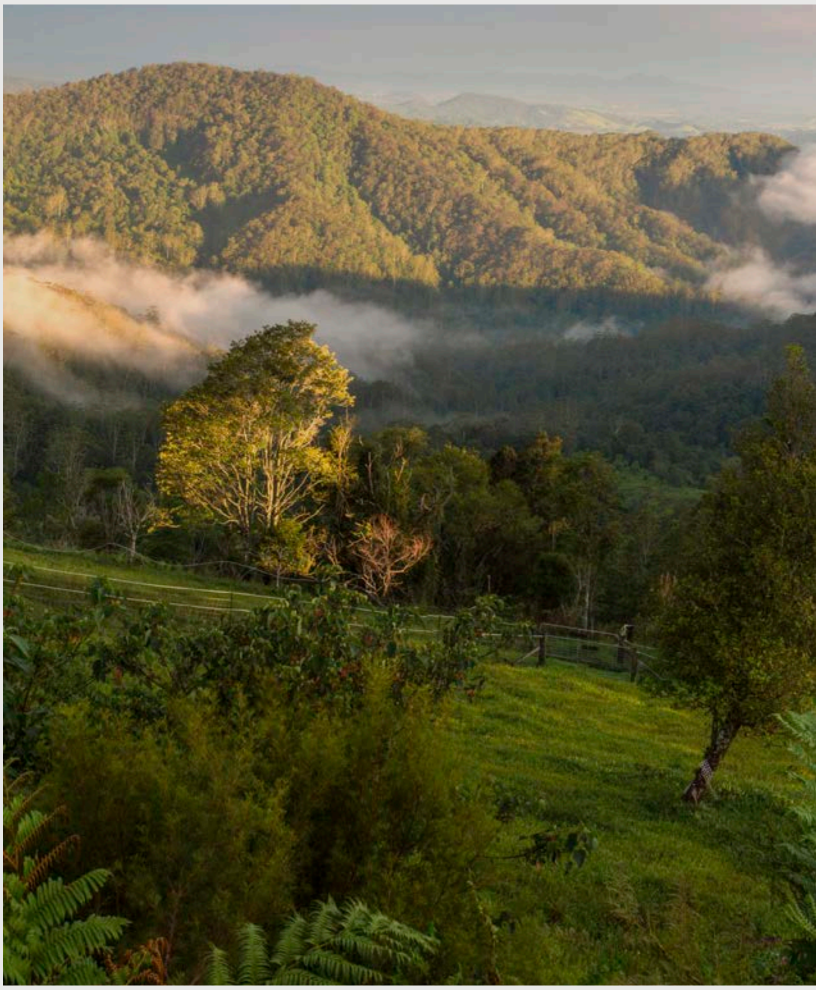
Changes in atmospheric concentrations of aerosols and greenhouse gases are important forcing mechanisms that produce changes in global climate. For this reason it is important to improve the representation in models of atmospheric chemistry of reactive gases, such as methane and ozone, and the treatment of aerosols and their interactions in the atmosphere. This project is developing the aerosol and chemistry components of ACCESS, so that it can perform as a world-class Earth system model for climate applications.

### Improved dust and tropospheric chemistry modelling

During the development of ACCESS-1.4, dust-uplift settings were determined in order to provide and maintain realistic global dust amounts. Over Australia, the simulated dust emissions peaked over the north-west rather than over the Lake Eyre basin as they do in observations. A preferential source term was incorporated, leading to an improved distribution of dust uplift.

Researchers made significant enhancements to the tropospheric chemistry component of ACCESS. There was incorporation of annually-varying chemical emissions, work accounting for production of oxides of nitrogen due to lightning, and better initialisation of methane.

Increases in carbon monoxide can indirectly produce increases in tropospheric ozone concentrations, enhancing global warming. Scientists have compared model estimates of carbon monoxide with measurements from Mawson, Antarctica. The model reproduces the seasonal variation well, but overestimates the minimum values.



The complex task of developing and evaluating tropospheric chemistry and aerosol capability in ACCESS will continue. A priority will be development of the aerosol scheme and optimisation of dust and interaction with the CABLE land surface scheme. A new generation of aerosol model, GLOMAP-Mode, will be tested within ACCESS-CM2 and used to explore aerosol-chemistry interactions.

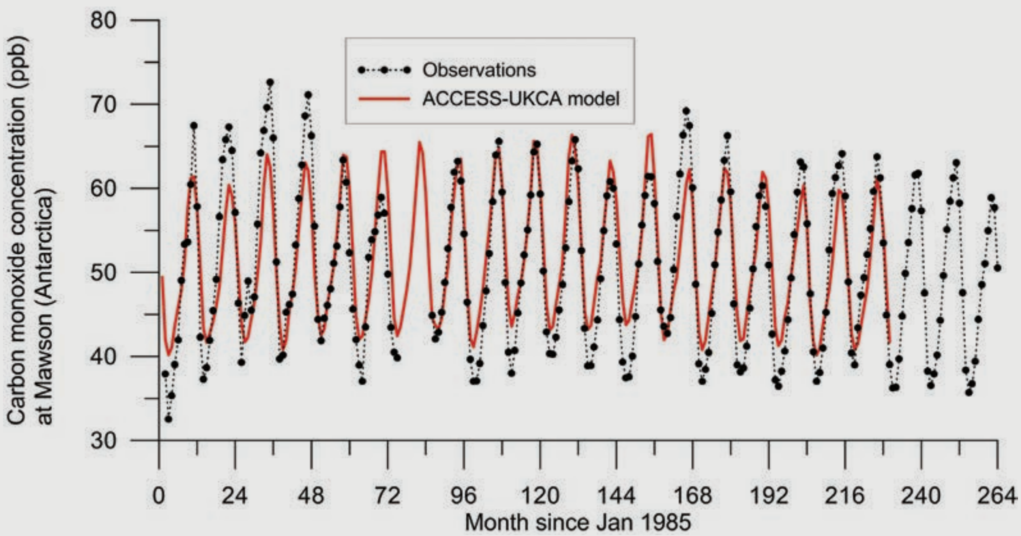



Figure 12: Time series of monthly-mean atmospheric carbon monoxide concentration at Mawson (Antarctica) covering the period January 1985 – December 2006. The solid line is the variation simulated by the ACCESS model and the black dots are the observations based on the analysis of flask samples by CSIRO's GASLAB facility at Aspendale.

## REDUCING GLOBAL MODEL PRECIPITATION BIASES OVER THE MARITIME CONTINENT

The Maritime Continent is a term used for the archipelagos of Indonesia, New Guinea, and Malaysia, and the surrounding shallow seas. It is important to Australia's regional climate, as it is characterised by extensive areas of high precipitation, forms a significant part of the regional monsoon circulation, and is a major global heat source. Using data analysis, model evaluation and model development, this project aims to reduce the large precipitation biases identified in ACCESS and other global climate models in this region in order to improve the accuracy of climate projections.

### Improved rainfall modelling over the Maritime Continent

Researchers created a database of satellite rainfall products, along with a database of rainfall products from ground based radar observations and from rain gauges over selected sites (the latter being used to validate the satellite rainfall products with ground reference). Assessment of these products highlighted large differences between satellite rainfall estimates. Results show that satellite derived rainfall estimates over the Maritime Continent can vary by as much as 50% between any individual satellite rainfall product and the ensemble average of five different estimates, with the largest differences typically occurring over the complex coastlines and mountainous regions.

The ARC Centre of Excellence for Climate System Science developed an algorithm to objectively identify rainfall features associated with coastline convection. Coastline-induced precipitation plays a pivotal role in the region, inducing up to 75% of the total rainfall.

Precipitation and cloud properties over the Maritime Continent in coupled and uncoupled (atmosphere only) ACCESS-1.3 simulations have been evaluated using the cloud satellite simulator package. The main finding is that the model overestimates precipitation over the Maritime Continent islands during the Australian monsoon season and produces too little precipitation over the ocean surrounding Sumatra, Java and Borneo.

Researchers have identified some of the reasons for the errors and developed methods to improve model performance. Making the convection scheme more dependent on the strength of the upward motion reduces the Australian summer seasonal rainfall error over the land and ocean components of the Maritime Continent by more than 80%.

# Australia's future climate

Climate change projections, developed with support of the ACCSP, provide important information for decision makers about our future climate. The projections help evaluate risk and opportunity from regional climate change.

25 YEARS OF CLIMATE SCIENCE

## Australia's future climate

The ACCSP's investment in the development of improved climate models for Australia has allowed the generation of projections of Australia's future climate that are used by governments, industry and communities to plan for and adapt to our changing climate.

Through the ACCSP, researchers in CSIRO's climate impact group developed the first climate change scenarios for Australia in 1992, with updated scenarios released in 1996 and 2001.

In 2007 CSIRO and the Bureau of Meteorology released the most comprehensive assessment of Australia's future climate to date. *Climate Change in Australia* provides details on observed climate change and its likely causes, and projections of changes in temperature, rainfall and other aspects of climate for the coming decades. For the first time, the projections presented probabilities of likely changes.

In 2014 CSIRO and the Bureau of Meteorology are releasing an updated assessment, drawing on improvements in climate models and our understanding of climate processes. The new projections are funded through the Regional Natural Resource Management (NRM) Planning for Climate Change Fund and include more climate variables and greater regional information. Extensive projections data will be available to support impact studies and adaptation planning.

Climate change projections for Australia are available at **www.climatechangeinaustralia.gov.au.**

Substantial increases in temperature extremes are projected by the end of the 21st century. It is virtually certain that the frequency and magnitude of hot days will increase, and cold extremes will decrease. Intensity of extreme rainfall is likely to increase in all regions of Australia, and winter rainfall is likely to decrease in southern and south-western Australia.

Impacts of climate change will mostly be felt through extreme events such as heat waves, cold snaps, tropical cyclones, storm surges, floods, droughts and bushfires. These events can have a serious impact on the environment and society, including loss of life, property and livelihoods.

A changing climate leads to changes in the frequency, duration and intensity of extreme events and will test the resilience of natural and human systems.

The ACCSP investigates extreme events to determine likely changes in their behaviour.

## SCIENCE HIGHLIGHTS

### REGIONAL CLIMATE PROJECTIONS SCIENCE

Climate simulations using sophisticated climate models are our best source of information to assess the range of potential future impacts of climate change and to plan to adapt. However, the outputs of models need to be transformed into climate projections that are credible and salient for the purpose of managing climate risk to Australia's communities, natural resources and many sectors of the economy. This project contributes to the production of useful projections by assessing and synthesising the outputs from global climate models as well as downscaling studies.

## New climate change projections science developed

The ACCSP has produced new and insightful research about the projection of heat stress, regional rainfall patterns and rainfall variability under future climate change scenarios. The research has underpinned development of new national climate change projections for Australia's natural resource management regions.

Heat stress indices show the impact of a rise in mean temperature on the accumulated heat that natural and human systems experience. Analysis shows that the impact of a rising mean temperature has dramatic effects on accumulated heat.

Regional rainfall projections were produced through the synthesis of outputs from the new CMIP5 set of global climate models and downscaling activities. Researchers produced a framework to handle this synthesis, including the consistent analysis of climate models complemented by the use of downscaling studies. Plausible patterns of regional rainfall change outside the range derived from climate models are revealed by downscaling from the CSIRO dynamical model CCAM, downscaling using the Bureau of Meteorology Statistical Downscaling Model and from previous regional projection projects. These plausible regional patterns include a strong rainfall reduction in south-western Victoria in autumn more in line with recent trends than CMIP5. Also, downscaling suggests that a rainfall decrease in western Tasmania is plausible in summer and autumn, in contrast to a possible rainfall increase in eastern Tasmania.

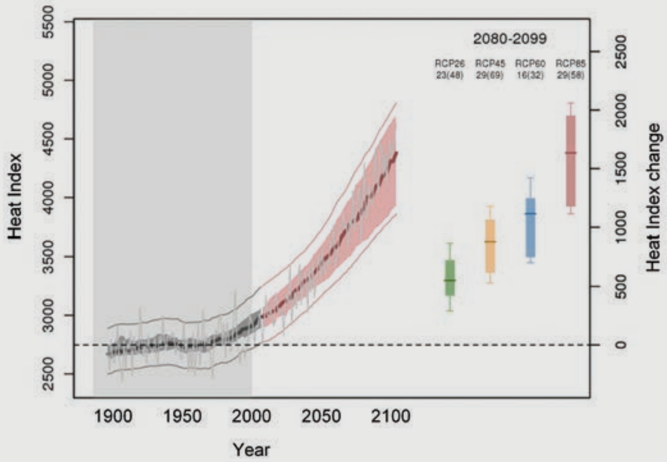



Figure 13: A time series of a heat index (in degree-days per year, threshold 15 °C) for inland Australia ('Rangelands' region) based on climate model simulations. The heat index measures the accumulation of the number of degrees that the daily mean temperature exceeds the threshold, and is potentially a more accurate indication of heat impact than simple means. The time series shows the 20th century and future under the RCP8.5 emissions scenario, while the bars show values at the end of the 21st century for four scenarios. Heavy lines show the medians. Shading shows the range for 20-year averages – the outer lines are for single years. The index series from a typical model depicts yearly variability. The left scale shows actual values of the index, the right the projected change relative to the 20th century mean.

A reduction in winter rainfall in the entire cool season due to a shift in the westerly atmospheric circulation is a very robust finding of climate projections, but the extent and intensity of the reduction is unclear. The rainfall reduction in downscaled projections is generally more intense and more restricted to west coasts where the interaction between westerly circulation and topography plays a greater role in determining rainfall than the reductions simulated by global climate models. Downscaling shows a weaker signal inland from the coast where the influence of westerly circulation is weaker. This gives a plausible spatial rainfall signal of rainfall change in south-east Australia that is a useful scenario to consider in regards to future planning.

Scientists have compared results from CMIP5 and CMIP3 models and from new downscaling studies. Downscaling can reveal likely future regional differences in rainfall. However, rainfall projections differ somewhat from various downscaling methods, confirming that the techniques offer benefits as well as producing some additional uncertainties.

Research on projection methods, drought, regional rainfall change, combining global climate models with downscaling and pattern scaling all contribute to the new national climate change projections scheduled for release later in 2014.

# NARROWING UNCERTAINTIES IN TROPICAL AUSTRALIAN RAINFALL PROJECTIONS

The Australian monsoon system provides most of the rainfall across the top end of Australia. Changes in the timing, positioning and intensity of the rainfall systems associated with the monsoon due to increased greenhouse gases would strongly affect various sectors of the Australian economy as well as infrastructure and social fabric. This project is examining representation in global climate models of tropical rainfall and the Australian monsoon.

## Warming over the Indian Ocean could delay the onset of the Australian monsoon

ACCSP researchers have investigated several climate process-related indices and their relationship to tropical rainfall and monsoon onset. As was the case with the previous generation (CMIP3) climate models, CMIP5 models show that El Niño–Southern Oscillation changes and warming over the Indian Ocean may lead to delay in the onset of the Australian monsoon in future climate.

The Australian monsoon provides most of the rainfall across the top end of Australia and generally lasts from December to March. It is associated with the inflow of moist west to north-westerly winds into the monsoon trough, producing convective cloud and heavy rainfall over northern Australia.

The regional impacts of any changes to the Australian monsoon are likely to be large, particularly on ecosystems and vulnerable indigenous communities on low-lying islands, such as the Torres Strait Islands.

ACCESS simulations are helping determine how much of the uncertainty in rainfall projections is related to differences in the representation of the surrounding tropical sea-surface temperatures. The results are being analysed using a methodology that can isolate the contributions from ocean and land processes.

As well as delays in onset, Australian monsoon variability is likely to increase on different time scales: daily, monthly and seasonal.

## ATTRIBUTION OF EXTREME EVENTS: MECHANISMS AND METHODS

Recent extreme events over Australia have broken meteorological records and caused widespread impacts. This project is using observations and models to analyse and diagnose the causes of recent extreme heat and rainfall events on a range of time scales and to develop methods to attribute the events to factors including the El Niño–Southern Oscillation, the Madden–Julian Oscillation, soil moisture, trends in sea-surface temperatures and the impact of global warming.

### A combination of features led to record Australian heat extremes in 2013

2013 set many records for heat extremes in Australia. It was Australia's warmest year since records began in 1910 and the Australian summer of 2012–13, spring 2013 and September 2013 also broke records for warmth. Above average temperatures were widespread and long lasting, with many episodes of persistent warmth during the year. These extreme temperature events occurred on a globally-averaged background warming of +0.9 °C since 1910, leading to the question of what role human-induced climate change may have played in their occurrence. With the Australian-average September temperature being 3.34 °C above average and breaking the previous record by almost a full degree, researchers sought to understand and explain the causes of this extraordinary event.

The record Australian temperatures in September 2013 arose from a combination of a highly unusual atmospheric circulation pattern, background warming, and the preceding dry and warm land-surface conditions. Up to 15% of the magnitude of the record temperature anomaly could be explained by the increase in global temperatures from 1982 to 2013. These conclusions were based on both a statistical regression model that was developed in the study and a novel use of sensitivity experiments with the Bureau's seasonal prediction system. A statistically-based approach was also used in a study investigating the causes of the record wet east Australian spring of 2010 and modelling experiments are underway to provide a more definitive quantification of cause and effect.

## IMPACT OF CLIMATE CHANGE ON THE IGNITION OF BUSHFIRES AND THE AUSTRALIAN CARBON BUDGET

Bushfires, with their large socio-economic impacts, are a feature of Australia's environment, with devastating fires featuring throughout our history. Consequently, there is a need to improve understanding and modelling of these fires to better understand how they are likely to change in the future. This project aims to address significant knowledge gaps relating to future fire regimes, vegetation modelling and the carbon budget of Australia.

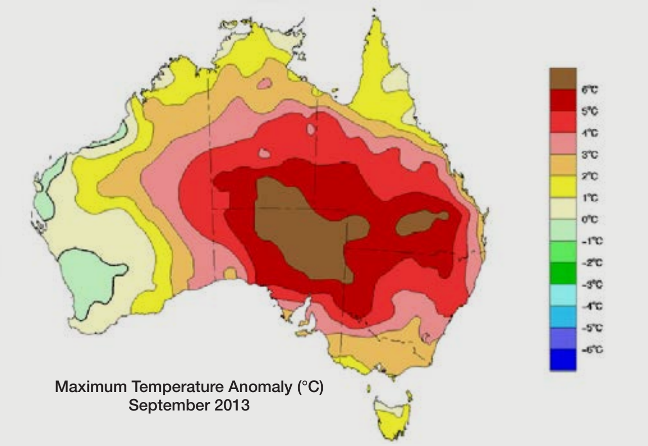



Figure 14: Maximum temperature anomalies over Australia in September 2013. Temperature anomalies are calculated with respect to the average over the 1961–1990 reference period.

### Australian lightning records updated

Lightning is responsible for a significant proportion of the area burnt by bushfires in Australia.

While ground-based lightning sensors provide good coverage for individual locations, they lack the wide spatial coverage provided by satellite-based instruments.

Researchers have updated lightning records, using data from two NASA satellite sensors for the period 1995 to 2012, to investigate lightning ground flashes – that is, lightning that hits the ground (rather than lightning that goes from one part of a cloud to another part of a cloud). This information is used by emergency management and insurance organisations, as well as for improving safety standards (e.g. as used in infrastructure planning and design).

The data were collected over a period more than twice as long as previous climatological investigations, resulting in significant advances, such as a reduced influence from short-term year-to-year variations and variability associated with phenomena such as El Niño–Southern Oscillation. The new climatology also provides greater information regarding seasonal variations, and coverage in maritime regions.

The research details the relationship between the El Niño–Southern Oscillation and other large-scale modes of climatic variability and lightning occurrence. The results show that seasonal forecasting of thunderstorms and lightning is feasible in some regions. Work has also commenced on examining long-term trends in lightning activity in Australia.

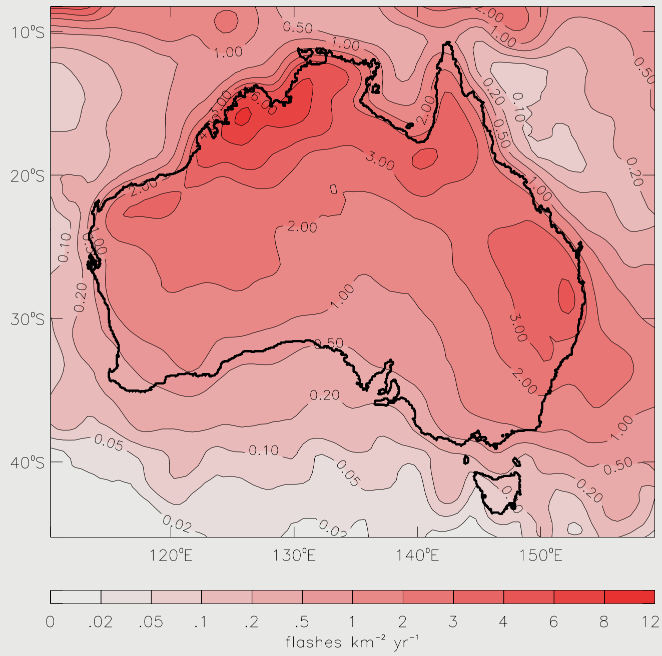



Figure 15: Map of average annual lightning ground flash density.

# Management and communication

**In addition to the six research components, the ACCSP has a management and communication component that oversees the coordination of the Programme. The ACCSP involves more than 100 CSIRO and Bureau scientists collaborating nationally and internationally on dozens of projects in a variety of research areas, so strong management, coordination and communication are essential to maximising the value and uptake of the Programme.**

Constant updating and renewal of the Programme sees new work proposed each year. The proposals are assessed for science excellence and relevance by a science evaluation panel, which includes senior representatives from relevant portfolios in CSIRO and the Bureau, and the Department of the Environment. There are also external reviews of the proposals.

A joint management team comprising senior representatives from the Department, CSIRO and the Bureau oversees the ACCSP. The team meets regularly to review progress, and to determine communication and briefing needs. The team is responsible for day-to-day management, progress reporting and finances.

The ACCSP management team ensures strong communication on progress of the research and on important research findings, both within the agencies and with the Department.

Formal progress reports and the annual report summarise achievements throughout the year. Each May, there is a review meeting in which researchers share and discuss highlights.

As Australia's largest climate change science programme, the ACCSP undertakes nationally and internationally acclaimed work. ACCSP scientists have made many presentations at national and international workshops and conferences. The Programme directly supports and organises scientific workshops and conferences.

A communication plan sets out the way in which the research findings are shared and explained. These findings assist with planning for, and managing, the expected environmental, social and economic impacts of climate change. Important audiences are government, industry and the public.

## Publications

In addition to peer-reviewed, technical and conference papers produced by researchers, the ACCSP develops information papers for non-technical audiences on key climate issues. This year papers were prepared on the topics of ocean acidification, the ACCESS model and attribution of climatic extremes.

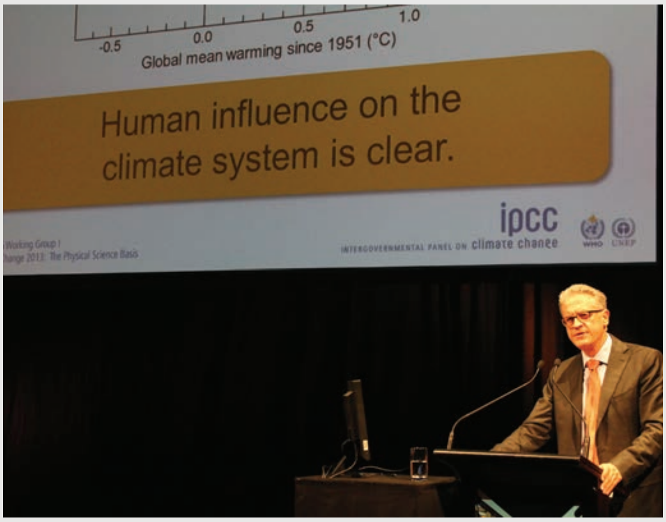
## Websites

The ACCSP maintains a presence across a number of websites to inform a wide audience about the science undertaken though the Programme.

The primary website is located at the Centre for Australian Climate and Weather Research (**www.cawcr.gov.au/projects/climatechange/**).

Additional ACCSP web pages can be found at:

- CSIRO (**www.csiro.au/Outcomes/Climate/Understanding/Australian-Climate-Change-Science-Program**)
- Department of the Environment (**www.climatechange.gov.au/climate-change/grants/australian-climate-change-science-program**).




Co-chair of IPCC Working Group I, Professor Thomas Stocker at GREENHOUSE 2013.

## GREENHOUSE 2013

GREENHOUSE 2013 was the seventh in Australia's pre-eminent climate change science conferences. It was held in Adelaide in October 2013, attracting 300 participants. The conference included four days of plenary and parallel presentations by Australian and international speakers. There was a strong focus in the plenary presentations on the findings of the IPCC Fifth Assessment Report, released just before the conference.

Conference presentations covered the following topics:

- Atmosphere, oceans, biosphere and the land: Observations, monitoring and trends
- Climate modelling and projections: Methods and advances; likely future climate
- Climate variability and extreme events: Large-scale drivers and dynamics
- Impacts, adaptation and mitigation: Agriculture, infrastructure, biodiversity, health, community; energy efficiency, emission reductions and renewable energy
- Communication and policy: Approaches, practice, case studies and research.

25 YEARS OF CLIMATE SCIENCE

## GREENHOUSE climate change science conferences

GREENHOUSE 2013 was the latest in a series of climate change conferences that stretch back to the 1980s.

The GREENHOUSE conferences include plenary and parallel presentations on a wide range of themes relating predominantly to climate change science. There are also many posters and an exhibition featuring displays from numerous organisations involved in research and application.

The conferences typically attract up to 500 delegates and communicate the latest national and international climate change science. They bring together researchers, students, and government and industry representatives.

Dr Graeme Pearman from CSIRO initiated and convened the first meeting, with GREENHOUSE 87 attracting some 260 participants. It was a five-day event held at Monash University in Clayton, Victoria, from 30 November to 4 December, 1987. *Greenhouse: Planning for Climate Change* was a publication containing conference papers.

GREENHOUSE 94 in Wellington, New Zealand followed, organised jointly by CSIRO and the National Institute of Water and Atmospheric Research (NIWA).

The new century saw GREENHOUSE 2005, back in Melbourne. The theme was action on climate change. Subsequent conferences were held in Sydney (2007), Perth (2009) and Cairns (2011).


## Workshops

In February 2014, the ACCSP convened a meeting of Hobart-based ocean acidification researchers at CSIRO's Hobart laboratories. Participants from CSIRO, the University of Tasmania, Antarctic Climate and Ecosystems CRC, and the Australian Antarctic Division used the event to share information, document research activities, encourage collaboration and identify important future research objectives.

Aus2K is a PAGES (Past Global Changes – a core project of the International Geosphere Biosphere Program) working group developing field palaeo reconstructions of the Australasian climate. ACCSP collaborated with the Aus2K steering committee to organise a cross-disciplinary workshop entitled 'Australasia's past climate variability: strengths drawn from palaeoclimate and model data over the last 2000 years'. The workshop was held in June 2014 at the Bureau of Meteorology in Melbourne.

(Left to right) Helen Cleugh (ACCSP management CSIRO), Graeme Pearman, Jo Mummery, Neville Nicholls and Rob Colman (ACCSP management BoM)

## Awards

As part of its 25th anniversary, the Programme recognised the influential, long-term, significant and sustained contributions of a number of current and former staff with special awards.

The ACCSP granted these awards to:

- Ms Jo Mummery, formerly Assistant Secretary, Science and International Adaptation, Department of the Environment
- Professor Neville Nicholls, Monash University, formerly a senior scientist at the Bureau of Meteorology
- Dr Graeme Pearman, Director, Graeme Pearman Consulting Pty Ltd, formerly Chief of CSIRO Atmospheric Research.

# Appendices

# Appendix 1

## COMPLETE LIST OF RESEARCH PROJECTS AND SCIENCE HIGHLIGHTS

| RESEARCH AREA | PROJECT TITLE | PRINCIPAL INVESTIGATORS | HIGHLIGHTS |
|---|---|---|---|
| **1. Global and regional carbon budgets** | 1.1 Global carbon budgets, analyses and delivery | Pep Canadell (CSIRO) | **Carbon dioxide emissions continue to increase**<br>Carbon dioxide emissions from fossil fuel burning and cement production increased by 2.1% in 2012, with a total of 9.7±0.5 GtC (billion tonnes of carbon) emitted to the atmosphere, 58% above 1990 emissions. (See page 12)<br><br>**Record-breaking rains turned semi-arid Australia into a carbon sink in 2011**<br>Analysis revealed that the size of the 2011 global land sink was unprecedented at least in the last 60 years, removing the equivalent of 40% of fossil fuel emissions that year. (See page 13)<br><br>**Online Global Carbon Atlas launched**<br>The new Global Carbon Atlas is a key online tool to provide the most up to date carbon data and information. (See page 13) |
| | 1.2 The Australian terrestrial carbon budget: The role of vegetation dynamics | Vanessa Haverd (CSIRO)<br><br>Pep Canadell (CSIRO) | **New woody vegetation dynamics model developed**<br>Researchers have developed a new terrestrial ecosystem modelling approach to predict woody vegetation dynamics and their effect on the terrestrial carbon cycle. (See page 14)<br><br>**Carbon and water observatory available online**<br>BIOS2 carbon/water model results for Australia at 5 × 5 km and monthly resolution are publicly available in the newly developed online carbon and water observatory. (See page 14)<br><br>**First steps taken in compiling methane budgets**<br>Researchers have conducted preliminary work on Australian regional methane fluxes to build datasets and capacity to deliver regional and national methane budgets. (See page 15) |
| | 1.3 The ocean carbon sink and acidification | Bronte Tilbrook (CSIRO)<br><br>Marcel van der Schoot (CSIRO) | **Surface ocean carbon dioxide atlas for the high latitudes delivered**<br>The atlas delivers a uniformly quality controlled surface carbon dioxide dataset, and is the major database for detecting changes in the ocean carbon sink and for testing ocean carbon cycle models. (See page 16)<br><br>**Carbon dioxide uptake enhanced following removal of glacier tongue**<br>Researchers have investigated how the removal of the Mertz Glacier tongue in 2010 influenced carbon dioxide uptake and ocean acidification. (See page 16)<br><br>**Whole-of-reef biogeochemical model developed**<br>A new model of a reef was published using Heron Island as a test bed. This model is the basis for scaling up from reef systems to the entire Great Barrier Reef and linking to global models such as ACCESS. (See page 17) |

| RESEARCH AREA | PROJECT TITLE | PRINCIPAL INVESTIGATORS | HIGHLIGHTS |
|---|---|---|---|
| | 1.4 Palaeo carbon cycle dynamics | David Etheridge (CSIRO)<br>Cathy Trudinger (CSIRO)<br>Richard Matear (CSIRO) | **Dust deposition derived from ice cores explains high variability in ocean carbon uptake**<br>Using Antarctic ice core measurements of dust concentration, researchers have derived the likely dust deposition across the global oceans. The iron associated with this dust stimulated biological carbon dioxide uptake. (See page 17)<br><br>**Little Ice Age carbon dioxide reduction due to land ecosystem**<br>Measurements of carbon dioxide and the carbon-13 isotope show that the land ecosystem was responsible for the carbon dioxide reduction during the cool period of the Little Ice Age. (See page 17) |
| **2. Land and air observations and processes** | 2.1 Aerosol and its impact on Australian climate | Leon Rotstayn (CSIRO)<br>Ross Mitchell (CSIRO) | **Impact of declining northern hemisphere aerosols on sea-level pressure is larger in the southern hemisphere than the northern hemisphere**<br>Human-generated aerosols have substantially 'masked' the warming effects of greenhouse gases. Human-generated aerosol emissions from the northern hemisphere are projected to decline sharply in the next few decades, and this is likely to cause an acceleration of the warming effects of increasing greenhouse gases. (See page 18)<br><br>**Australian tropical aerosol climatology derived**<br>Scientists have simulated the climatic effects of different aerosol types and made measurements of Australian aerosol. (See page 19)<br><br>**Aerosol loading over Australia derived from satellite data**<br>Researchers have developed a method to overcome difficulties due to the prevalence of bright surfaces to derive both aerosol loading and type over Australia. (See page 20) |
| | 2.2 Reducing uncertainties in climate projections by understanding, evaluating and intercomparing climate change feedbacks | Robert Colman (Bureau of Meteorology) | **Climate feedback leads to stronger projected Arctic sea ice retreat**<br>This work is revealing larger climate change at high northern latitudes, which has significant regional effects. It also affects temperature gradients, and therefore weather patterns across the hemisphere. (See page 20) |
| | 2.3 Ecosystem response to increased climate variability | Eva van Gorsel (CSIRO) | **Observational programme at Tumbarumba flux tower expanded**<br>ACCSP researchers have continued leadership in OzFlux, the Australian network of towers that continuously measures the exchanges of carbon dioxide, water vapour and energy between key terrestrial ecosystems and the atmosphere. (See page 22)<br><br>**Terrestrial carbon uptake tracked**<br>The ACCSP is part of a global effort to assess the skills of models to quantify carbon uptake by the world's terrestrial ecosystems using remote sensing and the FluxNet dataset as constraints. (See page 22) |

| RESEARCH AREA | PROJECT TITLE | PRINCIPAL INVESTIGATORS | HIGHLIGHTS |
|---|---|---|---|
| **3. Oceans and coasts observations and processes** | 3.1 Ocean monitoring to understand ocean control of the global and Australian climate | Susan Wijffels (CSIRO)<br>Ann Thresher (CSIRO)<br>Ken Ridgway (CSIRO) | **Argo profiling floats deployed**<br>Argo data have been central to documenting and relating the recent 'hiatus' in rising surface temperatures and the contemporaneous changes in the total heat content of the planet. This total planetary heat content continues to rise. (See page 24)<br><br>**East Australia Current dataset compiled**<br>The project has delivered the most definitive dataset describing Australia's major boundary current, the East Australia Current. (See page 25) |
| | 3.2 Understanding ocean drivers of regional and global climate variability and change | Bernadette Sloyan (CSIRO)<br>Steve Rintoul (CSIRO)<br>Terry O'Kane (CSIRO)<br>Susan Wijffels (CSIRO) | **Most complete assessment to date of changes in Antarctic bottom water undertaken**<br>Antarctic bottom water has warmed and freshened. The volume of the dense bottom water layer has decreased by 50% since the early 1970s. Freshening of the source waters, due to a change in precipitation or melting of Antarctic ice shelves, is the primary cause. (See page 26)<br><br>**Deep ocean currents transmit high latitude climate variability to the Pacific**<br>High latitude climate variability is being directly transmitted into the deep south-west Pacific Basin and the global deep ocean through dynamic deep western boundary currents. (See page 26)<br><br>**High latitude and tropical oceanic behaviour linked through ocean 'storms'**<br>Researchers have developed a theory to explain the observed large-scale wavelike variability in the eddy-rich regions of subtropical oceans. (See page 27) |
| | 3.3 Addressing key uncertainties in regional and global sea-level change, storm surges and waves | John Church (CSIRO)<br>Kathleen McInnes (CSIRO)<br>Mark Hemer (CSIRO) | **Sea levels continue to rise**<br>Analysis of models and their comparison with observations indicates the larger rate of sea-level rise since 1993 is largely a result of changes in natural forcing of climate and ongoing anthropogenic greenhouse gas emissions. (See page 28)<br><br>**Wind changes exacerbate extreme sea levels and coastal currents**<br>Changes to extreme sea levels and coastal currents are likely to be greatest where large changes in wind speed and direction are projected to occur. Potential future impacts have been investigated in two locations where such changes are projected. (See page 29)<br><br>**Wind-wave climate model extended**<br>The extension of the CSIRO global dynamical CMIP5-derived wind-wave climate model now provides a minimum ensemble size to investigate uncertainty in wave climate studies. (See page 29) |

| RESEARCH AREA | PROJECT TITLE | PRINCIPAL INVESTIGATORS | HIGHLIGHTS |
|---|---|---|---|
| **4. Modes of climate variability and change** | 4.1 The El Niño – Southern Oscillation and its impacts on Australasia in the 21st century | Scott Power (Bureau of Meteorology) | **Global warming alters the impact of El Niño on rainfall**<br>The impact of El Niño on tropical rainfall is likely to intensify in response to global warming. Projections include an intensification of both El-Niño-driven drying in the western Pacific Ocean and rainfall increases in the central and eastern equatorial Pacific. (See page 30) |
| | 4.2 Decadal variability in Australian and Indo-Pacific climate: predictability and prediction | Scott Power (Bureau of Meteorology) | **Research into the character and cause of decadal variability underway**<br>In the first year of a longer project examining decadal variability ACCSP researchers have downloaded and quality-checked data from the CMIP5 archive, established a detailed methodology and conducted preliminary analysis of the decadal variability evidence. |
| | 4.3 Response of Indo-Pacific climate variability to greenhouse warming and the impact on Australian climate: a focus on ocean-induced climates | Wenju Cai (CSIRO)<br>Tim Cowan (CSIRO) | **Frequency of extreme El Niño events to double**<br>Modelling studies reveal a future doubling in the occurrence of extreme El Niño episodes caused by increased surface warming of the eastern equatorial Pacific Ocean. The increased occurrence of these episodes is likely to lead to more frequent catastrophic weather events. (See page 32)<br><br>**Frequency of extreme Indian Ocean Dipole events to increase**<br>The frequency of extreme climate and weather events, such as flooding and drought around the Indian Ocean, is expected to also increase over the 21st century in response to high greenhouse gas emissions. (See page 32) |
| | 4.4 Attribution, projection and mechanisms of climatic extremes and change, modes of variability and regional weather systems. | Simon Grainger (Bureau of Meteorology)<br>Carsten Frederiksen (Bureau of Meteorology)<br>Jorgen Frederiksen (CSIRO) | **Human activity is changing the weather**<br>The prolonged trends in rainfall over south-west Western Australia in winter and north-west Australia in summer are likely the result of external influences such as changes in greenhouse gases, ozone and aerosols. (See page 32) |
| | 4.5 Variability and drivers of Australian climate over the last 1000 years in coupled model simulations | Pandora Hope (Bureau of Meteorology)<br>Josephine Brown (Bureau of Meteorology) | **The Australian impacts of El Niño/La Niña events vary over time**<br>A 1000-year climate simulation has shown that the relationship between east Australian spring rainfall and the presence of an El Niño or La Niña event weakens about once every century and at times becomes negligible. (See page 34) |
| | 4.6 Variability and dynamics of the Ningaloo Niño | Ming Feng (CSIRO)<br>Harry Hendon (Bureau of Meteorology) | **Most Ningaloo Niño events occur in strong La Niña years**<br>Most extreme Ningaloo Niño marine heat wave events occur during strong La Niña years. Moreover, most of the Ningaloo Niño events have their precursors in the south-east Indian Ocean, due to air sea interaction associated with a wind-evaporation-sea-surface-temperature feedback mechanism prior to the Australian summer monsoon. (See page 34)<br><br>**2011 Ningaloo Niño unprecedented in 200 years**<br>Researchers used coral proxy records to investigate the decadal variations of the Leeuwin Current strength from 1795 to 2010. (See page 35) |

| RESEARCH AREA | PROJECT TITLE | PRINCIPAL INVESTIGATORS | HIGHLIGHTS |
|---|---|---|---|
| **5. Earth systems and modelling data integration** | 5.1 ACCESS coupled climate model development | Kamal Puri (Bureau of Meteorology)<br>Tony Hirst (CSIRO)<br>Gary Dietachmayer (Bureau of Meteorology) | **Development of the next generation ACCESS underway**<br>The initial ACCESS-CM2 coupled model has been successfully configured and several decadal-length test simulations performed. (See page 36)<br><br>**New model evaluation methodology implemented**<br>A powerful new methodology aiding model evaluation and development has been implemented. (See page 36)<br><br>**Warm biases over the Southern Ocean addressed**<br>Warm biases over the Southern Ocean in ACCESS have been addressed through evaluation of cloud properties. (See page 38)<br><br>**New ACCESS user interface developed**<br>Enhanced and integrated ACCESS modelling infrastructure is being developed in conjunction with NeCTAR project. (See page 38)<br><br>**ACCESS prepared to serve as the basis of an Earth system model**<br>A revision of the CMIP5 ACCESS-1.3 coupled model, ACCESS-1.4, has been prepared to serve as the basis for the first ACCESS Earth system model, ACCESS-ESM1. (See page 38) |
| | 5.2 ACCESS carbon cycle modelling | Rachel Law (CSIRO)<br>Richard Matear (CSIRO) | **Carbon cycle changes modelled with ACCESS**<br>Land and ocean carbon cycle modules have been incorporated into ACCESS and simulations performed of the past and future. Simulated past ocean uptake and storage of carbon was consistent with observations. (See page 38) |
| | 5.3 Development of ACCESS for aerosol and chemistry | Ashok Luhar (CSIRO)<br>Peter Vohralik (CSIRO) | **Improved dust and tropospheric chemistry modelling**<br>ACCESS-1.4 is a considerably updated model including realistic global dust amounts and significant enhancements to the tropospheric chemistry component. (See page 40) |
| | 5.4 Reducing global model precipitation biases over the Maritime Continent | Alain Protat (Bureau of Meteorology)<br>Charmaine Franklin (CSIRO)<br>Christian Jakob (Monash University) | **Improved rainfall modelling over the Maritime Continent**<br>Researchers have identified some of the reasons for overestimations of precipitation over the Maritime Continent and developed methods to improve model performance. A new convection scheme reduces the Australian summer seasonal rainfall error over the land and ocean components of the Maritime Continent by more than 80%. (See page 41) |

| RESEARCH AREA | PROJECT TITLE | PRINCIPAL INVESTIGATORS | HIGHLIGHTS |
|---|---|---|---|
| **6. Australia's future climate** | 6.1 Regional climate projections science | Penny Whetton (CSIRO)<br><br>Michael Grose (CSIRO) | **New climate change projections science developed**<br>The ACCSP has produced new and insightful research about the projection of regional rainfall patterns, rainfall variability and heat stress under future climate change scenarios. The research has underpinned development of new national climate change projections for Australia's natural resource management regions. (See page 43) |
| | 6.2 Narrowing uncertainties in tropical Australian rainfall projections | Aurel Moise (Bureau of Meteorology)<br><br>Huqiang Zhang (Bureau of Meteorology) | **Warming over the Indian Ocean could delay the onset of the Australian monsoon**<br>El Niño–Southern Oscillation changes and warming over the Indian Ocean may lead to delay in the onset of the Australian monsoon in future climate. (See page 43) |
| | 6.3 Evaluation of tropical cyclone development in the Australian region | Yuriy Kuleshov (Bureau of Meteorology)<br><br>Harry Hendon (Bureau of Meteorology) | **Plans made for tropical cyclone research**<br>Researchers have developed a plan for future work within the ACCSP. |
| | 6.4 Attribution of extreme events: mechanisms and methods | Julie Arblaster (Bureau of Meteorology)<br><br>Eun-Pa Lim (Bureau of Meteorology) | **A combination of features led to record Australian heat extremes in 2013**<br>The record Australian temperatures in September 2013 arose from a combination of a highly unusual atmospheric circulation pattern, background warming, and the preceding dry and warm land-surface conditions. Up to 15% of the magnitude of the record temperature anomaly could be explained by the increase in global temperatures from 1982 to 2013. (See page 44) |
| | 6.5 Impact of climate change on the ignition of bushfires and the Australian carbon budget | Andrew Dowdy (Bureau of Meteorology)<br><br>Bryson Bates (CSIRO)<br><br>Bertrand Timbal (Bureau of Meteorology) | **Australian lightning records updated**<br>Researchers have updated lightning records using data from two NASA satellite sensors for the period 1995 to 2012. The data, collected over a period twice as long as previously, provide significant benefits in relation to emergency management, planning, insurance and safety standards for Australia. (See page 45) |

# Appendix 2

## PARTNERS AND COLLABORATORS

### Australia

Antarctic Climate and Ecosystems Cooperative Research Centre

ARC Centre of Excellence for Climate System Science

Australian Antarctic Division

Australian Institute of Marine Science

Australian National University

Australian Nuclear Science and Technology Organisation

Charles Darwin University

Integrated Marine Observing System

James Cook University

Macquarie University

Monash University

National Computational Infrastructure

Queensland Government Department of Science, Information Technology, Innovation and the Arts

Queensland University of Technology

Royal Australian Navy

Southern Cross University

Swinburne University

The Goyder Institute

University of Adelaide

University of Melbourne

University of New South Wales

University of Queensland

University of South Australia

University of Sydney

University of Tasmania – The Institute of Marine and Antarctic Studies

University of Technology, Sydney

University of Western Australia

University of Wollongong

### Austria

University of Innsbruck

### Brazil

Institute of Astronomy, Geophysics and Atmospheric Sciences, University of Sao Paulo

### Canada

Environment Canada, Toronto

University of Alberta

University of Lethbridge, Alberta

### China

College for Global Change and Earth System Science, Beijing Normal University

Institute of Atmospheric Physics, Chinese Academy of Sciences

Institute of Oceanology, Chinese Academy of Sciences

State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology

Third Institute of Oceanography, State Oceanic Administration

### Cook Islands

Meteorological Service

### Denmark

Centre for Ice and Climate, University of Copenhagen

### France

Centre National de la Recherche Scientifique, Laboratoire de Glaciologie et Géophysique de l’Environnement

Institut de Recherche pour le Développement New Caledonia/France

Laboratoire d’Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN)

Laboratoire des Sciences du Climat et de l’Environnement

Université Pierre et Marie Curie

### Germany

Alfred Wegener Institute for Polar and Marine Research

Geomar, Kiel

### India

Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune

## Japan

Department of Geophysics, Graduate School of Science, Tohoku University, Sendai

Disaster Prevention Research Institute, Kyoto University

Japan Agency for Marine-Earth Science and Technology

Low Temperature Research Laboratory

National Institute for Environmental Studies

## The Netherlands

Institute for Marine and Atmospheric Research Utrecht, Utrecht University

## New Zealand

National Institute for Water and Atmosphere

## Norway

Center for International Climate and Environmental Research

## Portugal

Escola Naval, CINAV, Lisbon

## South Korea

School of Earth and Environmental Sciences, Seoul National University

## Spain

Universitat de València

## Sweden

Department of Earth Sciences, Uppsala University

Lund University

## UK

British Antarctic Survey

MetOffice, Exeter

School of Environmental Sciences, University of East Anglia

Swansea University

Tyndall Center

University of Cambridge

University of Exeter

University of Leeds

University of Reading

## USA

Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration

California Institute of Technology

Carbon Dioxide Information and Analysis Center

Department of Earth and Environmental Sciences, University of Rochester

Department of Earth System Science, University of California

Department of Physical Oceanography, Woods Hole Oceanographic Institution

Departments of Earth & Planetary Science and of Chemistry, University of California

Duke University

Geophysical Fluid Dynamics Laboratory

Institute of Arctic and Alpine Research, University of Colorado

International Pacific Research Center, Hawaii

Lamont Doherty Earth Observatory

NASA Goddard Institute for Space Studies

NASA Goddard Space Flight Center

National Center for Atmospheric Research

National Oceanic and Atmospheric Administration

National Oceanographic Data Center

Oregon State University

Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration

Princeton University

Scripps Institution of Oceanography, University of California

University of Hawaii

## International

Global Carbon Project

International Argo Project
(more than 15 countries – see **www.argo.net**)

International Geosphere-Biosphere Programme

World Climate Research Programme

# Appendix 3

## PUBLICATIONS

### Peer-reviewed publications

ACCSP researchers publish their findings in peer-reviewed papers published in highly-regarded local and international scientific journals.

Scientists have written about their work in books and have served as editors for prestigious publications.

ACCSP researchers have made major contributions to the Intergovernmental Panel on Climate Change (IPCC) as lead authors and through dozens of cited publications.

In 2013–14, ACCSP researchers published 122 peer-reviewed papers or articles in Australian and international scientific publications. A further 34 papers were submitted for publishing and 16 others were accepted by the publisher and were ‘in press.’ A list of these papers has been sorted alphabetically by lead author under the ACCSP’s key climate research themes.

*Note: ‘DOI’ is the abbreviation for ‘Digital Object Identifier’, a character string used to uniquely identify an object such as an electronic document.*

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## Additional publications

In 2013–14, ACCSP researchers produced or contributed to a number of other publications including conference papers, technical reports (many are peer-reviewed internally), books, book chapters and information papers. A selection of these publications follows.

### Conference papers

Brook E, Blunier T, Chappellaz J, Etheridge D, Fischer H, Sowers T, White J, Wolff E, 2013, Long term trends and abrupt perturbations to the Late Quaternary methane budget, American Geophysical Union Fall Meeting, December 2013, San Francisco, USA.

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Dowdy AJ, Kuleshov Y, 2013, A climatology of lightning activity in Australia derived from satellite remote sensing observations (poster), 2013 Satellite User's Meeting, October 2013, Melbourne, Australia.

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Griffiths A, Treble P, Hope P, 2014, Downscaling the Climate Forecast System Reanalysis for Lagrangian models of moisture sources (poster), UNSW Weather Researching and Forecasting Model Workshop (Understanding weather systems to better use speleothem records for climate reconstructions in south-west WA), February 2014, Sydney.

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**Australian Climate Change Science Programme (ACCSP)**

CSIRO enquiries

1300 363 400
+61 3 9545 2176

enquiries@csiro.au
www.csiro.au