Australian ClimateChange ScienceProgramme

ANNUAL REPORT 2012–13

Australian Government
Department of the Environment

CSIRO

Australian Government
Bureau of Meteorology

The Australian Climate Change Science Programme – An Australian Government initiative

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FOREWORD

The Australian Climate Change Science Programme (ACCSP) plays a major role in informing Australia's decision makers and improving the understanding of the causes, nature, timing and consequences of climate change.

In 2012–13, more than 100 climate scientists throughout the country worked on 22 projects across seven key research themes that addressed the Australian Government's national climate priorities. These priorities are based on a series of questions that, when answered, will help inform Australia's climate change policies.

ACCSP research shows that greenhouse gas emissions are still rising and that Australia's ecosystems take up significant amounts of carbon from the atmosphere. However, ACCSP scientists do not yet know how much carbon these ecosystems can continue to take up in a warming planet. The research shows that global carbon dioxide emissions into the atmosphere have increased from 6.1 billion tonnes of carbon in 1990 to 9.5 billion tonnes in 2011. In 2012, the researchers estimate that emissions are likely to be 9.7 billion tonnes of carbon or 2.6 per cent higher than in 2011. This trend is in line with the most carbon-intensive emission scenarios identified by the Intergovernmental Panel on Climate Change.

Modelling by ACCSP researchers shows that in scenarios where greenhouse gas emissions continue to rise, Australia is likely to continue to see significant changes to its weather and climate.

There have been many new findings during 2012–13. For the first time, ACCSP researchers have measured how much carbon dioxide produced by human activity is transferred to the southern hemisphere oceans. Other research has clarified the likely climate factors that contributed to two extreme flooding periods in Australia in 1974 and 2011. This knowledge of the past can help us prepare for the future.

We have captured many science highlights in this report. We have also provided a list of 130 peer-reviewed publications our scientists published in highly regarded scientific journals – and others they published for workshops, conferences and other events they attended throughout Australia and overseas.

Australia's climate change science would not have been possible without the passion of our scientists and staff. These people are committed to improving Australia's understanding of climate change and the challenges ahead. We would also like to acknowledge the Department of the Environment, which has supported CSIRO and the Bureau of Meteorology as the providers of the climate science undertaken by the ACCSP.

The ACCSP plays an important role in helping the Australian Government answer key policy questions and deliver a national benefit. It also helps Australia's decision makers understand the impacts of climate change and provides the underpinning science that allows our country to develop ways to adapt to climate change, and manage greenhouse gas emissions.

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

Dr Robert Colman
Climate Processes and
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and Climate Research,
Bureau of Meteorology

In Australia, we have seen warmer and higher oceans, and we have felt prolonged and higher temperatures. There has also been a long-term drying trend in south-west Western Australia since the 1960s.

ABOUT

This report gives an overview of the performance of the Australian Climate Change Science Programme (ACCSP) during 2012–13.

It highlights the ACCSP climate change discoveries that will help Australia to:

- understand and plan for climate change impacts;
- increase community resilience and reduce the cost to society;
- understand the size of the mitigation challenge;
- set appropriate reduction targets for emissions of greenhouse gases; and
- strengthen our international negotiating position.

Who we are

The ACCSP is the Australian Government's largest and longest-standing climate change science programme.

This $15 million per year programme is a collaborative effort between the Department of the Environment (herein, 'The Department'), CSIRO, and the Bureau of Meteorology (the Bureau).

As the science providers for the ACCSP, CSIRO and the Bureau have a long history and solid track record of delivering credible and reliable science on Australia's climate.

In the past 25 years, the ACCSP has contributed to Australia's understanding of climate change through:

- significant advances in understanding how the atmosphere, ocean and biosphere have changed;
- improved understanding of climate and extreme weather;
- improved tracking of atmospheric greenhouse gas concentrations and aerosols; and
- more detailed projections of climate change for Australia.

What we do

More than 100 scientists throughout Australia undertake research across 22 projects within the following key climate research themes:

- Global and regional carbon budgets.
- Land and air observations and processes.
- Oceans and coasts observations, processes, and projections.
- Modes of climate variability and change.
- Earth systems modelling and data integration.
- Australia's future climate.

Our work helps inform Australia's decision makers and improves their understanding of the causes, nature, timing and consequences of climate change.

The world-leading science delivered through the ACCSP plays a significant role in informing Australia's climate change policy.

Our focus

Our science focuses on the southern hemisphere because most other climate change science is generated in the northern hemisphere and does not provide all the information needed for Australian decision making. Southern hemisphere science is also crucial to better understand the global climate system, particularly in terms of ocean processes.

We are improving our understanding of the climate system by studying:

- the global and Australian carbon cycle and how it is changing;
- how our land, air, oceans and coasts are changing;
- variations in the climate and how they are changing; and
- climate changes and projections about the likely future climate for Australia using climate models.

See Appendix 1 for a complete list of ACCSP projects in 2012–13.

Why climate science is important

While some change is part of the natural climate system, scientists around the world are concerned with the changes being caused by human activity (such as from burning fossil fuel and clearing land) and the fast rate at which those changes are happening.

One of the challenges facing scientists today is being able to determine to what extent climate change is due to natural climate variability and to what extent it is caused by human activity.

World-class science undertaken through the ACCSP is helping Australia to understand:

- what is happening to its climate;
- the causes;
- to what extent the changes are long-term or cyclical; and
- how the climate is likely to change in the future.

Without climate change science, which is based on data, observations, understanding and modelling, Australia would not have the information needed to manage carbon in its landscape and to understand and plan for the impacts of climate change.

The changing climate

The Intergovernmental Panel on Climate Change Fifth Assessment Report (released 27 September 2013) shows the first decade of the 21st century was the warmest decade recorded since modern measurements began in about 1850. During this decade, there were many examples of climate and weather extremes such as heatwaves, floods, hurricanes, cyclones, and long-term droughts.

In Australia, we have seen warmer and higher oceans, and we have felt prolonged and higher temperatures. From 1997 to 2009, southeast Australia experienced the worst drought, known as the Millennium Drought, on record[1]. There has also been a long-term drying trend in south-west Western Australia since the 1960s[2].

The State of the Climate 2012 provides a summary of long-term climate trends in Australia:

- The concentrations of long-lived greenhouse gases in the atmosphere reached a new high in 2011.
- Each decade has been warmer than the previous decade since the 1950s.
- Observed warming trends around Australia are consistent with global-scale warming that has been measured during recent decades – despite 2010 and 2011 being the coolest years recorded in Australia since 2001.
- 2011 was the world's 11th warmest year and the warmest year on record during a La Niña event.
- There has been a general trend towards increased spring and summer monsoonal rainfall across Australia's north during recent decades, and decreased late autumn and winter rainfall across southern Australia.
- The increase in global sea level and sea-level rise around Australia since 1993 is greater than, or equal to, the global average.
- Sea-surface temperatures around Australia have increased faster than the global average.

1. CSIRO, 2012, Climate and water availability in south-eastern Australia: A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), CSIRO, Australia

2. Indian Ocean Climate Initiative, 2012, Western Australia's Weather and Climate: A Synthesis of Indian Ocean Climate Initiative Stage 3 Research, CSIRO and the Bureau of Meteorology, Australia

Australia's climate science priorities

Australia's climate change policy is underpinned by science. It is important to know what questions need to be answered by climate science to inform and support Australia's decision makers.

For example,

1. How much greenhouse gas are we emitting and what will the consequences be?
2. How can we ensure that climate change adaptation is supported by the best available information?
3. How are we tracking to limit warming to specific targets (such as the 2 °C target) and what level of emissions reduction is needed to meet targets?

The Australian Government has provided a framework for climate change science. *The National Framework for Climate Change Science* guides decisions over the long term so that Australia's investment is directed towards science that addresses national benefits. The framework describes the climate change science challenges to be addressed and that will support Australia's climate change policy. It also describes the capabilities required to deliver this science.

Each decade has been warmer than the previous decade since the 1950s.

The Government has also developed *A Plan for Implementing Climate Change Science in Australia (the plan)* which identifies the science priorities to guide investment decisions and ensure that the maximum national benefit is delivered to the Australian community.

The plan outlines a series of key policy questions that help ensure the science delivers outcomes that address national policy needs.

Policy questions within these areas are helping deliver outcomes for a national benefit. These questions also encourage scientific rigour, enable agencies to work together, improve prioritisation, integration, coordination and collaboration, and support the delivery of world-class climate change science.

Within each '*Key climate research theme*' section of this report, we have provided a table showing what key policy questions the ACCSP is addressing.

International collaboration

The ACCSP ensures that Australian climate change science continues to be recognised internationally by:

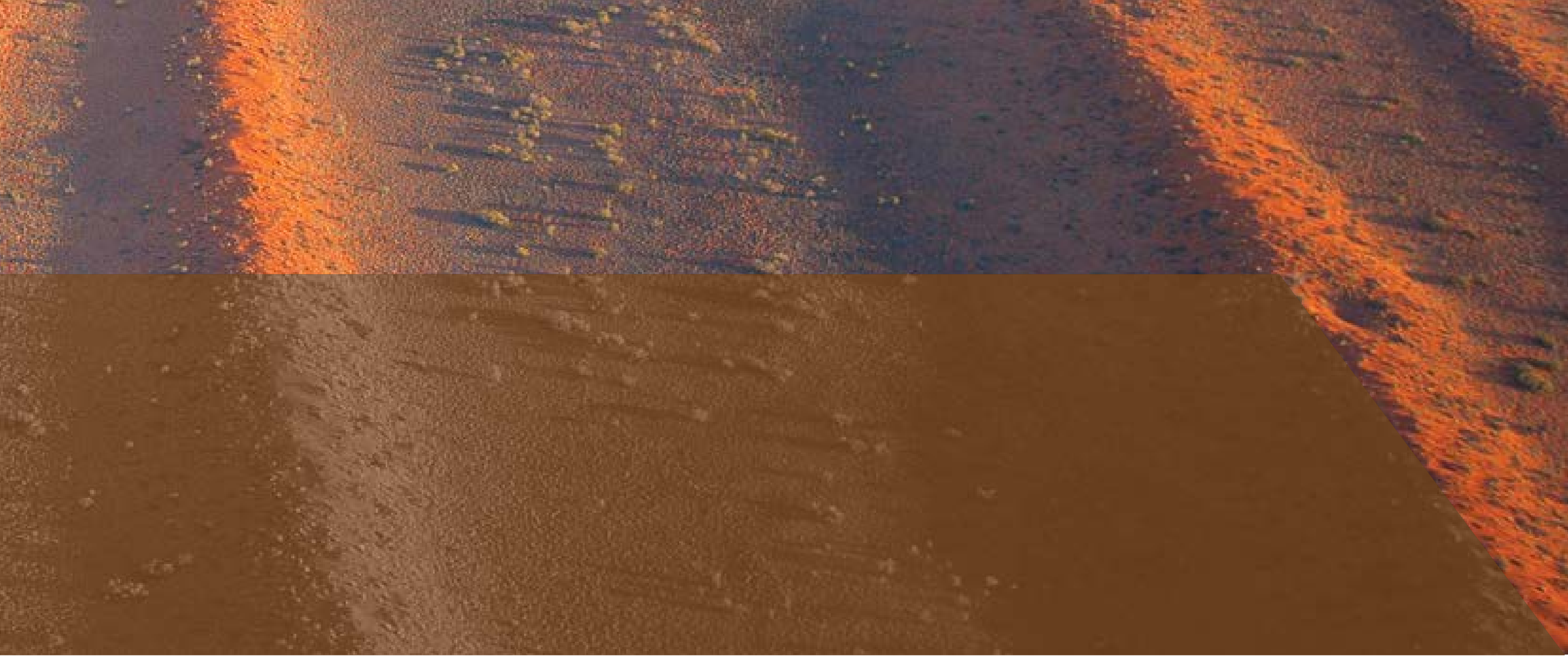
- investing in high-quality climate change research that contributes to peer-reviewed publications in national and international journals;
- ACCSP publications cited in the Assessment Reports produced by the Intergovernmental Panel on Climate Change;
- supporting scientists' contributions to important bilateral and multilateral relationships between Australia and other countries;
- supporting Australia's participation in international research, and our influence in international research priorities through such bodies as the World Climate Research Programme and the International Geosphere-Biosphere Programme; and
- supporting the Global Carbon Project, which aims to develop a comprehensive policy-relevant understanding of the global carbon cycle.

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

SCIENCE HIGHLIGHTS AT A GLANCE

Table 1. A snapshot of some of the science highlights within this report. These highlights are presented under seven key climate research themes.

KEY CLIMATE RESEARCH THEME	SOME SCIENCE HIGHLIGHTS	PAGE
Global and regional carbon budgets	**Greenhouse gas emissions still rising** Research shows that greenhouse gas emissions are still rising. To keep the global increase in temperature at levels of 2 °C or below, we need to significantly and quickly reduce greenhouse gas emissions.	16
	Full carbon balance for Australian continent A comprehensive assessment of the carbon stocks and flows in the Australian continent has found that its vegetation and soils are absorbing carbon dioxide from the atmosphere—but this uptake is low by global standards. On a unit-area basis, the Australian terrestrial carbon sink operates at only 40 per cent of the strength of the global average sink.	18
Land and air observations and processes	**Carbon uptake by Australia's temperate forests variable** Data from the Tumbarumba flux station confirms that the amount of carbon taken up by Australian cool temperate forest ecosystems can be highly variable. The data also shows that these ecosystems have the greatest rate of carbon uptake globally but that they are vulnerable to disturbance.	22
	Aerosols weakening subtropical jet Increasing atmospheric aerosols from the northern hemisphere in the latter part of the 20th century are likely to have contributed to a weakening of the southern hemisphere subtropical jet. This is in contrast to the effects of increasing greenhouse gases, which tend to strengthen the jet in climate model simulations.	24
Oceans and coasts observations, processes, and projections	**Ocean robots collect one millionth record** In 2012, the global Argo project involving Australia's leading ocean scientists collected its one millionth deep ocean temperature and salinity profile. The data collected from the 3,525 active Argo floats in the world's oceans is essential for tracking the changes in global and regional ocean heat and salinity patterns—which in turn affect the rate at which the level of the seas and oceans rise and reflect changes to the global water cycle.	30
	New measurements for ocean uptake of carbon dioxide Scientists have used ocean observations to directly measure the transfer of anthropogenic carbon dioxide (the extra carbon dioxide added by human activities like burning of fossil fuels) into the southern hemisphere oceans for the first time.	32



KEY CLIMATE RESEARCH THEME	SOME SCIENCE HIGHLIGHTS	PAGE
Modes of climate variability and change	**La Niña affects low-pressure systems** Innovative research has provided a possible explanation for two extreme flooding periods in January 1974 and January 2011. These simulations of past large-scale long-lasting climatic extremes will help researchers understand the roles of greenhouse gases and natural variability in the changing Australian climate.	40
	Future South Pacific climate more extreme Climate model projections show that future greenhouse warming could almost double the number of extreme floods, droughts, and tropical cyclones in South Pacific Island nations in the next 100 years.	42
Earth systems modelling and data integration	**Greenhouse gases cause faster warming** Climate simulations show that greenhouse gas emissions caused much faster warming than any other factor in the past 50 years.	46
	Ocean too acidic for marine life In little more than 50 years, it is likely that much of the ocean around Australia will no longer be suitable for coral formation. The increasing acidification in our oceans from greenhouse gas emissions won't just harm coral; it is also likely to harm the marine snails in the Southern Ocean.	47
Australia's future climate	**Warmer seas fuel tropical cyclones** Higher sea-surface temperatures from increasing greenhouse gas emissions may make tropical cyclones in northern Australia more intense and produce more rainfall.	52
	Fewer large waves from East Coast Lows The central east coast of Australia is likely to experience fewer days with large storm waves if greenhouse gas emissions continue to rise.	53
Management and communication	**Telling the climate change science story** Peer-reviewed work by more than 100 ACCSP scientists shows that human activities are affecting climate in the southern hemisphere and around the globe. This consistent finding is captured in 130 peer-reviewed papers that were published this year in well-known and highly-regarded local and international scientific journals.	58

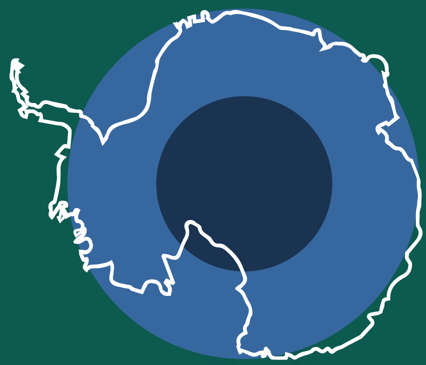
Go to *The year in review* to read all the science highlights and Appendix 1 for a complete list of ACCSP projects.

THE YEAR IN REVIEW

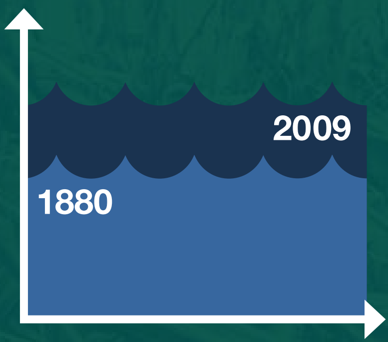
Key climate research themes:

14	Global and regional carbon budgets
20	Land and air observations and processes
28	Oceans and coasts observations, processes, and projections
36	Modes of climate variability and change
44	Earth systems modelling and data integration
48	Australia's future climate
56	Management and communication

IN LITTLE MORE THAN 50 YEARS,
it is likely that much of the ocean around Australia will no longer be suitable for coral formation.



THE OZONE ABOVE ANTARCTICA
has declined by more than 50 per cent since the 1970s.



THE SEA HAS RISEN BY 210 MM
between 1880 and 2009. It is continuing to rise at an average rate of more than 3 mm per year.

130

PEER-REVIEWED PAPERS
were published this year in highly-regarded local and international scientific journals.

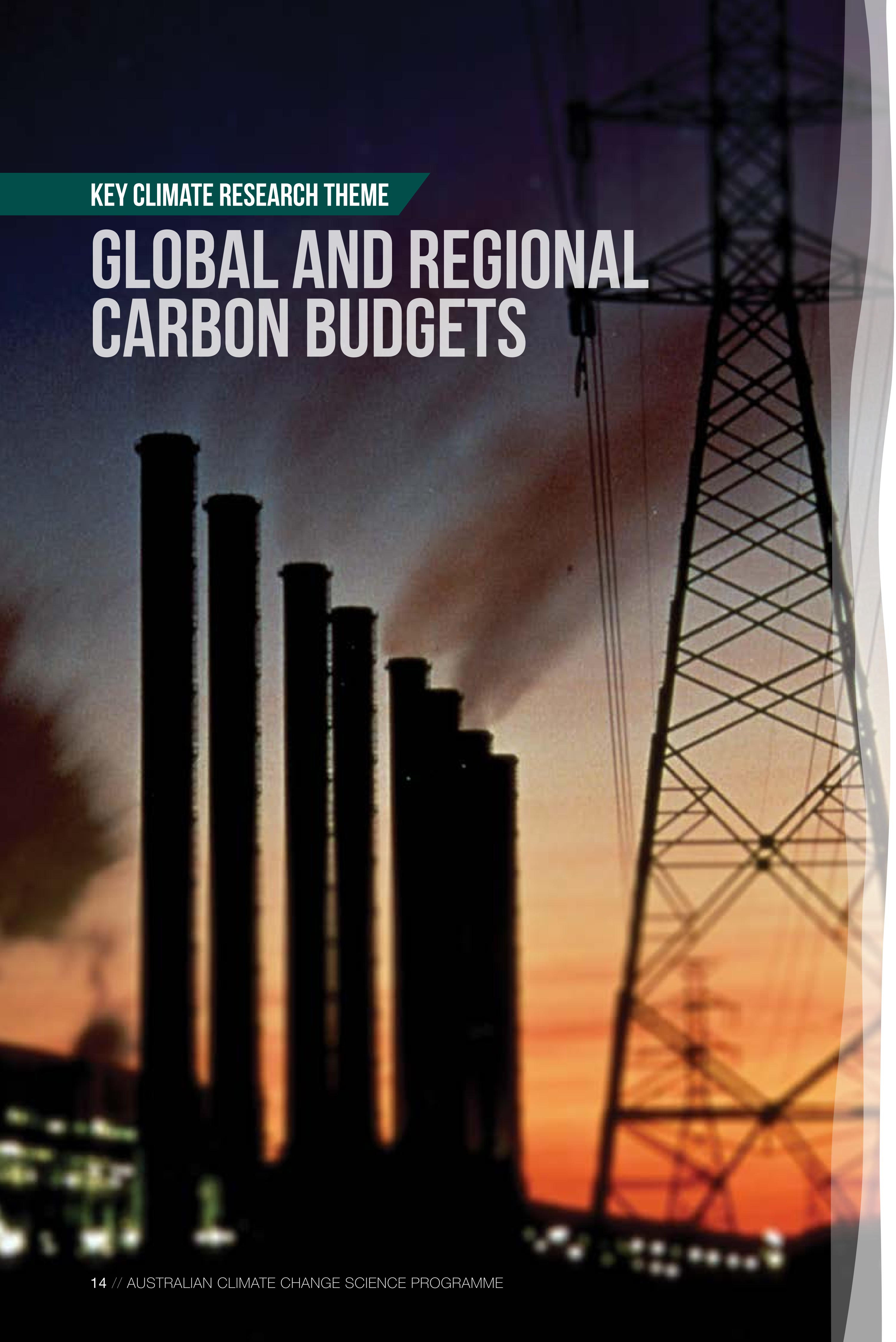
ACTIVE ARGO FLOATS
in the world's oceans in June 2013.

GLOBAL CARBON DIOXIDE
emissions in our atmosphere have increased from 6.1 billion tonnes of carbon in 1990 to an estimated 9.7 billion tonnes in 2012.

RECORD HOT WEATHER
affected much of Australia in the summer of 2012–13.

KEY CLIMATE RESEARCH THEME

GLOBAL AND REGIONAL CARBON BUDGETS



Climate change in the 21st century is being driven largely by increasing levels of atmospheric greenhouse gases generated by human activities.

A challenge is to track, understand and predict changes in greenhouse gas levels, and their movement through the atmosphere, land and oceans.

This is important because half of the atmospheric carbon dioxide is removed by terrestrial ecosystems (largely forests) and oceans, and there is uncertainty about their future capacity to continue storing carbon. Recent research suggests there is a weakening in the Southern Ocean's capacity to store carbon.

Methane and nitrous oxide are the second and third most important long-lived greenhouse gases after carbon dioxide. We also need to understand their sources and sinks to monitor and help predict future accumulation of these gases in the atmosphere.

A greater focus is needed on how rising temperatures and atmospheric carbon dioxide, changing moisture availability, and altered fire regimes will affect natural sinks. Observations and modelling of present (decades) and past (centennial to millennial) dynamics will help to unravel the processes controlling the accumulation of atmospheric greenhouse gases.

Robust knowledge on how the terrestrial and ocean sinks behave now and are likely to behave in the future is fundamental for guiding decisions on reducing emissions to achieve a given climate stabilisation target. This will inform national and international emission reduction targets.

Table 2. The *Global and regional carbon budgets* climate research theme is addressing the following policy questions.

SCIENCE INFORMING POLICY	KEY POLICY QUESTIONS
Mitigation	How much greenhouse gas are we emitting and what will the consequences be? What is the role of natural land and ocean sinks, in sequestering emissions and what will happen to these processes in the future? How can we use our natural land sinks and other natural processes to mitigate Australian emissions?
International	How are we tracking to limit warming to specific targets (such as the 2 °C warming target) and what level of emissions reduction is needed to meet targets? How can Australia contribute to and influence international negotiations? Is the 2 °C warming limit sufficient and what are the implications of going beyond the 2 °C target?

Greenhouse gas emissions still rising

Research shows that greenhouse gas emissions are still rising. To keep the global increase in temperature at levels of 2 °C or below, we need to significantly and quickly reduce greenhouse gas emissions[3].

Global carbon dioxide emissions in our atmosphere have increased from 6.1 billion tonnes of carbon in 1990 to 9.5 billion tonnes in 2011. This is an average annual growth rate of 1.9 per cent each year in the 1980s, 1 per cent each year in the 1990s, and 3.1 per cent each year since 2000.

CSIRO project leader Dr Pep Canadell estimates that in 2012 emissions are likely to be 9.7 billion tonnes of carbon or 2.6 per cent above 2011. This highlights the mitigation challenge, because this increase is in line with the most carbon-intensive emission scenarios identified by the Intergovernmental Panel on Climate Change (IPCC) (Figure 1).

3. Peters et al., 2013, The challenge to keep global warming below 2 °C, Nature Climate and The relationship between peak warming and cumulative CO_2 emissions, and its use to quantify vulnerabilities in the carbon–climate–human system, *Tellus B* – see Appendix 3.

Methane – the other culprit

Carbon dioxide is not the only culprit in greenhouse gas emissions. Methane is the second most important greenhouse gas driving human induced-climate change.

Methane in the atmosphere has also increased in the past four years after a period of relative stability. Dr Canadell said the likely cause is increased emissions from fossil fuel burning and emissions from wetlands in the tropics and boreal regions (Figure 2).

This is a highlight of the peer-reviewed paper called 'The challenge to keep global warming below 2 °C' – see Appendix 3 for more details.

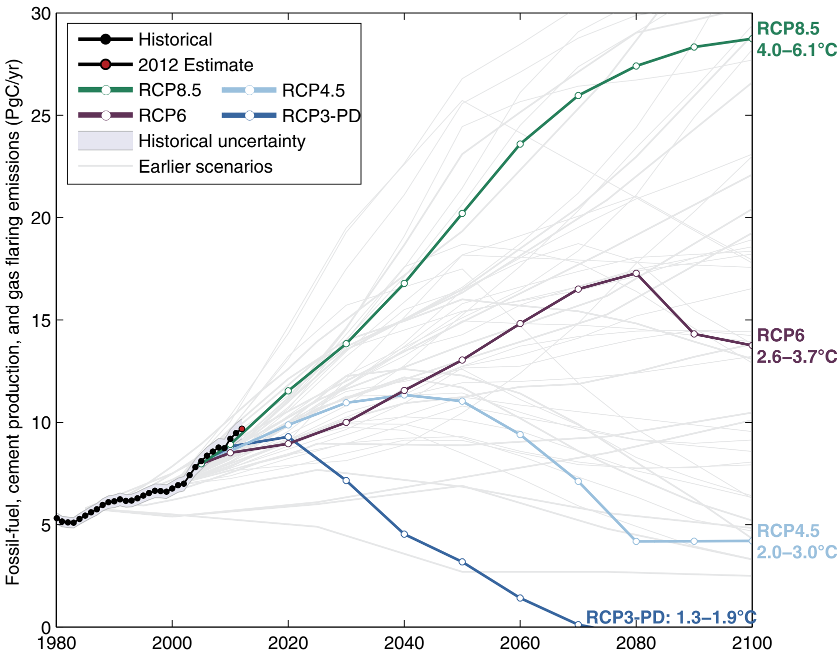


Figure 1. Observed fossil fuel emissions of carbon dioxide and the Intergovernmental Panel on Climate Change (IPCC) emission scenarios show that if greenhouse gas emissions continue to increase as fast as they are doing now, then the global temperature is estimated to reach 4–6 °C above preindustrial levels by 2100. The graph shows the uncertainties in observed fossil fuel, cement, and gas flaring emissions of carbon dioxide from 1980 to 2012 due to inaccurate reporting, particularly from less developed countries. Four IPCC scenarios are shown to 2100 which range from low (blue line) to high (red line). These scenarios or RCPs (called Representative Concentration Pathways) are used in the IPCC 5th Assessment Report. The graph also shows other older scenarios from the literature (faint lines).

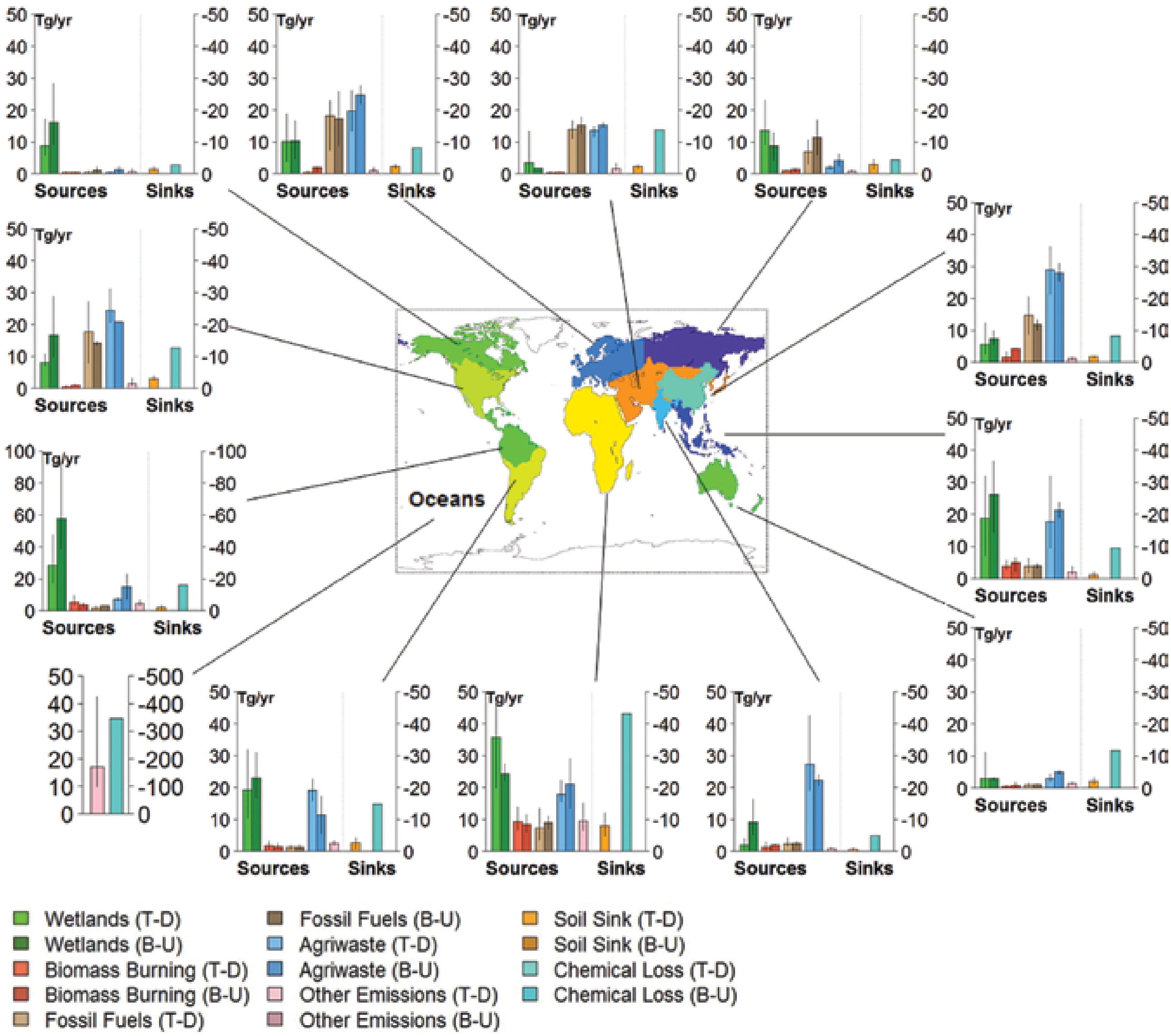


Figure 2. The likely causes of increased emissions methane gases are from burning fossil fuels and emissions from wetlands in the tropics and boreal regions. This map shows nine regions of the globe, plus separate regions for India, China, and Southeast Asia and one region for oceans. The human and natural sources and sinks for each region show seven types of greenhouse gas emissions. Each of these groups show Top-Down (T-D) estimates, i.e. using observations of atmospheric changes; and Bottom-Up estimates (B-U) i.e. using inventories, and biogeochemical modelling. Oceans are considered one large region with ocean emissions and chemical loss occurring over the ocean. Source: Centre for Australian Weather and Climate Research.

Full carbon balance for Australian continent

A comprehensive assessment of the carbon stocks and flows in the Australian continent has found that its vegetation and soils are absorbing carbon dioxide from the atmosphere – but this uptake is low by global standards.

On a unit-area basis, the Australian terrestrial carbon sink operates at only 40 per cent of the strength of the global average terrestrial sink.

CSIRO project leader Dr Vanessa Haverd said that in Australia (and globally) carbon uptake is largely due to the effect of rising carbon dioxide on vegetation growth, with a smaller contribution from natural and human-induced climate variations. She said the uptake varies from year to year depending on whether it's wet or dry – more carbon is absorbed in wet years when plant growth is greater, and in dry years, much of this carbon is returned to the atmosphere.

Higher temperatures from rising greenhouse gas emissions will affect the ability of the Australian landscape to take up more carbon.

Under likely future scenarios of rising greenhouse gas emissions, the net carbon uptake by the Australian continent is likely to increase due to rising carbon dioxide. However, it will simultaneously decrease by almost the same amount through the warming caused by increasing greenhouse gas emissions.

This project also uses the deep connections between the carbon and water cycles to find the sensitivities of the Australian terrestrial water balance to human-induced climate change and natural climate variability.
A significant new result is that evaporation and water runoff also respond to warming and rising carbon dioxide – warming increases evaporation and reduces runoff, while rising carbon dioxide has the opposite effect. Under likely future scenarios, these effects nearly cancel each other.

This is a highlight of peer-reviewed papers called 'The Australian terrestrial carbon budget' and 'Sensitivities of the Australian terrestrial water and carbon balances to climate change and variability' – see Appendix 3 for more details.

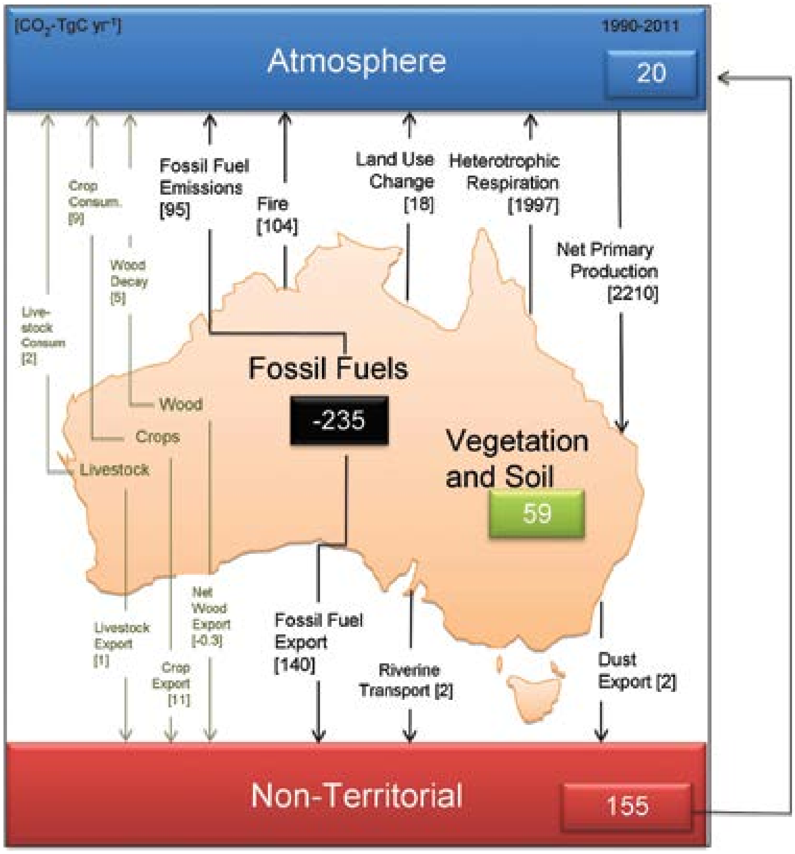


Figure 3. The Australian Terrestrial Carbon Budget (1990–2011) shows the magnitude of carbon exchanges between the Australian territory, the atmosphere, and non-territorial stocks. The positive numbers in the boxes represent net carbon flows per year into carbon stocks, with negative numbers representing outflow. Arrows show the direction of all carbon flows contributing to these changes.

Net Primary Production (plant growth) represents a flux of 2,210 TgC (teragrams of carbon) per year into vegetation. This is largely offset by heterotrophic respiration (decay) at 1,997 TgC per year, with smaller contributions from fire, land-use change, harvest and export by rivers and dust. Together, all these processes result in a net carbon uptake of 59 ± 35 TgC per year into Australian vegetation and soils.

Fossil fuel emissions from the Australian territory (95 ± 6 TgC per year) and fossil-fuel exports (140 ± 8 TgC per year), together make up a total flow of carbon out of Australian fossil-fuel stocks to the atmosphere of 235 ± 15 TgC per year.

New record of past atmospheric changes

Measurements of air from polar ice cores and firn (compacted snow) have provided a new record of the changes in the concentration and isotopic composition of carbon dioxide for the past 1,000 years. This record provides a new benchmark for modelling the carbon cycle and climate of the industrial period and the preceding centuries.

CSIRO project leader Dr David Etheridge looked at the isotopes of carbon dioxide to trace the movement of carbon between its main sources and sinks. He said the new record reveals decadal changes in carbon dioxide exchanges with the terrestrial biosphere and the ocean (Figure 4). He said both of these reservoirs took up significant amounts of the carbon dioxide emissions from about 1850 AD. The isotopic record confirms that emissions from industrial and land-use sources caused the overall increase in carbon dioxide over this period.

Dr Etheridge's team and other researchers will use carbon cycle models to simulate the carbon dioxide variations so they can improve the ability of climate models to represent carbon sinks in a future warming climate.

Other research findings from measurements of polar ice include:

- Non-methane hydrocarbons (such as ethane and propane) emissions in the atmosphere increased from the 1940s to about 1970–1980 and declined thereafter. Automotive emissions controls and changing practices in natural gas production were the likely causes of these changes and suggest that similar changes in the growth rate of atmospheric methane were also linked to changes in fossil fuel emissions.
- Deep ice cores extracted from Greenland suggest that the reduction of the Antarctic ice sheet was a greater cause of the higher global sea levels during the last interglacial (warm period) than previously thought. This suggests that Antarctic ice may be more vulnerable to future warming caused by increasing greenhouse gas emissions.

Future research will continue to measure the atmospheric variations of the main greenhouse gases over past tens to thousands of years to help improve the performance of models being used for long-term future simulations of the atmosphere and climate.

This is a highlight of the peer-reviewed paper called 'A revised 1000 year atmospheric ^{13}C–CO_2 record from Law Dome and South Pole' – see Appendix 3 for more details.

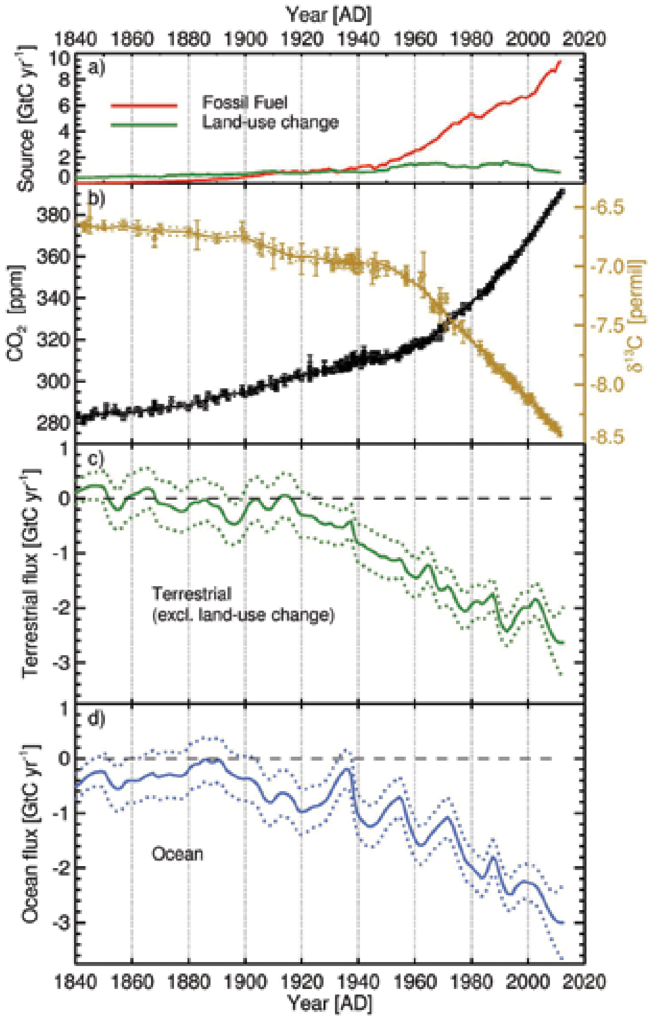
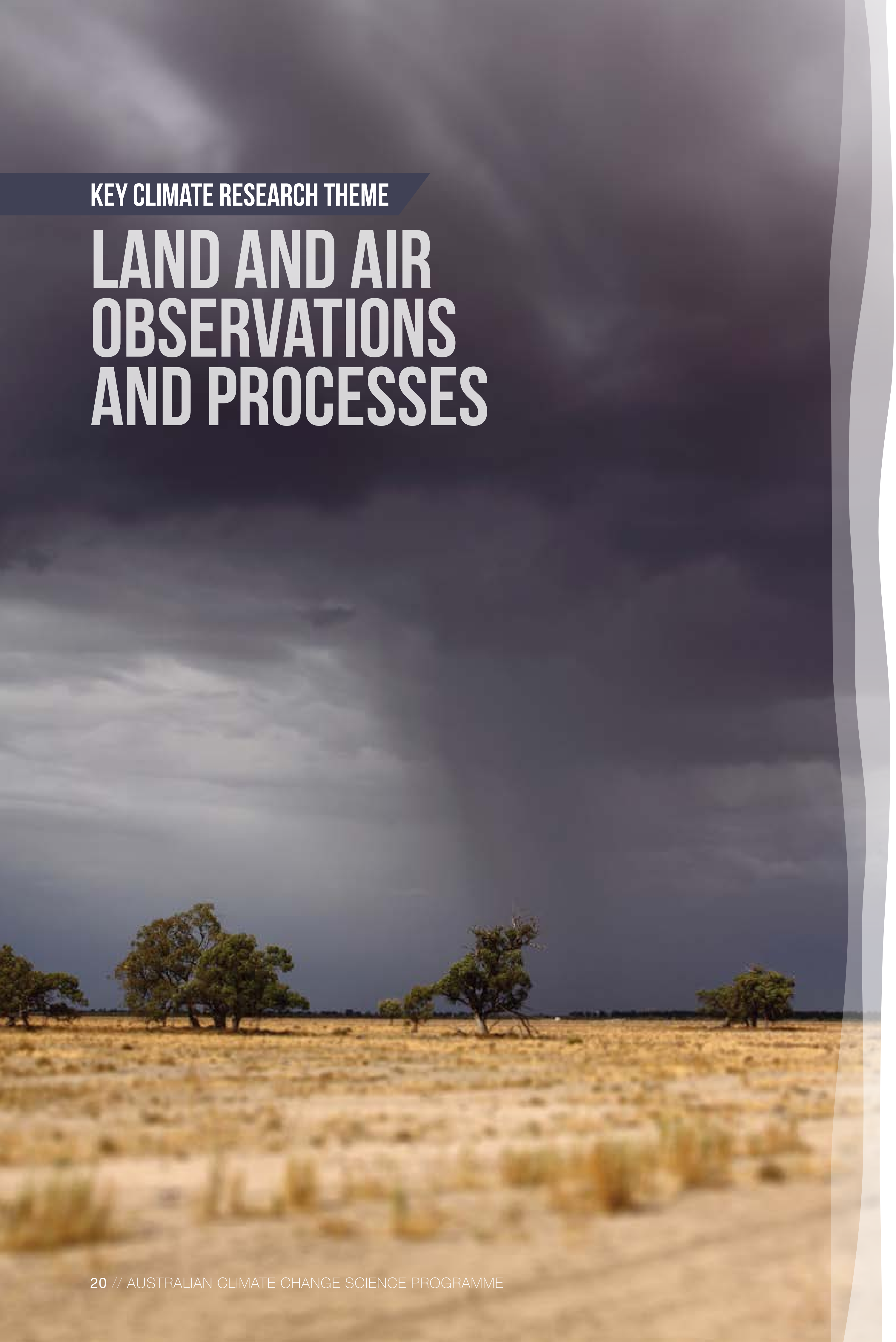


Figure 4. This series of four graphs covers the period 1840 to the present. The first graph shows the rise in emissions of carbon from fossil fuel use from virtually zero to approximately 10 gigatonnes of carbon per year. However emissions from land use change, although significant; now represent a decreasing fraction of total global emissions. The second graph shows an increase in atmospheric carbon dioxide concentration from 280 parts per million to almost 400 parts per million with a simultaneous decline in carbon-13 levels. The third graph shows terrestrial uptake of carbon increasing from the early 1900s to approximately 2 gigatonnes of carbon per year now. The fourth graph shows oceanic uptake of carbon increasing from the mid-1900s to almost 3 gigatonnes of carbon per year now.



KEY CLIMATE RESEARCH THEME

LAND AND AIR OBSERVATIONS AND PROCESSES

A challenge is to improve our ability to predict atmospheric behaviour across various time scales. To do this, we need to address major gaps that remain in our understanding of atmospheric behaviour and its effects on the weather, the seasonal climate and interactions with marine and terrestrial ecosystems.

Australia's climate is susceptible to atmospheric changes in carbon dioxide, aerosols and stratospheric ozone.

While Australian ecosystems can absorb significant amounts of carbon from the atmosphere, we do not know how much carbon they can continue taking up as greenhouse gases continue increasing. We are also unsure how vulnerable they are to future warming.

Although human-generated aerosols have long been known to exert a cooling effect on the climate, the extent to which they do so is one of the major uncertainties in climate change. Without this 'masking' of the effects of increasing greenhouse gases, current global warming would be more severe than it is, but the size of this effect is poorly known.

There is also increasing evidence that these aerosols have changed wind and rainfall patterns in the southern hemisphere and the Australian region. Global emissions of human-generated aerosols are projected to decrease sharply in the next few decades – this will accelerate global warming, and reverse aerosol-induced effects on weather patterns that have developed over recent decades.

More work is needed to refine climate projections in this area by improving our understanding of key atmospheric processes that are treated in climate models. These include:

- aerosols;
- aerosol-cloud interaction;
- atmospheric chemistry;
- atmospheric transfer of radiation;
- clouds and convection;
- stratospheric ozone depletion; and
- how the warming or cooling effects from greenhouse gases, aerosols and ozone (and the associated feedbacks) interact with the atmospheric/ocean events that influence Australian climate, for example:
  - the El Niño–Southern Oscillation;
  - the Sub-Tropical Ridge;
  - the Indian Ocean Dipole; and
  - the Southern Annular Mode.

In scenarios where greenhouse gas emissions continue to rise, Australia is likely to continue to see significant changes to its weather and climate.

Table 3. The *Land and air observations and processes* climate research theme is addressing the following policy questions.

SCIENCE INFORMING POLICY	KEY POLICY QUESTIONS
Mitigation	How much greenhouse gas are we emitting and what will the consequences be? What is the role of natural land and ocean sinks in sequestering emissions and what will happen to these processes in the future? How can we use our natural land sinks and other natural processes to mitigate Australian emissions?
Adaptation	How has the climate changed in the past and what can this tell us about the future? What changes in the climate are we observing today and can we attribute them to human influences? What changes in climate and extreme weather events are likely on timescales of years to decades to a century? How can we best prepare for low likelihood but high impact consequences of climate change?

Carbon uptake by Australia's temperate forests variable

Data from the Tumbarumba flux station confirms that the amount of carbon taken up by Australian cool temperate forest ecosystems can be highly variable. The data also shows that these ecosystems have the greatest rate of carbon uptake globally but that they are vulnerable to disturbance. This finding is based on the high-quality ecosystem data from the Tumbarumba flux tower in the Bago State forest in south-eastern New South Wales.

The Tumbarumba flux station is part of OzFlux – the national ecosystem research network that provides the Australian and global ecosystem modelling communities with consistent observations of energy, carbon and water exchange between the atmosphere and key Australian ecosystems.

Project leader Dr Eva van Gorsel said CSIRO's micrometeorology team has increased the Tumbarumba dataset from 11 to 12 years. This has enabled the team to explain why carbon exchange varies so much from year to year (Figure 5). Incoming shortwave radiation, spring minimum temperatures, and varying amounts of leaf cover on the trees explain most of the variability in annual net ecosystem exchange of carbon in Tumbarumba. Disturbance is another other big factor. In 2003, an insect attack in Tumbarumba was triggered when climate conditions turned from cool and wet to hot and dry, which strongly affected the ecosystem's ability to take up carbon.

OzFlux data, which has good coverage in space and time, will help researchers to better identify key climate processes and responses to increased greenhouse gas emissions. It will also help researchers understand how the sink strength of terrestrial ecosystems is affected by meteorological drivers. Long time series, such as the Tumbarumba dataset, are particularly valuable when the researchers start looking at potential changes in these drivers.

The Tumbarumba flux station datasets can be accessed at www.portal.tern.org.au and www.ozflux.org.au

This is a highlight of the peer-reviewed paper called 'Primary and secondary effects of climate variability on net ecosystem carbon exchange in an evergreen Eucalyptus forest' – see Appendix 3 for more details.

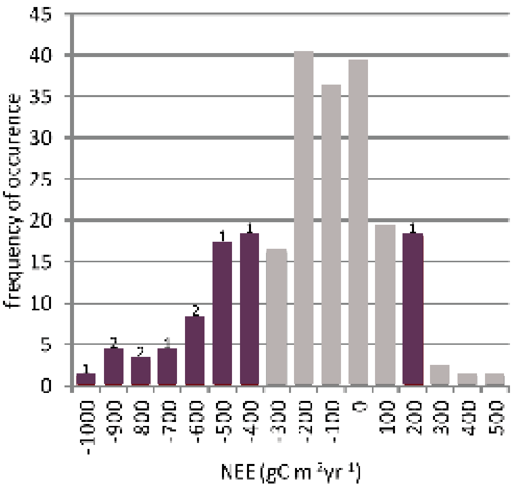


Figure 5. Australian cool temperate forest ecosystems can have very high inter-annual variability of carbon exchange. This can be seen by the comparing the distribution of a total 227 years of net ecosystem carbon exchange data in the global flux network with the distribution observed in Tumbarumba. Red bars indicate bins that include data from Tumbarumba. The number on top of each red bin indicates the number of years of data from Tumbarumba in that bin. Bars to the left (large negative numbers) show the years where an ecosystem has taken up carbon, and bars to the right (positive numbers) show the years where an ecosystem has lost carbon to the atmosphere. This is what happened in 2003–2004 when an insect attack in Tumbarumba was triggered by a change in weather conditions – see the only red bar on the right hand side with a positive number for the net ecosystem exchange. NEE is the abbreviation for net ecosystem exchange.

MORE ABOUT TUMBARUMBA FLUX STATION

The Tumbarumba flux station is located in the Bago State forest in south eastern New South Wales: 35° 39’ 23.8” S 148° 09’ 06” E.

The forest is classified as wet sclerophyll – the dominant species is *Eucalyptus delegatensis*, and average tree height is 40 m. Site elevation is 1,200 m and average annual rainfall is 1,000 mm. The Bago and Maragle State Forests are adjacent to the south-west slopes of southern New South Wales and the 48,400 ha of native forest have been managed for wood production for more than 100 years.

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

This network of towers is the OzFlux Facility of Australia’s Terrestrial Ecosystem Research Network and is part of a global network of more than 400 flux towers, most of which are located in the northern hemisphere.

Data collected from OzFlux is used to improve our understanding of the response of carbon and water cycles in Australian ecosystems to climate variability, disturbance (fire, insects), land management and future changes in rainfall, temperature and carbon dioxide levels. It is also being used to test and develop land-surface models.

Aerosols weakening subtropical jet

Increasing atmospheric aerosols (tiny airborne particles such as soot and dust) from the northern hemisphere in the latter part of the 20th century are likely to have contributed to a weakening of the southern hemisphere subtropical jet. This is in contrast to the effects of increasing greenhouse gases, which tend to strengthen the jet in climate model simulations.

CSIRO researcher Dr Leon Rotstayn said it is important to understand the causes of the observed weakening of the jet during the past few decades, because the weaker jet has been linked to decreasing rainfall over south-west Western Australia. The jet refers to strong westerly winds in the upper atmosphere that are most prominent around latitude 30°S over Australia (Figure 6) – these winds provide an important energy source for winter storm formation.

Newer generation climate model simulations explain how increasing aerosols in the northern hemisphere are likely to have weakened the jet, by changing the temperature difference between the northern and southern hemispheres. Climate projections for the 21st century are driven by a combination of increasing greenhouse gases and decreasing aerosols – this research is a key step towards teasing apart the roles of these different drivers, which will help to reduce the uncertainties in rainfall projections.

This work – which focuses on the connections between aerosols in the northern hemisphere and Australian climate – is supported by research on Australian tropical aerosols based on 14 years of data collected by CSIRO and the Bureau of Meteorology from three sites in the Northern Territory. CSIRO researcher Dr Ross Mitchell said that the observed data shows great similarity among the three sites (Figure 7). This means the seasonal influence of aerosols on Australia's tropical climate can now be included in climate models to represent the aerosol effects across the top end of the Northern Territory using relatively coarse resolution in space and time.

While aerosol simulations can successfully capture the seasonal cycle of Australian tropical aerosol, further work is needed to integrate model simulations with observed data to understand and explain the processes that contribute to Australian aerosol.

Future aerosol trends also need investigating because human-generated aerosols from the northern hemisphere are projected to decrease in the next few decades, whereas future Australian tropical aerosol trends are unclear. This research will give a clearer picture of the ways in which future changes in aerosols – both in the northern hemisphere and in Australia – contribute to Australian climate change.

This is a highlight of the peer-reviewed papers called 'Anthropogenic effects on the subtropical jet in the southern hemisphere: aerosols versus long-lived greenhouse gases' and 'The climatology of Australian tropical aerosol: Evidence for regional correlation' – see Appendix 3 for more details.

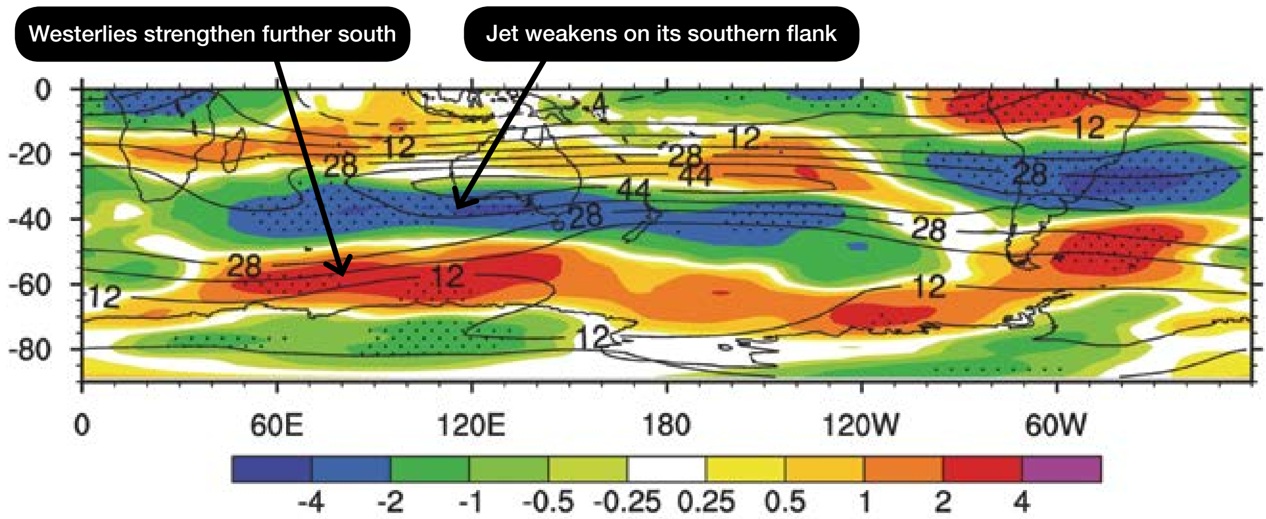


Figure 6. This simulation from a newer-generation climate model shows winter westerly wind trends induced by increasing human-generated aerosols from 1950 to 2005 in the southern hemisphere at 300 hPa altitude (about 9,000 metres). The cool colours show weakening westerly wind trends, and the warm colours show strengthening westerly wind trends. The colour shading is overlaid on contours of the mean winter westerly winds at the same altitude (averaged over the period 1986 to 2005). The contours show that the mean westerly winds at this altitude are strongest around latitude 30°S, especially in the vicinity of Australia and the western Pacific Ocean – this feature is called the subtropical jet. Increasing atmospheric aerosols over tropical Australia in the latter part of the 20th century are likely to have contributed to a weakening of the subtropical jet, especially on its southern flank. There is also likely to have been a strengthening of the westerly winds over the Southern Ocean, which has been seen in observed trends over the past few decades.

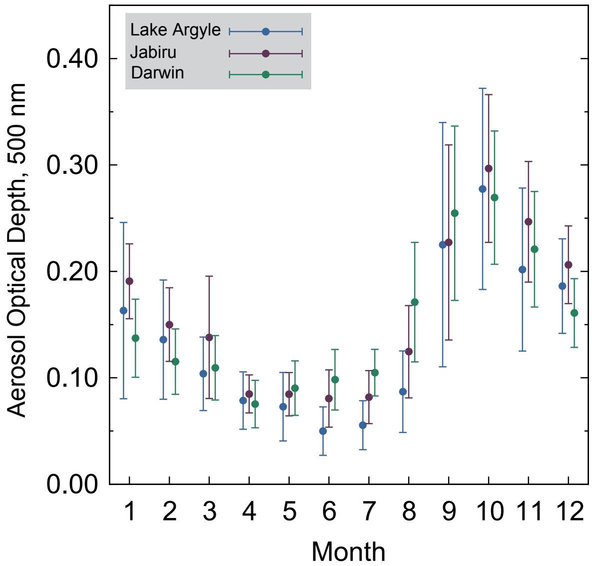


Figure 7. A time series of the annual cycle of aerosol optical depth at three stations in Northern Australia (Lake Argyle, Jabiru and Darwin) shows that aerosol loading is lowest in the late autumn and peaks in spring. The filled circles indicate monthly means, while the vertical bars represent the uncertainty. Aerosol optical depth is a measure of the total aerosol loading for particle sizes that are effective at reflecting or absorbing solar radiation. There is also a high degree of coherence among the three sites, both in the seasonal variation and magnitude of aerosol optical depth.

MORE ABOUT AEROSOLS

Aerosols are fine particles suspended in the atmosphere, which tend to exert a cooling effect on the climate. Natural aerosol sources include volcanoes, dust storms and sea spray. Sources of human-generated aerosols include industry, motor vehicles and burning vegetation. The main Australian sources are dust and particles produced from burning tropical vegetation.

The projected decrease in global emissions from human-generated aerosols in the next few decades may accelerate the warming effect of greenhouse gases. It may also reverse recent climate trends caused by increasing aerosols. There is huge uncertainty about the effects of aerosols from Asia, the largest source of human-generated aerosols. It is therefore important for researchers to distinguish the climatic effects of human-generated aerosols from those of greenhouse gases.

Recent research suggests that wind patterns close to Australia – such as the subtropical jet – are sensitive to changes in aerosol emissions from the northern hemisphere. We currently know little about the effects of Australian aerosols on wind and rainfall – any future work would combine modelling and observations to determine the effects of aerosols from both Australian and distant sources.

New sea ice and snow feedback findings

New model analysis shows that Arctic sea ice is likely to be more responsive to warming caused by greenhouse gas emissions than to natural climate variability. The simulations also show that Antarctic sea ice is likely to respond to natural shorter-term temperature fluctuations in the same way as it does for warming caused by greenhouse gas emissions.

These findings are significant. For the first time climate models have explored sea ice and snow responses (or albedo feedbacks) to warming from rising greenhouse gas emissions over a range of timescales. Called 'albedo' feedback – because sea ice and snow change the surface reflectivity or 'albedo,' – the research has unveiled new findings for seasonal, interannual, decadal, and climate change (hundreds of years) timescales.

In the Arctic, the average modelled climate response on interannual and decadal timescales is much weaker compared with longer climate change timescales (Figure 8). Project leader Dr Rob Colman said this was likely because sea ice is unable to change rapidly in response to short-term (say year-to-year) natural climate variability in comparison to longer (multi-decadal) warming caused by greenhouse gas emissions. By contrast, albedo over northern land responds similarly at all timescales (including seasonal) because snow melts quickly when temperatures are increased.

Dr Colman said the surprising result is that Antarctic sea ice appears to respond rapidly – in models at least – to natural shorter-term temperature fluctuations. One hypothesis for the different behaviour is that the Arctic ice is 'trapped' within a land boundary, whereas Antarctic sea ice extends unconstrained into the Southern Ocean.

Further research is needed to clarify the different behaviours and processes operating in the Antarctic and Arctic. This will also help assess the effectiveness of this modelling and other modelling for water vapour, cloud and temperature feedbacks.

This is a highlight of the peer-reviewed paper called 'Surface albedo feedbacks from climate variability and change' – see Appendix 3 for more details.

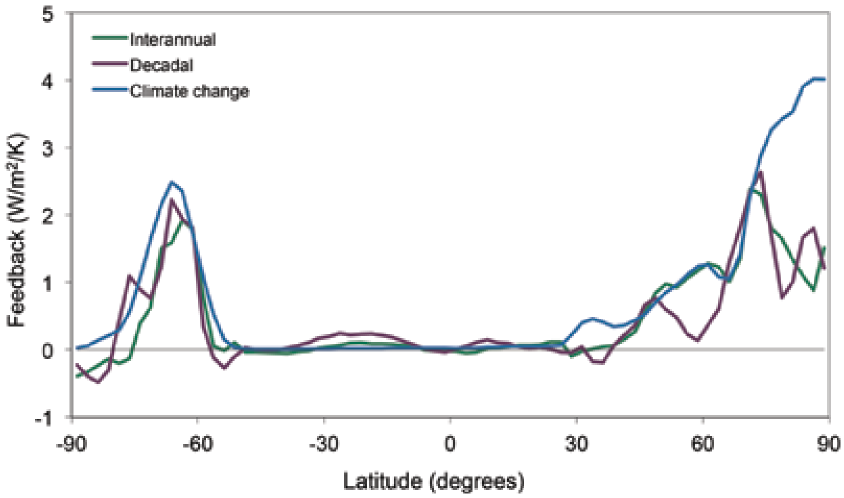


Figure 8. On average, Coupled Model Intercomparison Phase 3 models show that in the Arctic, climate response to a global increase in temperature on interannual and decadal timescales is weaker compared with longer climate change timescales. The plot shows 'feedback', which is the extra reinforcing warming (in W/m^2 or Watts per square metre) which occurs when global temperature increases by 1 Kelvin (or 1 °C). While feedbacks can occur on a range of timescales, the ones shown here are from interannual temperature variations, from decadal temperature changes and from the multi-decadal to centennial timescale of climate changes. The lines agree quite closely over southern latitudes (regions of Antarctic sea ice, far left), over northern hemisphere mid-latitudes (continental snow), but disagree over the high Arctic (Arctic sea ice regions, far right).

MORE ABOUT CLIMATE FEEDBACKS

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 amplifies or dampens the climate response to any changes in greenhouse gases generated by humans.

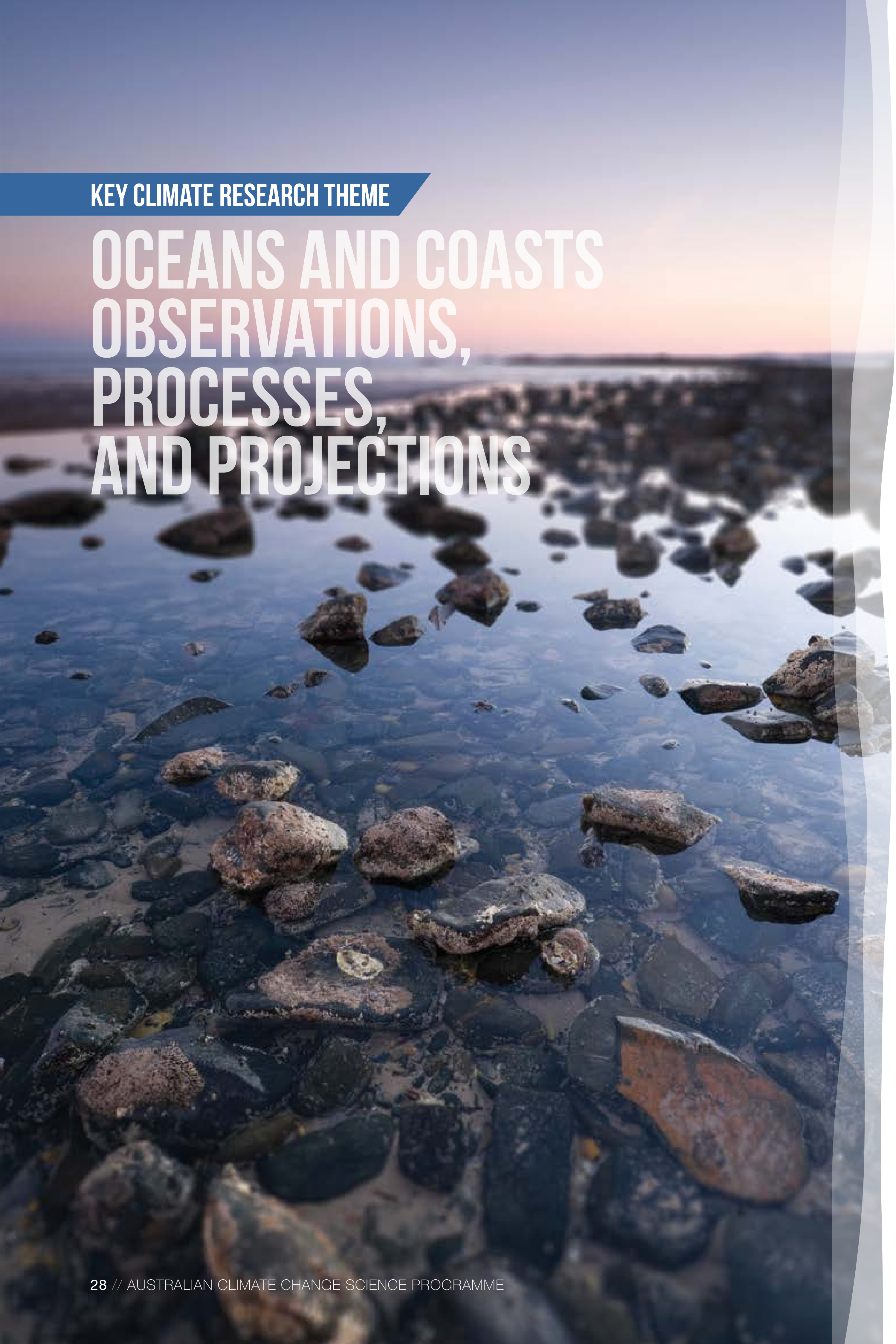
Researchers are unable to directly measure or evaluate most climate change feedbacks that occur over decades or centuries because there are insufficient climate records for these long timescales.

The researchers therefore look at observed processes that occur within shorter timescales – for example, changes to water vapour over the 'natural' variations in climate during a seasonal cycle, say, from summer to winter, from year to year or from decade to decade.

If the researchers can better understand and model these 'feedbacks,' then they can reduce the uncertainties in global climate change modelling for a given set of greenhouse emissions. This will also decrease uncertainties for regional-scale projections and help decision makers develop policies for adapting to climate change and set reduction targets.

KEY CLIMATE RESEARCH THEME

OCEANS AND COASTS OBSERVATIONS, PROCESSES, AND PROJECTIONS



Sea level is rising and oceans are getting warmer and more acidic. Their salinities and currents are also changing. This is affecting many marine species by changing the distribution of their available habitats and putting some ecosystems at risk. In Australia, we are already seeing the impact of this on the corals of the Great Barrier Reef and the kelp forests off north-eastern Tasmania.

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.

Australian rainfall is tightly linked to temperature and circulation patterns in the Indian, Pacific and Southern Oceans. Changes in the oceans may therefore affect water availability on land.

Changes in ocean properties can also be used to track climate change – more than 90 per cent 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.

As ocean temperatures rise, the global water cycle intensifies due to the ability of warmer air to hold and redistribute more moisture. This means areas that are wet will get wetter and those that are dry will get drier. This could have a significant impact on the Australian climate which is already highly variable. The only way to meet the challenge of these changes is to study and understand the underlying causes.

The challenge is to provide quality science-based information about the likely changes in sea level, storm surge and extreme weather events so that decision makers can manage the risks associated with and minimise the consequences of climate change caused by human activity.

To address these challenges, Australian science is:

- looking at the major effects of rising sea levels, past sea-level changes, the factors contributing to rising sea-levels, how extreme sea-level events might change, what is known in each area, and what research and observations are needed to reduce the uncertainties in our understanding of sea-level rise so that more reliable projections can be made;
- monitoring changes in sea-surface temperature and the circulation of the Southern, Indian and Pacific Oceans to help us understand their influence on rainfall patterns across southern Australia and the impacts for society and ecosystems;
- tracking changes in ocean carbon sinks using atmospheric and ocean monitoring to determine how the global carbon budget is responding to climate change, and to constrain estimates of carbon sinks on land;
- investigating the extent and timing of ocean acidification so we can determine the vulnerability of ecosystems from tropical coral reefs to the high latitude waters of Antarctica shelfs; and
- detecting and attributing changes in the oceans, and understanding how they constrain rates of warming in the present and in the future.

Table 4. The *Oceans and coasts observations, processes, and projections* climate research theme is addressing the following policy questions.

SCIENCE INFORMING POLICY	KEY POLICY QUESTIONS
Mitigation	How much greenhouse gas are we emitting and what will the consequences be? What is the role of natural land and ocean sinks, in sequestering emissions and what will happen to these processes in the future?
Adaptation	How has the climate changed in the past and what can this tell us about the future? What changes in the climate are we observing today and can we attribute them to human influences? What changes in climate and extreme weather events are likely on timescales of years to decades to a century?
International	How are we tracking to limit warming to specific targets (such as the 2 °C warming target) and what level of emissions reduction is needed to meet targets? How can Australia contribute to and influence international negotiations?

Ocean robots collect one millionth record

In 2012, the global Argo project involving Australia's leading ocean scientists collected its one millionth deep ocean temperature and salinity profile.

The data collected from the 3,525 active Argo floats in the world's oceans is essential for tracking the changes in global and regional ocean heat and salinity patterns—which in turn affect the rate at which the level of the seas and oceans rise and reflect changes to the global water cycle. Argo floats also track the source and start of ocean-driven climate modes that affect Australian climate extremes, such as El Niño and the Indian Ocean Dipole.

CSIRO's Dr Susan Wijffels, who leads Australia's contribution to the Argo project, said this Argo milestone is a significant achievement compared to the past 150 years during which the global research vessel fleet collected little more than half a million comparable deep ocean profiles (Figure 9). Very few of these profiles were in the southern hemisphere ocean around Australia. Through strong involvement with Australia's Integrated Marine Observing System (IMOS), Australia now has 371 active floats—the second largest number of floats globally (Figure 10).

The Australian research team further contributes to national and international tracking of ocean change and processes by:

- combining 20-year time series data to look at the changes in the circulation of the Tasman/Coral Sea over decades;
- monitoring the inflows and outflows of the Tasman and Coral seas and identifying areas with warm water pathways;
- monitoring, in a national first, the full ocean boundary current off Brisbane in collaboration with IMOS;
- leading and completing a new study on quantifying more accurately, small but climatically important, biases in historical and modern ocean data—this work is now the basis of corrections being carried out by international data centres and groups interested in planetary heat and sea-level budgets (including those assembled for the Intergovernmental Panel on Climate Change 5th Assessment Report); and
- organising an international workshop on further assembling and quality-controlling all historical ocean profile data.

This is a highlight of the peer-reviewed paper called 'Robust evidence of human-induced global ocean warming on multi-decadal time scales'— *see Appendix 3 for more details.*

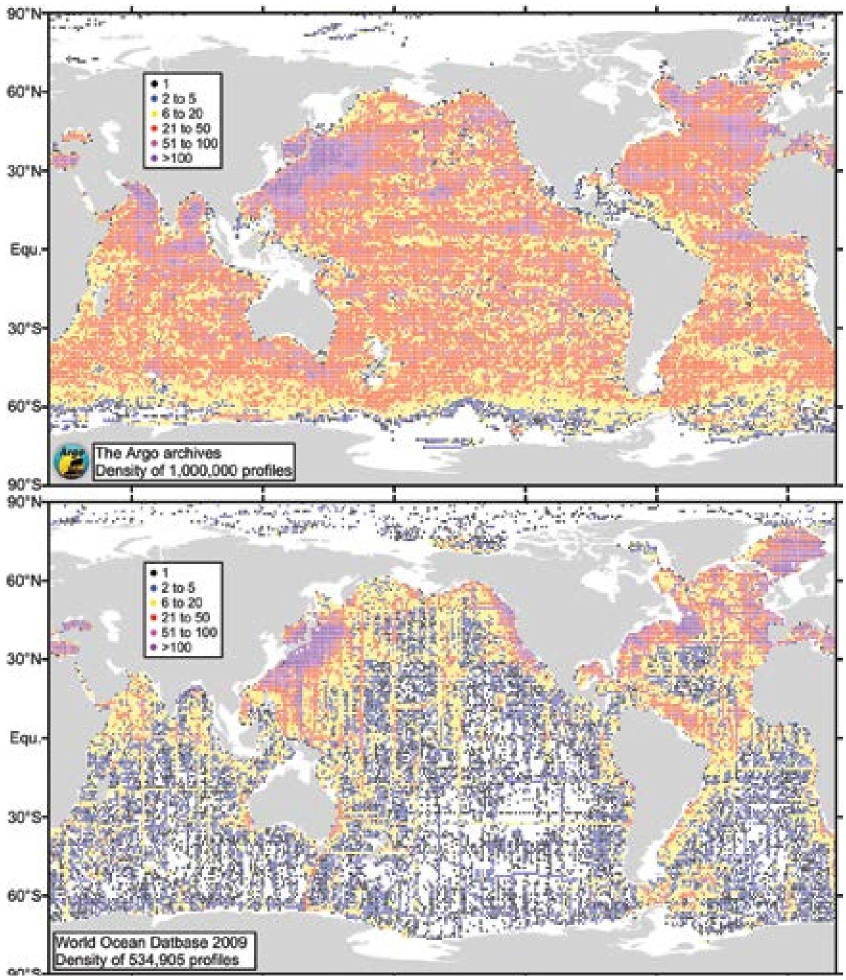


Figure 9. In 10 years, the Argo project has significantly increased the number of high-quality deep ocean temperature and salinity profiles compared to the total taken in the previous 150 years. As a result, coverage in the southern hemisphere has been radically changed. This is shown by the number of profiles in 1° by 1° squares. The lower panel shows from 1860 to 2009 there were 534,905 ship-based salinity profiles to a depth of 1,000 m. The upper panel shows the equivalent plot for Argo data for the past 10 years (Source Howard Freeland).

MORE ABOUT ARGO FLOATS

The average life span of the latest APEX Argo floats is around three and a half years or approximately 135 cycles. Australia's Argo floats are lasting about seven years. However, there are several floats that have been operating for almost nine years and are still returning good data.

Argo floats provide temperature and salinity measurements of the upper 2,000 m of the water column at 10 day intervals. The measurements reveal the detailed structure of the ocean beneath the sea surface. When not profiling, the floats drift with the ocean currents at a particular 'parking' depth (usually 1,000 m for Australian floats) which enables estimates of deep current velocity to be obtained.

Argo floats provide the following data:

- Profile – temperature and salinity measurements with depth.
- Trajectory – where the floats have drifted. For example, an Argo float that was initially set up in the south of Tasmania in the Southern Ocean has drifted at 1,000 m depth for six years with the Antarctic Circumpolar Current and is currently approaching Drake Passage.

- Real time – Argo data is freely and publicly available within 24 hours of the float transmitting its profile data.
- Delayed – The delayed mode data stream is subject to an internationally standardised and rigorous quality control procedure by oceanographic experts. Sensors are checked and adjusted for drift in pressure and salinity by comparison with ship-based water mapping data.

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

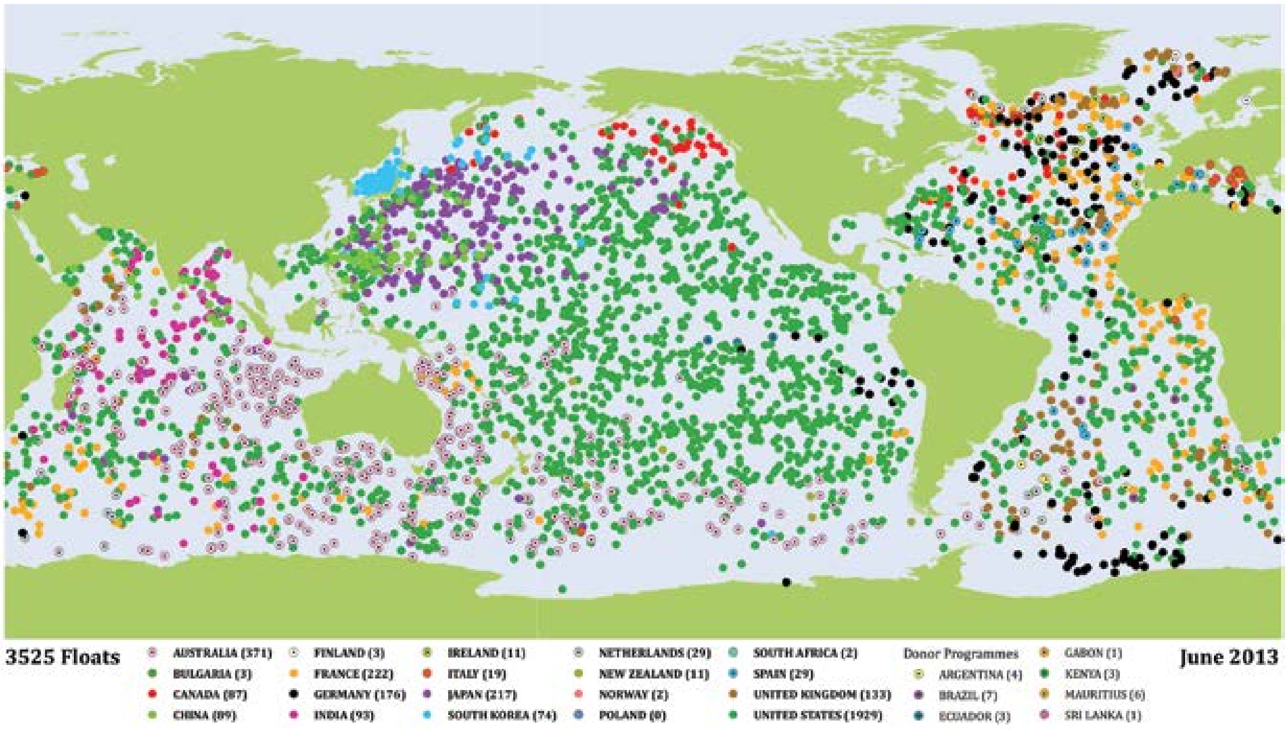


Figure 10. Argo floats are uniformly distributed across the globe, except for areas covered by sea ice. In June 2013, there were 3,525 active Argo floats in the world's oceans. While about 20 nations deploy Argo floats, only a handful maintain most of the array. After the USA, with more than 50 per cent of the Argo floats, Australia is one of the next most significant contributors with 371 active floats.

New measurements for ocean uptake of carbon dioxide

Scientists have used ocean observations to directly measure the transfer of anthropogenic carbon dioxide into the southern hemisphere oceans for the first time.

The study shows that 0.42 ± 0.2 billion tonnes per year of anthropogenic carbon dioxide (the extra carbon dioxide added by human activities like burning of fossil fuels) is transferred from the surface mixed layer into the ocean interior between 35° S and the marginal sea-ice zone.

CSIRO project leader Dr Steve Rintoul said the results were a surprise because most of the transfer occurs in very localised regions. They also suggest that ocean carbon storage is sensitive to wind, ocean eddies, and changes in the surface mixed layer—all properties that are likely to change in a climate responding to increasing greenhouse gas emissions.

These findings are significant because the Southern Ocean is considered to be one of the most important regions on earth for removing carbon dioxide from the atmosphere. There are also concerns that the ocean's ability to take up carbon dioxide will decrease with increasing greenhouse emissions.

Worldwide, oceans have helped slow the rate of climate change by taking up about 25 per cent of carbon dioxide emissions. The Southern Ocean is particularly important because it accounts for about 40 per cent of the total ocean storage of carbon produced by human activities.

Future work will continue to address key uncertainties in ocean climate science using observations and modelling to further understand the drivers of climate variability and change and to help improve their representation in climate models.

This is a highlight of the peer-reviewed paper called 'Localised subduction of anthropogenic carbon dioxide in the southern hemisphere'—see Appendix 3 for more details.

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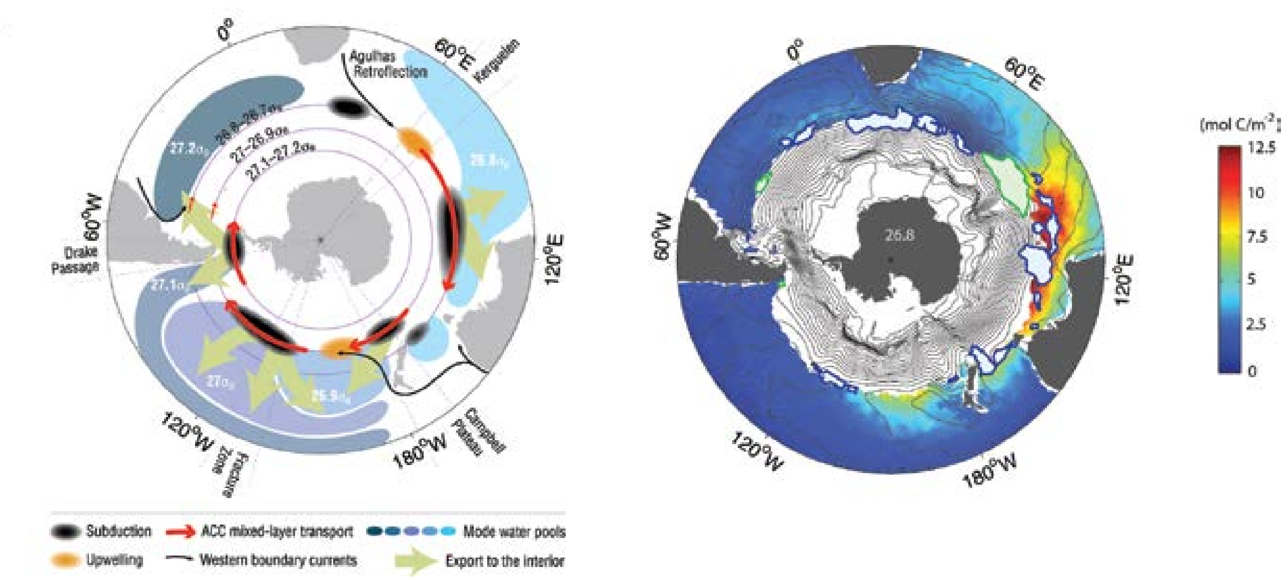


Figure 11. Two diagrams show how the ocean uptake the ocean uptake of carbon dioxide generated by humans has been quantified from observations for the first time. The left diagram shows a view of the localised windows in the southern hemisphere oceans, where carbon dioxide is transferred from the surface mixed layer into the ocean interior. Each density surface 'breathes' through a narrow region, where wind forcing, eddy fluxes and variations in mixed layer depth along the flow cause the transfer of carbon dioxide. The right diagram shows anthropogenic carbon dioxide entering the ocean through the subduction windows. The plume of anthropogenic carbon dioxide (red and yellow colours) can be seen entering the Indian Ocean from a transfer window in the south-eastern part of the basin. The black lines indicate flow paths.

Reasons for rising seas much clearer

The rises we have observed in global and regional sea levels since 1990 are due to a combination of factors including the ocean expanding as it gets warmer, melting glaciers and ice sheets, and natural climate processes, such as the El Niño–Southern Oscillation.

This has been confirmed by an evaluation of the ability of newer generation climate and glacier models to simulate sea-level rises that occurred in the 20th century while taking into account these natural processes and increasing greenhouse gas emissions. CSIRO researcher Dr John Church said the simulations agree with the observed sea-level records and give researchers more confidence in sea-level projections for this century.

Closer to home, projections for Australia's coastline show that future changes to extreme rises in sea levels, caused by changes in the weather, are likely to be within 5–10 cm of current climate values. This indicates that future changes will be dominated by the changes in the average sea level due to warming oceans and melting glaciers and ice sheets.

CSIRO project leader Dr Kathleen McInnes said while increases in sea levels from weather changes are generally small, the impacts may be large in some locations. For example, some projections indicate there may be larger increases in extreme sea levels over the Gulf of Carpentaria. This appears to be connected to changes in the monsoon winds in austral summer and potential changes in natural variability in the tropical climate system.

The projections also show a likely southward shift of the subtropical ridge and new global wave projections indicate higher waves in the Southern Ocean. The change in these weather patterns could lead to more frequent easterly winds and local waves together with higher Southern Ocean swell reaching exposed coastlines in south-eastern Australia.

Future research will include updating and improving in situ and satellite estimates of the changes in sea levels and maintaining an international role in verifying and calibrating satellite readings. This will help researchers to understand the causes of the observed changes to sea levels and how these changes may influence our coastlines.

This is a highlight of the peer-reviewed paper called 'Twentieth-century global-mean sea-level rise: is the whole greater than the sum of the parts'— see Appendix 3 for more details.

MORE ABOUT SEA-LEVEL RISE

Increasing greenhouse gas emissions will cause changes to sea levels and changes to extreme sea-level events. Even if there are no changes in extreme weather conditions (e.g. increases in tropical cyclone intensity), rising sea-levels would cause more frequent extreme sea level events. Depending on local conditions, events that occur once every 100 years could occur as frequently as once every few years by 2100.

Globally, the sea has risen by 210 mm between 1880 and 2009. It is continuing to rise at a fairly steady rate of more than 3 mm per year. The speed at which it is rising is contributing to the flooding problems of low-lying island states like Tuvalu, Kiribati and the Maldives. It is also exacerbated in some areas (e.g. Gippsland, Victoria and the Gulf coast of the US) where land is subsiding.

Find out more about sea-level rise at www.cmar.csiro.au/sealevel/sl_impacts_sea_level.html

Simulations agree on carbon uptake

Atmospheric and ocean simulations are agreeing more on how much carbon is being taken up by the Southern Ocean each year.

Dr Bronte Tilbrook and Dr Andrew Lenton led an international effort that looked at how models that simulate the amounts of carbon taken up by the Southern Ocean compare with estimates based on observations.

The study involving 26 atmospheric and ocean simulations shows that for the entire Southern Ocean, the annual uptake of carbon for all models is consistent with an estimate based on observations. Despite this good result, none of the models were capable of simulating both the seasonal changes in the carbon uptake and the regional patterns seen in observations.
Dr Tilbrook said this raises concerns about using the existing models, which need to be improved, to project future changes in the Southern Ocean carbon sink.

This work is helping the researchers identify where the processes represented in the models can be improved. This will lead to greater confidence in the predictions of the future ocean carbon sink in response to climate change and variability.

The study is the first comprehensive one of its kind in the Southern Ocean. It was made possible by the increasing number of carbon measurements made in recent years. The measurements provide more confidence in the observational-based estimates of the sea-air exchange and are the foundation for understanding the physical and biological interactions that control the exchange.

Findings from this research are building our understanding of the Southern Ocean—one of the most important regions on earth for removing carbon dioxide from the atmosphere.

This is a highlight of the peer-reviewed paper called 'Sea-air CO_2 fluxes in the Southern Ocean for the period 1990–2009'—see Appendix 3 for more details.

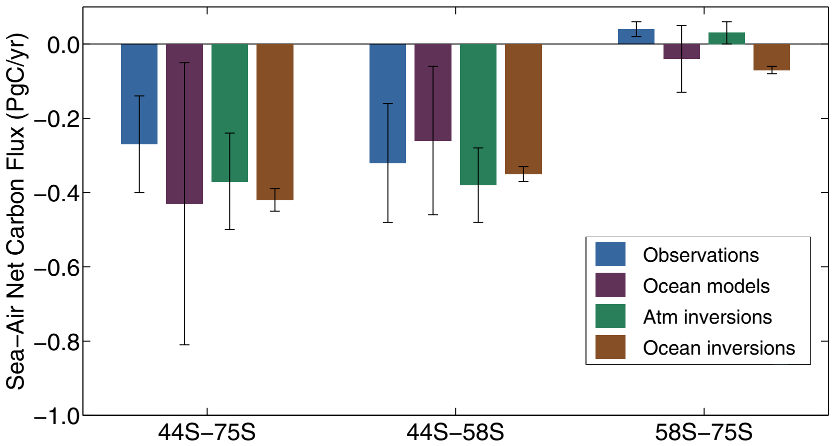
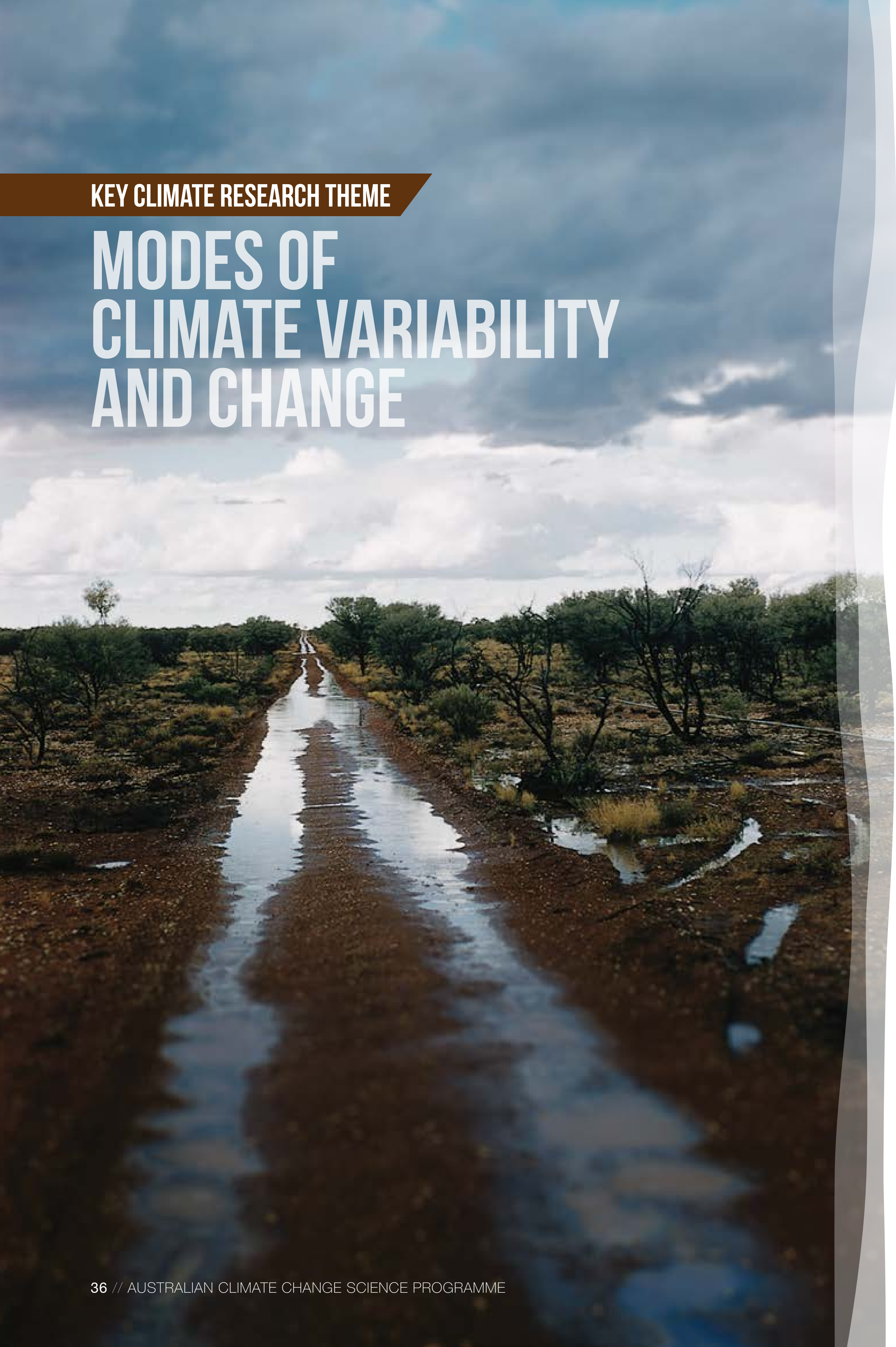


Figure 12. Comparison of three groups of atmospheric and ocean simulations show that for the entire Southern Ocean, the annual uptake of carbon for all models is consistent with an estimate based on observations. The annual sea-air flux estimates are measured in petagrams of carbon per year (PgC/yr). The observations and models show general agreement when integrated over the year for the entire Southern Ocean from 44°S to 75°S latitude (44S–75S), with most annual uptake occurring in the sub-polar region to 58°S latitude (44S–58S). The annual sea-air flux for the high latitude band, poleward of 58°S latitude (58S–75S) is smaller than and more variable than the sub-polar region with observations and atmospheric inversions indicating a slight release of carbon dioxide to the atmosphere (positive sea-air flux) and ocean biogeochemical models and ocean inversions suggesting a small uptake of carbon. The rate that carbon is absorbed by the ocean is called the sea-air flux—negative values show a net uptake of carbon by the surface ocean and positive values show a net release of carbon to the atmosphere.

KEY CLIMATE RESEARCH THEME

MODES OF CLIMATE VARIABILITY AND CHANGE



Australia's climate is highly variable across the continent, as well as from year to year. Extreme weather events such as tropical cyclones and East Coast Lows produce high rainfall over short timeframes, often with significant impacts.

In recent decades, we have seen:

- increased spring and summer monsoonal rainfall across Australia's north;
- higher than normal rainfall across central parts of the continent; and
- decreased late autumn and winter rainfall across the south.

A challenge is to provide better information about likely future climates to help manage Australia's water resources in a changing environment.

Our demand for water is continuing to grow to meet the needs of expanding urban areas, agriculture, and energy. However, climate model projections suggest long-term drying over southern areas during winter and over southern and eastern areas during spring.

Research also indicates that long periods of diminished rainfall and increased evaporation may become more frequent as a result of changes to the climate from rising greenhouse gas emissions.

We therefore need to study the observed changes in rainfall, weather systems, and the climate system more broadly to understand if, and how, they are affected by rising greenhouse gas emissions. This has the potential to improve our ability to predict water availability on seasonal and longer scales, to help with adaptation and decision-making. The areas we need to study are:

- large scale drivers of interannual and decadal variability in the hydrological cycle—El Niño–Southern Oscillation, the Indian Ocean Dipole (IOD), and the Southern Annular Mode; and
- links between climate change and the hydrological cycle, with particular reference to changes in the strength of the monsoon, the Walker circulation and the IOD.

Table 5. The *Modes of climate variability and change* climate research theme is addressing the following policy questions.

SCIENCE INFORMING POLICY	KEY POLICY QUESTIONS
Adaptation	What changes in the climate are we observing today and can we attribute them to human influences? What changes in climate and extreme weather events are likely on timescales of years to decades to a century?
International	How can Australia contribute to and influence international negotiations?

Walker Circulation has strengthened

The Walker Circulation, one of the world's largest and most important wind systems, has strengthened, offsetting the weakening over much of the 20th century identified by previous research. Changes in the Walker circulation drive changes in rainfall, severe weather, agricultural production, and river flow in many parts of the world, including Australia.

Despite good progress in the ability of models to simulate many aspects of climate, the latest generation of climate models do not seem able to reproduce this strengthening, observed during 1980–2012. If these findings from preliminary research that compared 20 global climate models hold true, then this lowers the confidence in the ability of these models to project changes later this century to the Walker circulation. Bureau researcher Dr Greg Kociuba said further work is needed to understand how and why the Walker circulation might have already changed.

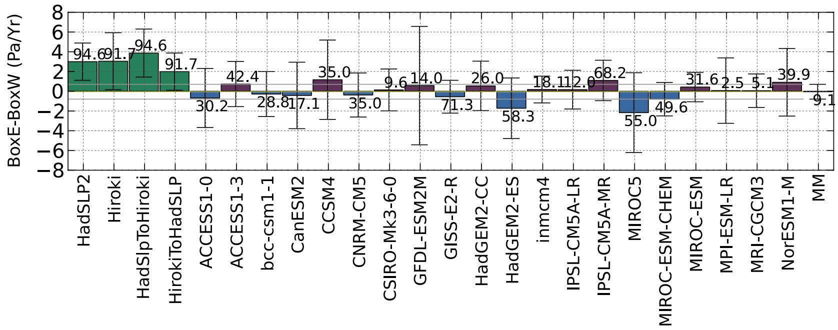


Figure 13. Changes in the strength of the Walker Circulation from 1980–2012 can be seen using four observational estimates (green) and 20 Coupled Model Intercomparison Phase 5 models (purple for positive trends, and blue for negative trends). All of the observational estimates show a statistically significant strengthening. In contrast, there is no agreement among the models on the sign of the trend and none of the model trends are statistically significant. The strength of the Walker circulation was measured using the difference in mean sea-level pressure, averaged over two boxes: one in the western equatorial Pacific, the other in the eastern equatorial Pacific.

MORE ABOUT THE WALKER CIRCULATION

Changes in the Walker Circulation are linked to changes in rainfall, temperature, river flow, disease, crop yield and fire risk. Previous ACCSP research showed that the Walker Circulation was weaker during 1977–2006 than at any other time in recorded history. This more recent research indicates that the Walker circulation strengthened during 1980–2012, offsetting earlier weakening.

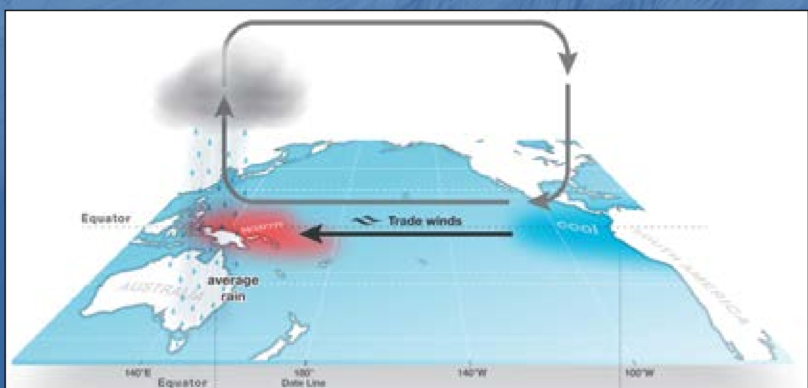


Figure 14. The Walker Circulation (see the grey arrows moving in clockwise direction) comprises the equatorial easterly trade winds near the surface of the ocean, rising air in the west to the north of Australia, westerly winds in the upper atmosphere, and subsiding air in the east. The trade winds push the warm equatorial surface waters to the west, while at the same time driving the upwelling of cool waters in the east.

Monsoonal rainfall likely to be more variable

Newer generation climate models show the Australian monsoon system could become more variable year to year by the end of this century due to increasing greenhouse gas emissions. Extreme daily rainfall events could also intensify across the Australian tropics.

Bureau researcher Dr Aurel Moise said this work built on previous analysis of projected changes to the Australian monsoon. He assessed new generation coupled global circulation models for their ability to project changes in average rainfall and changes to the variability of rainfall in response to global warming. This information is critical because a more variable rainfall climate could lead to a more extreme rainfall across northern Australia.

The models show wet years are likely to become relatively wetter and dry years are likely to become relatively drier (Figure 15). If the levels of greenhouse gases are increased, then the changes in extreme rainfall are likely to be more pronounced than any changes in average rainfall. More extreme rainfall is linked with a stronger percentage of change compared to recent decades (Figure 16).

These results were presented at the *Understanding and prediction of monsoon* climate four-day workshop which was held in Melbourne in November 2012. This workshop brought together a large group of international and national researchers. There were 58 presentations covering topics from monsoon weather, seasonal prediction and climate change.

This is a highlight of the peer-reviewed paper called 'Climate projections for Australia: a first glance at CMIP5' – see Appendix 3 for more details.

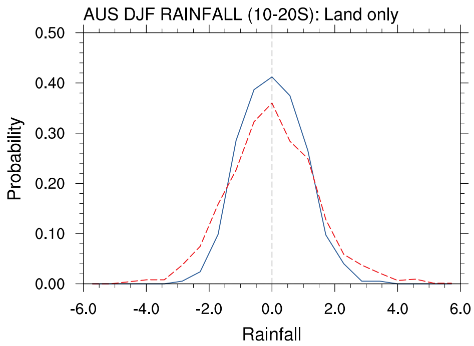


Figure 15. Australian summer rainfall across the tropics will become more variable under increased greenhouse gas conditions. The black solid curve represents rainfall variability over the recent decades, while the red dashed curve indicates projected rainfall variability during the last decades in the 21st century. This indicates that wet monsoon years will become relatively wetter and dry monsoon years will become relatively drier by the end of the 21st century.

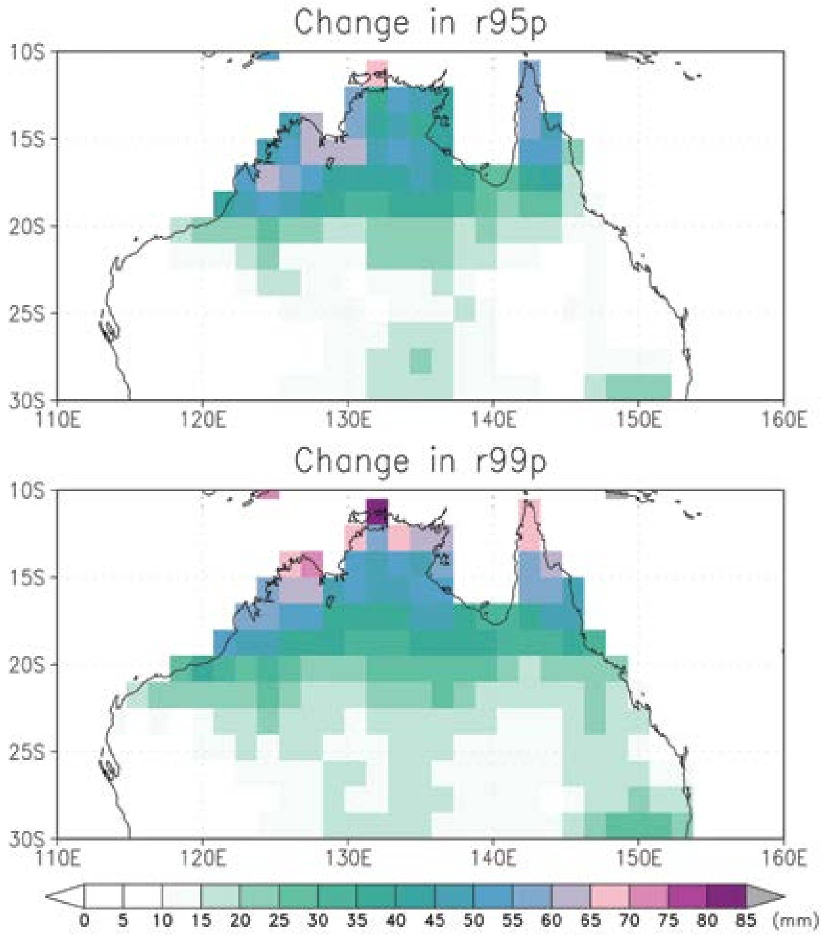


Figure 16. Two maps of tropical Australia each show changes in different strength of extreme rainfall across the region. New generation climate model simulations find that the intensity of extreme daily rainfall events will intensify (blue to purple colours further north in both maps) across tropical Australia with increased greenhouse gas conditions. There is a stronger increase in the intensity of the more extreme daily rainfall events (bottom map – r99p, representing the top 1 per cent of rainfall events) compared to the less extreme rainfall events (top map – r95p, representing the top 5 per cent of rainfall events).

MORE ABOUT THE AUSTRALIAN MONSOON

The Australian monsoon system 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. These moisture-laden winds originate from the Indian Ocean and southern Asian waters. The north Australian wet season includes the monsoon months but can extend several months on either side. Parts of the north Queensland coast also receive significant rainfall throughout the cooler months. In the top-end of the Northern Territory, the wet season generally occurs from October through to April, while in some other parts of tropical Australia, particularly in Western Australia, the wet months are often only from about January to March.

Any changes in the timing, positioning and intensity of the rainfall systems associated with the Australian monsoon, due to increasing greenhouse gases caused by humans, would affect the mining and grazing industries which are located in tropical Australia and vulnerable to wet season rainfall.

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 in Northern Australia.

La Niña affects low-pressure systems

Innovative research has provided a possible explanation for two extreme flooding periods in January 1974 and January 2011. These simulations of past large-scale long-lasting climatic extremes will help researchers understand the roles of greenhouse gases and natural variability in the changing Australian climate.

CSIRO researcher Dr Jorgen Frederiksen said in terms of rainfall and flooding in Australia, the 1973–1976 and 2010–2012 periods are considered the two most severe La Niña events since 1900. He said analysis of these events showed that in 2011 higher sea surface temperatures (SSTs) in the western Pacific, due to an unusually strong negative Indian Ocean Dipole (IOD), caused lower pressure over the Indian Ocean, Australia, Indonesia and the western Pacific (Figure 17). The higher SSTs also caused above-average levels of atmospheric moisture. These low pressure systems persisted over Australia with help from blocking high-pressure systems in the Tasman Sea and easterly onshore winds (Figure 17). There was a similar case in January 1974, though with a weaker negative IOD and smaller SST variances. In both cases, the persistent low pressure systems were increased by unusually rapidly growing tropical atmospheric disturbances.

This work helps researchers understand whether any trends in rainfall and weather systems throughout Australia are predominantly ongoing or random. The outcomes of this work give decision makers a better understanding of the future likelihood, risks and impacts of similar extreme events.

Future research will integrate statistical and modelling methods to understand the roles of natural climate change and that caused by humans. It will also try to understand the three-way interaction between climate change, modes of variability, and weather systems.

This is a highlight of the peer-reviewed paper called 'Synoptic and dynamical analyses of ENSO extreme events over Australia'—see Appendix 3 for more details.

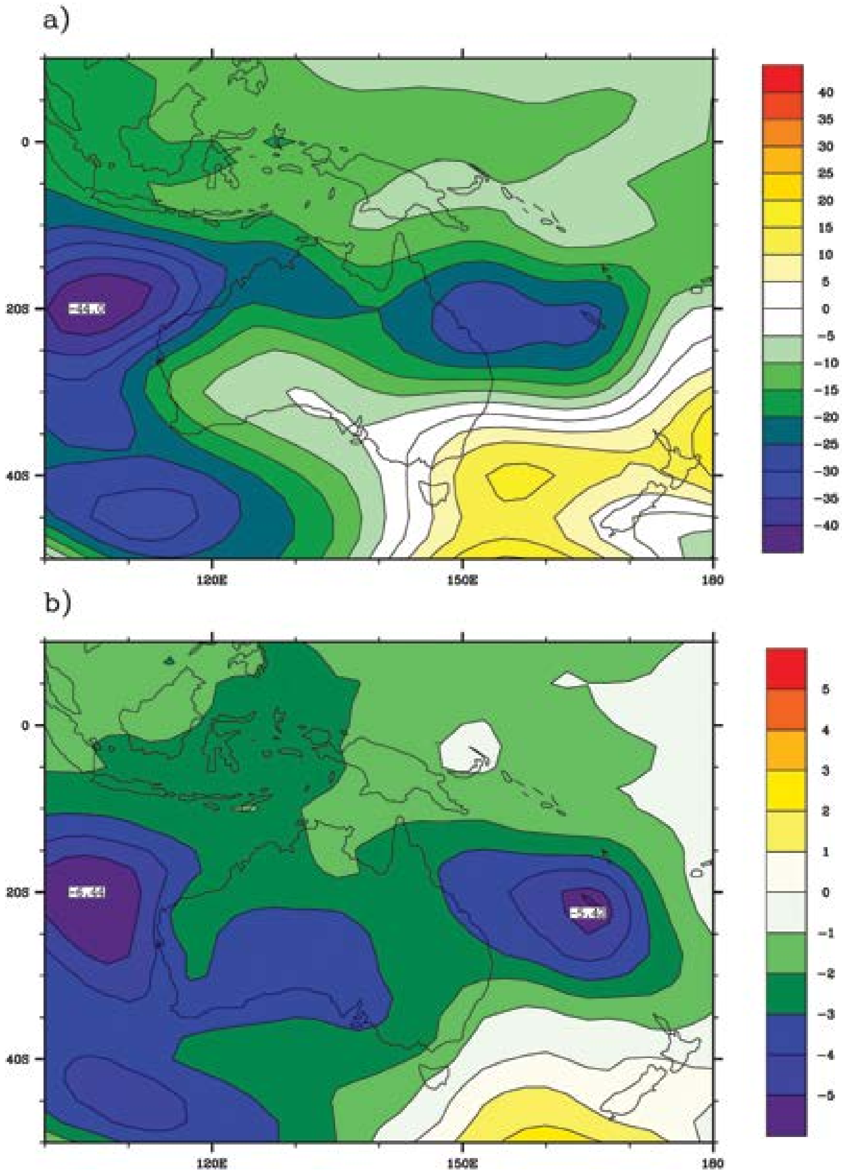


Figure 17. La Niña conditions typically bring lower pressure over the top half of Australia, but in January 2011 analysis showed these were much lower and resulted in extreme flooding events in Queensland. These contour plots (a and b) over the region 10N–50°S and 100–180°E show differences in January 2011 relative to the 1949–2009 climatological mean for (a) the 700 hPa (hectopascal) geopotential height (i.e. the height of the 700 hPa pressure surface) and (b) the sea-level pressure. In (a) there is an anomaly of up to 44 m over the eastern Indian Ocean, centred at 20°S and 110°E, extending westward into a moderate negative anomaly over northern/central Australia and into the western Pacific—this indicates there is a strong anomaly in geopotential height and pressure during La Niña that is associated with the anomalous rainfall. Positive height differences over 20 m exist in the Tasman Sea from 150°E to past 180°E, from 20°S to past 50°S indicating blocking high pressure systems. At sea level, negative pressure differences cover almost the entire area. The two main lows of around 6 hPa can be seen off the west Australian coast and just off the eastern coast, both around 20°S.

MORE ABOUT LA NIÑA

La Niña is the positive phase of the El Niño–Southern Oscillation, sometimes thought of as the 'opposite of El Niño.' A La Niña event is indicated by sustained positive Southern Oscillation Index values.

La Niña refers to the extensive cooling of the central and eastern tropical Pacific Ocean, often accompanied by warmer-than-normal sea surface temperatures in the western Pacific, and to the north of Australia. La Niña events are associated with increased probability of wetter conditions over much of Australia, particularly over eastern and northern areas. La Niña events have been associated with higher numbers of tropical cyclones during the cyclone season (November to April).

Future South Pacific climate more extreme

Climate model projections show that future greenhouse warming could almost double the number of extreme floods, droughts, and tropical cyclones in South Pacific Island nations in the next 100 years.

This is because the South Pacific Convergence Zone (SPCZ), the largest rainband in the southern hemisphere, is likely to experience more extreme shifts toward the equator by up to 1,000 km. These shifts are referred to as zonal SPCZ events and scientists know from observations that they are associated with extreme floods, droughts, and tropical cyclones.

CSIRO researcher Dr Wenju Cai said the main reason behind more zonal SPCZ events is due to climate change causing a larger warming rate along the equatorial than the off-equatorial region. This tends to decrease the north-south temperature gradient in the central equatorial Pacific and move the SPCZ towards the equator.

The South Pacific rainband is the largest and most persistent of the southern hemisphere spanning the Pacific from south of the Equator, south-eastward to French Polynesia.

Examining the extensive database of general circulation models submitted for the fourth and fifth assessments for the Intergovernmental Panel on Climate Change, the research confirms the number of times the zonal SPCZ events are likely to occur despite the models not agreeing on how the cycle of El Niños and La Niñas might change in this century.

The research also shows that there is a likely 32 per cent increase in strong El Niño events, although only about half of the zonal SPCZ events are projected to occur during such strong El Niños.

Future research will focus on ocean-induced climate extremes and their changes in a warming climate and how extreme El Niño and Indian Ocean Dipole events will change. This will help researchers understand how extreme tropical variability will change in response to increasing greenhouse gases. It will also help them understand how the relationship between the Australian climate and tropical Indo-Pacific variability will change in the future.

This is a highlight of the peer-reviewed paper called 'More extreme swings of the South Pacific Convergence Zone due to greenhouse warming'— see Appendix 3 for more details.

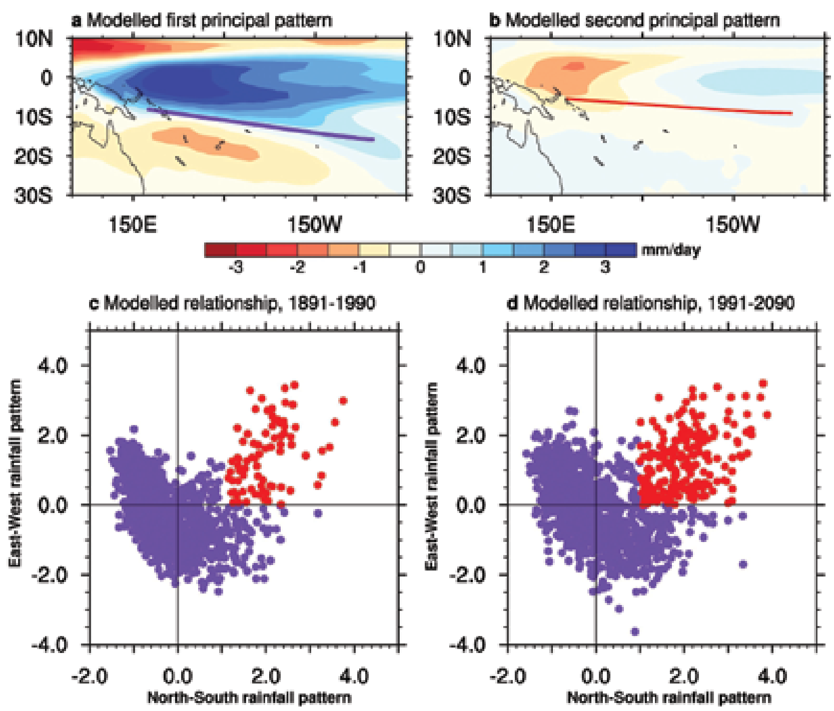


Figure 18. Newer generation climate projections based on 15 experiments with eight Coupled Model Intercomparison Phase 5 models show patterns of rainfall variability in the South Pacific region. They show that South Pacific Island nations could experience almost double the number of extreme floods, droughts, and tropical cyclones in the next 100 years. Plot (a) shows the leading pattern of rainfall (north-south pattern), and (b) shows the pattern that leads to zonal SPCZ events (east-west pattern). The colour scale below the panels gives rainfall in mm/day; blue contours indicate increased rainfall, and red contours indicate decreased rainfall per one standard deviation change. The charts (c and d) show changes in number of occurrences (red dots) in which South Pacific Island nations will experience extreme floods, droughts, and tropical cyclones, from the present-day climate (c) to the future climate (d). The change in the frequency of zonal SPCZ events is from (c) one SPCZ event is projected to occur every 16 years to (d) one SPCZ event is projected to occur every 7.5 years in the next 100 years.

Ozone affects atmosphere and rainfall

Ozone depletion over Antarctica has little to no impact on global temperatures; however, new simulations suggest a likely significant impact on the atmospheric circulation and rainfall in austral summer.

This discovery was made possible with new climate modelling frameworks that incorporated interactive chemistry and ocean components together for the first time. This enabled researchers to investigate and assess projected ozone recovery and its impact on the southern hemisphere climate.

Bureau researcher Dr Julie Arblaster said the magnitude of future changes in the Southern Annular Mode (SAM; which affects southern Australian rainfall) varies widely between climate models. She said the new experimental techniques and climate modelling simulations available this year help explore this uncertainty and understand the drivers behind changes to atmospheric circulation.

The simulations show a large spread in projections across the newer generation of climate models using interactive or semi-offline chemistry. They suggest that both the rate of ozone recovery and the rate of future greenhouse gas concentrations are important in determining the future position of the austral summer jet and the SAM. This highlights the importance of future ozone changes to southern hemisphere rainfall projections and the need to incorporate realistic ozone changes into climate simulations.

The new projections show that ozone recovery is likely to offset the poleward shift of the SAM to some extent in austral summer as greenhouse gas concentrations continue to increase. They also show that positive summertime SAM trends in the next 50 years are likely to be weaker than they were in the past 50 years.

The next step for this project will be to use observations and climate model runs to understand the role of various drivers of the extreme rainfall in spring 2010 and the extreme heat in January 2013.

MORE ABOUT OZONE

Since the 1970s, the amount of ozone above Antarctica has declined by more than 50 per cent. The Antarctic ozone hole forms every spring and its size and strength vary from year to year. Recovery of the ozone hole will depend on future emissions of chlorofluorocarbons and other ozone depleting substances, which are controlled by the Montreal Protocol, as well as the impact of climate change on these substances. For scientists to project when this recovery will occur, they need climate models with interactive chemistry components so they can simulate the complex interactions between radiation, chemistry and dynamics on ozone formation.

KEY CLIMATE RESEARCH THEME

EARTH SYSTEMS MODELLING AND DATA INTEGRATION

Climate models (simulators) have become increasingly sophisticated and are essential tools for understanding past and future changes in climate.

Climate models are based on the laws of physics and are represented as mathematical equations in a computer programme. They simulate the processes responsible for interactions of the atmosphere, oceans, land surfaces and sea ice. Future changes to the climate can be simulated using projected greenhouse gas and aerosol emission (or concentration) scenarios.

As well as representing the atmosphere, ocean, land surface, and sea ice, many global climate models now include aerosols, the carbon cycle, and atmospheric chemistry so they can more realistically replicate the earth's systems and responses. These models are commonly known as 'earth system models'. Ultimately, social and economic systems may be included in the models to see the effect of policy changes at local and global scales.

Global climate models typically have atmospheric grid-points spaced 50 to 200 km apart, so they provide only broad-scale projections of climate change. Regional models (downscaling) can be driven by input from global climate models, and have grid-points with closer spacing. This enables them to 'zoom down' to regional and local scales giving better representation of regional processes such as weather and coastal and mountain effects, although limitations remain due to biases in the 'driving' global model.

A challenge is to ensure that Australia develops and maintains a sophisticated climate modelling capacity to:

- ensure that southern hemisphere climate processes are captured;
- enable downscaled modelling for the Australian region, in particular to address what changes in extreme weather may be expected in the future;
- facilitate world-class Australian science in the areas of detection and attribution of climate change, climate sensitivity and feedbacks in response to specific causes and drivers of climate change, and the role of natural land and ocean sinks in taking up carbon from emissions;
- help understand how we may use our natural land sinks to mitigate emissions; and
- provide capacity to assess the potential impact of the range of geoengineering options on Australian climate.

This work is being done through Australian Community Climate and Earth System Simulator (ACCESS), a world-class climate and weather prediction model, which is delivering a new generation of numerical models to improve climate and weather research in Australia.

Table 6. The *Earth systems modelling and data integration* climate research theme is addressing the following policy questions.

SCIENCE INFORMING POLICY	KEY POLICY QUESTIONS
Mitigation	How much greenhouse gas are we emitting and what will the consequences be? What is the role of natural land and ocean sinks, in sequestering emissions and what will happen to these processes in the future? How can we use our natural land sinks and other natural processes to mitigate Australian emissions?
Adaptation	How has the climate changed in the past and what can this tell us about the future? What changes in the climate are we observing today and can we attribute them to human influences? What changes in climate and extreme weather events are likely on timescales of years to decades to a century? How can we best prepare for low likelihood but high impact consequences of climate change? How can we ensure that climate change adaptation is supported by the best available information?
International	How are we tracking to limit warming to specific targets (such as the 2 °C warming target) and what level of emissions reduction is needed to meet targets? How can Australia contribute to and influence international negotiations?

Greenhouse gases cause faster warming

Climate simulations show that greenhouse gas emissions caused much faster warming than any other factor in the past 50 years.

CSIRO project leader Dr Tony Hirst said the Australian Community Climate and Earth System Simulator projections for a greenhouse gas only scenario show that from 1960 the warming is much quicker than a scenario that included all the possible causes of climate change.

He said the quicker warming in the model demonstrates the profound warming effect of increasing greenhouse gas concentrations.

The projections also show the strong cooling effect of other factors—mostly aerosol emissions produced by humans. These emissions partly offset or 'mask' the warming, leaving only a relatively modest net warming. The cooling effect is a concern because aerosol emissions are projected to progressively decrease from late 20th century levels. This reduction could lead to a progressive 'un-masking' of the large greenhouse gas-induced warming and potentially much higher temperatures.

The simulations were carried out by scientists investigating the reasons for climate change from pre-industrial to modern times (1850 to 2005). This work was a collaborative effort between the Centre of Excellence for Climate System Science and the Centre for Australian Weather and Climate Research.

Next year, ACCESS will focus on introducing powerful new model evaluation tools. It will also start to develop the next generation of the ACCESS coupled climate models for use by the Australian research community and so that researchers can contribute to future Intergovernmental Panel on Climate Change assessment reports.

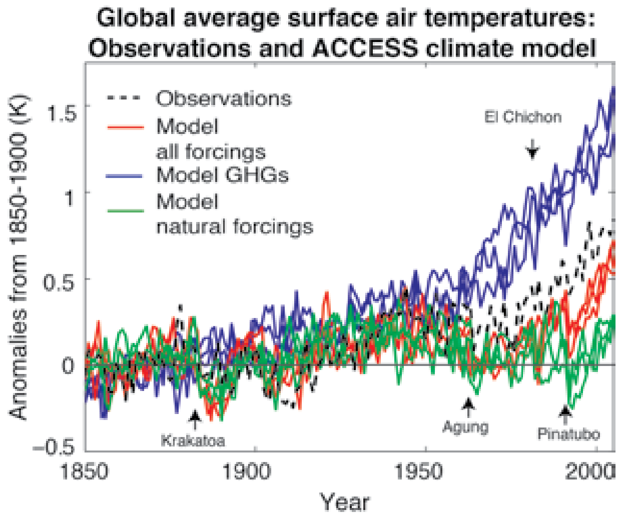


Figure 19. ACCESS climate simulations show that greenhouse gas emissions (blue) cause much faster warming than any other factor from about 1960—with warming by 2005 of about 1.4 °C. The simulations for natural climate variability factors only (green) show little warming over the historical period (at most 0.1 °C), while the simulations with all factors for the changes (red) shows a moderate warming, mostly since 1980, of about 0.6 °C by 2005. This increase is slightly less than the observed warming of about 0.8 °C. (Source: Sophie Lewis and David Karoly of the Centre of Excellence for Climate System Science). Note: El Chichon, Agung and Pintaubo refer to volcanic eruptions.

MORE ABOUT ACCESS

ACCESS delivers a new-generation numerical model that includes atmosphere, ocean, land surface, and sea ice components to improve climate and weather research in Australia. ACCESS supports 'mitigation' science through simulating and projecting changes in natural carbon sources and sinks, with emphasis on Australia and the Southern Ocean. It supports 'adaptation' science through simulating changes in climate and extreme weather with a particular focus on improved simulation of climate drivers in the southern hemisphere. More than 70 climate model comparison studies used ACCESS model outputs this year.

ACCESS also supports the shaping of international action and collaboration through ongoing development as a leading climate model and by contributing to international programmes aiming to understand southern hemisphere climate processes and change. Information from the ACCESS model is used for the United Nations' Intergovernmental Panel on Climate Change 5th Assessment Report (AR5). Local and international model evaluation studies show that ACCESS is one of the top performing climate models used in the AR5 because it produces among the most realistic simulations across a range of climate metrics.

Ocean too acidic for marine life

In little more than 50 years, it is likely that much of the ocean around Australia will no longer be suitable for coral formation. The increasing acidification in our oceans from greenhouse gas emissions won't just harm coral; it is also likely to harm the marine snails in the Southern Ocean.

This is the stark finding by scientists using newer generation climate models to simulate the saturation of aragonite—the soluble mineral comprising calcium carbonate—that many marine organisms use to build their skeletons and shells.

CSIRO project leader Dr Richard Matear said ocean carbon-cycle projections, using the Australian Community Climate Earth System Simulator, show in 2100 there is likely to be a reduction in the stability of calcium carbonate in the surface of the oceans. He said the projections show the Southern Ocean will become corrosive to the aragonite form of calcium carbonate. This means it will become an unsuitable habitat for organisms like marine snails (or pteropods) because their aragonite shells are likely to dissolve. Australia's coral reefs also need ocean water that is super-saturated with aragonite so they can produce skeletons composed of calcium carbonate. These projections indicate that by 2100 this will become extremely difficult.

When the ocean takes in the carbon dioxide from greenhouse gas emissions in the atmosphere, it reacts with water to form carbonic acid. This weak acid dissolves aragonite and therefore makes it more difficult for organisms to form aragonite-based shells or hard skeletons.

The research team will continue to produce carbon cycle projections using the land and ocean carbon modules that have recently been combined into the one version of ACCESS.

This is a highlight of the peer-reviewed paper called 'Biogeochemical consequences of ocean acidification and feedbacks to the Earth system'—see Appendix 3 for more details.

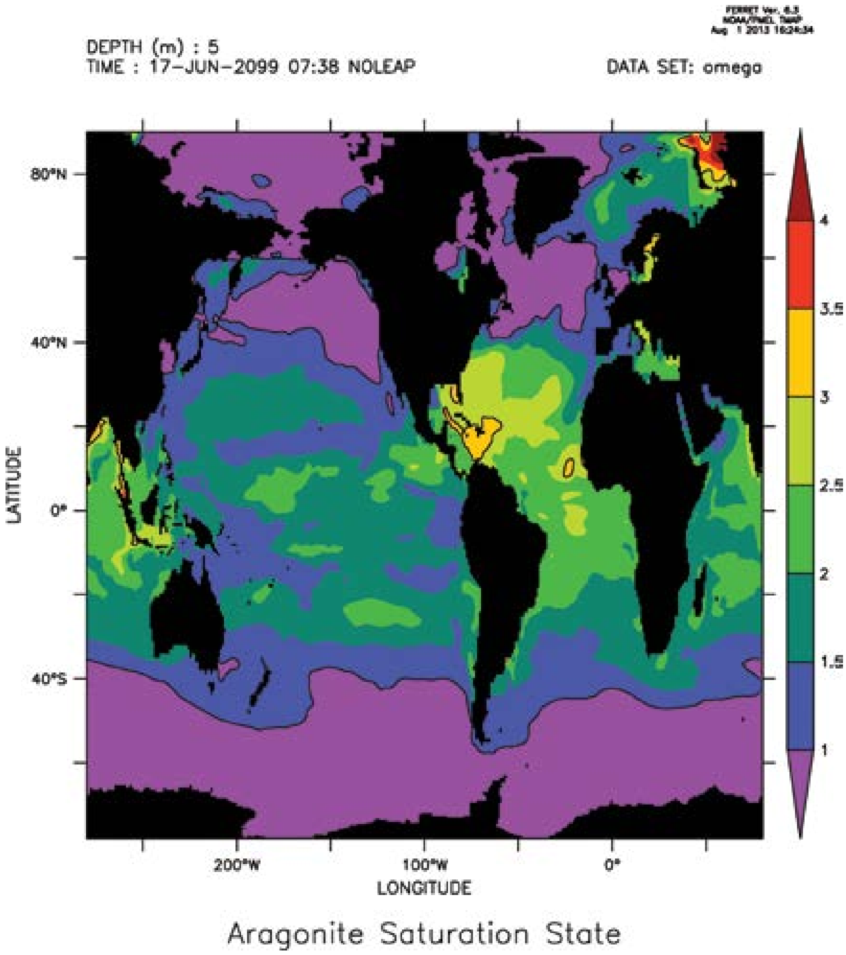


Figure 20. Ocean carbon-cycle projections using the Australian Community Climate Earth System Simulator show that by 2100 there is likely to be a reduction in the stability of the aragonite form of calcium carbonate in the surface of the oceans. The map shows the averaged aragonite saturation state of surface water across the world's oceans. In the Southern Ocean, where values are less than one (purple), the water is corrosive to aragonite and is an unsuitable habitat for marine snails because their aragonite shells are likely to dissolve. Australia's coral reefs need a saturation state greater than three (orange or red). By 2100, the projections show that much of their suitable habitat will disappear.

KEY CLIMATE RESEARCH THEME

AUSTRALIA'S FUTURE CLIMATE

Computer-generated climate models are the best tools scientists have for understanding our climate system and examining what changes we are likely to see under different future scenarios of greenhouse gas emissions. While the insights gained from climate modelling help decision makers plan for a future Australian climate, the gap between modelling and application needs to be bridged.

Regional climate change projections science forms an important interface between climate modelling (including high resolution downscaling) and climate impact and adaptation studies. The key objectives of this science are identifying plausible and likely future regional climates and how to provide future climate data sets in a form that is suitable for use in impact and adaptation studies. Because there is great demand from a wide variety of interested stakeholders in the tools and information produced by regional climate science, this research area heavily invests in outreach and delivery.

Scientists develop climate projections by assessing and combining information from multiple climate models, including downscaling approaches, or using observations to constrain regional projections. They also produce locally relevant, application-ready data sets that represent our climate change understanding. These processes ensure that the projection information is what users want and in the form they want.

Scientists also need to update projections to include new climate models and to address new projection questions so they can refine their understanding of regional climate change. They also need to develop new methods of producing application-ready datasets to better represent our latest understanding of the climate and to suit the needs of impact and adaptation planning.

Climate projection information includes changing climatic averages but it also needs to include changes to extreme events. Extreme climate events can have a serious impact on the environment and society, including loss of life, property and livelihoods. Record hot weather affected much of Australia in the summer of 2012–13. Both Sydney (45.8 °C) and Hobart (41.8 °C) experienced their hottest days on record and associated bushfires in Tasmania destroyed more than 100 homes. The impact of climate change is likely to be particularly felt through changes to extreme climate events such as heat waves, cold snaps, tropical cyclones, storm surges, floods, droughts and bushfires.

A key challenge is to provide users with access to the latest information on how extreme events are likely to vary under the range of likely future greenhouse gas emissions. This means considerable research effort goes into improving our understanding of what the future may hold for extreme climate events.

Table 7. To address these challenges, *Australia's future climate research* theme is addressing the following policy questions.

SCIENCE INFORMING POLICY	KEY POLICY QUESTIONS
Adaptation	What changes in climate and extreme weather events are likely on timescales of years to decades to a century? How can we ensure that climate change adaptation is supported by the best available information?
International	Is the 2 °C warming limit sufficient and what are the implications of going beyond the 2 °C target?

Downscaling adds value in some regions

A comparison of three different downscaled projections from older generation climate models confirms that some add value when looking at the average rainfall in a warmer climate scenario for this century.

Project leader Dr Penny Whetton said some downscaled projections appear to have clear 'added value' related to topography and coasts compared to the global models. This can be seen with projections of summer rainfall in Tasmania which reveal fine-scale patterns in the projected changes in average rainfall between 1980–1999 and 2080–2099 (Figure 21).

However, Dr Whetton said the study also highlighted that in many cases different downscaling methods can project different climate changes for reasons linked with the particular model used. An example of this can be seen with projections for north-west Western Australia in summer, which show variable projections for changes in average rainfall over the same period (Fig 22).

The analysis shows that in some cases the downscaling produces a robust picture of likely regional change regardless of the method used, while in other cases the picture is less clear. The results from one particular downscaling method may give an incomplete projection of possible future climates.

Now that the research team has identified various differences between the results from different downscaling methods, it will focus on explaining the causes of those differences and identifying where one set of results is preferred over another. Another priority for the research team is to explore the downscaling projections produced with newer generation models. This will help the researchers check the current understanding of the issues, and to explore any new issues around producing highly regionalised climate projections. This information will underpin the new regional climate projection information that is expected to be available in mid-2014.

This is a highlight of the draft paper called 'Regional changes of climate extremes over Australia,'—see Appendix 3 for more details.

Another priority for the research team is to explore the downscaling projections produced with newer generation models.

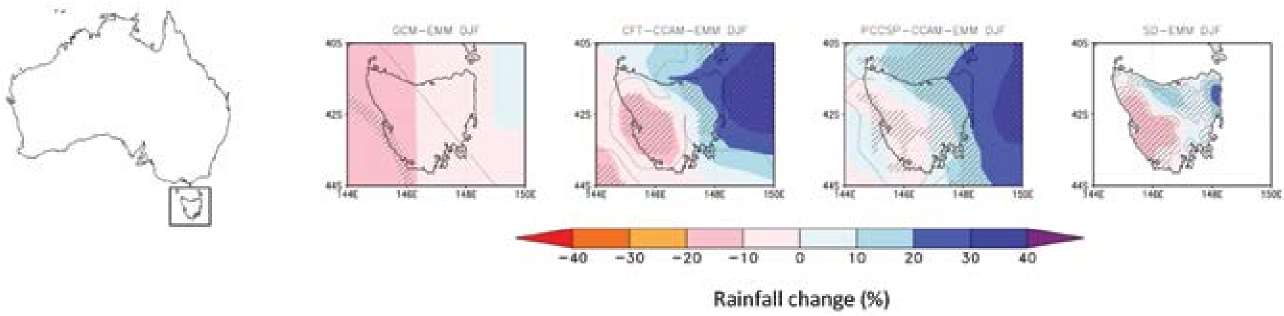


Figure 21. Downscaling reveals fine-scale patterns in the projected average rainfall change for a warmer climate in Tasmania during summer (December to February) between 1980–1999 and 2080–2099. The map of Australia shows the location of the downscaling. To the right of this map, the first panel shows the average result from six global climate models. This panel shows decreasing rainfall across the state. The next three panels show a consistent result from three different downscaling methods, a projected decreasing rainfall in western Tasmania and an increase in north-east Tasmania of more than 20 per cent in places. The shading indicates where the majority of models agree on the direction of change.

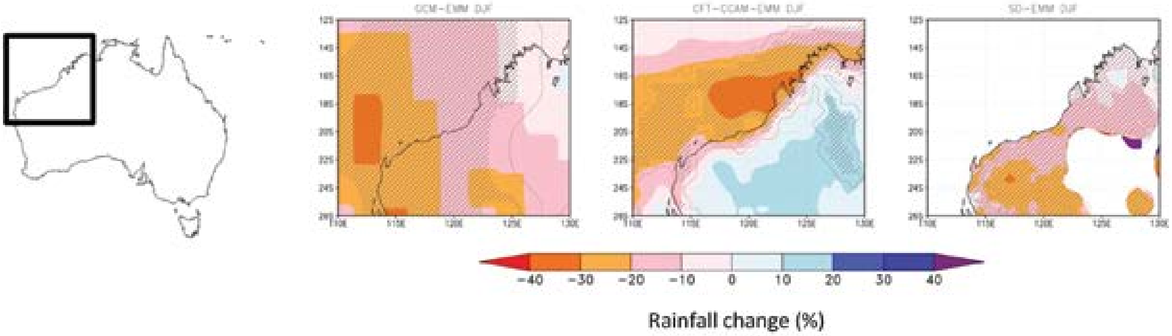
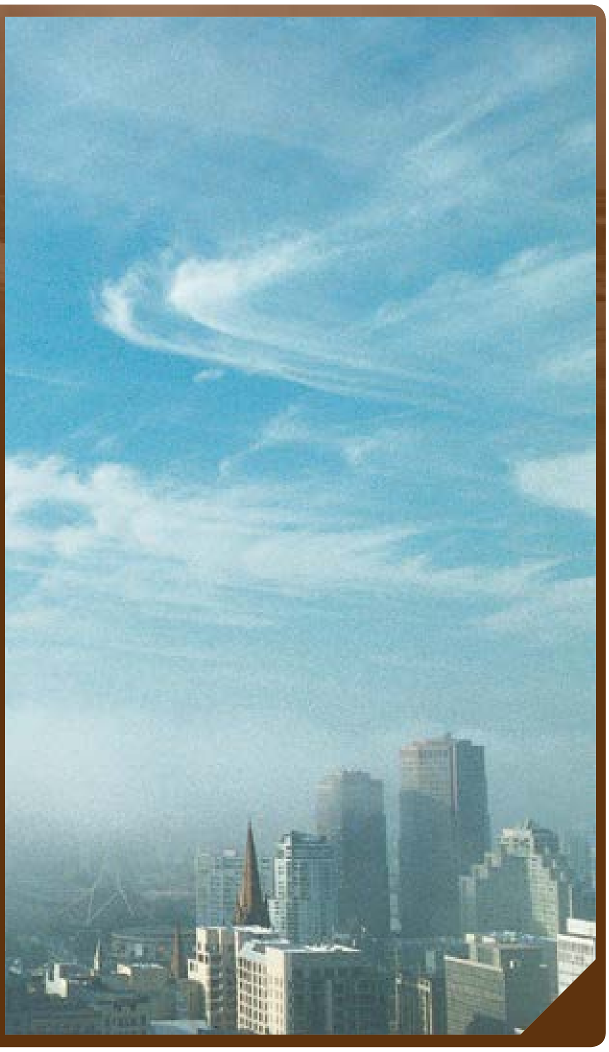


Figure 22. Different downscaling methods show variable projections for average rainfall change for a warmer climate in northwest Western Australia during summer (December to February) between 1980–1999 and 2080–2099. The map of Australia shows the location of the downscaling. The first panel shows the average result from six global climate models, with a consistent decrease in rainfall projected across the region. The middle panel with the dynamical downscaling result shows a decrease in rainfall over the ocean but little change or rainfall increase over land. The panel on the right with the statistical downscaling method shows a decrease over land similar to the global models and no results over ocean (the method produces results only for land areas). Shading indicates where the majority of models agree on the direction of change.

MORE ABOUT DOWNSCALING

Many industries and communities need plausible future climate scenarios at regional and local scales with sound representation of regional processes (such as weather and coastal and mountain effects) so they can prepare for the impact of a warming climate. While global climate models are our best tool for making climate projections out to 2100, they reproduce larger-scale climate scenarios for atmospheric grid cells that are 70–280 km wide.

There are several different techniques for getting information at a finer scale or ‘downscaling.’ Each method has its own characteristics, strengths and weaknesses. While all methods of downscaling produce finer-scale datasets that look more like observations, they vary in their potential to produce information about the most likely pattern of climate change in the future. If the different methods show a consistent pattern of regional change in a warmer climate scenario, and this pattern has a plausible physical basis, then it is likely the downscaling has ‘added value’ to the projected changes.



Warmer seas fuel tropical cyclones

Higher sea-surface temperatures from increasing greenhouse gas emissions may make tropical cyclones in northern Australia more intense and produce more rainfall.

In February 2011, record higher ocean temperatures, caused in part by a La Niña, provided heat and moisture that helped fuel tropical cyclone *Yasi*, which crossed the coastline of north Queensland. *Yasi* produced extreme rainfall and strong winds that caused significant damage along its track. It was the most severe storm to affect the Queensland coastline in almost 100 years.

A modelling study by Dr Sally Lavender looking at sea-surface temperatures indicates they are likely to make a cyclone like *Yasi* more intense and likely to move further south. CSIRO project leader Dr Debbie Abbs said the preliminary results also show that the associated storm rainfall is likely to be about 30 per cent greater for each one degree increase in the temperature of the surface of the sea.

Dr Abbs said climate investigations using previous research on closed lows over northern Australia show clear trends that explain a large proportion of the increasing rainfall trend seen in the past 20 years (Figure 23). The investigations show there is an increase in the number of vertically organised, intense rainfall systems in the north of Australia. These systems are accompanied by an increase in warm, moist air flow in the north east. The research also shows the opposite trend is occurring in the south-east of the continent.

It is important to understand what is happening with our weather systems. This will help researchers to assess if similar trends are found in climate models and to identify if these trends are likely to continue into the future. It will also help researchers to evaluate possible changes in Australia's water resources.

This is a highlight of the peer-reviewed paper called 'Trends in Australian rainfall: contribution of tropical cyclones and closed lows'—see Appendix 3 for more details.

MORE ABOUT CLOSED LOWS

Closed low pressure systems, including tropical and extra-tropical cyclones, Monsoon Lows, East Coast Lows and Cut-off Lows are known to have a large influence on Australian rainfall. More than 60 per cent of annual rainfall in some regions, notably the northwest, can be attributed to these closed low systems.

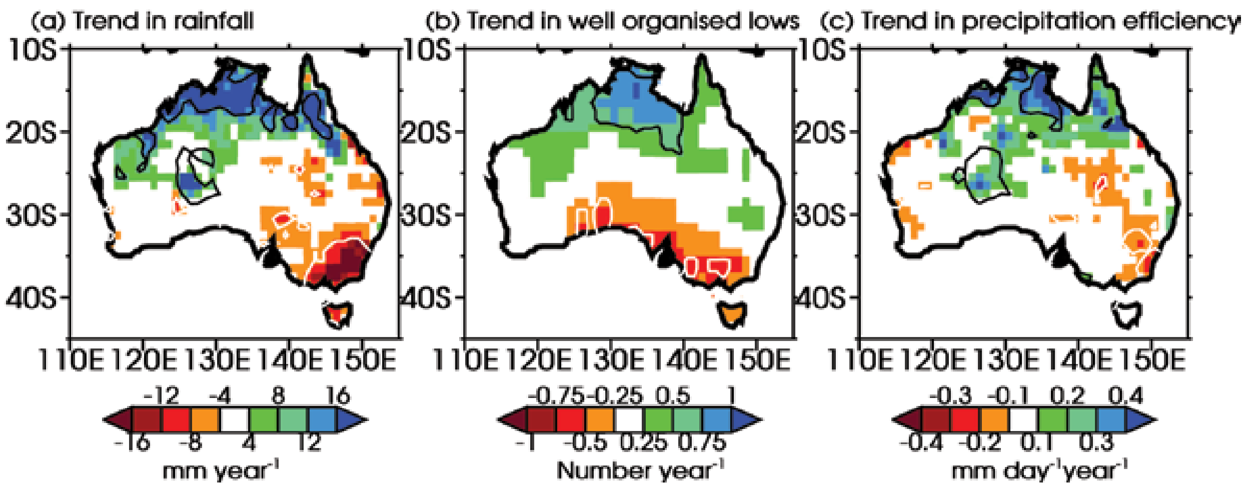


Figure 23. Clear rainfall trends in northern Australia explain a large proportion of the increasing rainfall trend observed in the past twenty years. Map (a) shows trends in Australian rainfall (1989–2009) based upon the Australian Water Availability Project data. Map (b) shows an increase in the number of well-organised, intense systems in the north of Australia; the opposite trend can be seen in the south-east of the continent. The trend in rainfall efficiency (or the amount of rainfall, in mm, per closed low each day) is shown in (c). Increasing trends in rainfall efficiency in the north-east are due to an increase in warm, moist air flow from the north-east; the opposite is occurring in the south-east.

Fewer large waves from East Coast Lows

The central east coast of Australia is likely to experience fewer days with large storm waves if greenhouse gas emissions continue to rise.

Projections from an East Coast Low (ECL) diagnostic tool applied to newer generation climate models show that by the end of this century there are likely to be about 30 per cent fewer days with large storm waves than we see today (Figure 24). The research also shows that East Coast Lows are the sole cause of waves that are 7 metres high or higher (as measured by a series of ocean buoys during the study period) along the central and southern parts of Australia's east coast.

Bureau project leader Dr Andrew Dowdy's novel method produced projections which show a remarkably high level of agreement among different climate models in contrast to previous studies. This approach was also applied to older generation climate models to examine projections of the influence of greenhouse gas emissions on heavy rainfall in the eastern seaboard of Australia. The projections show that with high emissions, there are likely to be fewer ECLs. This will result in a likely decrease in the frequency of these heavy rainfall events ranging from about 8 per cent to 25 per cent by the end of this century (Table 8). Dr Dowdy said the size of the decrease will depend on season and latitude.

This research examined the influence of increasing greenhouse gas emissions on the frequency of ECLs and associated extreme weather events, rather than the intensity of these events. However, Dr Dowdy said it may be worth noting that although the frequency of occurrence is projected to decrease, it is also possible that the intensity of these events may also change.

This is a highlight of the peer-reviewed papers called 'Fewer large waves projected for eastern Australia (submitted)' and 'Understanding rainfall projections in relation to extratropical cyclones in eastern Australia (in press)' —see Appendix 3 for more details.

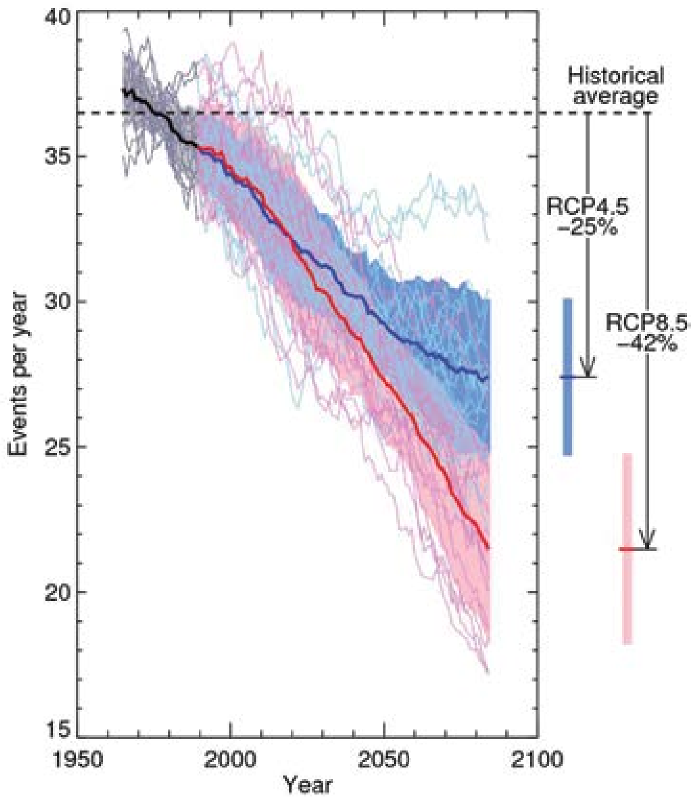


Figure 24. The average annual number of large wave events from 1950 to 2100 is shown by projections from an east coast low diagnostic applied to 18 global climate models. The results for the low greenhouse gas emission pathway (blue) show that the average number of large wave events could reduce by about 25 per cent by the second half of the this century. The higher greenhouse gas emission pathway (red) indicates a 42 per cent reduction could be expected.

Table 8. There is likely to be a decrease in the frequency of heavy rainfall events caused by east coast lows by between about 8 per cent and 25 per cent by the end of this century. This table shows the likely changes in the frequency of heavy rainfall events based on the projected change in east coast low events. The bolded numbers indicate results with a higher degree of confidence. Four different types of heavy rainfall events were examined. This is shown during both summer and winter, as well as for a northern region (from northern NSW to southern QLD) and a southern region (from eastern VIC to central NSW).

	NORTHERN REGION		SOUTHERN REGION	
	SUMMER	WINTER	SUMMER	WINTER
Localised rain event	-14 %	-20 %	**-8 %**	**-22 %**
Widespread rain event	-13 %	**-19 %**	**-11 %**	**-19 %**
Cluster rain event	-13 %	**-23 %**	**-10 %**	**-21 %**
Large inflow event	-14 %	**-24 %**	-10 %	**-25 %**

MORE ABOUT

EAST COAST LOWS

East coast lows (ECLs) are intense low-pressure systems which occur on average several times each year along the eastern coast of Australia—particularly in southern Queensland, New South Wales and eastern Victoria. Although they can occur at any time of the year, they are more common during autumn and winter and are most frequent in June.

ECLs can generate one or more of the following:

- Gale or storm-force winds along the coast and adjacent waters.
- Heavy widespread rainfall leading to flash and/or major river flooding.
- Very rough seas and large waves over coastal and ocean waters that can cause damage to the coastline.

ECLs contribute to annual rainfall, and replenish rivers and reservoirs.

Rainfall change linked to ocean temperatures

Rainfall over Australia may change with global warming. However, for much of the continent, whether the climate model projections show decreases or increases in rainfall is linked to the modelled pattern of warming.

Projections from the latest generation climate model from Australia indicate there is likely to be more warming this century in the Pacific Ocean to the east of New Guinea. They show less warming to the west in the Indian Ocean. To demonstrate that these changes can drive a decline in summer rainfall in this model, Dr Ian Watterson and his team experimented with only the ocean surface temperatures. The researchers discovered that modified equatorial temperatures produced large changes in rainfall and atmospheric moisture locally. They found the changes in temperature also affect the moisture flow into the atmosphere above Australia in summer, leading to less accumulation of atmospheric moisture and less rainfall (Figure 25). The researchers also found that in the following autumn there was less evaporation from the land surface, further contributing to a drier atmosphere.

When the researchers averaged all projections from the current Australian and overseas climate models, they found there is a relatively small decline in Australian rainfall. However, Dr Ian Watterson said there are clearly a range of possibilities, in part due to uncertainty in the warming pattern of the surface of the sea.

The researchers will look further into the processes that can drive greater surface warming in the equatorial Pacific in some models, but greater warming in the Indian Ocean in others.

This topic features in the peer-reviewed paper called 'Climate change simulated by full and mixed-layer ocean versions of CSIRO Mk3.5 and Mk3.0: the Asia-Pacific region'—see Appendix 3 for more details.

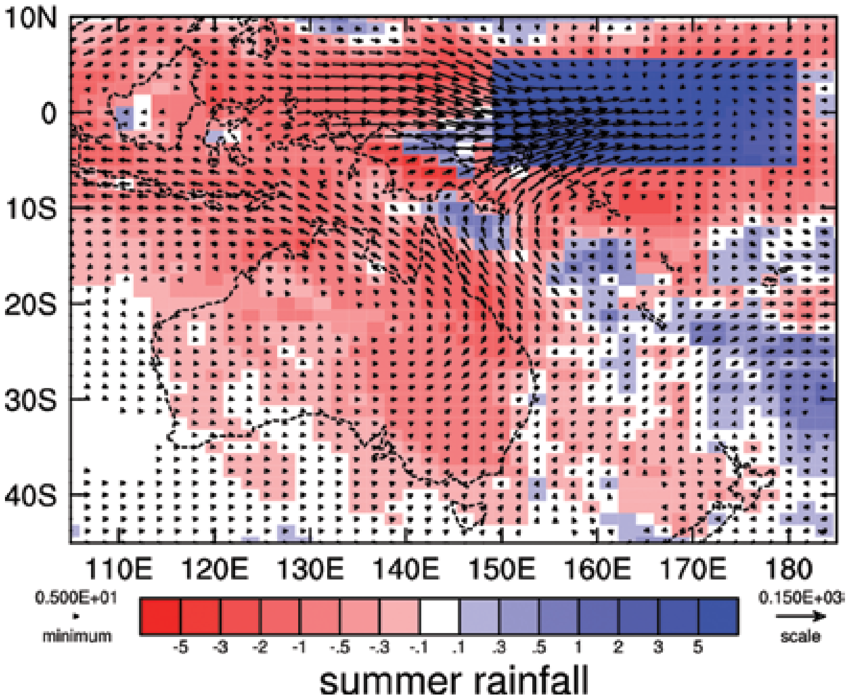
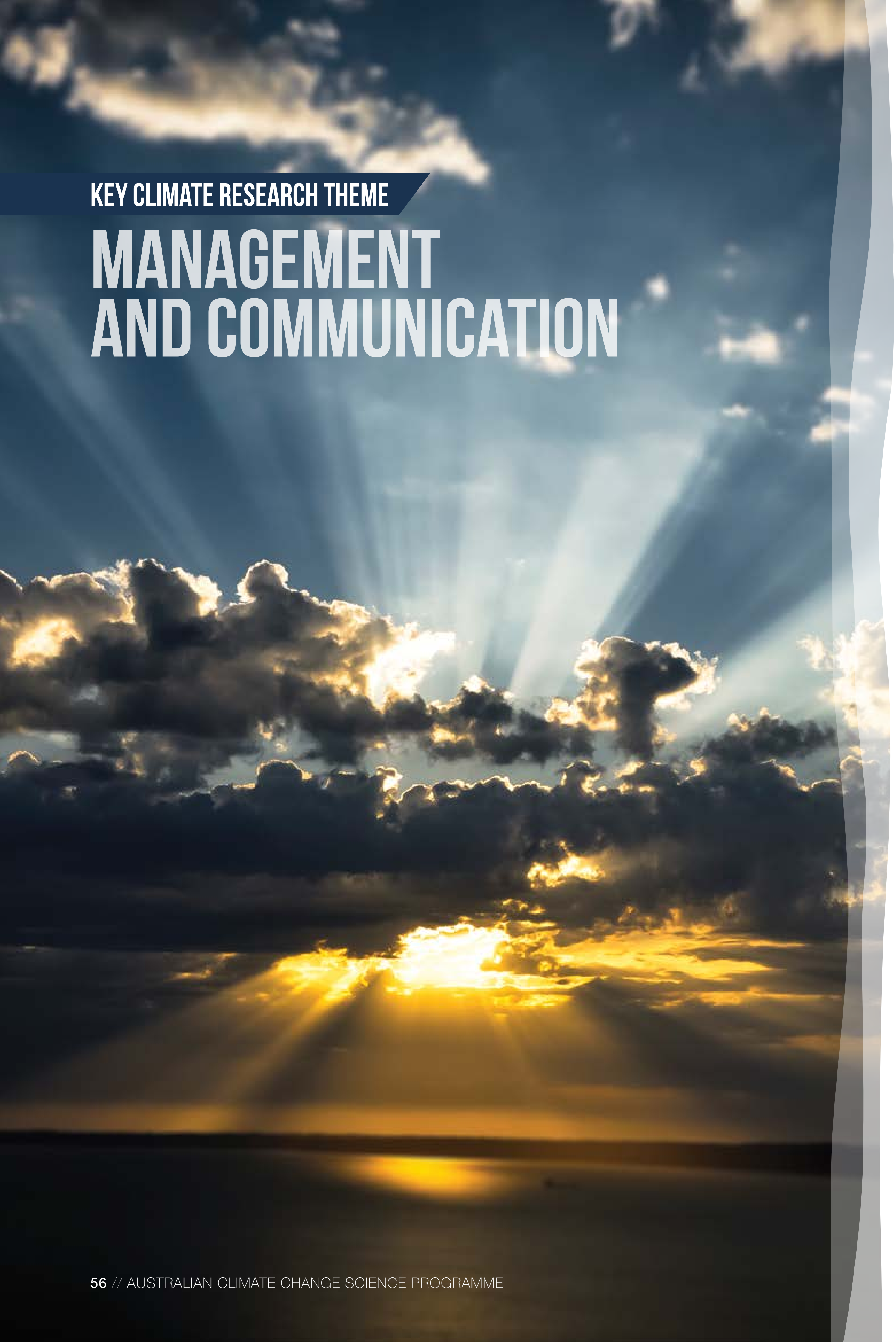


Figure 25. Projections by the latest Australian climate model (ACCESS) show that with increasing greenhouse emissions west equatorial Pacific surface temperatures are likely to get warmer than elsewhere in the region. By simply raising sea-surface temperatures in the west Pacific by one degree over the summer season, the model demonstrates that this is likely to modify the atmospheric water flow in a way that results in lower rainfall over Australia. This can be seen on the map which shows that over the warmer ocean, there is a strong increase in rainfall. Over Australia, the change in flow takes moisture from the continent, leading to decreased rainfall. The change in the atmospheric moisture flow is shown by the arrows. The change in precipitation is shown with colours, ranging from a decrease (red shades) of 5 mm per day to an increase (blue shades) of 5 mm per day.

KEY CLIMATE RESEARCH THEME

MANAGEMENT AND COMMUNICATION



Sound management is essential for the most efficient use of resources and for delivering good outcomes to the Australian research community and government, and to contribute to international science initiatives.

A joint management team comprising senior representatives from the Department, CSIRO and the Bureau oversees the ACCSP. The team meets quarterly to review progress, and to determine communication and briefing needs. The team is responsible for day-to-day management, progress reporting, and finances. It is also responsible for the project review and assessment processes, including those associated with the science evaluation panel.

The science evaluation panel includes senior representatives from relevant portfolios and programmes in CSIRO and the Bureau, and a nominee from The Department. The panel meets annually to review proposals and recommend the package of research for ACCSP funding each year.

Once the research is funded and underway, there is regular checking and reporting on research milestone delivery. The ACCSP management team is an interface between the research agencies and the Department. This ensures strong communication on progress of the research and on important research findings.

Research delivery is regularly summarised through formal progress reports and the annual report. Each May, there is a review meeting where the researchers share and discuss highlights of the reporting year.

In 2012–13, we managed 22 projects across seven programme areas. See Appendix 1.

Communication

Good communication is critical for getting the results of the science into the hands of the people who need it—Government, industry and communities need this information to plan for and manage the expected environmental, social and economic impacts of climate change for all Australians.

This year our communication activities focused on:

- raising awareness about why climate change science is important and how it can underpin relevant policy, and
- in partnership with CSIRO and the Bureau, communicating new science and research findings relating to the causes and impacts of climate change.

Our annual communication plan describes how we do this, the key messages we deliver, and the communication tools we use.

Telling the climate change science story

Peer-reviewed work by more than 100 ACCSP scientists shows that human activities are affecting climate in the southern hemisphere and around the globe. This consistent finding is captured in 130 peer-reviewed papers that were published this year in highly-regarded local and international scientific journals.

All of the ACCSP's papers that are published in journals and book chapters have been reviewed by other Australian and international scientists and organisations prior to publishing. This ensures the findings are objective, unbiased and conform to accepted scientific standards. As well as documenting their findings, our scientists gave lectures and presentations throughout Australia and the world. See Appendix 3.

Climate science that focuses on the southern hemisphere is critical for helping the Australian Government to answer and respond to the policy questions that need to be supported

by climate science in this region. The scientific findings, based on data and observations, underpin government and other policies that help Australia to manage the effects of the changing climate and contribute to a global solution.

While the Australian Government and decision makers are our key stakeholders, it is also important that we make our findings available to the wider community. We cannot just rely on communicating climate change findings through scientific journals and scientific conferences. To reach a wider audience and to communicate our work in everyday language, we communicate via the media and through our website, and our partner websites.

News releases

We regularly distribute news releases about research findings and reports to mainstream, specialist science and environmental media. Our scientists are regularly approached by the media to comment on ACCSP ocean atmosphere and climate science issues.

We monitor the effectiveness of our news releases. The results show they generate commentary on ACCSP science in the Australian media (capital city and regional print, radio, television, and online). Our news releases also generate commentary and stories about the changing climate in international publications such as the New York Times, and online in the BBC. See Appendix 4.

Websites

To ensure we could reach the wider community, this year we developed a dedicated online presence for the ACCSP. We will be publishing our research activities and findings on this website and our partner websites. See Appendix 5.

Events

The ACCSP supports and organises scientific workshops and conferences. In November 2012, we sponsored the '*Understanding and prediction of monsoon weather and climate*' event in Melbourne. This event attracted 120 Australian and international delegates.

This year we also prepared for the GREENHOUSE 2013 conference. This is Australia's pre-eminent climate change science meeting. The seventh in the long-running series, it was held in Adelaide in October 2013.

Celebrating 25 years

In 2014, the ACCSP celebrates its 25th anniversary. We will take the opportunity to promote the importance of climate change science for the southern hemisphere, outcomes of the work undertaken, and the significance of Australia's long-serving climate science programme.

APPENDICES

60	Appendix 1. Complete list of projects and science highlights
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Appendix 1. Complete list of projects and science highlights

The ACCSP delivers projects that improve our understanding of the climate in the southern hemisphere and that add great value to the Australian research community, to government, and to international science.

Table 9. In 2012–13, the ACCSP delivered 22 projects across seven programme areas.

Key climate research theme	Research programme area	Project title	Research organisation	Science highlight
Greenhouse gases	1. Global and regional carbon budgets	1.1 Global Carbon Project	CSIRO	**Greenhouse gas emissions still rising** Research shows that greenhouse gas emissions are still rising. To keep the global increase in temperature at levels of 2 °C or below, we need to significantly and quickly reduce greenhouse gas emissions. *See full highlight on page 16.*
		1.2 The Australian continental carbon balance	CSIRO	**Full carbon balance for Australian continent** A comprehensive assessment of the carbon stocks and flows in the Australian continent has found that its vegetation and soils are absorbing carbon dioxide from the atmosphere—but this uptake is low by global standards. On a unit-area basis, the Australian terrestrial carbon sink operates at only 40 per cent of the strength of the global average sink. *See full highlight on page 18.*
		1.3 Land and ocean carbon feedbacks in the paleo record	CSIRO	**New record of past atmospheric changes** Measurements of air from polar ice cores and firn (compacted snow) have provided a new record of the changes in the concentration and isotopic composition of carbon dioxide for the past 1,000 years. This record provides a new benchmark for modelling the carbon cycle and climate of the industrial period and the preceding centuries. *See full highlight on page 19.*
Atmosphere	2. Land & air (observations and processes)	2.1 Carbon and water exchanges between land surface and atmosphere from ecosystem to continental scales	CSIRO	**Carbon uptake by Australia's temperate forests variable** Data from the Tumbarumba flux station confirms that the amount of carbon taken up by Australian cool temperate forest ecosystems can be highly variable. The data also shows that these ecosystems have the greatest rate of carbon uptake globally but that they are vulnerable to disturbance. *See full highlight on page 22.*
		2.2 Aerosol and its impact on Australian climate	CSIRO	**Aerosols weakening subtropical jet** Increasing atmospheric aerosols from the northern hemisphere in the latter part of the 20th century are likely to have contributed to a weakening of the southern hemisphere subtropical jet. This is in contrast to the effects of increasing greenhouse gases, which tend to strengthen the jet in climate model simulations. *See full highlight on page 24.*

Key climate research theme	Research programme area	Project title	Research organisation	Science highlight
		2.3 Reducing uncertainties in climate projections by understanding, evaluating and intercomparing climate change feedbacks	The Bureau	**New sea ice and snow feedback findings** New model analysis shows that Arctic sea ice is likely to be more responsive to warming caused by greenhouse gas emissions than to natural climate variability. The simulations also show that Antarctic sea ice is likely to respond to natural shorter-term temperature fluctuations in the same way as it does for warming caused by greenhouse gas emissions. *See full highlight on page 26.*
Oceans & coasts	3. Oceans & coasts (observations and processes)	3.1 Ocean climate data partnerships: securing and improving climate-quality essential ocean data streams for ACCSP	CSIRO	**Ocean robots collect one millionth record** In 2012, the global Argo project involving Australia's leading ocean scientists collected its one millionth deep ocean temperature and salinity profile. The data collected from the 3,525 active Argo floats in the world's oceans is essential for tracking the changes in global and regional ocean heat and salinity patterns—which in turn affect the rate at which the level of the seas and oceans rise and reflect changes to the global water cycle. *See full highlight on page 30.*
		3.2 Ocean climate processes: Understanding ocean change and influence on global and Australian climate	CSIRO	**New measurements for ocean uptake of carbon dioxide** Scientists have used ocean observations to directly measure the transfer of anthropogenic carbon dioxide into the southern hemisphere oceans for the first time. *See full highlight on page 32.*
		3.3 Improving sea-level, wind-wave and storm surge projections	CSIRO	**Reasons for rising seas much clearer** The rises we have observed in global and regional sea levels since 1990 are due to a combination of factors including the ocean expanding as it gets warmer, melting glaciers and ice sheets, and natural climate processes, such as the El Niño–Southern Oscillation. *See full highlight on page 33.*
		3.4 Ocean carbon and acidification	CSIRO	**Simulations agree on carbon uptake** Atmospheric and ocean simulations are agreeing more on how much carbon is being taken up by the Southern Ocean each year. *See full highlight on page 35.*
Water	4. Modes of climate variability and change	4.1 Global warming, the Walker circulation and the El Niño–Southern Oscillation	The Bureau	**Walker circulation has strengthened** The Walker circulation, one of the world's largest and most important wind systems, has strengthened, offsetting the weakening over much of the 20th century identified by previous research. Changes in the Walker circulation drive changes in rainfall, severe weather, agricultural production, and river flow in many parts of the world, including Australia. *See full highlight on page 38.*

Key climate research theme	Research programme area	Project title	Research organisation	Science highlight
		4.2 The Australian monsoon: Processes, projections and extreme rainfall	The Bureau	**Monsoonal rainfall likely to be more variable** Newer generation climate models show the Australian monsoon system could become more variable year to year by the end of this century due to increasing greenhouse gas emissions. Extreme daily rainfall events could also intensify across the Australian tropics. *See full highlight on page 39.*
		4.3 Attribution, projection and interactions of Australian climate change, modes of variability and weather systems	CSIRO	**La Niña affects low-pressure systems** Innovative research has provided a possible explanation for two extreme flooding periods in January 1974 and January 2011. These simulations of past large-scale long-lasting climatic extremes will help researchers understand the roles of greenhouse gases and natural variability in the changing Australian climate. *See full highlight on page 40.*
		4.4 The response of Indo-Pacific ocean variability to climate change and its impact on the Australian climate	CSIRO	**Future South Pacific climate more extreme** Climate model projections show that future greenhouse warming could almost double the number of extreme floods, droughts, and tropical cyclones in South Pacific Island nations in the next 100 years. *See full highlight on page 42.*
		4.5 Understanding southern hemisphere climate projections using sensitivity experiments with the ACCESS model	The Bureau	**Ozone affects atmosphere and rainfall** Ozone depletion over Antarctica has little to no impact on global temperatures; however, new simulations suggest a likely significant impact on the atmospheric circulation and rainfall in austral summer. *See full highlight on page 43.*
An Australian climate modelling system	5. Earth system modelling and data integration	5.1 Development of the ACCESS coupled modelling system	CSIRO	**Greenhouse gases cause faster warming** Climate simulations show that greenhouse gas emissions caused much faster warming than any other factor in the past 50 years. *See full highlight on page 46.*
		5.2 Development of the ACCESS Earth system model	CSIRO	**Ocean too acidic for marine life** In little more than 50 years, it is likely that much of the ocean around Australia will no longer be suitable for coral formation. The increasing acidification in our oceans from greenhouse gas emissions won't just harm coral; it is also likely to harm the marine snails in the Southern Ocean. *See full highlight on page 47.*
Extremes	6. Future climate predictions	6.1 Regional climate projections science including downscaling	CSIRO	**Downscaling adds value in some regions** A comparison of three different downscaled projections from older generation climate models confirms that some add value when looking at the average rainfall in a warmer climate scenario for this century. *See full highlight on page 50.*
		6.2 Trends and projected changes in cyclonic rainfall	CSIRO	**Warmer seas fuel tropical cyclones** Higher sea-surface temperatures from increasing greenhouse gas emissions may make tropical cyclones in northern Australia more intense and produce more rainfall. *See full highlight on page 52.*

Key climate research theme	Research programme area	Project title	Research organisation	Science highlight
		6.3 The influence of climate change on extratropical lows and associated extreme weather events.	The Bureau	**Fewer large waves from East Coast Lows** The central east coast of Australia is likely to experience fewer days with large storm waves if greenhouse gas emissions continue to rise. *See full highlight on page 53.*
		6.4 Understanding tropical SST changes and their teleconnection to Australian rainfall.	CSIRO	**Rainfall change linked to ocean temperatures** Rainfall over Australia may change with global warming. However, for much of the continent, whether the climate model projections show decreases or increases in rainfall is linked to the modelled pattern of warming. *See full highlight on page 55.*
Communication	7. Coordination and communication	7.1 ACCSP – Programme management, coordination, and communication	CSIRO and the Bureau	**Telling the climate change science story** Peer-reviewed work by more than 100 ACCSP scientists shows that human activities are affecting climate in the southern hemisphere and around the globe. This consistent finding is captured in 130 peer-reviewed papers that were published this year in highly-regarded local and international scientific journals. *See full highlight on page 58.*

Appendix 2. Our research partners

In 2012–13 the ACCSP collaborated with the following partners:

Universities

- Australian National University
- Charles Darwin University
- James Cook University
- Macquarie University
- Monash University
- Queensland University of Technology
- Southern Cross University
- Swinburne University
- 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

National

- Antarctic Climate and Ecosystems Cooperative Research Centre
- ARC Centre of Excellence for Climate System Science, UNSW, Australia
- Australia's Integrated Marine Observing System
- Australian Antarctic Division
- Australian Institute of Marine Science
- Australian Nuclear Science and Technology Organisation
- Bureau of Meteorology – Marine Operations
- Centre of Excellence for Climate System Science, Monash University
- Climate Change Research Centre, UNSW, Australia
- Department of Science, Information Technology, Innovation and the Arts, Dutton Park, Queensland
- Integrated Marine Observing system
- National Computational Infrastructure
- Queensland Climate Change Centre of Excellence
- Royal Australian Navy
- The Goyder Institute

International

- Alfred Wegener Institute for Polar and Marine Research, Germany
- Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, USA
- British Antarctic Survey, UK
- California Institute of Technology, Pasadena, California, USA
- Carbon Dioxide Information and Analysis Center, DOE, USA.
- Center for International Climate and Environmental Research, Norway
- Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune, India
- Centre for Ice and Climate, University of Copenhagen, Denmark
- Centre National de la Recherche Scientifique, Laboratoire de Glaciologie et Géophysique de l'Environnement, France
- College for Global Change and Earth System Science, Beijing Normal University China
- Department of Earth and Environmental Sciences, University of Rochester, USA
- Department of Earth Sciences, Uppsala University, Sweden
- Department of Earth System Science, University of California USA
- Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan Laboratoire d'Océanographie et du Climat, France
- Department of Meteorology, University of Hawaii at Manoa USA
- Department of Oceanography, University of Hawaii at Manoa USA
- Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, USA
- Departments of Earth & Planetary Science and of Chemistry, University of California, USA
- Disaster Prevention Research Institute, Kyoto University, Japan
- Duke University, USA
- Environment Canada, Toronto, Canada
- Escola Naval, CINAV, Lisbon, Portugal,
- Geomar, Kiel, Germany.
- Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA
- Institut de Recherche pour le Développement New Caledonia/ France
- Institut de Recherche pour le Développement, Noumea, New Caledonia
- Institute for Marine and Atmospheric research Utrecht, Utrecht University, The Netherlands
- Institute of Arctic and Alpine Research, University of Colorado, Boulder, USA
- Institute of Astronomy, Geophysics and Atmospheric Sciences, University of Sao Paulo, Brazil
- Institute of Atmospheric Physics, Chinese Academy of Sciences, China
- Institute of Oceanology, Chinese Academy of Sciences, China
- International Argo programme (more than 15 countries – www.argo.ucsd.edu)
- International Geosphere-Biosphere Programme, Stockholm, Sweden
- International Pacific Research Center USA
- Japan Agency for Marine Science and Technology
- Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN), France

- Laboratoire des Sciences du Climat et de l'Environnement, France
- Laboratoire d'Océanographie et du Climat : Expérimentation et Approches Numériques, Institut Pierre Simon Laplace, France
- Lamont Doherty Earth Observatory, USA
- Low Temperature research laboratory, Japan
- Lund University, Sweden
- Meteorological Service Cook Islands
- MetOffice, Exeter, UK
- NASA Goddard Institute for Space Studies, USA
- NASA Goddard Space Flight Center, USA
- National Center for Atmospheric Research, USA
- National Institute for Environmental Studies, Japan
- National Institute for Water and Atmosphere, New Zealand
- National Oceanic and Atmospheric Administration, USA
- National Oceanographic Data Centre, USA
- NOAA/Pacific Marine Environmental Laboratory USA
- Oregon State University, USA
- Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, USA
- Pacific Marine Environmental Laboratory, USA
- Princeton University, USA
- School of Earth and Environmental Sciences, Seoul National University, Republic of Korea
- School of Environmental Sciences, University of East Anglia, United Kingdom
- Scripps Institution of Oceanography, University of California, San Diego, USA
- Seoul National University, Korea
- SKLTO China
- State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology (SKLTO) China
- Swansea University, Swansea, United Kingdom
- The National Center for Atmospheric Research, USA
- Third Institute of Oceanography, State Oceanic Administration China
- Tyndall Center, United Kingdom
- Universitat de València, Spain
- Université Pierre et Marie Curie, France
- University of Alberta, Alberta, Canada
- University of Cambridge, UK
- University of Exeter, UK
- University of Hawaii, USA
- University of Innsbruck, Innsbruck, Austria
- University of Leeds, UK
- University of Lethbridge, Alberta, Canada
- University of Reading, United Kingdom

Appendix 3. Peer-reviewed publications

In 2012–13, ACCSP researchers published 130 peer-reviewed papers or articles in Australian and international scientific publications. A further 25 papers were submitted for publishing and 25 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.

ACCSP scientific papers in journals and book chapters are peer reviewed to ensure that the published findings are objective, unbiased and conform to accepted scientific standards.

In some groups of journals, the review process is public so the submitted paper goes online in the ‘Discussions’ version of the journal. When the paper has been reviewed and revised, the final paper goes in the companion journal with the same name but without the ‘Discussions’ in the title. More information about these journals can be found at http://www.egu.eu/publications/open-access-journals/

Note: ‘DOI’ is the abbreviation for ‘Digital Object Identifier.’

Global and regional carbon budgets

Basu S, Guerlet S, Butz A, Houweling S, Hasekamp O, Aben I, Krummel P, Steele P, Langenfelds R, Torn M, Biraud S, Stephens B, Andrews A, and Worthy D, 2013, Global CO_2 fluxes estimated from GOSAT retrievals of total column CO_2, *Atmospheric Chemistry and Physics Discussion*, 13, 4535–4600

Ciais P, Gasser T, Paris JD, Caldeira K, Raupach MR, Canadell JG, Patwardhan A, Friedlingstein P, Piao SL, and Gitz V, 2013, Attributing the increase of atmospheric CO_2 to emitters and absorbers, *Nature Climate Change*, 1758–6798, DOI:10.1038/nclimate1942

Cressot C, Chevallier F, Bousquet P, Crevoisier C, Dlugokencky E, Fortems-Cheiney A, Frankenberg C, Parker R, Pison I, Scheepmaker R, Montzka S, Krummel P, Steele P, and Langenfelds R, 2013, On the consistency between global and regional methane emissions inferred from SCIAMACHY, TANSO-FTS, IASI and surface measurements, ACPD, *Atmospheric Chemistry and Physics Discussion*, 13, 8023–8064

Enting I, et al., 2012, Carbon cycle uncertainty in REgional Carbon Cycle Assessment and Processes (RECCAP), *Biogeosciences*, 9, 2889–2904, DOI:10.5194/bg-9-2889-2012

Francey R, Trudinger C, van der Schoot M, Law R, Krummel P, Langenfelds R, Steele P, Allison C, Stavert A, Andres R, and Rödenbeck C, 2013, Reply to ‘Anthropogenic CO_2 emissions’, *Nature Climate Change*, 3, 604, 2013, DOI:10.1038/nclimate1925

Francey RJ, Trudinger CM, van der Schoot M, Law RM, Krummel PB, Langenfelds RL, Steele LP, Allison CE, Stavert AR, Andres RJ, and Rödenbeck C, 2013, Atmospheric verification of anthropogenic CO_2 emission trends, *Nature Climate Change*, 3, 520–524, doi:10.1038/nclimate1817

Fraser A, Palmer P, Feng L, Boesch H, Cogan A, Parker R, Dlugokencky E, Fraser P, Krummel P, Langenfelds R, O’Doherty S, Prinn R, Steele P, van der Schoot M, and Weiss R, 2013, Estimating regional methane surface fluxes: the relative importance of surface and GOSAT mole fraction measurements, *Atmospheric Chemistry and Physics*, 13, 5697–5713, DOI:10.5194/acp-13-5697-2013

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Appendix 4. News releases

Table 10. The ACCSP distributes research findings to mainstream and specialist science and environmental media. In 2012–13, the following news releases arose directly from ACCSP research or publicised relevant work.

Media release	Date distributed	Web link
Warming causes more extreme shifts of the southern hemisphere's largest rain band South Pacific countries will experience more extreme floods and droughts, in response to increasing greenhouse gas emissions, according to a paper out today in the journal *Nature*.	16 Aug 2012	www.csiro.au/Portals/Media/Warming-causes-more-extreme-shifts.aspx
Southern hemisphere becoming drier A decline in April-May rainfall over south-east Australia is associated with a southward expansion of the subtropical dry-zone according to research published today in Scientific Reports, a primary research journal from the publishers of *Nature*.	3 Oct 2012	www.csiro.au/Portals/Media/Southern-Hemisphere-becoming-drier.aspx
The widening gap between present emissions and the two-degree target Carbon dioxide emission reductions required to limit global warming to 2 °C are becoming a receding goal based on new figures reported today in the latest Global Carbon Project (GCP) calculations published today in the advanced online edition of *Nature Climate Change*.	3 Dec 2012	www.csiro.au/Portals/Media/The-widening-gap-between-present-emissions-and-the-two-degree-target.aspx
Greenland ice core records provide a vision of the future Ice cores drilled in the Greenland ice sheet, recounting the history of the last great warming period more than 120,00 years ago, are giving scientists their clearest insight to a world that was warmer than today.	24 Jan 2013	www.csiro.au/Portals/Media/Greenland-ice-core-records-provide-a-vision-of-the-future.aspx
Landmark carbon assessment developed for Australia The Australian landscape soaked up one third of the carbon emitted by fossil fuels in Australia over the past twenty years, according to a new CSIRO study released last week.	20 Feb 2013	www.csiro.au/Portals/Media/landmark-carbon-assessment-developed-for-Australia.aspx
Changing wave heights projected as the atmosphere warms Climate scientists studying the impact of changing wave behaviour on the world's coastlines are reporting a likely decrease in average wave heights across 25 per cent of the global ocean.	12 Apr 2013	www.csiro.au/Portals/Media/Changing-wave-heights-projected-as-the-atmosphere-warms.aspx
Climate tug of war disrupting Australian atmospheric circulation patterns Further evidence of climate change shifting atmospheric circulation in the southern Australian-New Zealand region has been identified in a new study.	21 Jun 2013	www.csiro.au/en/Portals/Media/Climate-tug-of-war-disrupting-Australian-atmospheric-circulation-patterns.aspx

Appendix 5. Climate change websites

Table 11. In 2012-13, we made Australia's climate change science information available online to a wide audience. Our research activities and findings are available on the following websites.

What	Organisation	Web address	Comments
About the ACCSP	CSIRO	www.csiro.au/org/Australian-Climate-Change-Science-Program.html	There is also general climate change information on this website
About the Australian Climate Change Science Programme (ACCSP)	CSIRO, the Bureau, The Department	www.cawcr.gov.au/projects/climatechange/	The ACCSP is the Australian Government's largest and longest running climate change science programme. Its science and research is crucial to helping understand what is happening, what Australia's climate will be like in the future, and how best to prepare.
Australian Climate Change Science	The Department	www.climatechange.gov.au/climate-change/grants/australian-climate-change-science-program	The Australian Government's plan for implementing climate change science in Australia
Australian climate scenario generator	CSIRO	www.csiro.au/ozclim/home.do	The climate change scenario generator is free to use, but you need to register
Australian national and state-wide climate projections	CSIRO, the Bureau, The Department	www.climatechangeinaustralia.gov.au/	A map of Australia that can be clicked on to get the latest climate projections in a region of interest. The projections are freely available
Greenhouse gas emission measurements	CSIRO	www.csiro.au/greenhouse-gases/	Monthly greenhouse gas data from one of the cleanest air sources in the world, Cape Grim, on Tasmania's west coast
Observed Australian climate trends	The Bureau	www.bom.gov.au/climate/	The Bureau collects information from across Australia, including rainfall, wind, temperature, fog, thunder, humidity, pressure, ocean temperatures and sunshine data. Its seasonal and longer-range outlooks also enable it to look at Australia's future climate
Tackling the challenge of climate change	The Department	www.climatechange.gov.au/	How the Australian Government is contributing to developing climate change solutions, mitigating greenhouse gas emissions, and promoting energy efficiency
Understanding climate change	CSIRO	www.csiro.au/science/Changing-Climate	How the Earth's climate system works through observation, measurement and modelling
Understanding sea-level rise	CSIRO and Antarctic Climate and Ecosystems Cooperative Research Centre	www.cmar.csiro.au/sealevel/index.html	Sea-level measurements using data from tide gauges and satellite altimeters to determine past changes in global mean and regional sea level for understanding the reasons for past changes and improving projections of future sea-level rise

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Figure 1. Observed fossil fuel emissions of carbon dioxide and the Intergovernmental Panel on Climate Change (IPCC) emission scenarios show that if greenhouse gas emissions continue to increase as fast as they are doing now, then the global temperature is estimated to reach 4–6 °C above preindustrial levels by 2100. The graph shows the uncertainties in observed fossil fuel, cement, and gas flaring emissions of carbon dioxide from 1980 to 2012 due to inaccurate reporting, particularly from less developed countries. Four IPCC scenarios are shown to 2100, which range from low (blue line) to high (red line). These scenarios or RCPs (called Representative Concentration Pathways) are used in the IPCC 5th Assessment Report. The graph also shows other older scenarios from the literature (faint lines).......... 16

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Figure 10. Argo floats are uniformly distributed across the globe, except for areas covered by sea ice. In June 2013, there were 3,525 active Argo floats in the world's oceans. While about 20 nations deploy Argo floats, only a handful maintain most of the array. After the USA, with more than 50 per cent of the Argo floats, Australia is one of the next most significant contributors with 371 active floats. 31

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