Australian Climate Change Science Programme

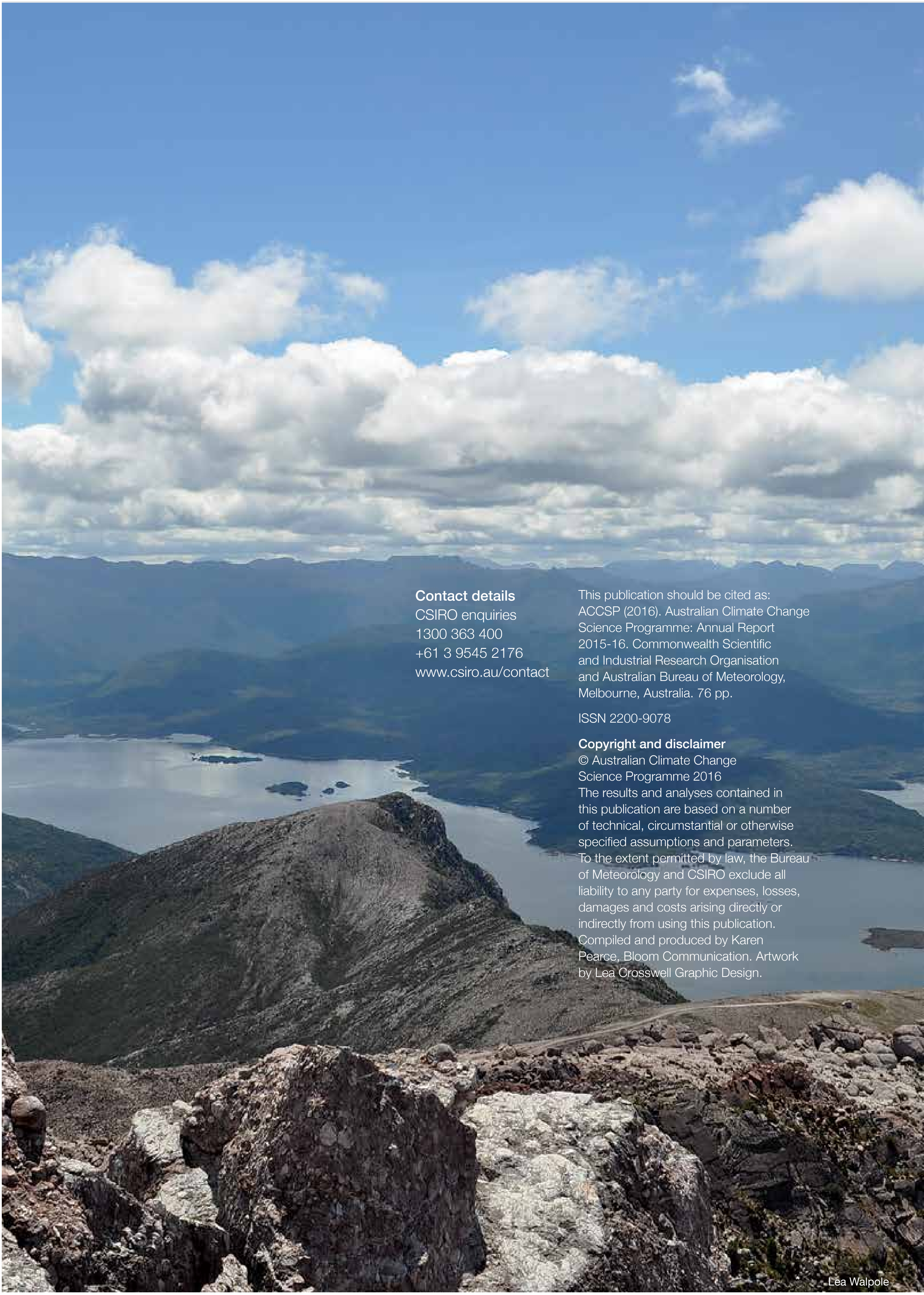
ANNUAL REPORT 2015–16

Australian Government
Department of the Environment and Energy

CSIRO

Australian Government
Bureau of Meteorology

The Australian Climate Change Science Programme – an Australian Government initiative



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Contents

FOREWORD 2

ABOUT 4

The Programme 4

Research 4

Collaboration 4

Global climate snapshot 4

Australia's changing climate 5

PROGRAM HIGHLIGHTS

Component 1: Global and regional carbon budgets 6

Component 2: Land and air observations and processes 14

Component 3: Oceans and coasts observations and processes 19

Component 4: Modes of climate variability and change 27

Component 5: Earth systems modelling and data integration 33

Component 6: Australia's future climate 42

Component 7: Management, coordination and communication 52

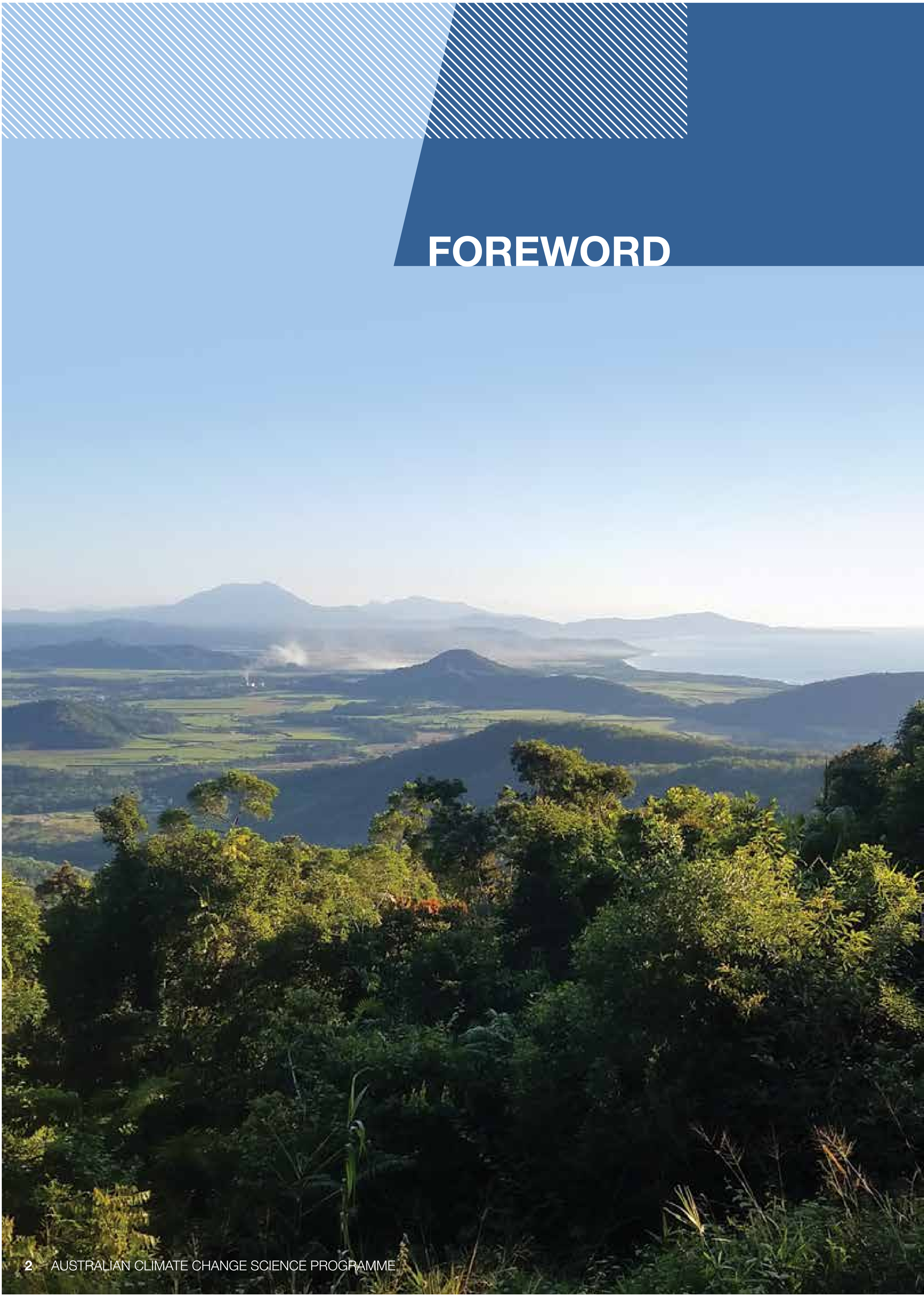
APPENDICES

A1 Research projects 55

A2 Collaborators 58

A3 Publications 60

FOREWORD



For the past 27 years, the Australian Climate Change Science Programme (ACCSP) and its predecessors have played a major role in informing Australia's decision makers and improving the understanding of the causes, nature, timing and consequences of climate change.

While 2015–16 was the final year of the ACCSP, the science did not slow down. Our land, air and ocean observations continued to illuminate our understanding of climate processes and interactions, feeding in to the ongoing development of ACCESS, our national climate model. Our understanding of the processes that influence Australia's climate, such as El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), tropical cyclones and the monsoon, continued to grow.

Among the many highlights in this last year of the ACCSP are many firsts. In 2015–16, ACCSP researchers:

- quantified for the first time the natural versus human-induced processes that cause sea-level rise (Project 3.3)
- developed the first maps of seasonal seawater carbon chemistry change around Australia's shelves and regional seas (Project 3.4)
- conducted the first study to examine the non-linearities in the relationship between Australian rainfall and ENSO across all seasons and over all of Australia (Project 4.1)
- developed the first multi-decadal climatology of individual heat low events over Australia (Project 6.2)
- developed the world's first method for seasonal forecasting of thunderstorms and lightning activity (Project 6.5)
- developed projections of the change in occurrence frequency of environments conducive to dry lightning, the first results of their kind to have been produced for any region of the world (Project 6.5).

As in past years, our researchers have shared their work with science colleagues, stakeholders and the community. They have presented their findings at workshops, conferences and many local and international events, and published in peer-reviewed papers in Australian and international journals and in publications for workshops, conferences and other events.

In this, our final annual report, we wish to acknowledge the dedication and passion of our scientists and staff for their work to improve Australia's understanding of climate change and the challenges ahead. We would also like to acknowledge the Department of the Environment and Energy, which has supported CSIRO and the Bureau of Meteorology as the providers of the climate science undertaken by the ACCSP.

The role of providing Australia's climate change science now falls to the National Environmental Science Programme Earth Systems and Climate Change Hub, along with the new CSIRO Climate Science Centre and other related climate programs in the Bureau of Meteorology, universities (including the Centre of Excellence for Climate System Science), Antarctic and Climate Ecosystem CRC and the Australian Antarctic Division.

As climate records continue to be broken with seemingly increasing regularity, these research collaborations have an important task ahead. Now, more than ever, it is critical to provide the underpinning science to allow our country to develop ways to adapt to climate change and manage greenhouse gas emissions.

The legacy of the ACCSP sets them in good stead.

Dr Geoff Gooley
CSIRO

Manager, Australian Climate Change Science Programme

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

Dr Robert Colman
Bureau of Meteorology

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ABOUT

THE PROGRAMME

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

It was established in 1989 as the Climate Change Research Programme. Its name changed to the National Greenhouse Science Programme and then the Australian Greenhouse Science Programme prior to its current title. The ACCSP concluded in June 2016.

The Programme was a key driver of Australia's climate change research effort, providing climate research aimed at improving the understanding of the causes, nature, timing and consequences of climate change.

RESEARCH

In 2015–16 the ACCSP received funding of $11 million through a collaboration between the Department of the Environment and Energy, CSIRO and the Bureau of Meteorology. More than 100 scientists throughout Australia were involved in the programme, undertaking 22 projects across six key research areas.

See Appendix 1 for a complete project list.

COLLABORATION

Extensive collaboration and engagement with the Australian Government and Australian and international research agencies has helped to ensure our research is stakeholder relevant, effectively leveraged and leading edge.

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

Over the past 12 months, ACCSP researchers played leading roles in international bodies such as the World Climate Research Programme and the Global Carbon Project. The ACCSP also supported Australia's participation in global observation programs such as the International Argo Project, the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) and the global flux network and database (FluxNet).

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

GLOBAL CLIMATE SNAPSHOT

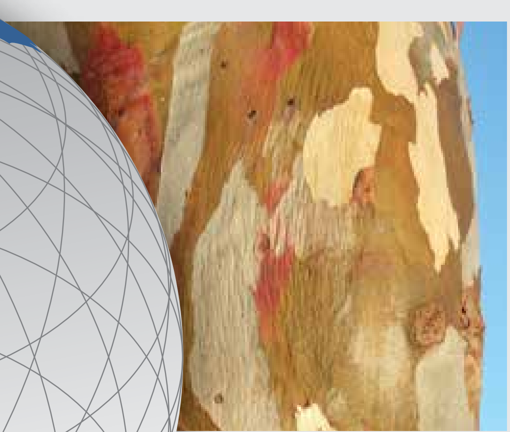
2015 was the warmest year on record for the globe since reliable global records began in 1880. Fifteen of the 16 warmest years on record have occurred in the last 15 years.

July 2016 was the 15th consecutive month of record heat for land and oceans.

July 2016 was the 379th consecutive month with temperatures above the 20th century average. (December 1984 was the last month with below-20th century average temperatures.)

Global annual average CO_2 level was 399 ppm in 2015, likely the highest level in at least the past two million years. The 2016 global annual average CO_2 level will exceed 400 ppm.

CO_2 increases in 2015 are the highest ever observed, resulting from a combination of ongoing large human emissions and a weakening of land uptake of CO_2 due to the 2015–16 El Niño.




Flickr/Sascha Grant

AUSTRALIA'S CHANGING CLIMATE

PAST	FUTURE
Surface air temperature has warmed by around 1 °C since 1910. The number of days per year over 35 °C has increased in recent decades, except in parts of northern Australia.	By late this century, Australia's average temperature is projected to increase by 3–5 °C. These are projected to continue increasing through the century.
There has been an increase in the number of days with weather conducive to fire in southern and eastern Australia.	The number of such days is projected to double by the end of the century.
Across parts of northern Australia, rainfall has increased since the 1970s. In the south-west, May–July rainfall has reduced by around 19 per cent since 1970. In the continental south-east, here has been a decline in rainfall of around 11 per cent since the mid-1990s over the April–October growing season.	Winter rainfall is projected to decrease across southern Australia, by a median of 17 per cent with a range of 2–32 per cent by the end of the century, with more time spent in drought. Extreme rainfall events are projected to increase in intensity by the end of the century across Australia (i.e. the wettest day of the year will become wetter).
Sea surface temperature has warmed by around 1 °C since 1910	Oceans will continue to warm.
Since the 1880s, the pH of surface waters around Australia is estimated to have decreased by about 0.1.	Ocean acidification will continue.
Global sea level has risen about 20 cm over the past century.	Sea level will rise by around 6–19 cm by 2030, and further beyond this.

Projections are relative to the 1986–2005 baseline, under the current global trajectory of greenhouse gas emissions.

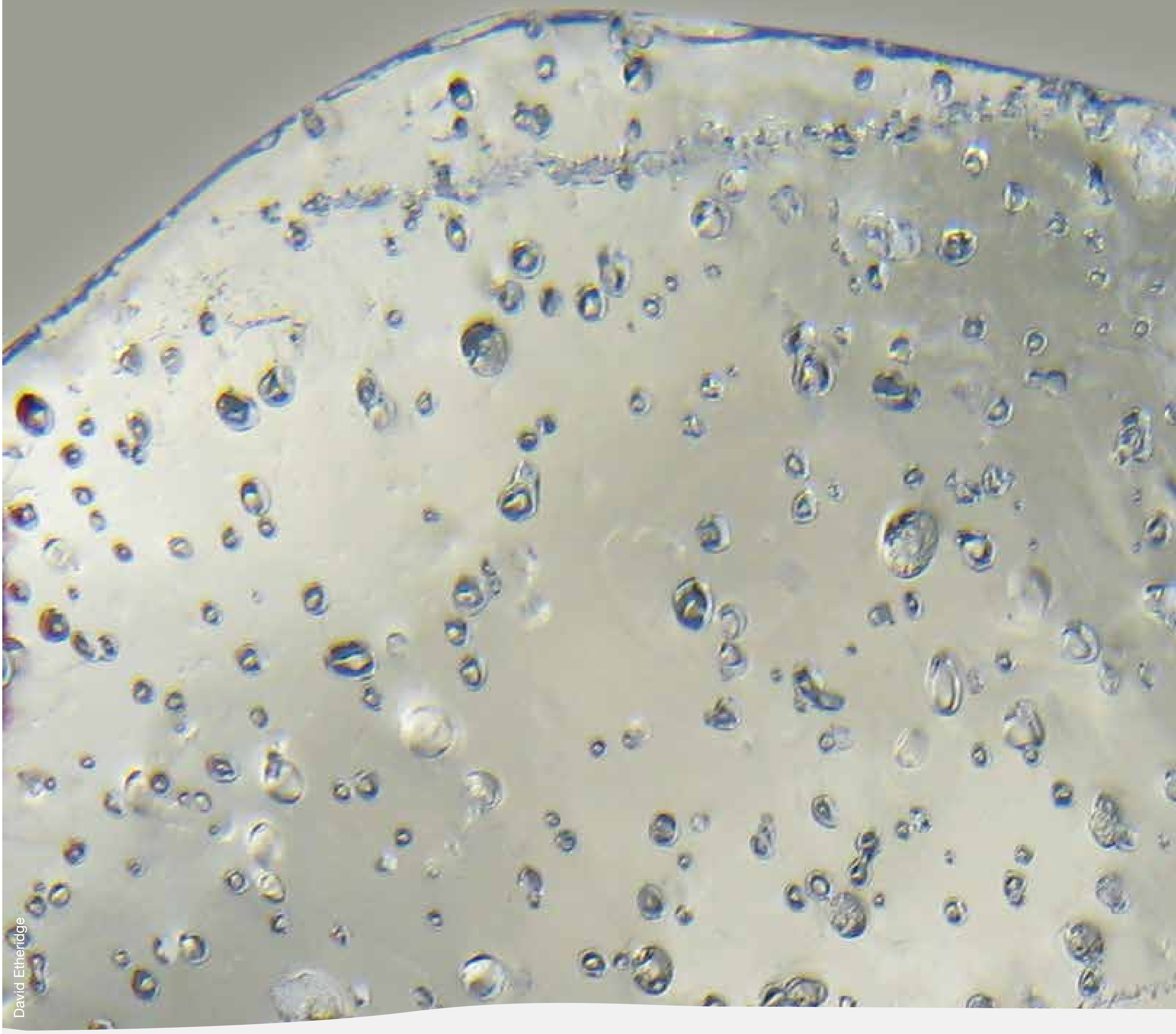
For detailed projections visit **www.climatechangeinaustralia.gov.au**

1

2015–16 Highlights

Global and regional carbon budgets

The ACCSP undertook research to track, understand and predict changes in greenhouse gas levels, and in the stocks and flows of carbon. This provided information on changes to greenhouse gas emissions and concentrations, nationally and internationally, and how these affect our environment.



1.1 GLOBAL CARBON BUDGETS, ANALYSES AND DELIVERY

SCIENCE TO INFORM DECISION-MAKING

Improving our understanding of the carbon cycle – how carbon is taken up and released, and what processes impact on carbon flows – informs the development of concentration scenarios for climate modelling and allows us to improve climate models (and climate projections). It also highlights areas of focus for mitigation policy.

Carbon dioxide fertilisation greening the Earth

Despite widespread droughts and increasing global temperatures, globally, land is greener today it has been over the past three decades.

In ACCSP-supported research, greening and browning trends over the 30-year period for which satellite data has been available were analysed, using three different satellite data sets. The trends from the satellite data were then matched with land surface models, including CABLE, to determine which processes were responsible for the greening. Researchers found that carbon dioxide fertilisation effect on plant growth was the single most important driver of greening. Only 4 per cent of the land surface became browner during the same period.

These greening trends are consistent with previous estimates on the capacity of the land to remove atmospheric carbon dioxide. It also provides further strong evidence of how people have become a major force in the Earth's functioning.

READ MORE | Zhu *et al*. 2016. Greening the Earth and its drivers. *Nature Climate Change*, 6, 791–5.

Up to 50% of all vegetated land is greener today than 30 years ago and only 4% is browner today than it was.

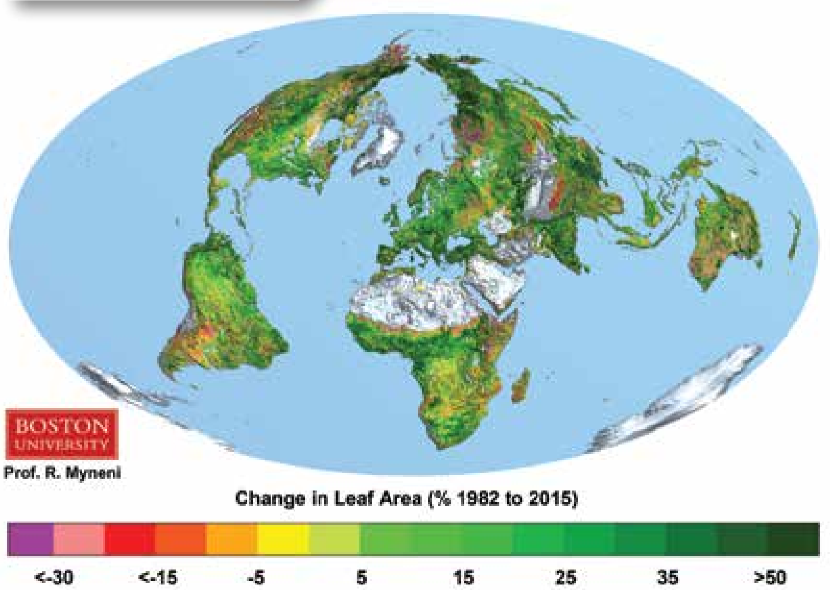


Figure 1.1
Changes in leaf area (a surrogate for greening) over the period 1982 to 2015.

The **Community Atmosphere Biosphere Land Exchange (CABLE) model** is a land surface model that is used to calculate flows of momentum, energy, water and carbon between the land surface and the atmosphere, and to model major biogeochemical cycles of the land ecosystem. CABLE provides the land surface component of ACCESS (see section 5), and can also be run as a standalone model.

1

2015–16 Highlights

Non-carbon dioxide emissions from global food production are becoming bigger players in climate change

> Methane, nitrous oxide and carbon dioxide emissions from the global food system are equivalent to more than half of the emissions from fossil fuels.

While carbon dioxide emissions from the global energy system have leveled off over the past two years, non-carbon dioxide emissions from the global food system are rapidly growing.

ACCSP-supported researchers ran 10 biosphere-land models from the pre-industrial period to present day, using observations of carbon dioxide, methane and nitrous oxide. They found that the warming potential of the emissions of methane and nitrous oxide, largely from producing food, are counteracting the benefits of the terrestrial carbon sink in the fight against climate change.

This work shows that while the main emphasis on fossil fuel emissions is justified, an equally significant mitigation effort needs to address the reduction of non-carbon dioxide emissions (methane and nitrous oxide), largely coming from the food system. This is potentially a growing problem, as population increases and food production needs to keep up with demand.

READ MORE | Tian *et al*. 2016. The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. *Nature*, 531, 525–228.

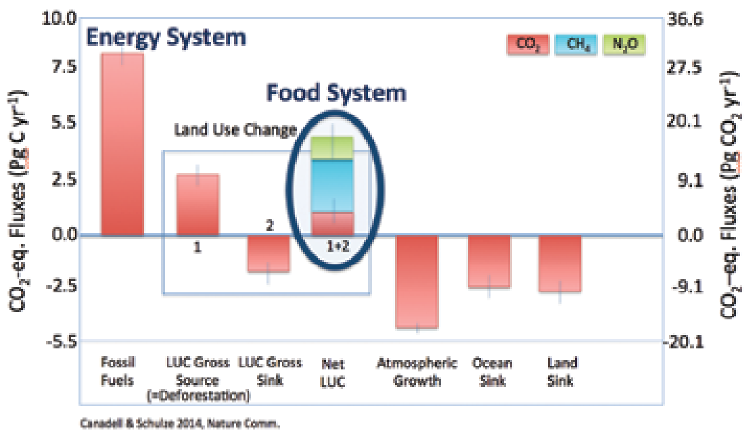


Figure 1.2
Global greenhouse gas emissions associated with human activities. The left hand scale shows carbon fluxes and the right hand scale shows fluxes in carbon dioxide equivalents to be able to compare CO_2, CH_4 and N_2O. 1 Pg is 10^{12} g or 1 Gigatonne (1 billion tonnes).

Emissions from the food system are as great as more than half the amount of emissions from fossil fuels.

A **carbon sink** removes carbon dioxide from the atmosphere. The terrestrial biosphere (vegetation) has taken up some of the anthropogenic carbon dioxide emissions over the past 150 years and currently absorbs about a quarter of global emissions. However, warming is expected to reduce terrestrial uptake, leaving more carbon dioxide in the atmosphere, which in turn makes it warmer still in a positive feedback. The future response of the terrestrial biosphere sink to climate change is a large cause of uncertainty in climate projections.

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

SCIENCE TO INFORM DECISION-MAKING

Understanding the natural variability of Australian semi-arid ecosystems is an important pre-requisite for assessing the vulnerability (to drought and fire) of carbon sequestered in these environments as part of land-based mitigation efforts.

Year-to-year variation in carbon uptake in Australian ecosystems is largely due to variations in eastern savanna productivity

The Earth's vegetation removes the equivalent of over a quarter of anthropogenic carbon dioxide emissions from the atmosphere. The amount varies from year to year, largely due to changes in soil water availability, and its impact on ecosystem productivity.

ACCSP researchers found that in Australia, the savannas (grassy woodlands and grasslands) in the east of the continent make the greatest contribution to variability in net carbon uptake (Fig. 1.3). This variability it linked to variable rainfall (Fig. 1.4), driven predominantly by the El Niño–Southern Oscillation.

> This research, based on continental carbon and water cycle modelling (using CABLE), showed that year-to-year variations in continental net carbon uptake are largely due to the variable productivity of savanna vegetation in the east of the content (Fig. 1.3). There is a significant offset of this variability by variable decomposition of organic matter in these ecosystems. Fire plays only a minor role in Australian continental-scale carbon cycle variations (Fig. 1.4).

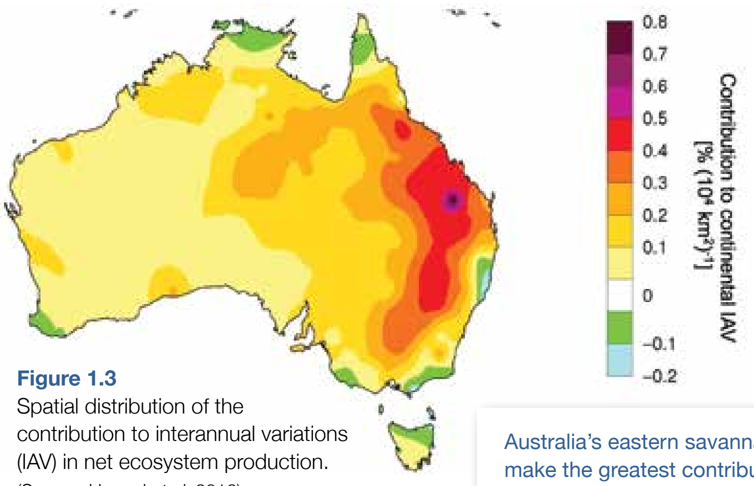


Figure 1.3
Spatial distribution of the contribution to interannual variations (IAV) in net ecosystem production.
(Source: Haverd *et al*. 2016)

Australia's eastern savannas make the greatest contribution to year-to-year variations in carbon uptake by Australian ecosystems.

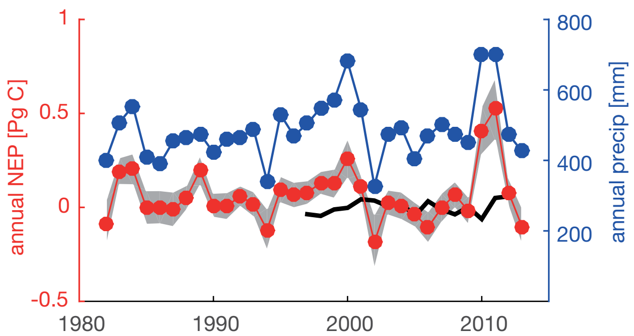


Figure 1.4
Australian continental annual net ecosystem production (NEP) (red) and precipitation (blue). Grey shading represents the two standard deviations uncertainty associated with parameter uncertainty. The solid black line (left axis) represents gross continental fire emission anomalies from the Global Fire Emissions Data Base. (Source: Haverd *et al.* 2016).

Year-to-year variations in carbon uptake by Australian ecosystems (red) are generally associated with variable rainfall (blue).

READ MORE | Haverd *et al.* 2016. Process contributions of Australian ecosystems to interannual variations in the carbon cycle. *Environmental Research Letters*, 11, 054013.

1.3 PALAEO CARBON CYCLE DYNAMICS

SCIENCE TO INFORM DECISION-MAKING

Air measurements from ice cores, firn (the upper layer of ice sheets), air archives and direct atmospheric observations allow researchers to prepare long-term greenhouse gas concentration data for driving model simulations of climate, carbon and chemistry. Changes in atmospheric concentrations of different gases are used to understand their past impacts, verify their emissions and validate models that predict their future levels and impacts.

Greenhouse gas mitigation verified by the palaeo-atmospheric record

Perfluorocarbons (PFCs) and halons are trace gases in the atmosphere that have impacts on climate and, in the case of halons, stratospheric ozone, but have only been measured in the atmosphere in recent decades.

> **Ice-core measurements show that emissions reductions and lower concentrations of these gases reduce their climate forcing and, in the case of the halons, are contributing to the recovery of the stratospheric ozone layer.**

ACCSP researchers measured the changes in PFCs and halons in air extracted from polar ice cores, firn and the Cape Grim air archive, and linked them to atmospheric observations. Together they show a complete record over the past century or more, from zero concentrations (except for PFC-14 which has a small natural source) before they were produced and emitted by human activities to the present.

Researchers calculated the emissions that caused the measured concentrations and attributed the trends to industrial emissions, economic changes and the impacts of mitigation that resulted from emissions protocols and management. The emissions calculated from the atmospheric changes provide a verification of the emissions compiled from bottom-up inventories and emissions accounting.

Emissions of perfluorocarbons PFC-14 (CF_4), PFC-116 (C_2F_6) and PFC-218 (C_3F_8) peaked between 1980 and 2000 and have since declined, largely due to reduced emissions from aluminium smelting and the semiconductor industries. A peak in PFC-14 emissions coincided with World War II and is attributed to aircraft manufacture.

Perfluorocarbons are about 7000–11 000 times more powerful greenhouse gases than carbon dioxide (on a weight emitted basis over a 100-year timescale) and have atmospheric lifetimes of thousands of years. Their main sources are aluminium smelting and the semiconductor industry. **Halons** are also greenhouse gases and now contribute to about 30 per cent of the emissions of all anthropogenic gases that deplete stratospheric ozone. Halons are used as fire suppressants.

Bottom-up methods estimate emissions based on inventories, process studies or small scale measurements, which are scaled up to represent continental, national or global amounts. **Top-down** methods measure the changes in the atmosphere and infer what emissions must have caused the changes. Both methods have their own strengths and weaknesses. Emissions in the more distant past (before the past several decades) are often better known from top-down methods because the atmospheric changes are measurable in air preserved in ice sheets, while bottom-up methods rely on records that often don't exist or are highly uncertain.

The emissions results can be combined with aluminium industry data to give emissions factors, which show significant improvement (reductions) in PFC emissions per tonne of aluminium production (Fig. 1.5). This is a result of improved smelting processes, and shows the role of management and technology in mitigating emissions while the industry can still grow. However, the concentrations of perfluorocarbons continue to grow due to their extremely long lifetimes.

READ MORE Trudinger *et al*. 2016. Atmospheric abundance and global emissions of perfluorocarbons CF_4, C_2F_6 and C_3F_8 since 1900 inferred from ice core, firn, air archive and in situ measurement. *Atmospheric Chemistry and Physics* (in press).

PFC-14 emissions (middle) are declining but atmospheric concentrations (top) continue to grow due to the gas's extremely long lifetime.

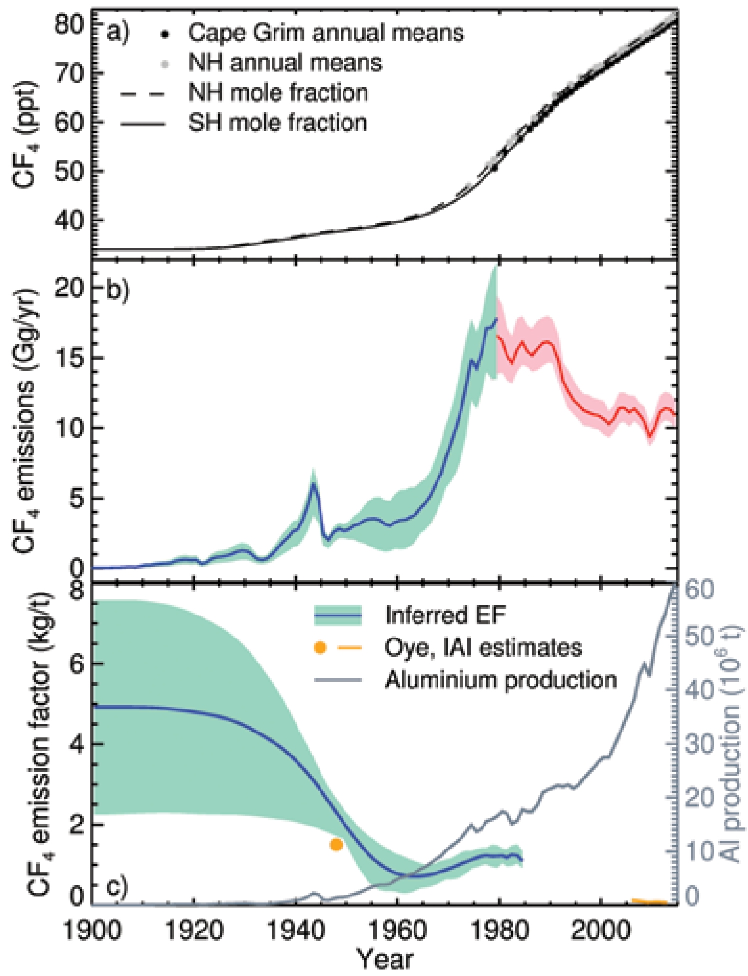


Figure 1.5
Atmospheric concentrations (top) of PFC-14 (CF_4) in the Northern and Southern Hemispheres from measurements of air in ice, firn and the air archive and direct measurements at Cape Grim; emissions derived from inversion of the concentration measurements (ice and firn, blue; direct and air archive, red) with uncertainties (middle); emissions factor (EF, bottom) in blue per million tonnes of aluminium produced (grey) compared to industry estimates for recent times and for 1948 (yellow). (Source: adapted from Trudinger *et al.* 2016)

2015–16 Highlights

The emissions of the halons H-1211 ($CBrClF_2$), H-2402 ($CBrF_2CBrF_2$) and H-1301 ($CBrF_3$) derived from concentration measurements (Fig. 1.6) have reduced under the regulatory framework of the Montreal Protocol (since the late 1980s for H-2402, around 1990 for H-1301 and the late 1990s for H-1211). However, because of their long life time in the atmosphere (16 to 65 years), concentrations of H-1211 and H-2402 have only been decreasing since the early 2000s, and the atmospheric concentration of H-1301 continues to increase.

READ MORE | Vollmer *et al.* 2016. Atmospheric histories and global emissions of halons H-1211 (CBrClF2), H-1301 (CBrF3), and H-2402 (CBrF2CBrF2). *Journal of Geophysical Research–Atmospheres*, 121, 3663–86.

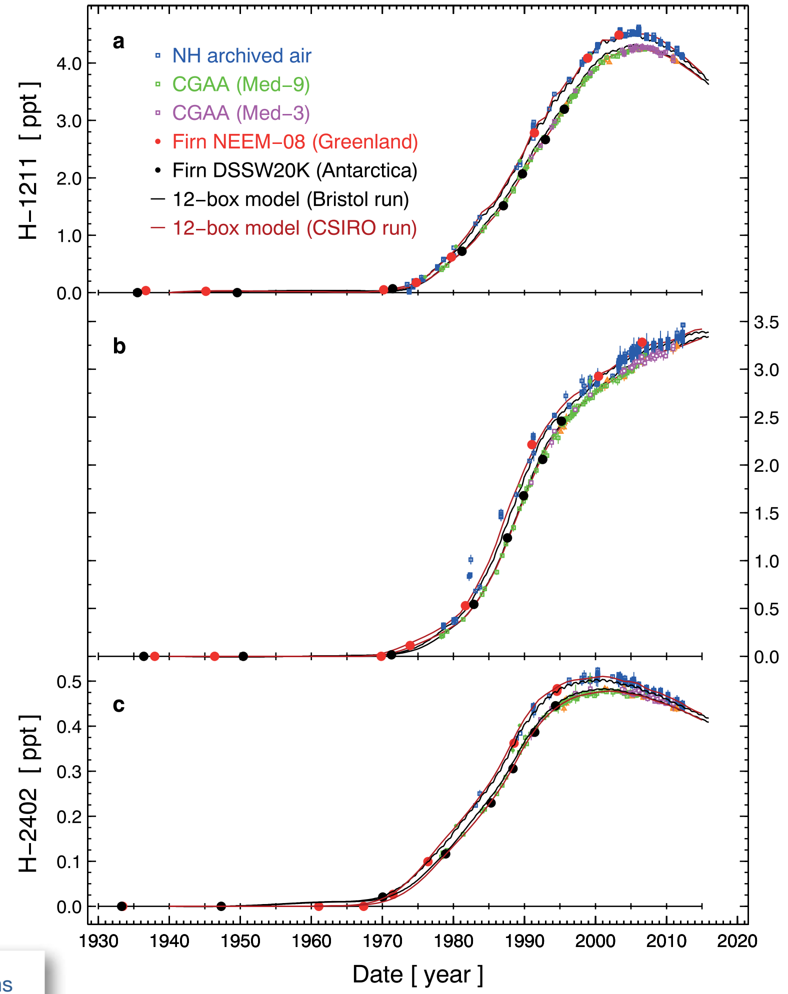


Figure 1.6
Atmospheric histories of the halons (a) H-1211, (b) H-1301, and (c) H-2402 from archived air samples and firn. Open squares show the archived air samples from the Northern Hemisphere (blue) and from the Southern Hemisphere (Cape Grim Air Archive, CGAA, in green and magenta). Their vertical bars denote the measurement precisions (1σ), which are often smaller than the plotting symbol. Filled circles show measurements of air entrapped in polar firn from Greenland (NEEM-08, red) and Antarctica (DSSW20K, black). The solid lines denote the modelled mole fractions for the two hemispheres based on the 12-box AGAGE model (independently run by Bristol and CSIRO) and are based on the data shown here and on the AGAGE in situ measurements and the King Sejong Antarctica flask samples. The measurements are plotted on the SIO primary calibration scales for the halons. (Source: Vollmer *et al.* 2016)

Concentrations of halons H-1211 and H-2402 have decreased, but H-1301 is still increasing.

Positive carbon dioxide feedback from the terrestrial biosphere due to temperature

Our understanding of the effect that temperature has on the carbon cycle has been improved by studying carbon in air extracted from Antarctic ice cores.

ACCSP researchers measured carbon dioxide and two carbon cycle tracers—the carbon-13 isotope of carbon dioxide and the trace gas carbonyl sulfide (COS)—in air samples extending back over the past 1000 years.

> **They found that for every 1 °C of warming, 10 to 90 PgC less carbon is taken up from the atmosphere by the terrestrial biosphere (plants and soils). This causes a positive feedback: warming results in more carbon dioxide in the atmosphere, which results in further warming.**

Changes in the amount of carbon-13 in air samples from the Little Ice Age confirm that changes of 5–10 ppm in atmospheric carbon dioxide over this period originated from the terrestrial biosphere. Variations in the concentration of COS, which is taken up from the atmosphere by land plants, confirmed that the lower Little Ice Age carbon dioxide was caused by net terrestrial uptake of carbon dioxide due to cooling, rather than regrowth following reductions in land use.

READ MORE | Rubino *et al.* 2016. Low atmospheric CO_2 during the Little Ice Age due to cooling-induced terrestrial uptake, *Nature Geoscience*, in press.

The **Little Ice Age** (1500–1750) was a widespread cool period that coincided with relatively low carbon dioxide concentrations. Because the carbon dioxide change made only a minor contribution to the cooling, the Little Ice Age is a suitable period from which to determine the effect that temperature has on the carbon cycle.

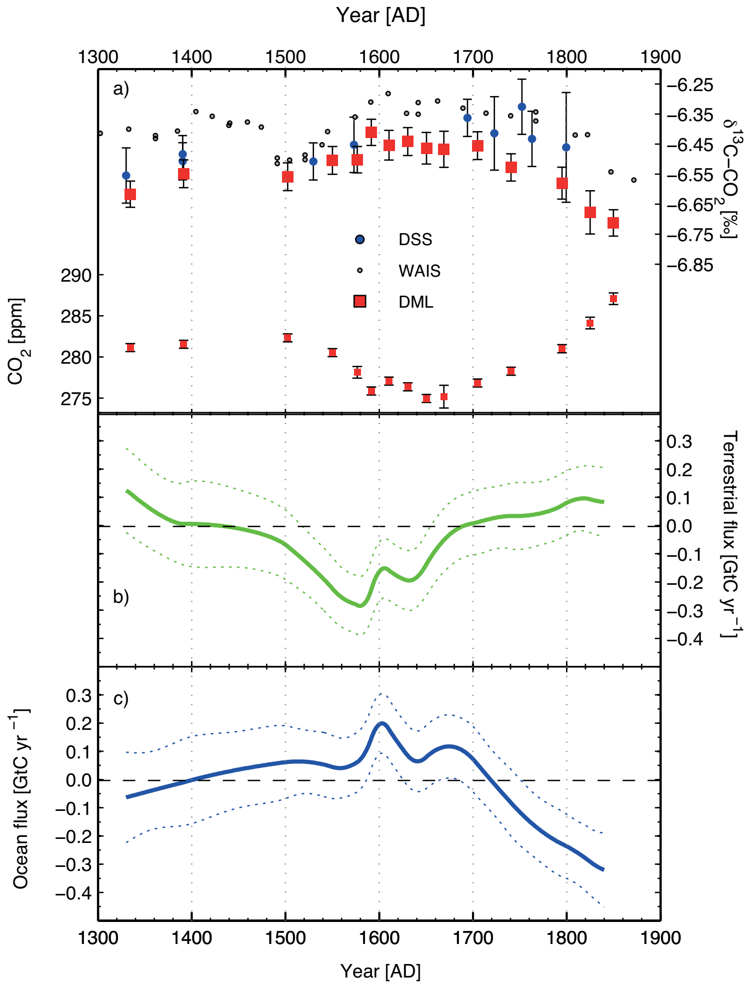


Figure 1.7
(Top) Carbon dioxide (CO_2) concentration and carbon-13 of CO_2 through the pre-industrial 600 years, showing lower CO_2 during the Little Ice Age. Terrestrial (middle) and oceanic (bottom) CO_2 fluxes. (Source: Rubino *et al.* 2016)

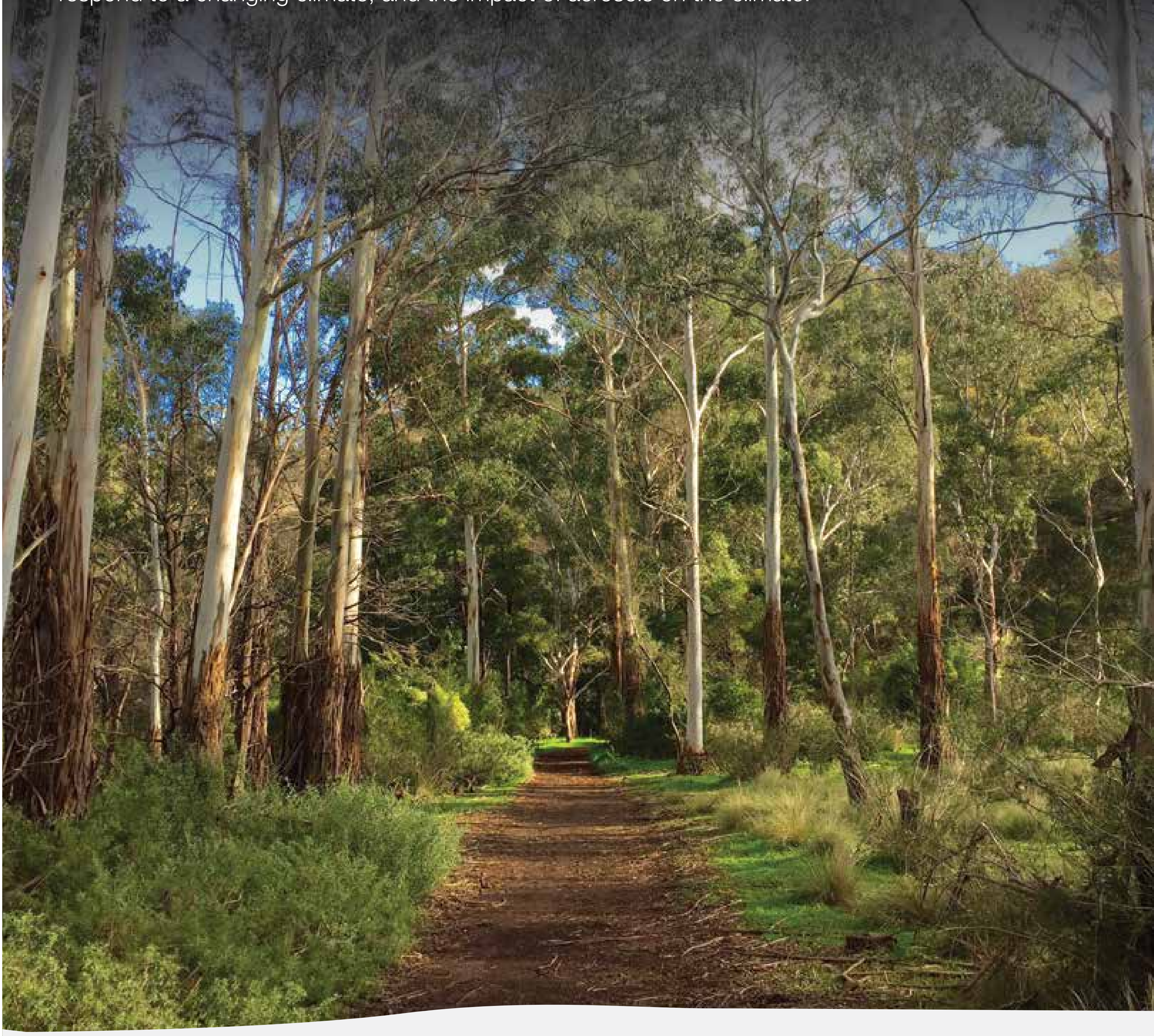
The terrestrial biosphere gains carbon as a response to cooling and loses carbon in response to warming. 0.5 to 1 °C cooling occurred from about 1500 to 1750 AD.

2

2015–16 Highlights

Land and air observations and processes

The ACCSP examined atmospheric behaviour and the way in which it is likely to change as concentrations of greenhouse gases rise. Focus areas were how Australian ecosystems, which absorb significant amounts of carbon from the atmosphere, respond to a changing climate, and the impact of aerosols on the climate.



2.1 AEROSOL AND ITS IMPACT ON AUSTRALIAN CLIMATE

SCIENCE TO INFORM DECISION-MAKING

Australian climate is affected by aerosol pollution in other parts of the world, in the same way that greenhouse gases emitted in countries far away from Australia impact on our climate. Reduction in aerosol concentrations could increase global warming, as aerosols have a cooling effect on the climate. Climate models can be used to estimate the amount of aerosol cooling.

Cooling effect of aerosol pollution is slowing down

Aerosol emissions increased strongly last century, peaking during the 1990s. They have since declined, and are projected to decline strongly over the coming decades. This is because aerosols directly affect air quality, and nations are expected to mandate a decrease in their emissions. Because of the short lifetime of aerosols in the atmosphere, decreases in emissions rapidly translate to decreases in the aerosol burden in the atmosphere.

> **Aerosols provide an offsetting 'cooling' of the climate, although the strength of that cooling is poorly understood and has a high degree of uncertainty. With the aerosol burden projected to strongly reduce from current levels, the cooling effect of these aerosols will decline.**

ACCSP researchers used the ACCESS-1.4 climate model to estimate cooling from anthropogenic (human-generated) aerosols both globally and over Australia. Calculations over the period 1850–2030 were done with greenhouse gases only, with anthropogenic aerosols only, and with both greenhouse gases and anthropogenic aerosols, based on the averages of three-member ensembles for each scenario.

Without anthropogenic aerosols, the temperature increase over the 20th century is determined mostly by greenhouse gas emissions (Fig. 2.1, green curves). While anthropogenic aerosols are emitted mostly from the industrialised regions of the northern hemisphere, their impacts are felt globally. Anthropogenic aerosols offset about one-third of the global warming from greenhouse gases. The magnitude of greenhouse gas warming and the aerosol-related cooling varies with

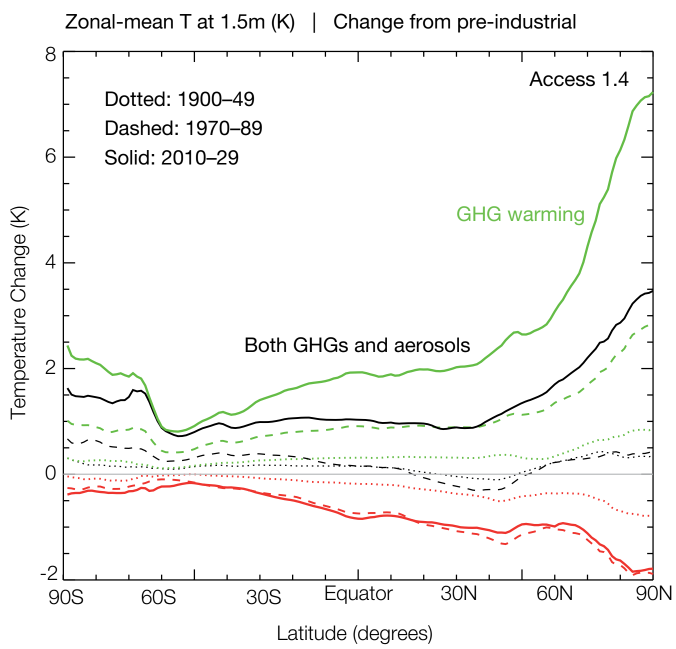


Figure 2.1
Results from the ACCESS-1.4 climate model showing temperature changes since pre-industrial times (1850) as a function of latitude for different time periods. Model results are shown with greenhouse gases only (green), with anthropogenic aerosols only (red) and with both greenhouse gases and anthropogenic aerosols (black). When all climate forcings are included (black), the modelled temperatures reflect increases from greenhouse gas emissions and cooling from aerosols. Model results are calculated using monthly anomalies from the mean of the pre-industrial control run, smoothed with a 13-month running mean, with inputs after 2005 based on IPCC's RCP8.5 scenario.

Aerosols offset about one third of the greenhouse gas warming.

location, with the largest changes in both model results and observations occurring at higher northern latitudes.

The amount of warming over Australia which was offset by cooling from global aerosol emissions in the ACCESS-1.4 model peaked around 1 °C at the end of the 20th century. If anthropogenic aerosol pollution is reduced into the future, the cooling effect of these aerosols will get smaller while temperatures continue increasing in response to accumulated greenhouse gases present in the atmosphere.

Southward shift of Australian pressure ridge counteracted by aerosols

Weather patterns are affected by changes in the mean sea-level pressure. There is a ridge of high pressure which sits over Australia, with maximum pressures located around 34°S. If the location of the southern mid-latitude pressure ridge shifts in response to a changing climate, prevailing westerlies and associated rainfall patterns may also change.

Aerosols are tiny airborne solid or liquid particles that reside in the atmosphere for hours to weeks. They may be either naturally occurring (e.g. dust) or generated by humans (e.g. sulphate aerosols, smoke and soot from fossil fuel burning or deforestation). Aerosols directly influence the climate by absorbing and reflecting solar radiation. They also have an indirect influence through their role in cloud formation (cloud drops form around aerosols) and in how they modify the optical properties of clouds (how bright or reflective they are) and their lifetime (how long they persist).

Results from the ACCESS climate model show how the pressure ridge at southern mid-latitudes shifts southward as a result of increasing greenhouse gas emissions (Fig. 2.2, green curves), with anthropogenic aerosol emissions offsetting part of this shift (Fig. 2.2, red curves).

Comparing ACCESS-1.4 results with observed global-mean temperatures suggests cooling from aerosols may be overestimated in the ACCESS model (reported in last year's annual report); using 70 per cent of the aerosol effect on temperature improves this agreement.

Further evaluation of aerosol processes in current and future versions of the ACCESS climate model will help to better understand and constrain the uncertainties which currently exist in our understanding of aerosol processes and their role in the climate system.

Greenhouse gases shift the Australian pressure ridge southward.

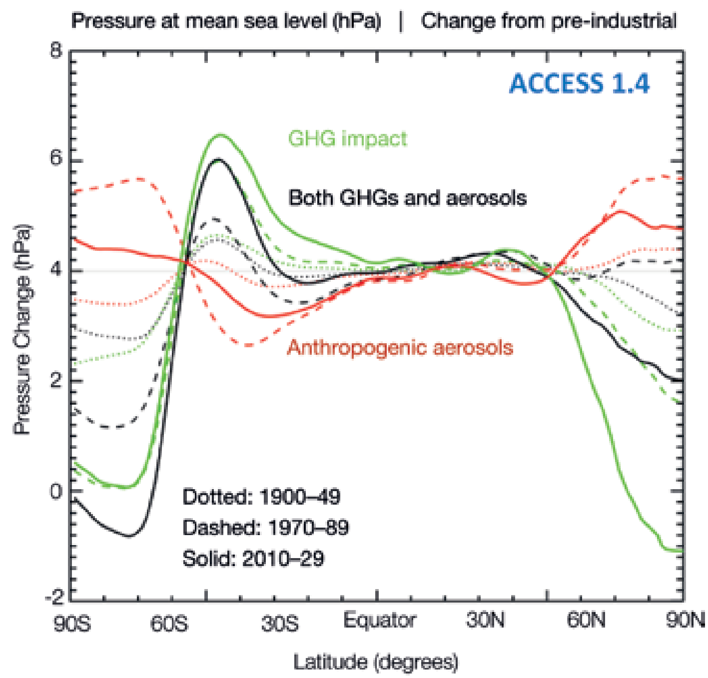


Figure 2.2
Results from the ACCESS-1.4 climate model showing changes in mean sea-level pressure since pre-industrial times (1850) as a function of latitude for different time periods. Model results are shown with greenhouse gases only (green), with anthropogenic aerosols only (red) and with both greenhouse gases and anthropogenic aerosols (black). Increasing greenhouse gases cause the pressure ridge located at southern mid latitudes (peak at 34°S) to move further south. As is the case for temperatures (Fig. 2.1), anthropogenic aerosol emissions tend to counteract some of the change caused by greenhouse gases.

2.2 REDUCING UNCERTAINTIES IN CLIMATE PROJECTIONS BY UNDERSTANDING, EVALUATING AND INTERCOMPARING CLIMATE CHANGE FEEDBACKS

SCIENCE TO INFORM DECISION-MAKING

Most of the range in Australian temperature projections is caused by uncertainties in feedbacks, particularly cloud feedback. Understanding and constraining processes which control cloud feedback will reduce this uncertainty, with profound impacts on adaptation and mitigation planning policy.

Feedbacks are climate processes that respond to the push or 'forcing' from increased greenhouse gases, and act to further amplify the temperature increase (positive feedback), or dampen it (negative feedback). The strongest positive feedback is from the increase in atmospheric water vapour that occurs in a warmer world, essentially because a warmer atmosphere can hold more moisture. Greatest uncertainty in climate change projections arises from cloud changes as the climate warms. **Clouds** can change in myriad ways, including the height, depth, amount, distribution, type and water/ ice content. Because of these complexities, cloud feedbacks are the focus of intense international research, and understanding critical physical processes is fundamental to further progress.

New method used to investigate cloud feedbacks in ACCESS

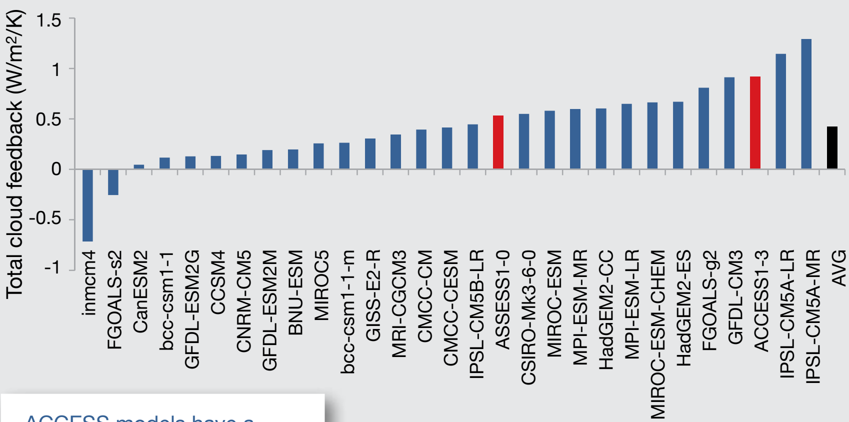
The greatest uncertainty in climate projections for a given emissions scenario lies in how strong the response in climate models is to a given increase in greenhouse gases. This range in sensitivity is mostly caused by cloud feedback (differences in the way clouds respond as the climate warms).

Last year ACCSP researchers developed and tested a methodology for evaluating cloud feedbacks in ACCESS. This year they used the methodology to see how some of the physical parameters associated with convection, precipitation and cloud formation affect cloud feedback in the model.

Researchers ran a series of experiments in ACCESS, in which they changed some of the settings in the model (e.g. the way the model treats convection, the formation of rainfall and the way ice particles fall within clouds). They found that although changes to these parameters can indeed change the model's (current) climate significantly, they have very little impact on the overall way in which the model responds to increased carbon dioxide.

This is a critical finding: it shows that the model climate change results are not sensitive to the relatively modest changes in parameters that occur during the 'tuning' process, when setting the model up. However, the effect of large changes to these parameters, such as when entirely new model versions are introduced, remains to be determined.

This analysis should prove an important new facility within the ACCESS modelling framework, as well as providing understanding of how the details of the settings within the model affect the model's response to carbon dioxide increases.



ACCESS models have a relatively strong temperature response to carbon dioxide increases due to strong positive cloud feedbacks.

Figure 2.3
Total cloud feedback in two versions of the ACCESS models (shown in red), compared with other CMIP5 models. The average is shown on the right (black).

2.3 ECOSYSTEM RESPONSE TO INCREASED CLIMATE VARIABILITY

SCIENCE TO INFORM DECISION-MAKING

High temperature extremes are expected to become more prevalent in the future, along with an increase in the frequency of droughts. It is crucial to better understand the response of terrestrial ecosystems to these temperature extremes for predicting land-surface feedbacks in a changing climate.

Woodland carbon uptake decreased during extreme heatwave

ACCSP researchers used measurements from seven woodland and forest sites across climate zones in southern Australia and model simulations from the CABLE land surface model to investigate the effect of the record-breaking 2012/13 summer heatwave on the carbon and water exchange of terrestrial ecosystems.

During the most intense part of the heatwave, the water-limited woodlands experienced decreased evapotranspiration and reduced carbon uptake. During the same period, the energy-limited forest ecosystem had increased evapotranspiration and increased carbon uptake.

Evapotranspiration is the transfer of moisture from the earth to the atmosphere by evaporation of water and transpiration from plants.

Ecosystem respiration was increased at all sites resulting in reduced net ecosystem productivity in the woodlands and constant net ecosystem productivity in the forest. The carbon sink provided by woodlands turned into a carbon source during the heatwave, but recovered after rains and started sequestering carbon again.

Precipitation after the most intense first part of the heatwave and slightly cooler temperatures led to increased evaporative cooling. Carbon uptake in the temperate woodlands and forest also recovered quickly but respiration remained high.

While woodlands and forest proved relatively resistant to this short-term heat extreme these carbon sinks may not be sustainable in a future with an increased number, intensity and duration of heatwaves.

READ MORE | van Gorsel *et al.* 2016. Carbon uptake and water use in woodlands and forests in southern Australia during an extreme heat wave event in the 'Angry Summer' of 2012/2013. *Biogeosciences Discussions*, doi:10.5194/bg-2016-183.

3

2015–16 Highlights

Oceans and coasts observations and processes

The ACCSP gathered and analysed ocean data for global studies on oceans, climate and weather systems that is fundamental for detection, attribution, model improvement and real-time tracking of the global climate system response. The ACCSP also provided information about likely changes to sea levels, storm surges and extreme events to enable better coastal and marine planning.

3

2015–16 Highlights

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

SCIENCE TO INFORM DECISION-MAKING

Monitoring the heat stored in the ocean allows us to track the warming that is the net result of greenhouse gas-driven warming and cooling forced by aerosol pollution. The pattern of ocean warming also strongly controls regional sea level.

Argo coverage maintained around Australia

Global ocean warming is a fundamental index of the speed of climate change: it is directly related to the global radiation imbalance caused by greenhouse gas emissions and it drives a large component of sea level rise.

With national and international partners, ACCSP researchers maintained the global and regional Argo coverage to enable monitoring of ocean heat and freshwater changes.

Using another year of high quality Argo data they showed that the ocean is chronicling a very steady global warming rate, despite relatively wild swings in surface temperature (Fig. 3.2). Rates of warming in the oceans around Australia remain high relative to the global average.

Australia makes the second largest contribution to the Argo program in terms of floats, a contribution that is critical for coverage of oceans around Australia.

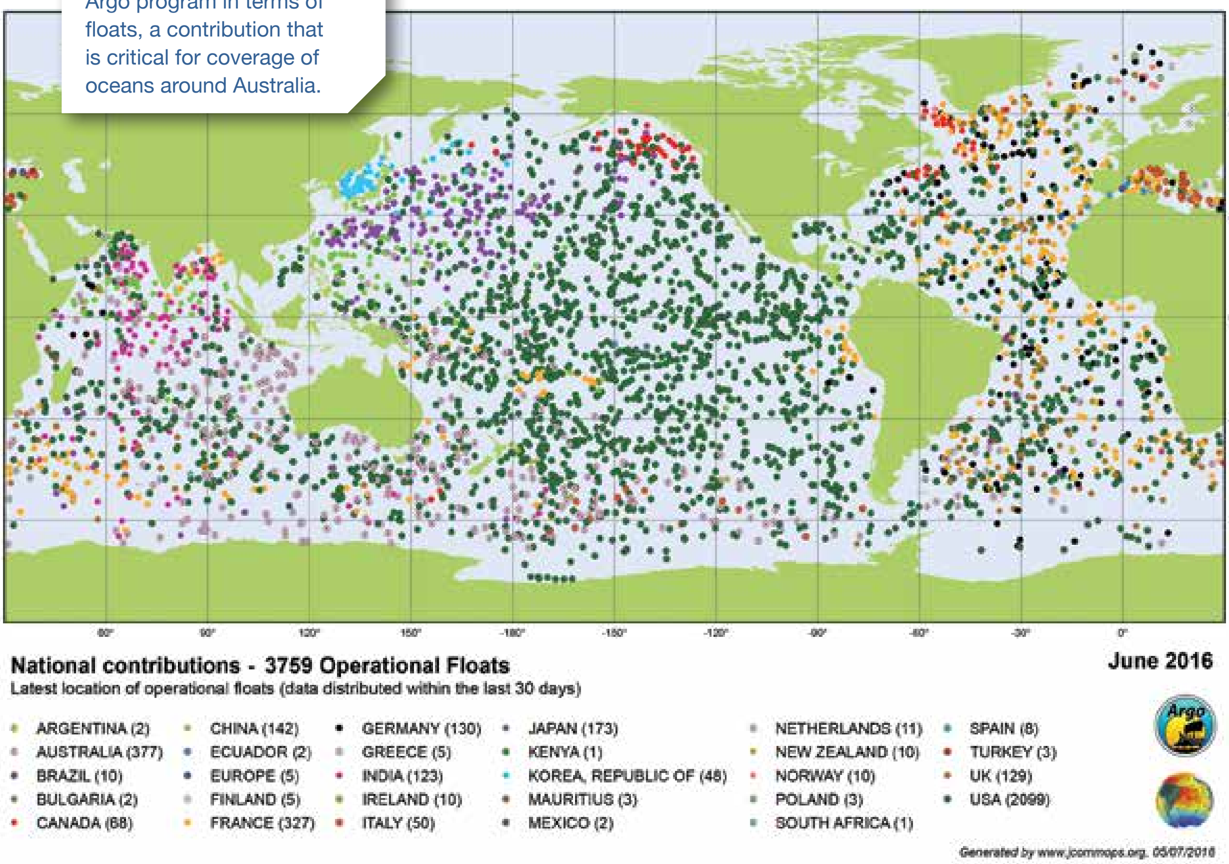
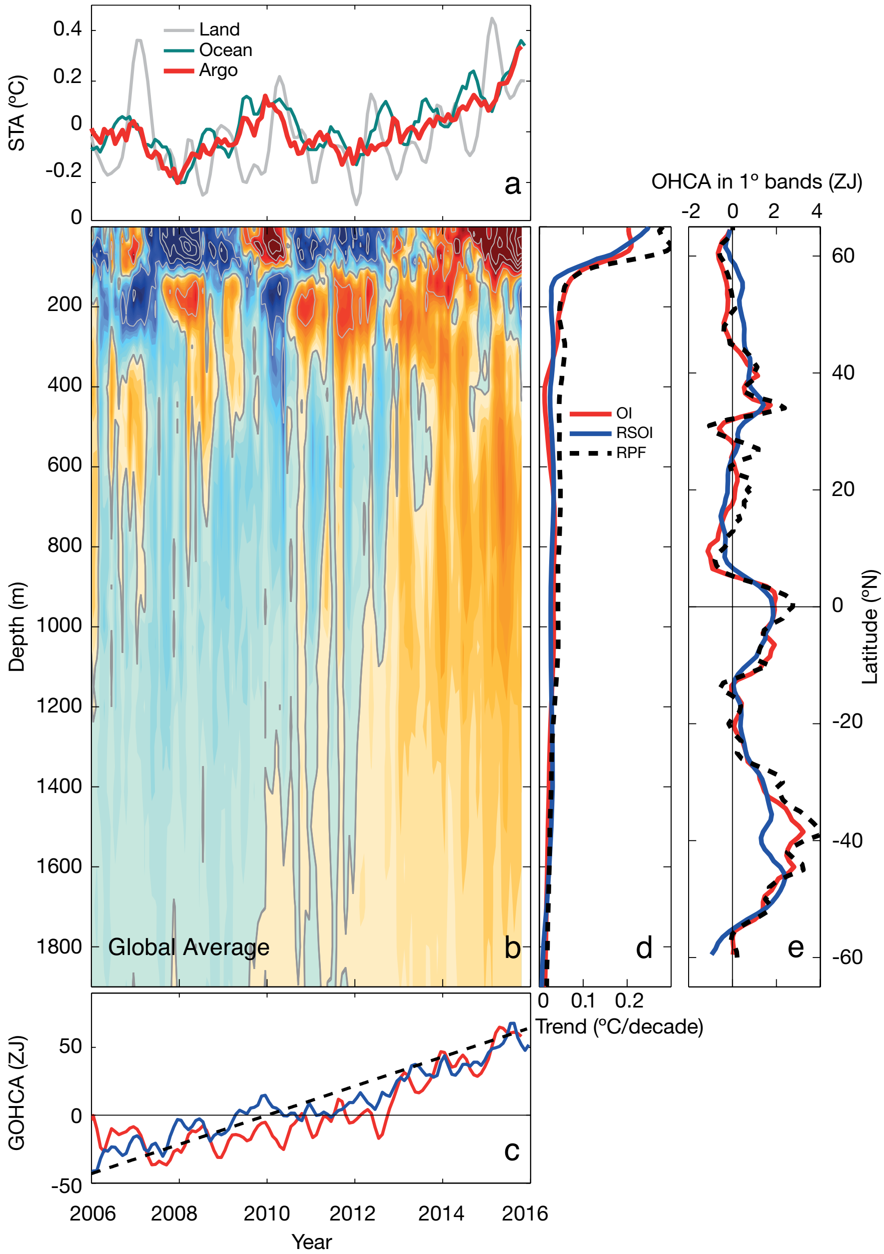


Figure 3.1
Location of operational Argo floats at June 2016. Different colours represent the contribution of different countries to the program. (Source: Argo, generated by www.jcommops.org)

Figure 3.2
Ocean warming rates and distributions. (a) Globally-averaged surface temperature anomaly (STA-°C), from 5-m Argo OI (optimal interpolation) temperature (red), NOAA global ocean (green/blue) and a 6-month running mean of NOAA global land averages (grey) (retrieved 20 December 2015 from http://www.ncdc.noaa.gov/sotc/global/201511). (b) Global average ocean temperature anomalies from the Argo OI (contour interval is 0.01 for colours, 0.05 °C in grey). (c) Global ocean 0-2000m heat content anomaly (ZJ – 1021J) as a function of time, with the OI version a 4 month running mean. (d) Global average 2006–November 2015 potential temperature trend (°C/decade). (e) Zonally integrated heat content trends in 1° latitude bands from the three mapping methods. For line plots c, d and e, the sources are: OI (red), RSOal (blue) and RPF (black-dashed). All figures are monthly means unless otherwise noted. Three interpolation methods were used: OI = optimal interpolation, RSOI = reduced space optimal interpolation, RPF = robust parametric fit. (Source: Wijffels *et al.* 2016)



Global average surface temperatures can be quite variable (a), but when you look at temperatures at all depths (b) you can see that a lot of that variability is shallow, and that the deeper waters are warming consistently. Over the Argo period (since 2006), a lot of the heat is building up in the Southern Hemisphere (and around Australia) (e).

The **Argo** program provides high quality, global and deep reaching (2000 m) temperature and salinity measurements across the globe, through a network of more than 3700 autonomous profiling floats. Every 10 days, each float moves from the surface to a depth of 2000 m and back again, collecting data and transmitting it to a satellite. The data is publicly available within 24 hours of collection. More information is available at **www.argo.net**.

READ MORE | Wijffels *et al.* 2016. Ocean temperatures chronicle the ongoing warming of Earth. *Nature Climate Change*, 6, 116–18, doi:10.1038/nclimate2924.

READ MORE | Palmer *et al.* 2016. Ocean heat content increase reveals unabated global warming. In: *WMO Statement on the Status of the Global Climate in 2015*. WMO-No. 1167, World Meteorological Organization, ISBN 978-92-63-11167-8.

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

SCIENCE TO INFORM DECISION-MAKING

The ocean is a central component of the climate system, as well as being a store of excess heat and carbon. Long-term monitoring of ocean variability and changes identifies important trends, and helps us understand ocean and climate processes. It also informs climate modelling, leading to better climate projections.

Third repeat hydrographic survey of deep ocean section completed

While autonomous floats (Argo), satellite observations and data from single-point time series stations provide a wealth of ocean data, ship-based observations are currently the only way to obtain highly accurate measurements of physical and biogeochemical properties of the ocean, including carbon.

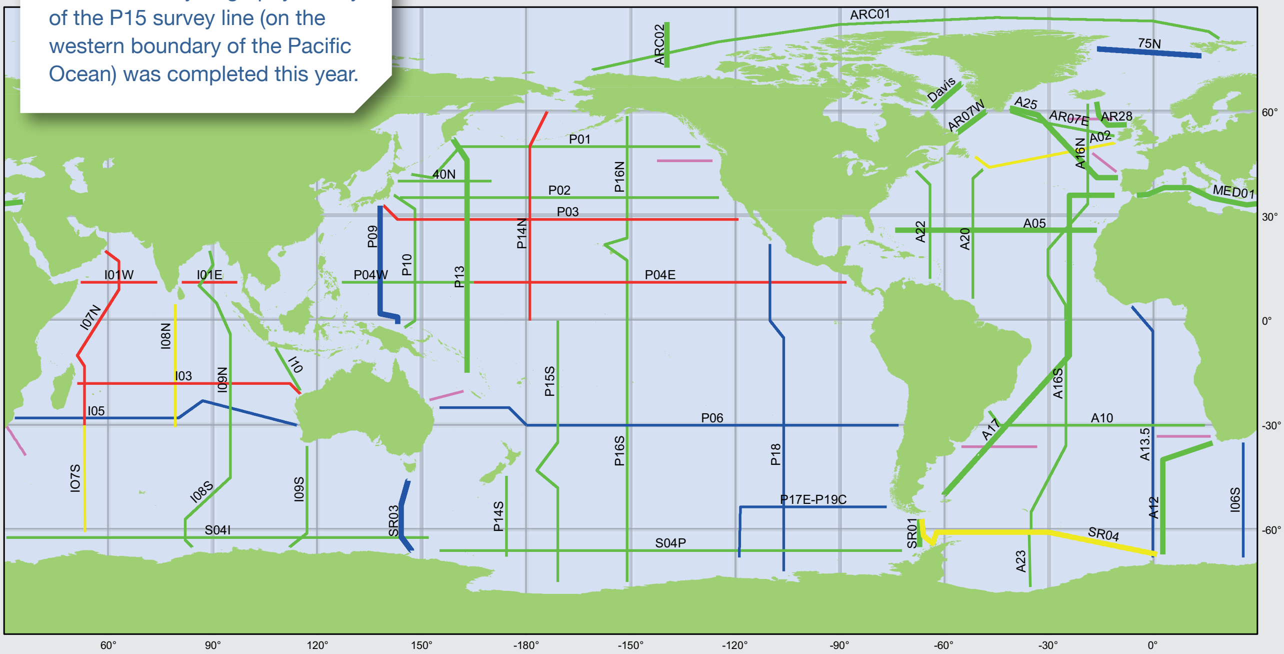
ACCSP funding supported Australia's participation in GO-SHIP, a coordinated global program to collect ship-based observations.

> **This year researchers on the RV *Investigator* collected physical and biogeochemical data along a survey line at 170°W (P15, Fig. 3.3), from the ice edge to the equator.**

This survey line is the only one on the western boundary of the Pacific Ocean, so is critical for tracking deep ocean changes in ocean heat and carbon content, and ventilation. This is the third time this line has been surveyed, so researchers have a long-term record with which they can monitor and investigate ocean changes and trends.

The **Global Ocean Ship-Based Hydrographic Investigations Program** (GO-SHIP) collects systematic decadal observations from select hydrographic sections with the goal of obtaining full-depth water column measurements of physical and chemical variables. These measurements are collected simultaneously, allowing connections between observations to be made. Data collected undergoes rigorous quality control, and so is used to benchmark data that is collected autonomously, such as from the Argo program. GO-SHIP is a component of the Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS). For more information visit **www.go-ship.org**.

The third full hydrography survey of the P15 survey line (on the western boundary of the Pacific Ocean) was completed this year.



Status of 2012-2023 Survey (61 Lines)
Bold lines: High Frequency (reduced requirements)
Thin lines: Decadal GO-SHIP (full requirements)

completed	planned
at sea	not planned yet
funded	associated & completed

Generated by www.jcommops.org 26 May 2016

Percentage of so far completed, funded or planned lines in the current survey: 87%

Figure 3.3
Status of 2012–23 GO-SHIP survey lines at May 2016. Bold lines are high frequency (reduced requirements); thin lines are decadal GO-SHIP (full requirements). Green lines are completed; blue are funded; yellow are planned and pink are associated and completed. (Source: GO-SHIP, generated by www.jcommops.org).

ACCSP researchers also contributed to a comprehensive review of ocean change, drawing on GO-SHIP data.

> **Ship-based observations show that the ocean is taking up most of Earth's excess anthropogenic heat, with about 19 per cent in the abyssal ocean beneath 2000 m, dominated by Southern Ocean warming. The ocean also has taken up about one quarter of anthropogenic carbon, resulting in acidification of the upper ocean.**

The oceans contain water of varying temperatures, salinities and chemical properties. The mixing of these different bodies of water drives ocean circulation, so has a significant influence on climate. Deep ocean mixing was thought to be small and uniform, but GO-SHIP mapping has shown that this is not the case. Not only is there intense deep mixing in certain regions, but the energy from this mixing sustains lower levels of background mixing in locations far removed from generation sites.

READ MORE | Talley *et al*. 2016. Changes in ocean heat, carbon content, and ventilation: review of the first decade of Global Repeat Hydrography (GO-SHIP). *Annual Review of Marine Science*, 8, 19.1–19.31, doi:10.1146/annurev-marine-052915-100829.

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

SCIENCE TO INFORM DECISION-MAKING

Accurate estimates of past and future rates of sea-level rise, together with accelerations or decelerations in the rates of rise are important for adaptation planning, particularly for low-lying, highly populated, highly productive and environmentally sensitive areas.

Trends in observed sea-level rise from satellites have been refined

Sea-level change estimates use a number of data sources: tide gauges, satellite measurements of ocean surface relative to the centre of the earth since 1993, as well as the data that describes individual factors that contribute to sea-level change such as the contribution from thermal expansion, glaciers, ice sheets and so on.

Previous work carried out by ACCSP researchers showed that satellite-derived sea-level rise was higher (3.2 ± 0.4 mm yr^{-1}) than the sea-level rise estimated from a sum of the contributing factors or from tide gauges. Reconciling the different estimates of sea-level change is important to build confidence in the observations as well as future projections.

ACCSP researchers were involved in correcting instrumental drifts in the early part of satellite records, leading to new satellite-derived estimates of sea-level rise of between 2.6 ± 0.4 mm yr^{-1} and 2.9 ± 0.4 mm yr^{-1} (Fig. 3.4). These rates are in much closer agreement with the rates obtained from tide gauges and the sum of contributing factors.

The lower rate of rise now estimated for the earlier part of the satellite record means that over this period, sea-level rise is accelerating, although the acceleration is not quite statistically significant at the 66 per cent confidence level.

READ MORE | Watson *et al*. 2015. Unabated global mean sea-level rise over the satellite altimeter era. *Nature Climate Change*, 5, 565–8.

Adjusted satellite sea level measurements (pink and brown lines) show lower rates of rise in the early record than the original estimate (blue line) but indicate an acceleration in sea-level rise.

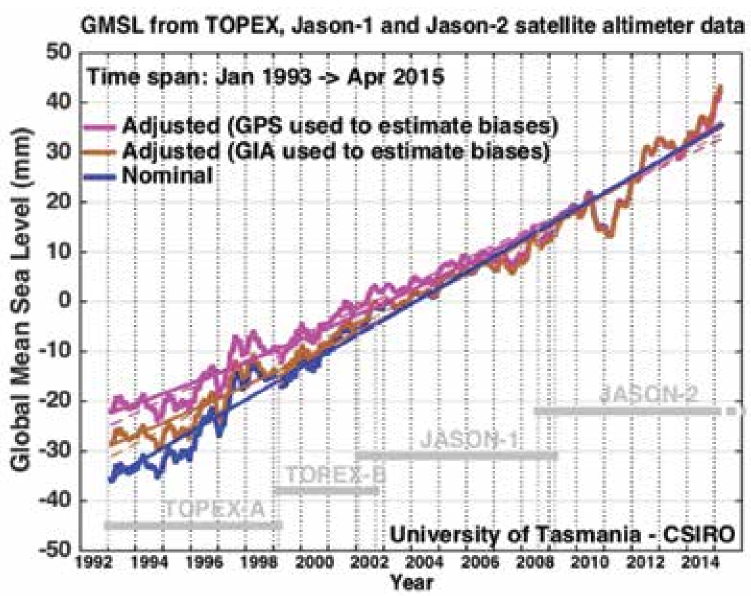


Figure 3.4
The satellite trend in sea levels (blue) prior to bias correction showing a steeper rate of rise in the earlier record compared to adjusted trends using a model for Glacial Isostatic Adjustment (GIA) or the Geostationary Positioning System (GPS), which lower the trend at the beginning of the record thereby indicating an acceleration (not quite statistically significant at the 66% confidence level) over the period of the satellite record. (Source: Watson *et al.* 2015)

Anthropogenic forcing dominates sea-level rise since 1970

SCIENCE TO INFORM DECISION-MAKING

Understanding how much of the sea-level rise that has occurred over the 20th century is due to natural and anthropogenic forces is important to refine future projections.

Research carried out by ACCSP scientists has quantified the causes of sea-level rise for the first time, using the output from a range of models including climate models.

Natural causes include variations in solar output, volcanic eruptions and slow changes in vertical land movement due to the rebounding effect of earth in response to shrinking glaciers. Anthropogenic effects include the warming effect of greenhouse gases and the cooling effect of aerosol pollution.

The results indicate that sea-level changes over the 20th century are due to both natural and human causes, with the relative contribution from each varying over the course of the century.

Prior to 1950, natural forces dominated sea-level variability accounting for 67 ± 23% of the observed rise whereas anthropogenic contributions accounted for 15 ± 55%. The natural contributions were mainly due to the ongoing effect of climate variations that occurred prior to 1900.

> **After 1970, natural contributions fall to 9 ± 18% and anthropogenic causes are dominant, accounting for 69 ± 31%.**

Sea level and coastal extremes research gaps identified

Sea-level extremes and their physical impacts in the coastal zone arise from a complex set of processes. These processes interact on a range of time and space scales and some may change in a changing climate (Fig. 3.5).

Sea level and coastal extremes can arise from single ocean phenomena such as storm surges but more commonly arise from a combination of natural phenomena that individually may not be extreme. This means that understanding how phenomena operating on a range of time and space scales interact in a particular coastal setting is important in describing coastal hazards.

A review led by ACCSP researchers examined the progress of coastal zone research with regards to understanding the causes of changes in sea level and coastal extremes. While the review indicated that significant progress has been made, a number of research questions, knowledge gaps and challenges remain. These include efforts to improve knowledge on past sea-level extremes, integrate a wider range of processes in projections of future changes to sea-level extremes, and a focus on efforts to understand long-term coastline response from the combination of contributing factors.

READ MORE | McInnes *et al*. 2016. Natural hazards in Australia: sea level and coastal extremes. *Climatic Change*, doi:10.1007/s10584-016-1647-8.

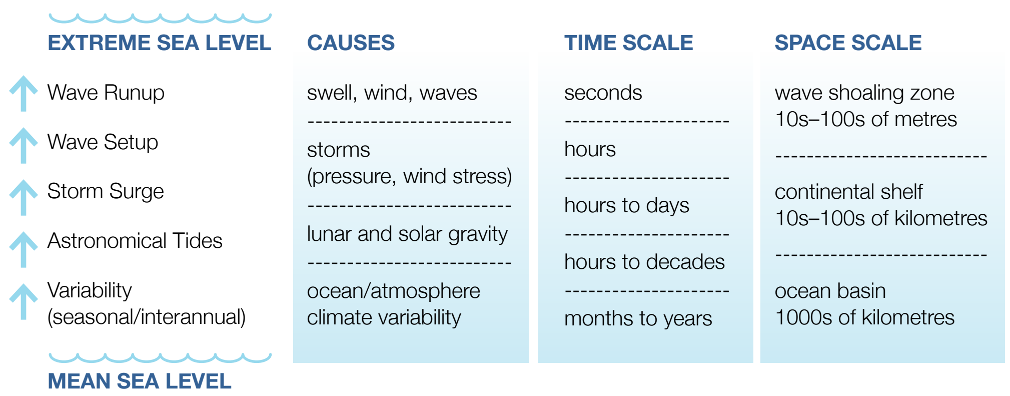


Figure 3.5 Oceanic phenomena that contribute to the total water levels at the coast during an extreme sea-level event, their causes and the time and space scales over which they operate.

3.4 OCEAN ACIDIFICATION

SCIENCE TO INFORM DECISION-MAKING

Estimates of ocean acidification change around Australia and through the Great Barrier Reef are necessary for the development of effective management and adaptation strategies. Australia's shellfish producers, in particular, are increasingly concerned about the need to future-proof their industry against ocean acidification.

Detailed estimates of ocean acidification change in Australian seas, including the Great Barrier Reef developed

ACCSP researchers measured seawater carbon chemistry around Australia, and combined their results with data from the Integrated Marine Observing System (IMOS) to develop the first maps of seasonal change around Australia's shelves and regional seas.

The surface ocean increase in carbon dioxide tracks increases in atmospheric carbon dioxide. This information was used along with the changes in atmospheric carbon dioxide concentrations measured in ice cores and at atmospheric observatories to project changes in ocean acidification back to the 1880s.

A more detailed assessment was carried out on the Great Barrier Reef. Data was collected and a biogeochemical model of reef processes developed. The successful eREEF project (external to ACCSP) used the data and model as a basis to build a whole-of-Great Barrier Reef model that included carbon cycling.

This allowed a first detailed map of how water flowing from offshore and coastal regions combines with local processes on the almost 3000 reefs of the Great Barrier Reef to determine the water chemistry and ocean acidification exposure of the reefs.

The combined model and observational work on the Great Barrier Reef from this project has help establish insights and measures of the metabolism of the many reefs on a scale not possible before. It has also helped identify important processes that will control ocean acidification on the reef, leading to improved ways to detect future change and stress on the reef under ocean acidification.

READ MORE | Lenton *et al.* 2016. Historical reconstruction of ocean acidification in the Australian region. *Biogeosciences*, 13, 1753–65, doi:10.5194/bg-13-1753-2016.

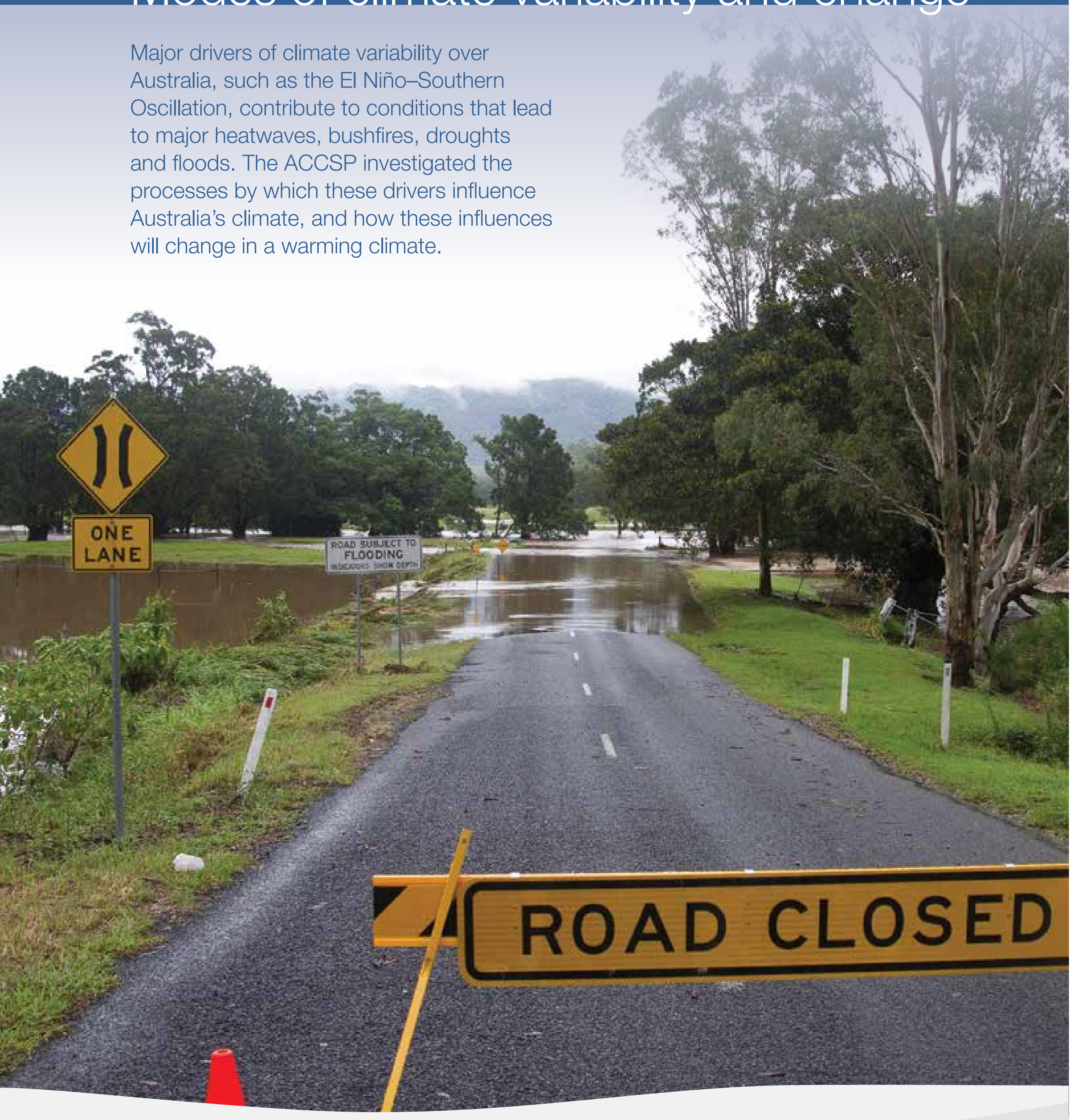
READ MORE | Mongin *et al.* 2016. The exposure of the Great Barrier Reef to ocean acidification, *Nature Communications*, 7, 10732, doi:10.1038/ncomms10732.

Ocean acidification is due to ocean surface waters absorbing carbon dioxide emissions from the atmosphere. The surface ocean now absorbs about 25 million tons of carbon dioxide emissions each day, or about one quarter of annual emissions. The absorbed carbon dioxide reacts in seawater, increasing the acidity level of the water (pH is lowered) and also decreasing the concentration of dissolved carbonate ions, both changes are referred to as ocean acidification. From sediment records we can see that the current rate of ocean acidity change is faster than at any time during the last 300 million years. **Impacts of ocean acidification on marine species vary.** Not all are vulnerable to ocean acidification, but many species that grow shells and skeletons of calcium carbonate, including reef building corals and shelled molluscs, do not grow as well with ocean acidification. Increased acidity can also alter the behaviour and physiology of fish. The changes predicted in the next 100 years are likely to have widespread impacts on marine ecosystems and food webs, influencing biodiversity and ecosystem health. Other stressors, like warming, will add to the problem.

2015–16 Highlights

Modes of climate variability and change

Major drivers of climate variability over Australia, such as the El Niño–Southern Oscillation, contribute to conditions that lead to major heatwaves, bushfires, droughts and floods. The ACCSP investigated the processes by which these drivers influence Australia's climate, and how these influences will change in a warming climate.



2015–16 Highlights

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

SCIENCE TO INFORM DECISION-MAKING

Understanding how the El Niño–Southern Oscillation influences Australia's climate, and how this may change in the future, will help to manage the risks and reduce the costs of the impacts such as bushfires, floods and droughts.

The **El Niño–Southern Oscillation (ENSO)** influences the climate of Australia through its two extremes: El Niño and La Niña events. El Niño years are characterised by warmer waters in the equatorial Pacific and are typically associated with drier conditions over eastern and northern Australia. During La Niña years, the equatorial Pacific cools and more rainfall occurs over eastern and northern Australia.

Nonlinear relationship between Australian rainfall and ENSO during spring and summer

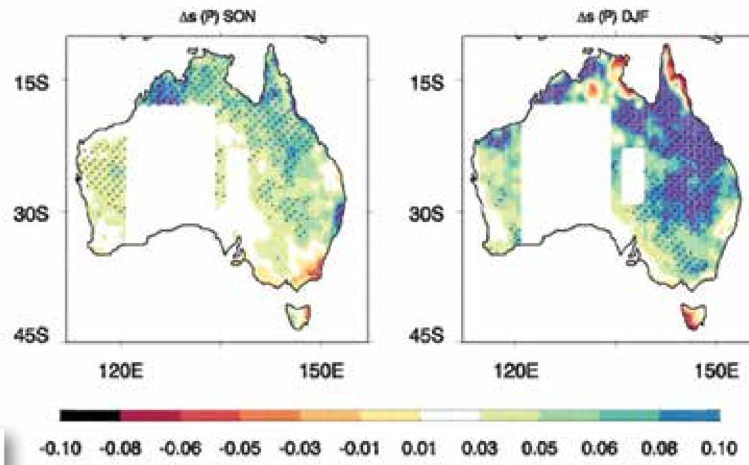
Because El Niño years are generally dry, and La Niña years are generally wet, it is a common perception is that there is a linear relationship between ENSO and rainfall; that is, that strong El Niño years result in severe droughts and strong La Niña years cause severe floods.

This is not necessarily true across the whole country. ACCSP researchers analysed 100 years of rainfall observations and identified regions and seasons in which the historical rainfall–ENSO relationship has not been linear.

In spring and summer there is a significant non-linear relationship between the amount of rainfall received and the strength of ENSO.

In particular, over northern Australia (spring) and north-eastern Australia (summer), strong El Niño years do not bring about as much drying as expected, and strong La Niña years bring about more rainfall than expected from a linear relationship.

This is the first study to examine this issue across all seasons and over all of Australia (where data is available).



On average, In the dark blue regions strong El Nino years result in less-than-expected drying, and strong La Nina years result in more-than-expected rainfall.

Figure 4.1
Nonlinearity in the rainfall–Southern Oscillation Index (SOI) relationship for spring (SON, left panel) and summer (DJF, right panel). Non-linearity is measured as the difference in linear regression coefficients between SOI>0 years and SOI<0 years. Stippling indicates where the slopes of SOI>0 years and SOI<0 years are significantly different at the 0.05 level.

4.2 DECADAL VARIABILITY IN AUSTRALIAN AND INDO-PACIFIC CLIMATE: PREDICTABILITY AND PREDICTION

SCIENCE TO INFORM DECISION-MAKING

Decadal climate prediction is important in aiding long-term planning. An important aspect of decadal prediction is understanding how naturally occurring processes contribute to climate variability over years and decades.

Tasman Sea temperatures could be useful indicators of future Southern Hemisphere climate conditions

ACCSP researchers analysed subsurface temperatures from 22 CMIP5 models to identify regions in the world's oceans that displayed a large fraction of naturally occurring decadal variability.

They found that subsurface temperature variability in the southern Tasman Sea primarily arises in response to preceding changes in Southern Hemisphere wind stress.

Once established, the long-lived subsurface temperature variability is linked to surface temperature in parts of the Southern Hemisphere up to eight years later, and Antarctic precipitation up to three years later.

This suggests that the southern Tasman Sea is a useful indicator of future Southern Hemisphere climatic conditions more broadly, providing the potential to predict Southern Hemisphere surface temperatures almost a decade ahead

The **Coupled Model Intercomparison Project (CMIP)** is an international standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models, established under the World Climate Research Program. The Phase 3 dataset (CMIP3) was used in the IPCC Fourth Assessment Report. The Phase 5 dataset (CMIP5) was used in the IPCC Fifth Assessment Report. Phase 6 (CMIP6) is underway. More information is available at www.wcrp-climate.org/wgcm-cmip/about-cmip

4.3 RESPONSE OF INDO-PACIFIC CLIMATE VARIABILITY TO GREENHOUSE WARMING AND THE IMPACT ON AUSTRALIAN CLIMATE: A FOCUS ON OCEAN-INDUCED CLIMATES

SCIENCE TO INFORM DECISION-MAKING

ENSO and Indian Ocean Dipole-related catastrophic weather events are likely to occur more frequently with unabated greenhouse gas emissions, and should be considered as we prepare to face the consequences of greenhouse warming.

Greenhouse warming increases the frequency of consecutive extreme climate events

Independently, extreme El Niño, La Niña and positive Indian Ocean Dipole events can have significant consequences for Indo-Pacific countries. When the three occur in sequence, the impacts can be devastating.

Using climate models, ACCSP researchers determined that consecutive extreme events (i.e. an extreme El Niño preceded by an extreme positive Indian Ocean Dipole event and followed by an extreme La Niña) would be much more frequent in a future with unabated greenhouse gas emissions (Fig. 4.2).

This catastrophic combination occurred in 1997–99, when the 1997/98 extreme El Niño event was preceded by an extreme positive Indian Ocean Dipole event and followed by an extreme La Niña. The extreme El Niño caused catastrophic floods in the eastern equatorial region of Ecuador and northern Peru. The South Pacific Convergence Zone, the largest rain band in the Southern Hemisphere, shifted equatorward by up to 1000 km, spurring floods and droughts in south Pacific countries and shifting tropical cyclones to regions normally not affected by such events. The positive Indian Ocean Dipole induced droughts and forest fires in the Indonesian and Australian region but floods over the East African countries affecting millions of people across Indian Ocean-rim countries. The extreme La Niña generated droughts in the southwest United States and eastern equatorial Pacific regions, but floods in the western Pacific and central American countries, and increased land-falling west Pacific tropical cyclones and Atlantic hurricanes.

Like the El Niño–Southern Oscillation, the **Indian Ocean Dipole** is a climate phenomenon that has significant bearing on rainfall variability in Australia. Just as ENSO is driven by changes in sea surface temperature in the equatorial Pacific Ocean, the Indian Ocean Dipole depends on sea surface temperature changes in the Indian Ocean. During a positive Indian Ocean Dipole event, the eastern Indian Ocean is colder than the west. This tends to result in less rainfall over southern Australia and the Top End. During a negative Indian Ocean Dipole event, when the eastern Indian Ocean is warmer than the west, there tends to be more rainfall in these regions.

READ MORE | Cai *et al*. 2015. ENSO and greenhouse warming. *Nature Climate Change*, 5, 849–59, doi:10.1038/nclimate2743.

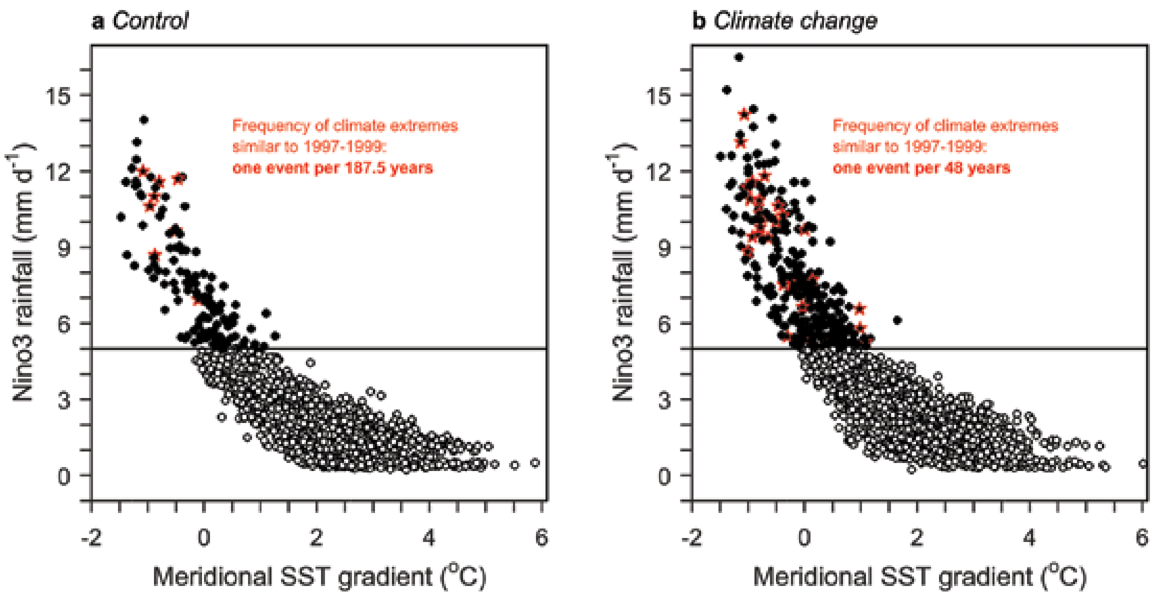


Figure 4.2
Greenhouse-warming-induced changes in climate extremes. The plots shown are based on outputs from CMIP5 experiments under historical and RCP8.5 scenarios using 21 models (out of 34 in total), focusing on austral summer (DJF). An extreme El Niño is defined as when Niño3 rainfall is greater than 5 mm per day, marked by the horizontal line. a,b, Extreme El Niño events (filled black dot) preceded by an extreme positive Indian Ocean Dipole and followed by an extreme La Niña (marked by red stars), similar to what happened in 1997–1999, for the 'Control' period (1900–1999) and 'Climate change' period (2000–2099), respectively. The meridional sea surface temperature gradients measure the difference between an off-equatorial eastern Pacific average and an equatorial eastern Pacific average (off-equatorial minus equatorial). (Source: Cai *et al*. 2015)

The incidence of extreme El Niño events preceded by an extreme positive Indian Ocean Dipole event and followed by an extreme La Niña (red stars) will increase in a changing climate.

4.4 ATTRIBUTION, PROJECTION AND MECHANISMS OF CLIMATIC EXTREMES AND CHANGE, MODES OF VARIABILITY AND REGIONAL WEATHER SYSTEMS

SCIENCE TO INFORM DECISION-MAKING

Increased understanding of Australian climate variability, and its underlying mechanisms, will give us greater confidence in regional climate change projections. Identifying the climate change signal in regional weather systems informs adaptation and mitigation responses.

Climate change component of Southern Hemisphere circulation variability detected

In order to determine, or attribute, the cause of changes in Australian regional climate variations and extremes, the change in climate due to human causes, such as greenhouse gas concentrations and aerosols, has to be distinguished from causes due to natural variations.

ACCSP researchers analysed CMIP5 model data, and found that the observed expansion of the tropics is due to climate change, via the action of expanding Hadley Cell circulation in the Southern Hemisphere summer. In the Southern Hemisphere winter, climate change causes a reduction in the strength of the poleward circulation of the Hadley Cell, which affects the formation of mid-latitude storms (see next highlight).

If greenhouse gas emissions continue unabated, the expansion of the tropics is projected to continue, and be enhanced, in the 21st century. This will lead to the Southern Annular Mode becoming an even more dominant feature of Southern Hemisphere climate variability.

READ MORE | Grainger *et al*. 2016. Projections of Southern Hemisphere atmospheric circulation interannual variability. *Climate Dynamics*, doi:10.1007/s00382-016-3135-2.

The **Hadley Cells** are large atmospheric circulation cells on either side of the equator. Warm air rises at the equator, moves poleward, then descends in the sub-tropics and travels back to the equator at the surface. This circulation causes trade winds and jet streams, as well as regions of sub-tropical dryness.

The **Southern Annular Mode** (SAM) is a belt of westerly winds circling Antarctica that influences the strength and position of cold fronts and mid-latitude storm systems. It is an important source of climate variability, and is a major driver of the Southern Ocean and its currents. The SAM is negative when the belt expands towards the equator, and positive when it contracts towards Antarctica.

2015–16 Highlights

Changes in mid-latitude storm formation due to climate change

ACCSP researchers have previously shown a strong link between the 20th century declines in southern Australian winter rainfall, especially for south-west Western Australia, and decreases in the likelihood of storm formation. Further work has now attributed these changes to increasing greenhouse gas concentrations.

CMIP5 model simulations under a business as usual (RCP8.5) scenario show significant decreases in Southern Hemisphere mid-latitude storm formation, and a tendency for more storms to form further south for all seasons especially west of Australia.

In contrast, under a scenario with greenhouse gas stabilisation (RCP4.5), no such trends are found, indicating that the change is due to increased emissions.

READ MORE | Frederiksen *et al.* 2016. Trends and projections of Southern Hemisphere baroclinicity: The role of external forcing and impact on Australian rainfall. *Climate Dynamics*, doi:10.1007/s00382-016-3263-8.

Representative Concentration Pathways (RCPs) are used in climate projections to describe future greenhouse gas concentration scenarios under different economic, policy and technology conditions. There are four scenarios: RCP2.6, RCP4.5, RCP6 and RCP8.5. RCP8.5 is often referred to as a 'business as usual' scenario, as it represents a future with little curbing of greenhouse gas emissions. The other RCPs assume varying levels of greenhouse gas mitigation.

Potentially predictable decadal sea surface temperatures detected

Understanding the climate processes that influence ocean circulation underpins our understanding of the feasibility of decadal forecasting and projections.

Natural variations in decadal mean sea surface temperature are related to year-to-year variability. While this variability may be predictable on annual time scales, as is the case with the El Niño–Southern Oscillation (ENSO), on the scale of decades, or longer, the year-to-year variations in ENSO are not predictable.

ACCSP researchers developed a method for estimating how much decadal variability is natural and how much is due to multi-decadal processes (including the Interdecadal Pacific Oscillation, IPO) and climate change. On a decadal time scale, multi-decadal processes are potentially predictable. That is, given a set of initial conditions, a model can potentially forecast the state of a multi-decadal process (e.g. the IPO) on the scale of several decades or less.

When this method was applied to sea surface temperature data from a CMIP5 model simulation, researchers found that the potentially predictable component is influenced by variations on multi-decadal time scales in the north Pacific (IPO) and north Atlantic Oceans.

The IPO does not influence sea surface temperature variability in the tropical central and eastern Pacific. In these regions ENSO is the main cause of decade-to-decade variability.

The separation of ENSO-related variability from multi-decadal processes affecting the Pacific Ocean shows the key processes that the models need to simulate in order to obtain good reliability (or predictability) for near-term climate projections on the scale of several decades or less.

READ MORE | Frederiksen *et al*. 2016. Simulated modes of inter-decadal predictability in sea surface temperature. *Climate Dynamics*, 46, 2231–45, doi:10.1007/s00382-015-2699-6.

5

2015–16 Highlights

Earth systems modelling and data integration

The ACCSP supported the development of ACCESS – the Australian Community Climate Earth System Simulator – bringing together the climate observations, research and modelling capability of the Bureau of Meteorology, CSIRO, Australian universities and international researchers. The result is a national weather, climate and Earth system simulation capability that is suited to Australian needs.

5.1 ACCESS COUPLED CLIMATE MODEL DEVELOPMENT

SCIENCE TO INFORM DECISION-MAKING

The development and application of ACCESS is geared towards providing state-of-the-art climate projections at global and national scales. Improving the realism of the simulation of key climate processes relevant to Australia allows for more confidence in the assessment of how Australian climate variability and Australia's regional oceans will respond to climate change, and hence supports policy and planning related to adaptation to climate change.

When running with high oceanic resolution, ACCESS-CM2 realistically simulates the pattern of sea surface temperature variation associated with the Indian Ocean Dipole.

ACCESS-CM2 is a global coupled model consisting of four components – atmosphere (UK Met Office Global Atmosphere 6 version, GA6), land surface (UK Met Office JULES), ocean (US Geophysical Fluid Dynamics Laboratory MOM5), and sea ice (US Los Alamos National Lab CICE5) – coupled together under the framework of a numerical coupler (OASIS3-MCT). This version is a prototype. The final production version will include an upgraded atmosphere component (Global Atmosphere 7, GA7) and the Australian community land surface model (CABLE).

Successful simulation of key Australian climate features in ACCESS-CM2 with high oceanic resolution

Using pre-industrial atmospheric greenhouse gas concentrations and aerosol emissions, ACCSP researchers performed multi-century climate simulations at two latitude/longitude resolutions for the ocean/sea ice components: 1 degree and 0.25 degrees.

At both resolutions, ACCESS-CM2 successfully reproduced a range of climate features and phenomena important for Australia. However, key climate-related processes (e.g. oceanic boundary currents and eddies) and some Australian climate drivers (including the Indian Ocean Dipole) were better simulated in the high oceanic resolution version.

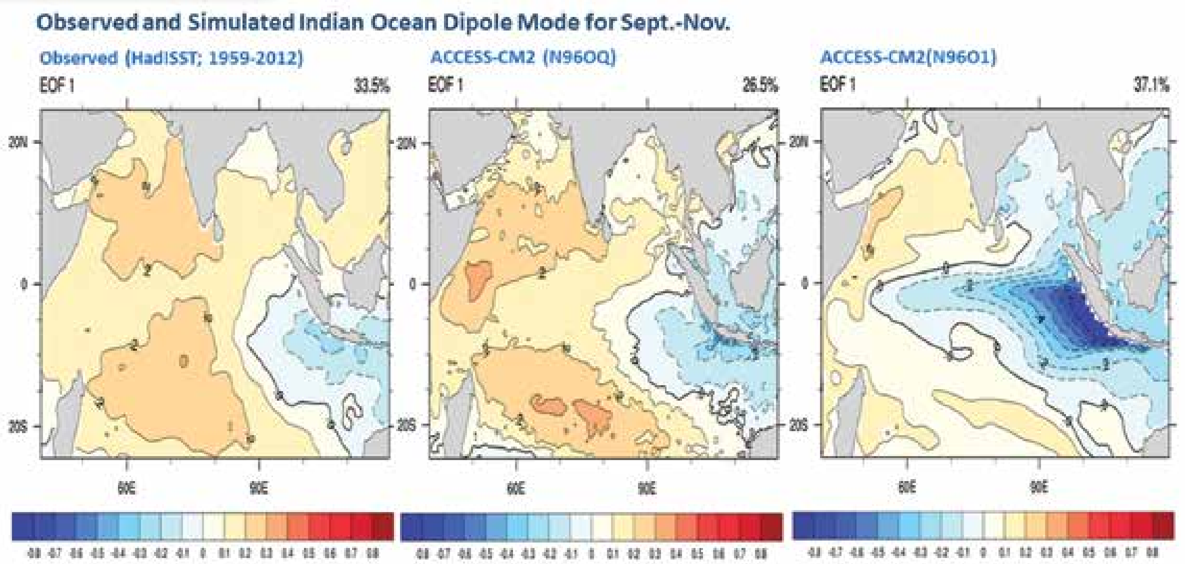


Figure 5.1
Observed (left panel) patterns of year-to-year sea surface temperature variation for September–November associated with the Indian Ocean Dipole compared to ACCESS-CM2 simulations, using higher (middle) and lower (right) oceanic resolution. Simulations are for model years 101–200.

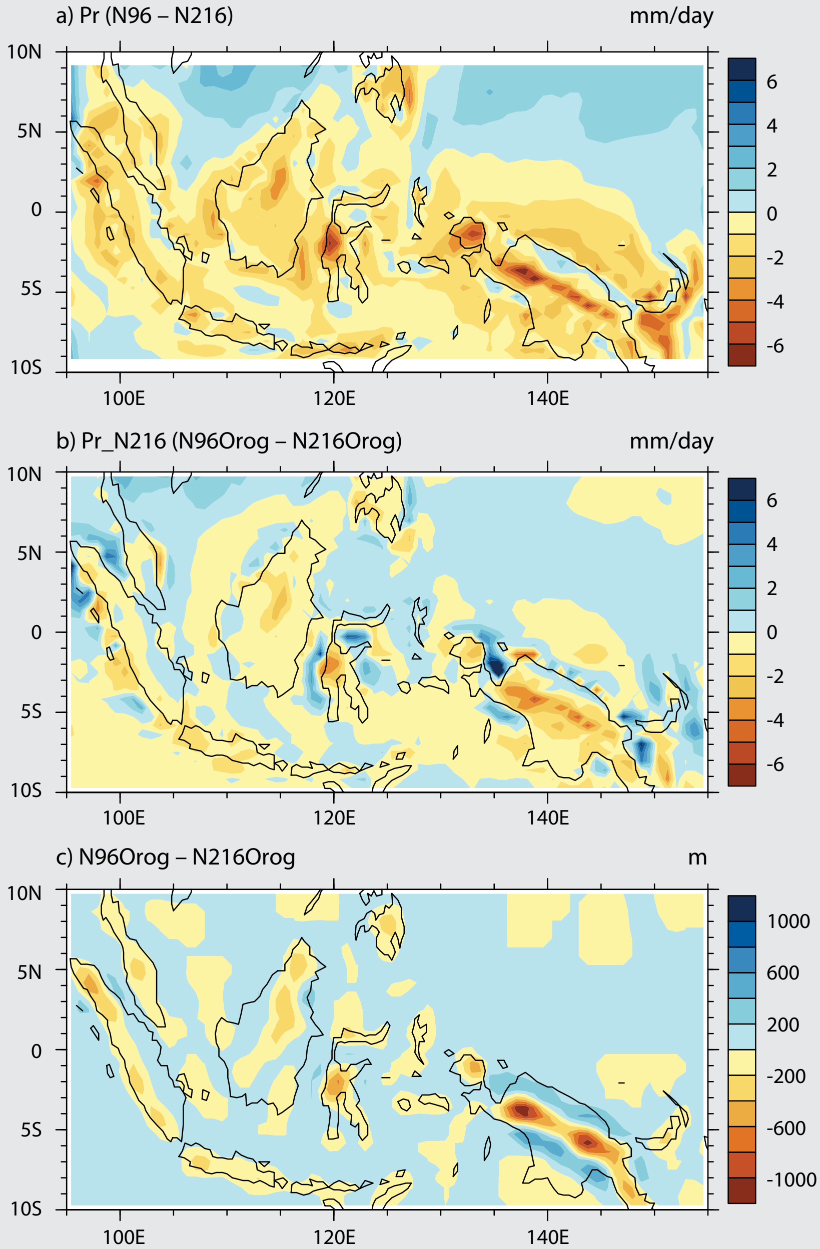
The increased oceanic resolution makes the model a more credible tool for climate projection and multi-annual/decadal prediction, hence more useful in supporting climate impact assessment and climate change science.

Dry rainfall bias over the Maritime Continent in ACCESS reduced with higher resolution modelling

The complex topography of The Maritime Continent – with many small and medium-sized islands with heights of up to ~2 km, surrounded by warm seas – is not well represented in coarse resolution climate models. Many models, including ACCESS, experience significant rainfall bias over the region.

ACCSP researchers investigated the causes of a prominent dry rainfall bias over the Maritime Continent in the atmospheric component of the ACCESS coupled model (GA6). They found that the bias was significantly reduced (i.e. the total rainfall amount was increased) when the horizontal resolution of the model was increased from ~135 km grid spacing to ~60 km.

Differences in time mean rainfall and orographic heights



> The dry bias over the Maritime Continent (a) is reduced when higher resolution modelling is used (b and c).

Figure 5.2
Spatial distributions of the rainfall differences (mm/day) arising from the difference in the specified orographic heights (m) in three atmospheric model experiments. Shown are the differences in (a) rainfall between the lower resolution N96 and higher resolution N216 experiments, (b) rainfall between the additional higher resolution experiment with lower resolution topography (N216_N96orog) and the standard higher resolution experiment N216, and (c) orographic height differences between the N96 and N216 configurations.

2015–16 Highlights

Due to high computational costs, long climate simulations (such as those submitted to the CMIP archive) are often performed at coarse resolutions. This work highlights the importance of representing the effect of high resolution topography in such simulations (Fig. 5.2). It also helps provide justification for moving to the higher atmospheric resolution for the whole coupled model as soon as sufficient computational resources become available.

PUBLICATION IN PROGRESS
Rashid and Hirst 2016. Mechanisms of improved rainfall simulation over the Maritime Continent due to increased horizontal resolution in an AGCM. *Climate Dynamics* (submitted).

The Maritime Continent, comprising the archipelagos of Indonesia, Borneo, New Guinea, the Philippine Islands, the Malay Peninsula, and the surrounding seas, is one of the most important regions influencing the global climate. Located at the centre of the Indo-Pacific warm pool, this region is characterised by sustained warm sea surface temperatures exceeding 28 °C, where widespread convective activity contributes to the rising branch of the Walker circulation. Convective activity over the Maritime Continent is closely related to large-scale variations in the climate system in both the tropics and mid latitudes, including over Australia.

ACCESS participation in international benchmarking projects

The Co-ordinated Ocean-ice Reference Experiments (CORE) studies are the state-of-science in global ocean climate model benchmarking. The CORE experimental protocol is increasingly being adopted for both model development (spotting outliers in behaviour) and participation in large multi-national intercomparisons to gain better understanding of key physical processes and their oceanic signatures. ACCESS has now participated in six CORE exercises.

ACCESS experiments that accord to the CORE protocol were contributed to three international benchmarking studies that focus on: Southern Ocean watermasses and sea-ice; Antarctic Circumpolar Current and Southern Ocean Meridional Overturning Circulation; and interannual to decadal predictability of the North Atlantic Ocean.

Through co-chairing of the World Climate Research Programme CLIVAR Ocean Model Development Panel, Dr Simon Marsland contributed to the inception of a new Ocean Model Intercomparison Project (OMIP), which has grown from the maturity of the CORE studies.

OMIP will be the key ocean modelling exercise for models participating in the forthcoming Climate Model Intercomparison Project – phase 6 (CMIP6) that will underpin the projections of future climate change scenarios in the Intergovernmental Panel on Climate Change Sixth Assessment Report.

READ MORE | Farneti *et al*. 2015. An assessment of Antarctic Circumpolar Current and Southern Ocean Meridional Overturning Circulation during 1958–2007 in a suite of interannual CORE-II simulations. *Ocean Modelling*, 93, 84–120. doi:10.1016/j.ocemod.2015.07.009.

READ MORE | Downes *et al*. 2015. An assessment of Southern Ocean water masses and sea ice during 1988–2007 in a suite of inter-annual CORE-II simulations. *Ocean Modelling*, 94, 67–94, doi:10.1016/j.ocemod.2015.07.022.

READ MORE | Danabasoglu *et al*. 2016. North Atlantic Simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part II: Inter-Annual to Decadal Variability. *Ocean Modelling*, 97, 65–90, doi:10.1016/j.ocemod.2015.11.007.

READ MORE | Griffies *et al*. 2016. Experimental and diagnostic protocol for the physical component of the CMIP6 Ocean Model Intercomparison Project (OMIP). *Geoscientific Model Development Discussions*, doi:10.5194/gmd-2016-77.

ACCESS-CM2 is planned to be the Australian modelling contribution to the Intergovernmental Panel on Climate Change Sixth Assessment Report, and the associated international modelling project Coupled Model Intercomparison Project phase 6 (CMIP6).

5.2 ACCESS CARBON CYCLE MODELLING

SCIENCE TO INFORM DECISION-MAKING

The ACCESS Earth system model (ACCESS-ESM1) includes carbon cycling, so can simulate changes in land and ocean productivity due to different emissions and mitigation strategies. This allows us to undertake simulations to explore what the impacts and feedbacks may be on key sectors of the Australian economy.

ACCESS-ESM1 is the version of ACCESS that enables both climate and the carbon cycle and their interactions to be modelled. It is derived from the ACCESS1.4 physical climate model (atmosphere, land, ice, ocean) with additional modules to simulate land and ocean carbon fluxes. The inclusion of an interactive carbon cycle is generally considered as the point of differentiation between an Earth system model and a physical climate model. The additional capability provided by an Earth system model allows the model to be used for a wider range of applications, particularly around assessing the sustainability or vulnerability of future carbon uptake and primary productivity.

ACCESS-ESM1 benchmarked ahead of CMIP6

Unlike most groups internationally, Australia did not deliver an Earth system model for use in the IPCC Fifth Assessment Report, only a coupled physical climate model. Consequently, Australian research groups have relied on simulations from groups outside of Australia to explore how climate may impact on carbon exchange and how this affects Australia and our industries.

ACCSP researchers completed all of the core experiments of the Coupled Model Intercomparison Project 5 (CMIP5) with ACCESS-ESM1, allowing this model to be benchmarked against simulations from other ESM groups outside Australia. Benchmarking shows that ACCESS-ESM1 results agree with published results from other groups, the IPCC Fifth Assessment Report and the Global Carbon Project.

This assessment identified the strengths and weaknesses of ACCESS-ESM1, and the key developments required to further improve model simulations.

Ocean uptake of carbon in ACCESS-ESM1 (red line) simulates historical ocean carbon uptake in line with other CMIP5 models and Global Carbon Project estimates.

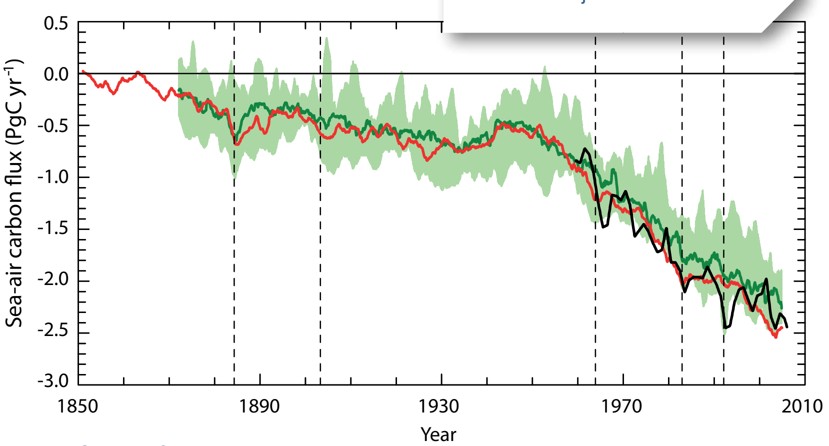


Figure 5.3
Ocean carbon uptake (sea-air flux; PgC/yr) in the period 1850–2005 from ACCESS-ESM1 (red) compared with the median of the CMIP5 models (solid green), the 10th and 90th percentiles of the CMIP5 models (green shading) and the estimated sea-air fluxes from the Global Carbon Project (Le Quéré *et al* 2015) (black). Vertical dashed lines indicate the timing of major volcano eruptions over the historical period.

READ MORE | Law *et al*. 2015. The carbon cycle in the Australian Community Climate and Earth System Simulator (ACCESS-ESM1)– Part 1: Model description and pre-industrial simulation. *Geoscientific Model Development Discussions*, 8, 8063–116, doi:10.5194/gmdd-8-8063-2015.

READ MORE | Ziehn *et al*. 2016. The carbon cycle in the Australian Community Climate and Earth System Simulator (ACCESS-ESM1) – Part 2: Historical simulations. *Geoscientific Model Development Discussions*, doi:10.5194/gmd-2016-14.

5

2015–16 Highlights

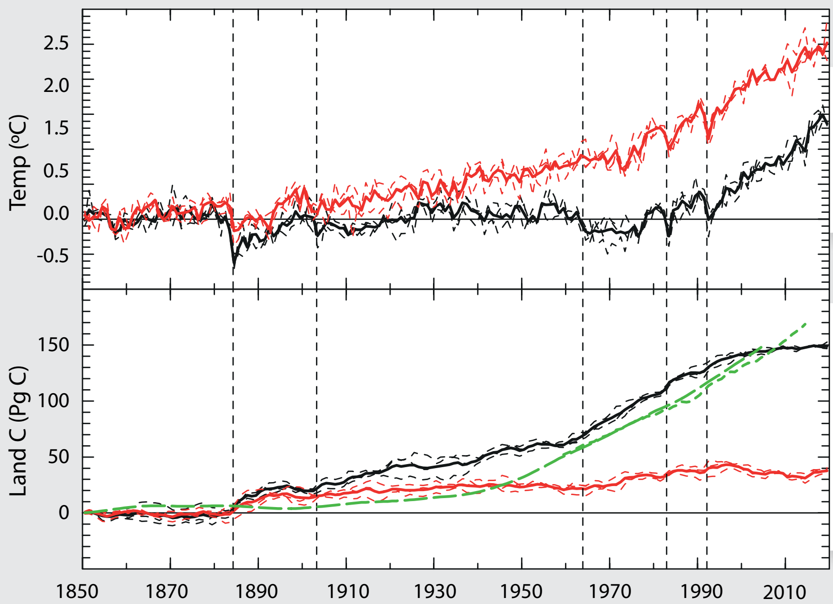
Historical land carbon uptake is significantly enhanced by the offsetting 'cooling', due to anthropogenic aerosols

Roughly one quarter of current anthropogenic emissions of carbon dioxide are taken up by the land biosphere. Without this uptake, carbon dioxide concentrations in the atmosphere would increase more rapidly, resulting in more rapid climate warming.

ACCSP researchers examined land carbon uptake over the period 1850–2020, using ACCESS-ESM1. They found that since around 1965, anthropogenic aerosols have kept warming 1 °C less than it would have otherwise been and, in turn, land carbon uptake is larger than it would have otherwise been.

The results suggest that so-called carbon dioxide fertilisation of plants due to increasing atmospheric carbon dioxide is not sufficient alone to explain historical land carbon uptake; the relative cooling of the climate (in fact, an offsetting of the warming that had occurred) due to anthropogenic aerosols is also required to explain the magnitude of land carbon uptake.

The implication is that any future reductions in anthropogenic aerosols may not only lead to a warmer climate but also to reduced land carbon uptake, and a positive feedback to more rapid increases in atmospheric carbon dioxide and more rapid warming.



A world without anthropogenic aerosols (red) would have been at least 1 °C warmer than otherwise (black) from about 1965 onwards.

ACCESS-ESM1 simulated land carbon uptake is similar to best estimates from the Global Carbon Project (green). When the model is run without anthropogenic aerosols, land carbon uptake is much smaller due to the warmer climate.

Figure 5.4
Temperature anomaly relative to 1850–1859 (top) and cumulative land carbon uptake from 1850 (bottom) for control ACCESS-ESM1 simulations (black), ACCESS-ESM1 simulations without anthropogenic aerosols (red) and global carbon budget estimates (green) from 1850 (dashed) and 1959 (solid) (Le Quéré *et al*. 2015.) For the simulations, the bold line is the ensemble mean and the dashed lines are the three ensemble

Carbon–climate feedbacks significantly influence the rate and magnitude of ocean acidification

Ocean acidification, a direct result of rising atmospheric carbon dioxide levels, is a significant risk to marine ecosystems. As the oceans absorb carbon from the atmosphere, slowing the rate of climate change, long-term changes of the chemistry of seawater occur. The impacts of ocean acidification are likely to affect the entire marine ecosystem—from microbial communities to top predators; through changes in reproductive health, organism growth and physiology, species composition and distributions, food web structure, and nutrient availability.

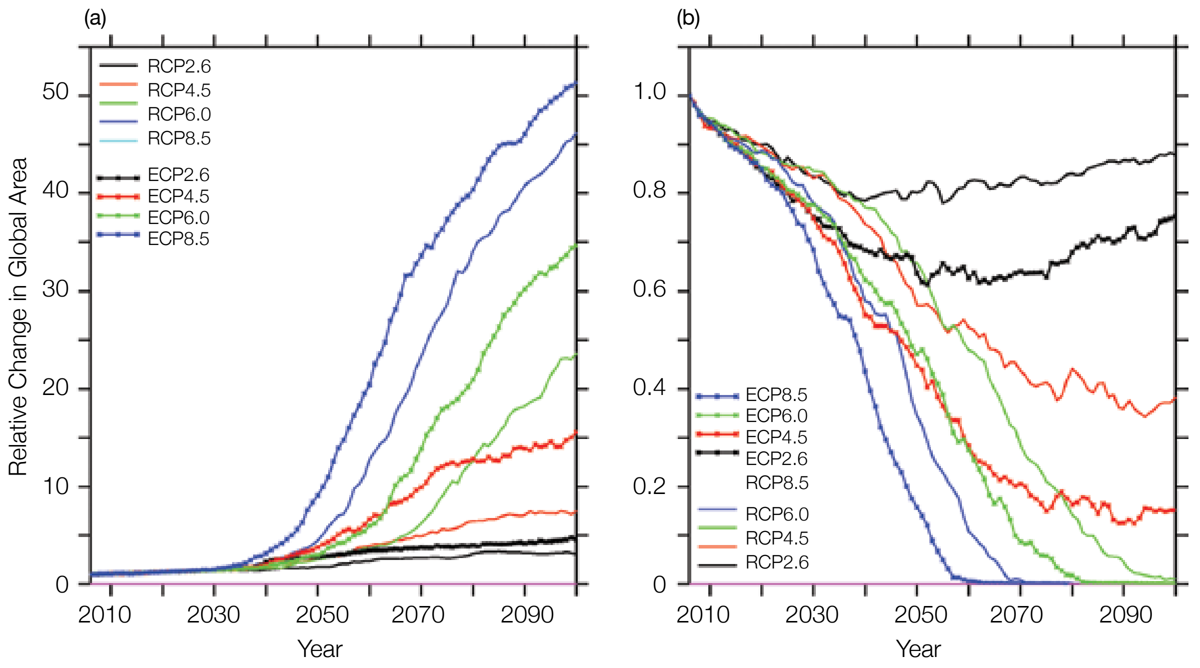
Understanding the rate and magnitude of ocean acidification is critical to understanding how the marine ecosystem will respond in the future, and what the implications will be for the critical ecosystem services they provide.

ACCSP research showed that simulated carbon–climate feedbacks lead to larger changes in ocean acidification than those anticipated in the IPCC Fifth Assessment Report.

Specifically, the onset of under-saturated conditions in the Southern Ocean and Arctic Ocean and passing critical thresholds for key species such as tropical coral will occur much sooner than anticipated. (In under-saturated conditions, the aragonite shells of marine organisms are liable to dissolve.) The largest change in affected area when carbon–climate feedbacks are included occurs under the RCP4.5 emissions scenario.

This has significant implications for developing policy to mitigate the impacts on the marine ecosystem and highlights the need to account for carbon cycle feedbacks in future projections.

Aragonite is a form of calcium carbonate. Its saturation state is used as an indicator of ocean acidification. The higher the pH of the water, the fewer carbonate ions available so the lower the saturation state.



Carbon–climate feedbacks (captured in ECP but not RCP simulations) accelerate ocean acidification impacts by more than a decade.

Figure 5.5
For the various RCP simulations and their corresponding emission-driven simulations (ECPs): a) change in area of surface water with aragonite saturation state less than 1 relative to the area in 2005, and b) change in area of the surface water suitable for coral reefs (aragonite saturation state greater than 3) relative to the area in 2005.

5.3 DEVELOPMENT OF THE ACCESS EARTH SYSTEM MODEL FOR AEROSOL AND CHEMISTRY

SCIENCE TO INFORM DECISION-MAKING

Quantifying and better understanding the role of aerosols in ACCESS will provide greater confidence in projections of future climate. Atmospheric chemistry controls the amount and distributions of a number of important greenhouse gases (e.g. methane and ozone in the troposphere) and, like aerosols, is an important climate driver contributing to regulating the Earth's radiation budget.

Earth's radiation (or energy) budget is the balance between incoming solar radiation and radiation emitted back into space from the Earth. Water vapour, greenhouse gases and aerosols absorb some of the energy emitted from the Earth, causing the greenhouse effect that keeps Earth habitable. Aerosols also scatter sunlight and change cloud properties, offsetting some of the warming. Greenhouse gases and aerosols added to the atmosphere by human activities have a net warming influence on the Earth's climate.

Aerosol effective radiative forcing quantified for ACCESS-1.4

Some of the largest uncertainties in modelling the Earth's changing energy budget are to do with aerosols.

Aerosol effective radiative forcing (ERF) is an indicator of cooling (negative value) or warming (positive value) of the Earth's climate system caused by anthropogenic aerosols.

ACCSP researchers calculated the ERF from aerosols in the ACCESS-1.4 climate model, relative to year 2000 emissions, and compared these results with other climate models.

The amount and behaviour of the aerosol ERF estimated by ACCESS was similar to that simulated by other climate models.

Although most climate models show qualitatively similar response to anthropogenic aerosols, the size of the aerosol impact on climate varies considerably from model to model, highlighting the need for ongoing research and model development to better represent and constrain the role of aerosols in the climate system.

Complementary work has quantified the climate-change impacts from both anthropogenic aerosol emissions and from greenhouse gas and other emissions using the ACCESS-1.4 climate model – see the highlight on page 16.

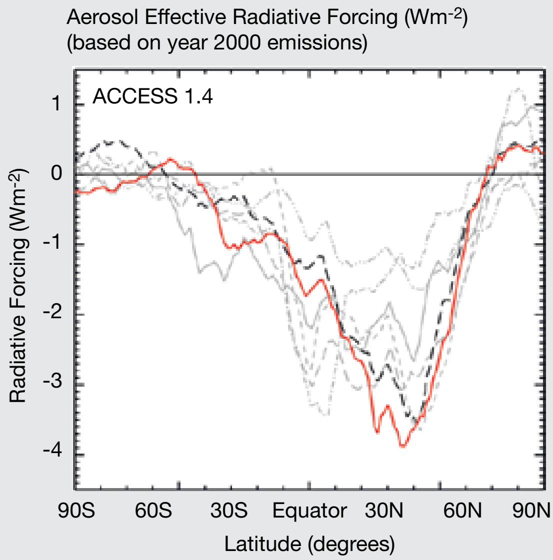


Figure 5.6
Effective radiative forcing (ERF) due to anthropogenic aerosols determined from the latest ACCESS-1.4 climate model (red line) as a function of latitude is compared with a number of models which participated in the fifth Climate Model Intercomparison Project (CMIP5) and for which ERF results are available. The black-dashed curve shows results from the HadGEM2 model, which shares common origins with the ACCESS model. The CSIRO Mark3.6 model is shown in solid-grey, while the various broken-grey curves show results from other CMIP5 models, namely GFDL-CM3, ISPL-CM5A-LR, MIROC5 and MRI-CGCM3.

ACCESS-1.4 (red) simulations of radiative forcing from aerosols compare well with other models.

New aerosol model for the next generation ACCESS-CM2 configured and evaluated

One reason for the large uncertainty in aerosol radiative forcing estimates obtained from climate models is the uncertainty in modelling the indirect aerosol radiative forcing. This uncertainty is caused by a poor understanding of the factors that control the links between aerosols and clouds, and modelling these interactions is challenging. It is important that the development of ACCESS keeps pace with state-of-the-art aerosol process modelling science in order to quantify the role of aerosols better and to reduce the uncertainty in their effect on the climate.

GLOMAP-mode is a new generation model that includes aerosol microphysics, and enables indirect aerosol effects, such as changes in cloud condensation nuclei (a form of aerosol that acts as a nucleus for cloud droplets), to be simulated much more realistically.

ACCSP researchers set up and tested GLOMAP-mode in an atmosphere-only version of ACCESS and found that it performed well in terms of modelling aerosol number concentration, mass concentration, burden and optical depth, and the number of cloud condensation nuclei. GLOMAP-mode will replace the current CLASSIC aerosol model in the next generation ACCESS.

READ MORE | Woodhouse *et al.* 2015. Australian reactive-gas emissions in a global chemistry-climate model and initial results. *Air Quality and Climate Change*, 49, 31–8.

Representation of the dry deposition of ozone to seawater in ACCESS-UKCA improved

Ozone is a greenhouse gas in the lower atmosphere. Global atmospheric chemistry models estimate global ozone dry deposition at between 600 and 1000 million tonnes annually. Ozone deposition into the oceans accounts for about one third of this total. It is essential that this deposition process is accurately represented in ACCESS for improved predictive capacity.

The ACCESS-UKCA chemistry model currently overestimates ozone deposition to the Southern Ocean, with implications for near-surface ozone concentration. ACCSP researchers formulated and implemented a more realistic model for ozone dry deposition to seawater in the ACCESS model.

Initial analysis shows that the new deposition model leads to better agreement with data on ozone deposition to the Southern Ocean and improves ozone concentration predictions.

Deposition is the process by which trace gases or aerosol particles are transferred from the atmosphere to the Earth's surface, decreasing their concentration in the air. Dry deposition describes the adsorption of gases or aerosols at the Earth's surface, whereas wet deposition occurs when soluble gases or aerosols are deposited by precipitation.

Atmospheric ozone is an oxidant as well as a precursor to the formation of hydroxyl and other chemical radicals. It plays a critical role in the chemical cycles of both the stratosphere (e.g. the ozone hole) and troposphere. In the troposphere, it also acts as a greenhouse gas.

6

2015–16 Highlights

Australia’s future climate

Changes to our climate have the potential to create major impacts on human and natural systems. Further changes to our climate are inevitable as concentrations of greenhouse gases continue to increase. The ACCSP has funded research to underpin national climate projections, which provide important information for decision-makers about our future climate.

6.1 REGIONAL CLIMATE PROJECTIONS SCIENCE

SCIENCE TO INFORM DECISION-MAKING

Climate projections underpin a wide range of important planning and policy decisions for the future, so it is critical that their development and delivery is effective. This review of past products and services provides useful information for the development of the next round of regional projections.

Past Australian regional climate projections evaluated to inform development and delivery of future projections

Climate projections products and services are the link between climate research and policy and planning.

ACCSP researchers documented and evaluated the trends, tensions and perennial issues in the 30 years of producing climate projections for Australia, from GREENHOUSE 1987 through to the 2015 projections.

They built upon this review by consulting with various groups through correspondence and a series of seminars about the needs, issues and decisions to be made about the next generation of climate projections.

This consultation and research will inform the development of these projections.

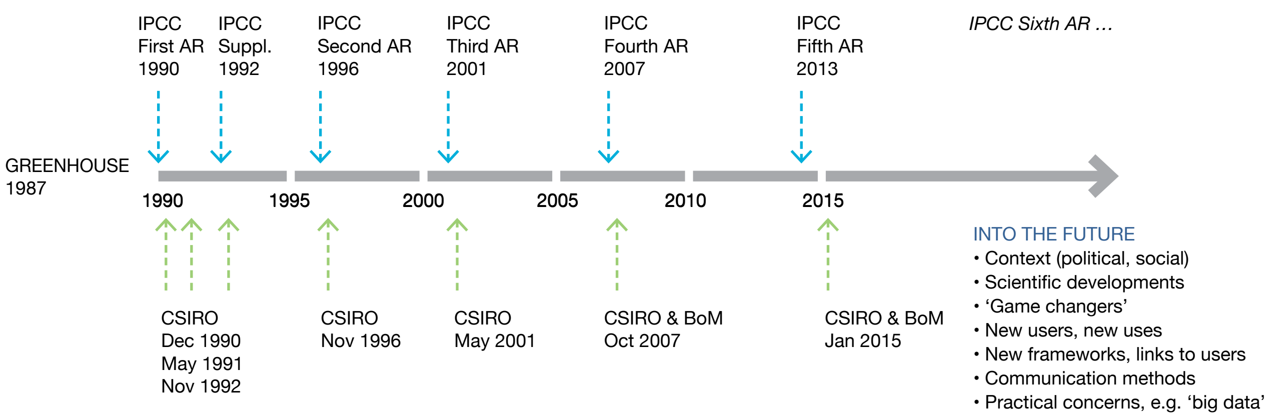


Figure 6.1
Timeline of Intergovernmental Panel on Climate Change (IPCC) assessment reports (AR) and Australian climate projections statements, noting some broad issues relevant to the next release.

READ MORE | Whetton *et al*. 2016. A short history of the future: Australian climate projections 1987–2015. *Climate Services*, doi:10.1016/j.cliser.2016.06.001.

6.2 UNDERSTANDING AND NARROWING UNCERTAINTIES IN TROPICAL AUSTRALIAN RAINFALL PROJECTIONS

SCIENCE TO INFORM DECISION-MAKING

The Australian monsoon is a critical feature for northern Australian climate. Its pronounced seasonal cycle in rainfall has a major influence on agriculture, ecosystems and society. Understanding the processes behind projected changes to the Australian monsoon can help reduce the uncertainty in projections of changes to tropical Australian rainfall and its variability under global warming, leading to increased confidence in rainfall projections.

Sources of uncertainty in projected tropical Australian rainfall changes identified

Globally, monsoon rainfall is likely to increase in both intensity and area over the 21st century. In part, this is because higher temperatures are expected to increase available moisture, despite anticipated general weakening of the tropical circulation.

However, projections for the Australian component of the Asian–Australian monsoon system are much less certain, with model projections ranging from around a 40 per cent increase to a 40 per cent decrease in summer monsoon rainfall.

ACCSP researchers examined several factors that may contribute to this range in the models. They found that in the models that simulate a drier monsoon under global warming, rain bearing systems move away from northern Australia, eastward into the Pacific. This does not occur in the models that simulate a wetter monsoon in the future, which show a slight intensification over the Maritime Continent.

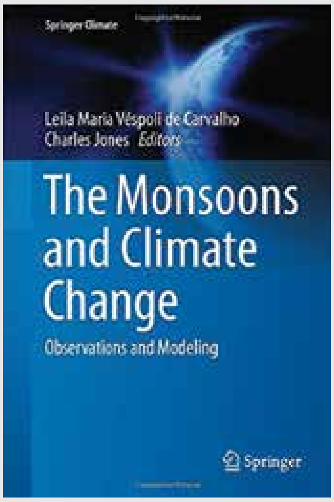
These spatial shifts in rainfall regimes are closely associated with patterns of sea surface temperature change. Reducing uncertainty in model sea surface warming patterns will therefore be crucial to further improve projections of Australian monsoon rainfall.

READ MORE | Brown *et al*. 2016. Will a warmer world mean a wetter or drier Australian monsoon? *Journal of Climate*, doi:10.1175/JCLI-D-15-0695.1.

Australian monsoon expertise recognised internationally

ACCSP researchers have been recognised internationally for their expertise on the Australian monsoon, with an invitation to contribute to a new book on the monsoons and climate change.

Their chapter provides an up-to-date summary of research with respect to the Australian monsoon and projected changes under global warming, and includes results from ACCSP-funded work.



READ MORE | Zhang and Moise 2016. The Australian summer monsoon in current and future climate. In: *The Monsoons and Climate Change – Observations and Modeling*. LMV de Carvalho and C Jones (Eds), Springer, pp. 67–120.

First climatology of Australian heat low events developed

The presence of heat lows in northern Australia during the monsoon build-up can influence the monsoon by transporting moist monsoonal air and intensifying the monsoon circulation. Additionally, the enhanced temperature difference between the land and sea resulting from heat lows may influence monsoon onset.

ACCSP researchers combined heat low detection techniques used over other heat low regions to develop the first ever multi-decadal climatology of individual heat low events over Australia.

> **They found that Australian heat lows occur most frequently over the north-west of the continent and exhibit a pronounced seasonal cycle in both their frequency and intensity. They are most common during the summer months, which is also when they are most intense in terms of the central pressure anomaly and low-level cyclonic circulation.**

Researchers can use this detection technique to examine the influence of individual heat lows on the monsoon circulation and other weather systems, and to assess the ability of global climate models to simulate Australian heat low frequency and structure.

READ MORE | Lavender 2016. A climatology of Australian heat low events. *International Journal of Climatology*, doi:10.1002/joc.4692.

The majority of heat lows occur over north-west Australia, and rarely remain stationary

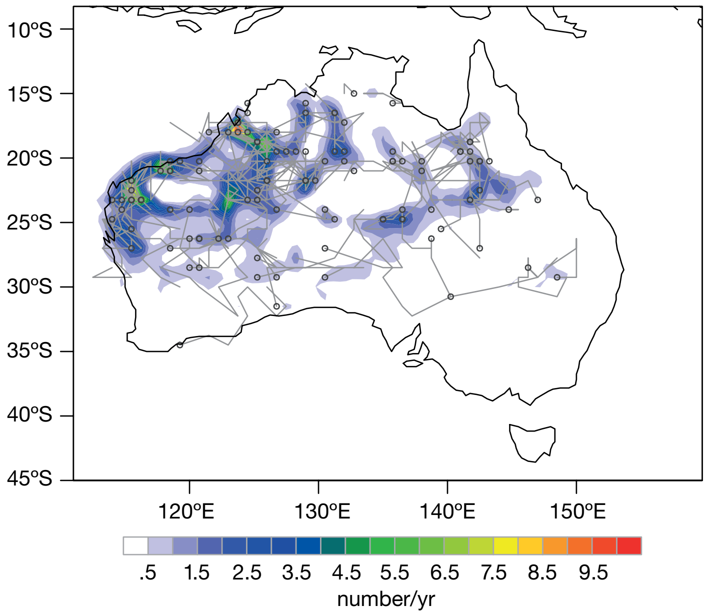


Figure 6.2
Frequency of heat low occurrence (absolute number per year) per 0.75° × 0.75° box averaged over 1979–2013. Location is based on the grid point where the minimum pressure occurs within the detected heat low. The grey open circles and lines represent the genesis positions and tracks for all heat lows occurring between July 2012 and June 2013. (Source: Lavender 2016)

Heat lows, or thermal lows, are a persistent feature over northern Australia between late spring and early autumn. They occur over many arid and semi-arid regions of the globe during the summer months, especially in the sub-tropics. They form due to the intense surface heating over land which drives broad-scale rising of air mass in the lower atmosphere. Away from the equator, this leads to inflow of air at low levels which spins off a typical circulation around this low. Heat lows are generally confined to the lower part of the atmosphere, typically below 700 hPa (which is ~ 3 km), and over many regions they remain almost stationary. However, over some regions such as Australia, heat lows can become mobile during the day and move hundreds of kilometres.

6

2015–16 Highlights

6.3 EVALUATION OF TROPICAL CYCLONE DEVELOPMENT IN THE AUSTRALIAN REGION

SCIENCE TO INFORM DECISION-MAKING

Improved knowledge of large-scale processes that influence tropical cyclone formation is vital for understanding changes in tropical cyclones under future climate scenarios. The reduced uncertainty and greater confidence in tropical cyclone projections will be important for environmental, social and economic risk assessment and adaptation planning. Improved preparedness will lead to reduced risk and enhanced resilience in relation to the impacts of tropical cyclones and associated extreme weather events.

Regions suitable for tropical cyclone formation identified

Spatial distribution of the region of tropical cyclone formation and propagation, and how it may evolve in a changing climate, is not well understood.

ACCSP researchers developed a diagnostic method that identifies geographic boundaries for regions where tropical cyclones can and cannot form.

The diagnostic was developed using 34 years of reanalysis data, and then applied to a selection of CMIP5 models to assess how well they reproduce geographic tropical cyclone distributions, and to determine if the model distributions might change in a future warmer world.

This work has helped fill in some of the knowledge gaps concerning tropical cyclone formation in the Australian region and also globally. The diagnostic helped identify which climate models performed poorly in the Australian region, and so which models were to be excluded in the development of a refined set of tropical cyclone projections for the Australian region.

The red lines enclose regions in which research suggests tropical cyclones can form. A comparison of the relative position of these regions – and the variables on which they are based – helps explain why the modelled tropical cyclone distribution (bottom) differs from the observed tropical cyclone distribution (top).

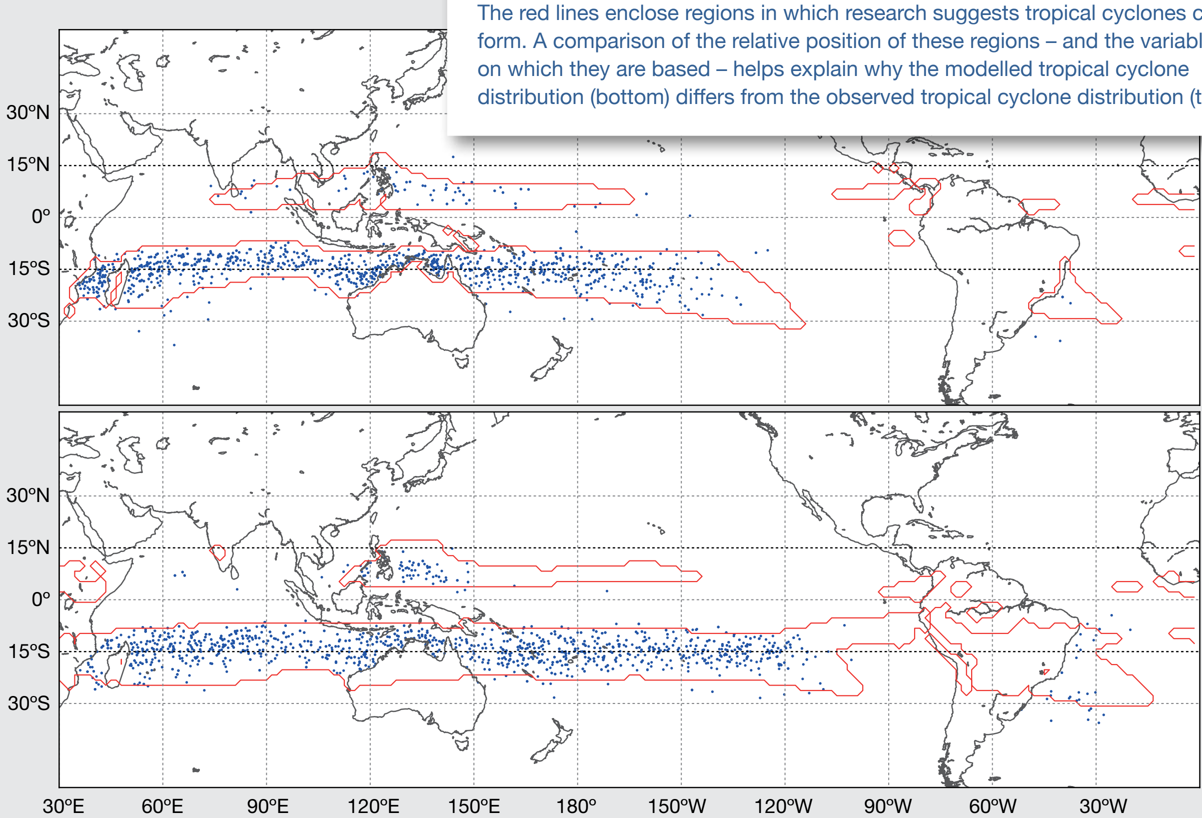


Figure 6.3

Tropical cyclone formation boundaries (red contours) and tropical cyclones (blue dots) from the observed recent climate (upper) and the modelled recent climate as represented by the bcc-csm1-1-m CMIP5 climate model (lower), for the southern hemisphere summer months (January—March). The tropical cyclone formation boundary diagnostic shows that the climate model tropical cyclones extend too far east into the South Pacific Ocean and slightly too far south in the southern Indian Ocean. Further analysis of the diagnostic showed that this was mostly due to the model being too humid.

Tropical cyclone track direction climatology and intraseasonal variability examined

Understanding how tropical cyclone track direction may change in the future is important for determining changes in the proportion of cyclones that make landfall.

> **ACCSP researchers produced a tropical cyclone track direction climatology throughout the Australian region.**

In contrast to previous studies that have focused on the mean direction of tropical cyclone movement, researchers examined the full spectrum of track directions for a given location or region (Fig. 6.4). This work identified a natural split at 135°E, based on track motion, that defined east and west sub-basins in subsequent model analysis. The climatology was also used to develop refined tropical cyclone projections for Australia (see next highlight).

Researchers also found that the intraseasonal variability in tropical cyclone track motion is influenced by the Madden–Julian Oscillation. The higher (lower) proportion of eastward moving systems in the enhanced (suppressed) phase of Madden–Julian Oscillation can be explained by the vertical and longitudinal structure of associated zonal wind anomalies.

PUBLICATION IN PROGRESS | Lavender and Dowdy 2016. Tropical cyclone track direction climatology and its intraseasonal variability in the Australian region. *Journal of Geophysical Research – Atmospheres* (submitted)

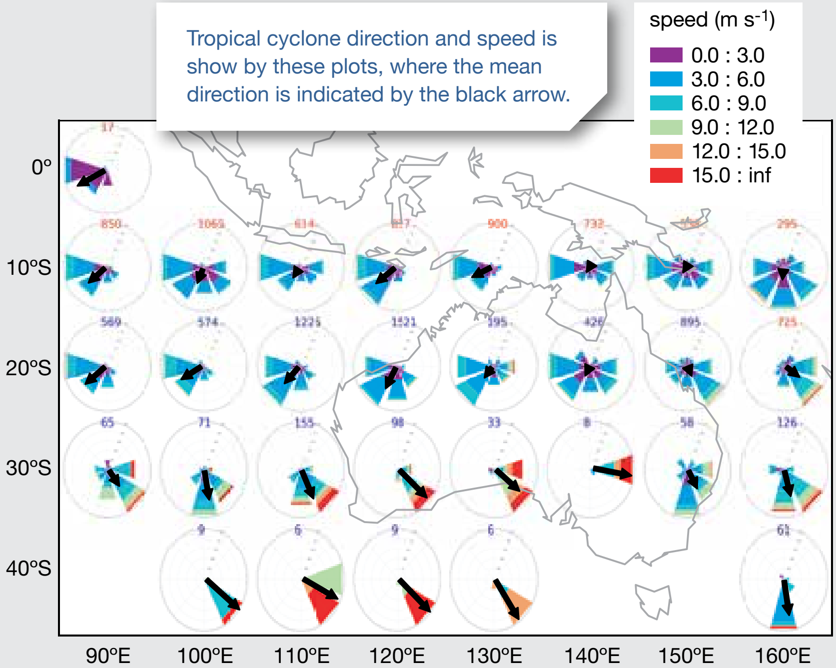


Figure 6.4
Polar plots for each 10x10 degree boxes for the Australian region, showing the relative proportion of translational tropical cyclone (TC) tracks in eight different directions. These directional distributions are based on 6-hourly TC occurrence data. The distribution of TC translation speed is also shown for each direction (represented by colours as shown in legend). The numbers listed for each 10x10 degree box represent the number of 6-hourly TC occurrences considered here for that particular regional location during the study period, with the colour of the numbers showing regions where TCs are intensifying (red) or dissipating (blue) on average. The black arrows represent the mean vector direction of the TC movement.

The **Madden–Julian Oscillation** is a mode of tropical climate variability associated with rainfall. Unlike the stationery El Niño–Southern Oscillation, the Madden–Julian Oscillation is eastward moving, at weekly to monthly timescales.

6

2015–16 Highlights

Refined projections of Australian tropical cyclones developed

ACCSP researchers developed a refined set of tropical cyclone projections for Australia, using insights into tropical cyclone formation and tracks from this project.

The projections show a strong decrease in the west, but a possible increase or little change in the east. This differs from previous results which included models that don't perform as well in the simulation of tropical cyclones in the Australian region.

Researchers analysed the ability of climate models to simulate tropical cyclones (using two different tropical cyclone detection methods), and selected five better-performing models. Two of these models use the same atmospheric model (ACCESS), so only one of these is used in the results.

Projections (RCP8.5, 2070–2100) suggest large decreases in tropical cyclone numbers west of 135°E due to a narrowing band of favourable conditions (Fig. 6.5). Numbers east of 135°E are less clear, with one detection method showing increases and the other showing a mix of increases and decreases.

The differences between the east and west basins are consistent with changes in large-scale atmospheric variables that are important for tropical cyclone formation.

Both methods project a southward shift in genesis latitude. However, there is little change in the proportion making landfall further south.

There is an increase in eastward moving tropical cyclones in the east, consistent with changes in the background winds.

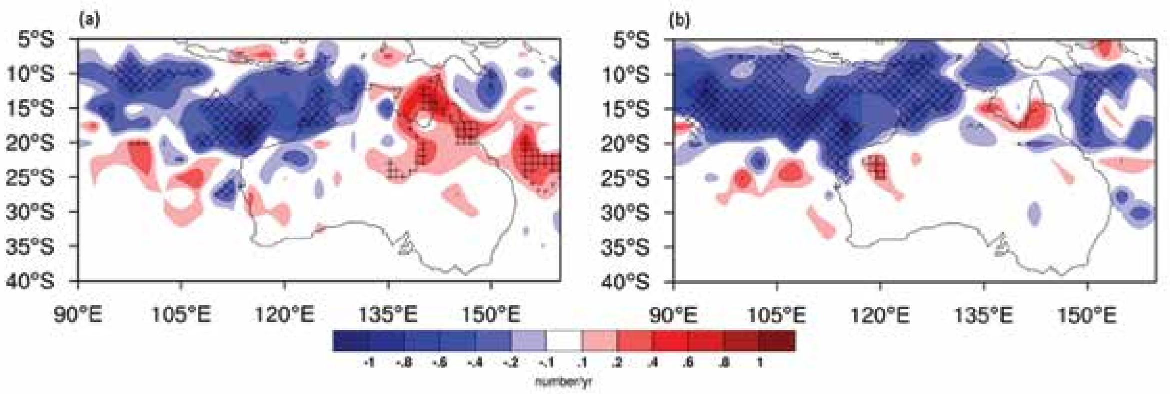


Figure 6.5
Ensemble mean change in tropical cyclone frequency between 2070-2100 under the RCP8.5 scenario and 1970-2000 under the historical scenario from detections using (a) the CSIRO Direct Detection scheme and (b) OWZ method. Stippling indicates where the majority of models agree on the sign of the change (3/4 models in this case).

Two different methods used to detect tropical cyclones in projections for 2070–2100 show a strong decrease tropical cyclone frequency west of 135°E, but the east is less conclusive.

6.4 ATTRIBUTION OF EXTREME EVENTS: MECHANISMS AND METHODS

SCIENCE TO INFORM DECISION-MAKING

Extreme weather and climate events often have a serious impact on our economy, environment and society. Researching extremes and understanding their causes is crucial for increasing our ability to manage and predict their impacts. Such research can also lead to increased skill in the prediction of extreme events for improved prevention, preparedness, response and recovery.

Climate models capture trends in climate extremes that are comparable to observed

Confirming the ability of climate models to simulate and detect changes in the occurrence or intensity of extremes is an important component of the development of attribution methods.

ACCSP researchers undertook the most comprehensive evaluation of temperature and precipitation extreme indices over Australia to date. They evaluated the CMIP5 models' ability to simulate a wide range of indices and trends over 1911–2010, and compared these results with two observational datasets.

> **Researchers found clear increases in the occurrence of warm extremes and reduction in the number of cool extremes over the past century in both observations and models.**

There are few observed significant trends for the various precipitation extremes indices. Models tend to underestimate the intensity and number of wet days, which should be taken into account in assessing the drivers of extreme daily rainfall events using these models.

Extreme October–November 2014 heat event due to influence of carbon dioxide

The attribution of the causes of single weather or climate events is difficult because each event is unique.

ACCSP researchers developed a new and unique method for attribution, based on the Bureau of Meteorology's operational seasonal forecasting system. The method can describe the exact event in question in a low (1960) or high (2014) carbon dioxide environment.

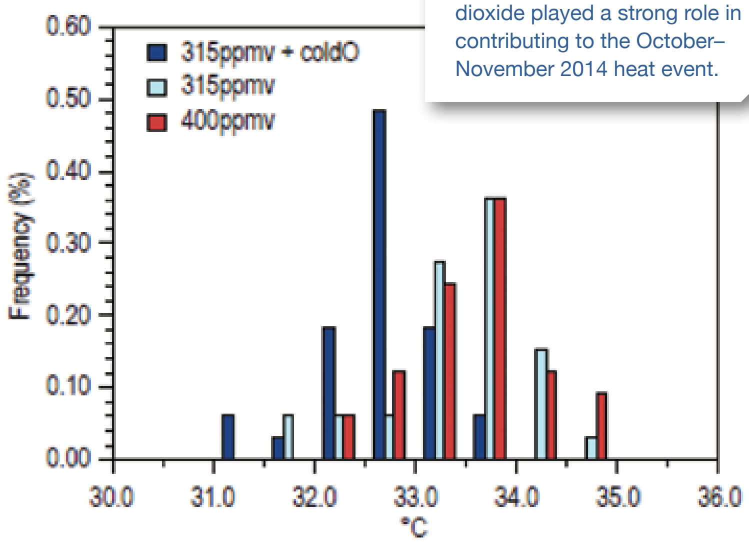
The method was used to attribute the drivers of the extreme Australia-wide temperatures of October and November 2014.

Three sets of hindcasts of this two-month period were made to quantify the influence of the growing levels of carbon dioxide over the past 55 years. The first hindcast set was generated with a current level of atmospheric carbon dioxide (400 ppm) and observed late September 2014 ocean, land and atmosphere initial conditions; the second set was produced with the same initial conditions but atmospheric carbon dioxide set to a 1960 level (315 ppm); and the third was produced with carbon dioxide at 315 ppm and the ocean initial conditions modified to remove the influence of increasing levels of atmospheric carbon dioxide over the past 55 years.

The experiment using atmospheric carbon dioxide at a 1960 level produced a generally cooler hindcast than the one using a current level, but the difference was not statistically different. In the modified ocean hindcast, there is a major cooling shift (Fig. 6.6), indicating that carbon dioxide strongly influenced the heat of the October–November 2014 event.

> A **hindcast** is a 'forecast' of the past. They are produced by setting up models with past observed conditions to test how well the models replicate weather and climate of a target period. Hindcasts can be used for attribution studies by exploring the forecast sensitivity of past weather and climate events to different forecast configurations (e.g. initial conditions for each component model and external forcings). This helps researchers to better understand the key factors that caused the weather or climate events being examined.

2015–16 Highlights



The cooling shift in the modified oceans experiment (dark blue) shows that carbon dioxide played a strong role in contributing to the October–November 2014 heat event.

Figure 6.6
Three sets of hindcasts of the Australia-wide October and November 2014 monthly temperatures, with the current level of atmospheric carbon dioxide (400 ppm, red); atmospheric carbon dioxide set to 1960 levels (315 ppm, light blue); and a 1960 level with ocean influences removed (dark blue). Each hindcast set has 33 ensemble members.

While intense high pressures over south-east Australia helped build much of the heat, researchers found that it was the influence of enhanced levels of atmospheric carbon dioxide that led to the event being a record.

READ MORE | Hope *et al*. 2015. Contributors to the record high temperatures across Australia in late spring 2014. Explaining extremes of 2014 from a climate perspective. SC Herring, MP Hoerling, TC Peterson and PA Stott (Eds). *Bulletin of the American Meteorological Society*, 96, S149–S153.

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

SCIENCE TO INFORM DECISION-MAKING

An improved understanding of the influence of climate change of the ignition of bushfires in Australia is important for planning and adaptation measures. An improved capability to model changes in fire regimes is important for carbon accounting applications.

New methods for modelling the climatological risk of thunderstorms and lightning

Thunderstorms can have severe impacts on regions throughout Australia, due to extreme rainfall and winds and in relation to the lightning activity that they produce. In particular, dry lightning is the primary non-human cause of bushfire ignition throughout Australia.

Dry lightning is lightning that occurs without significant rainfall (less than around 3 mm).

ACCSP researchers identified large-scale indicators of thunderstorm and lightning activity that are suitable for application to climate models. The indicators represent environmental conditions that are conducive to the formation of thunderstorm and lightning activity.

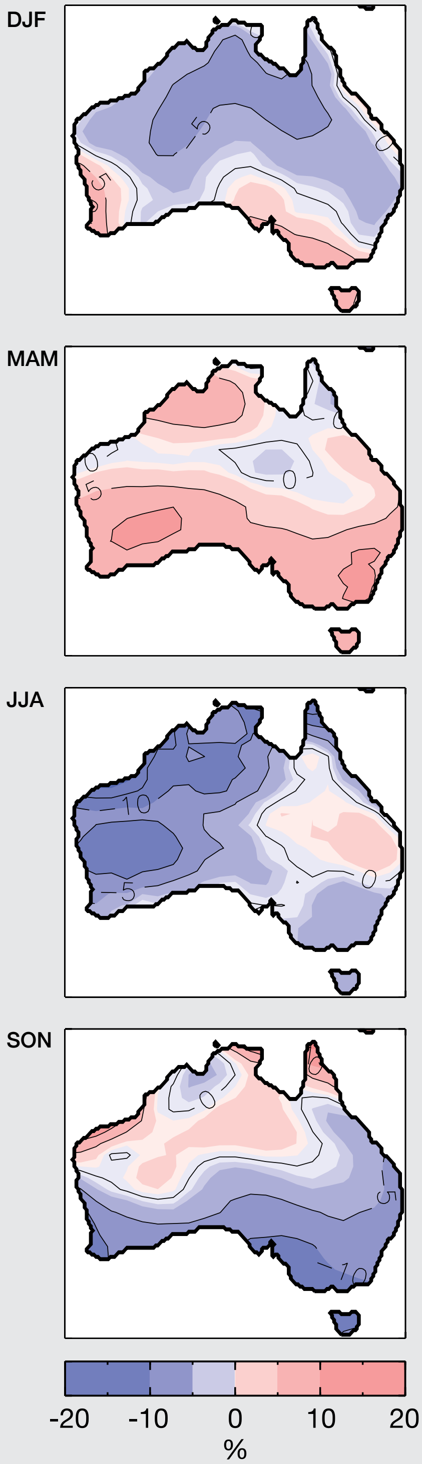
This allowed the development of the world's first method for seasonal forecasting of thunderstorms and lightning activity. It also allowed projections to be examined for the change in occurrence frequency of environments conducive to dry lightning (i.e. lightning that occurs with relatively little rainfall, Fig. 6.7).

These are the first results of their kind to have been produced for any region of the world to date. The projections show considerable variations in the direction of changes to days conducive to dry lightning between seasons and regions.

These projections of environments conducive to dry lightning were given to dynamic vegetation modellers to use in providing guidance in relation to model representations of changes in the natural drivers of burnt area and the Australian carbon budget.

READ MORE | Dowdy 2016. Seasonal forecasting of lightning and thunderstorm activity in tropical and temperate regions of the world. *Scientific Reports*, 6, doi:10.1038/srep20874.

READ MORE | Dowdy 2015. Large-scale modelling of environments favourable for dry lightning occurrence. In: *MODSIM2015*, 21st International Congress on Modelling and Simulation. T Weber, MJ McPhee and RS Anderssen (eds). Modelling and Simulation Society of Australia and New Zealand, December 2015, pp. 1524–30. ISBN: 978-0-9872143-5-5.



Results of the first projections of changes to days conducive to dry lightning show considerable variations in the direction of change between seasons and regions

Figure 6.7
Projected change in the number of days conducive to dry lightning (based on changes in the climate from 1990 to 2090 under RCP8.5), shown for each of the four seasons: summer (DFJ, upper panel), autumn (MAM, second panel), winter (JJA, third panel) and spring (SON, lower panel).

7

2015–16 Highlights

Management, coordination and communication

With CSIRO and Bureau of Meteorology scientists collaborating nationally and internationally on dozens of projects in a variety of research areas, strong management, coordination and communication were essential to optimising the uptake and value of ACCSP outputs and outcomes.

MANAGEMENT AND COORDINATION

The ACCSP was coordinated by a joint management team comprising senior representatives from the Department of the Environment and Energy, CSIRO and the Bureau. The team was responsible for day-to-day management, progress reporting and finances, and met regularly to review progress, and to identify and undertake stakeholder communication and briefing needs as appropriate. Formal progress reports and the published Annual Report (this document) were prepared to summarise key achievements of the Programme throughout the year.

Annual science meeting

In June 2016, 37 research, communication and management personnel representing CSIRO, the Bureau of Meteorology and the Department of the Environment and Energy gathered in Melbourne for the final ACCSP annual science meeting. Over the course of the ACCSP, these meetings have been a valuable forum for sharing science highlights with the Department and with colleagues across the Programme.

With the Programme wrapping up at the end of June, the meeting was an opportunity to reflect not only on the past 12 months but on 27 years of climate science achievements. These achievements will also be captured in a separate evaluation review of the ACCSP which is currently underway.

Archiving and data management

An Endnote library of all ACCSP journal publications and associated communication activities, including conference and seminar presentations, for the last three to five years of the Programme has been developed. This resource will be posted to the ACCSP website as part of the close out data management/archiving arrangements for the Programme.

A data/metadata stocktake of all ACCSP projects from the same period has also been completed, including undertaking final quality control/quality assurance on data repositories and associated curation arrangements as part of Programme close out. A consolidated metadata catalogue will be prepared and posted to the ACCSP website.

Final reporting

As the ACCSP draws to a close, work is underway to ensure that the legacy of 27 years of climate science is appropriately captured and communicated.

In addition to this Annual Report, covering the last 12 months of the ACCSP, an Achievements Report is in preparation, along with a Programme evaluation. These reports will be available on the ACCSP website.

Simon Torok, Scientell

Annual science meeting participants.

7

2015–16 Highlights

COMMUNICATION

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

A communication plan set out the way in which the research findings were strategically shared with and explained to key stakeholders. ACCSP findings have, and will continue to, assist with planning for, and managing, the expected environmental, social and economic impacts of climate change in Australia. Sharing and explaining the research findings to key stakeholders – government, industry and the public – was an important component of the ACCSP.

Nationally and internationally, the work of the ACCSP was disseminated through a range of channels. The Programme directly supported and organised scientific workshops and conferences, and ACCSP scientists regularly made presentations at national and international conferences, meetings and workshops.

Publications

In 2015–16, ACCSP researchers published 98 peer-reviewed papers or articles in Australian and international scientific publications. A further 44 papers were submitted for publishing but not published at the time of this Annual Report.

Refer to Appendix 3 for a list of ACCSP publications.

Websites

The primary ACCSP website has been supported by the Collaboration for Australian Climate and Weather Research (CAWCR) and is located at **www.cawcr.gov.au/projects/climatechange**. This website is being redeveloped into a legacy site to provide ongoing access to Programme information and achievements.

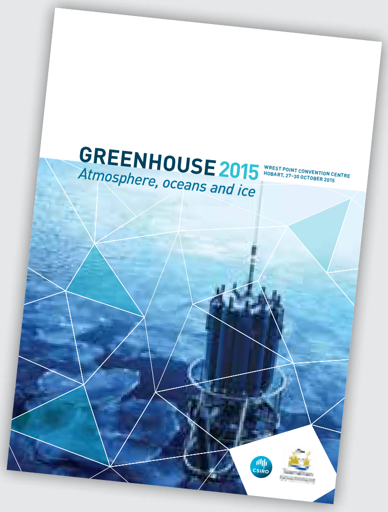
Information about the ACCSP also appears on the Dewpartment of the Environment and Energy website at **www.environment.gov.au/climate-change/climate-science/australian-climate-change-science-program** and on the CSIRO website at **www.csiro.au/en/Research/OandA/Areas/Assessing-our-climate/CAWCR/ACCSP**.

GREENHOUSE 2015

GREENHOUSE 2015, the latest conference in the influential series delivered by the ACCSP, was held in Hobart in October 2015.

GREENHOUSE events are designed to facilitate communication of the latest climate change science findings in Australia and to discuss challenges and future directions for climatology, meteorology and oceanography in Australia and internationally. Taking advantage of the strength of Southern Hemisphere climate change science in Tasmania, the theme of GREENHOUSE 2015 was ‘Atmosphere, oceans and ice’.

Over the four days of the conference there were 13 plenary presentations, six panel and special sessions, 51 presented papers, 22 poster presentations and two professional development sessions. A program highlight was the university science showcase featuring six early-career scientists from the ARC Centre for Climate Systems Science.



APPENDIX 1 Research projects

1 GLOBAL AND REGIONAL CARBON BUDGETS		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
1.1 Global carbon budgets, analyses and delivery	Pep Canadell (CSIRO)	Carbon dioxide fertilisation greening the Earth Non-carbon dioxide emissions from global food production are becoming bigger players in climate change
1.2 The Australian terrestrial carbon budget: the role of vegetation dynamics	Vanessa Haverd (CSIRO)	Year-to-year variation in carbon uptake in Australian ecosystems is largely due to variations in eastern savanna productivity
1.3 Palaeo carbon cycle dynamics	David Etheridge (CSIRO) Cathy Trudinger (CSIRO) Richard Matear (CSIRO)	Greenhouse gas mitigation verified by the palaeo-atmospheric record Positive carbon dioxide feedback from the terrestrial biosphere due to temperature

2 LAND AND AIR OBSERVATIONS AND PROCESSES		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
2.1 Aerosol and its impact on Australian climate	Peter Vohralik (CSIRO)	Cooling effect of aerosol pollution is slowing down Southward shift of Australian pressure ridge counteracted by aerosols
2.2 Reducing uncertainties in climate projections by understanding, evaluating and intercomparing climate change feedbacks	Rob Colman (Bureau of Meteorology)	New method used to investigate cloud feedbacks in ACCESS
2.3 Ecosystem response to increased climate variability	Eva van Gorsel (CSIRO)	Woodland carbon uptake decreased during extreme heatwave

3 OCEANS AND COASTS OBSERVATIONS AND PROCESSES		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
3.1 Ocean monitoring to understand ocean control of the global and Australian climate	Susan Wijffels (CSIRO)	Argo coverage maintained around Australia
3.2 Understanding ocean drivers of regional and global climate variability and change	Bernadette Sloyan (CSIRO) Steve Rintoul (CSIRO) Susan Wijffels (CSIRO) Terry O'Kane (CSIRO)	Third repeat hydrographic survey of deep ocean section completed
3.3 Addressing key uncertainties in regional and global sea-level change, storm surges and waves	John Church (CSIRO) Kathleen McInnes (CSIRO) Mark Hemer (CSIRO)	Trends in observed sea-level rise from satellites have been refined Anthropogenic forcing dominates sea-level rise since 1970 Sea level and coastal extremes research gaps identified
3.4 Ocean acidification	Bronte Tilbrook (CSIRO) Marcel van der Schoot (CSIRO)	Detailed estimates of ocean acidification change in Australian seas, including the Great Barrier Reef developed

4 MODES OF CLIMATE VARIABILITY AND CHANGE

PROJECT TITLE	PRINCIPAL INVESTIGATORS	HIGHLIGHTS
4.1 The El Nino–Southern Oscillation and its impacts on Australasia in the 21st century	Scott Power (Bureau of Meteorology)	Nonlinear relationship between Australian rainfall and ENSO during spring and summer
4.2 Decadal variability in Australian and Indo-Pacific climate: predictability and prediction	Scott Power (Bureau of Meteorology)	Tasman Sea temperatures could be useful indicators of future Southern Hemisphere climate conditions
4.3 Response of Indo-Pacific climate variability to greenhouse warming and the impact on Australian climate: a focus on ocean-induced climates	Wenju Cai (CSIRO) Guojian Wang (CSIRO)	Greenhouse warming increases the frequency of consecutive extreme climate events
4.4 Attribution, projection and mechanisms of climatic extremes and change, modes of variability and regional weather systems	Simon Grainger (Bureau of Meteorology) Stacey Osbrough (CSIRO)	Climate change component of Southern Hemisphere circulation variability detected Changes in mid-latitude storm formation due to climate change Potentially predictable decadal sea surface temperatures detected

5 EARTH SYSTEMS MODELLING AND DATA INTEGRATION

PROJECT TITLE	PRINCIPAL INVESTIGATORS	HIGHLIGHTS
5.1 ACCESS coupled climate model development	Tony Hirst (CSIRO) Gary Dietachmayer (Bureau of Meteorology)	Successful simulation of key Australian climate features in ACCESS-CM2 with high oceanic resolution Dry rainfall bias over the Maritime Continent in ACCESS reduced with higher resolution modelling ACCESS participation in international benchmarking projects
5.2 ACCESS carbon cycle modelling	Rachel Law (CSIRO) Richard Matear (CSIRO)	ACCESS-ESM1 benchmarked ahead of CMIP6 Historical land carbon uptake is significantly enhanced by the offsetting ‘cooling’ due to anthropogenic aerosols Carbon–climate feedbacks significantly influence the rate and magnitude of ocean acidification
5.3 Development of the ACCESS Earth system model for aerosol and chemistry	Ashok Luhar (CSIRO) Peter Vohralik (CSIRO)	Aerosol effective radiative forcing quantified for ACCESS-1.4 New aerosol model for the next generation ACCESS-CM2 configured and evaluated Representation of the dry deposition of ozone to seawater in ACCESS-UKCA improved

6 AUSTRALIA'S FUTURE CLIMATE		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
6.1 Regional climate projections science	Michael Grose (CSIRO)	Past Australian regional climate projections evaluated to inform development and delivery of future projections
6.2 Understanding and narrowing uncertainties in tropical Australian rainfall projections	Aurel Moise (Bureau of Meteorology)	Sources of uncertainty in projected tropical Australian rainfall changes identified First climatology of Australian heat low events developed Australian monsoon expertise recognised internationally
6.3 Evaluation of tropical cyclone development in the Australian region	Sally Lavender (CSIRO) Kevin Tory (Bureau of Meteorology)	Regions suitable for tropical cyclone formation identified Tropical cyclone track climatology and intraseasonal variability examined Refined projections of Australian tropical cyclones developed
6.4 Attribution of extreme events: mechanisms and methods	Pandora Hope (Bureau of Meteorology) Julie Arblaster (Bureau of Meteorology – now Monash University)	Climate models capture trends in climate extremes that are comparable to observed Extreme October–November 2014 heat event due to influence of carbon dioxide
6.5 Impact of climate change on the ignition of bushfires and the Australian carbon budget	Andrew Dowdy (Bureau of Meteorology) Bryson Bates (CSIRO) Bertrand Timbal (Bureau of Meteorology)	New methods for modelling the climatological risk of thunderstorms and lightning

APPENDIX 2 Collaborators

AUSTRALIA

- Antarctic Climate and Ecosystems Cooperative Research Centre
- Australian Research Council Centre of Excellence for Climate System Science
- Australian Antarctic Division
- Australian Institute of Marine Science
- Australian National University
- Australian Nuclear Science and Technology Organisation
- Curtain University
- Federation University
- Integrated Marine Observing System (IMOS)
- Macquarie University
- Monash University
- National Computational Infrastructure
- Southern Cross University
- University of Adelaide
- University of Melbourne
- University of New South Wales
- University of Queensland
- University of Tasmania
- University of Technology, Sydney
- University of Western Australia
- University of Wollongong

BRAZIL

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

CHINA

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

DENMARK

- Centre for Ice and Climate, University of Copenhagen

FRANCE

- Centre National de la Recherche Scientifique, Laboratoire de Glaciologie et Géophysique de l'Environnement
- Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN)
- Laboratoire des Sciences du Climat et de l'Environnement
- Université Pierre et Marie Curie

GERMANY

- Alfred Wegener Institute for Polar and Marine Research
- Geomar, Kiel
- Max Planck Institute for Chemistry

ITALY

- Dipartimento di matematica e fisica, Seconda Università di Napoli

JAPAN

- Japan Agency for Marine-Earth Science and Technology
- National Institute for Environmental Studies

THE NETHERLANDS

- Institute for Marine and Atmospheric Research Utrecht, Utrecht University

NEW ZEALAND

- National Institute of Water and Atmospheric Research (NIWA)

NORWAY

- Center for International Climate and Environmental Research

SOUTH KOREA

- Global Monsoon Climate Laboratory, Busan National University

SWEDEN

- Lund University

SWITZERLAND

- Empa – Laboratory for Air Pollution and Environmental Technology

UK

- British Antarctic Survey
- University College London
- MetOffice
- School of Environmental Sciences, University of East Anglia
- Swansea University
- The Open University
- Tyndall Center
- University of Cambridge
- University of Leeds
- University of Reading

USA

- Carbon Dioxide Information and Analysis Center
- Columbia University
- Department of Earth and Environmental Sciences, University of Rochester
- Duke University
- Geophysical Fluid Dynamics Laboratory
- Institute of Arctic and Alpine Research, University of Colorado
- Lamont Doherty Earth Observatory
- NASA Goddard Institute for Space Studies
- National Center for Atmospheric Research
- National Oceanic and Atmospheric Administration (NOAA)
- NOAA Atlantic Oceanographic and Meteorological Laboratory
- NOAA Pacific Marine Environmental Laboratory
- National Oceanographic Data Center
- Oregon State University
- Scripps Institution of Oceanography
- Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory

INTERNATIONAL

- Global Carbon Project
- International Argo Project
- World Climate Research Programme
- World Meteorological Organization Global Atmosphere Watch
- Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP)
- World Meteorological Organization Global Climate Observing System
- International: Global Ocean Acidification Observing Network, International Ocean Carbon Coordination Project

APPENDIX 3 Publications

PEER-REVIEWED JOURNALS

In 2015–16, ACCSP researchers published 98 peer-reviewed papers or articles in Australian and international scientific journals. A further 23 papers were in review, 13 were submitted for publishing and eight others were accepted for publication, but not published at the time of this Annual Report. These papers are listed here sorted alphabetically by lead author under the ACCSP's key climate research themes.

Papers in blue type are referred to in the science highlights.

GLOBAL AND REGIONAL CARBON BUDGETS

Bastos A, Ciais P, Barichivitch J, Bopp L, Brovkin V, Gasser T, Peng S, Pongratz J, Viovy N, Trudinger CM. 2016. Re-evaluating the 1940s CO_2 plateau. *Biogeosciences* (in press).

Buchanan P, Matear R, Lenton A, Phipps S, Chase Z, Etheridge D. 2016. The simulated climate of the Last Glacial Maximum and the insights into the global carbon cycle, *Climates of the Past* (submitted).

Dommergue A, Martinerie P, Courteaud J, Witrant E, Etheridge DM. 2016. A new reconstruction of atmospheric gaseous elemental mercury trend over the last 60 years from Greenland firn records. *Atmospheric Environment*, 136, 156–64.

Fogwill C, Turney C, Golledge N, Etheridge D, Rubino M, Thornton D, Woodward J, Winter K, van Ommen T, Moy A, Curran M, Davies S, Weber M, Bird M, Munksgaard N, Rootes C, Millman H, Rivera A, Cooper A. 2016. Antarctic ice-sheet discharge driven by atmosphere ocean feedbacks across the Last Glacial Termination. *Proceedings of the National Academy of Sciences* (submitted).

Haverd V, Ahlstrom A, Smith B, Canadell JG. 2016. Carbon cycle responses of semi-arid ecosystems to positive asymmetry in rainfall. *Global Change Biology* (in press).

Haverd V, Cuntz M, Nieradzik LP, Harman IN. 2016. Improved representations of coupled soil-canopy processes in the CABLE land surface. *Geoscientific Model Development Discussions*, 1–24.

Haverd V, Smith B, Raupach M, Briggs P, Nieradzik L, Beringer J, Hutley L., Trudinger CM, Cleverly J. 2016. Coupling carbon allocation with leaf and root phenology predicts tree-grass partitioning along a savanna rainfall gradient. *Biogeosciences*, 13, 761–79.

Haverd V, Smith B, Trudinger CM. 2016. Process contributions of Australian ecosystems to interannual variations in the carbon cycle. *Environmental Research Letters*, 11, 054013.

Haverd V, Smith B, Trudinger C. 2016. Dryland vegetation response to wet episode, not inherent shift in sensitivity to rainfall, behind Australia's role in 2011 global carbon sink anomaly. *Global Change Biology*, doi:10.1111/gcb.13202.

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INDEX

A

ACCESS (Australian Community Climate and Earth System Simulator), 4, 17, 33, 34–8, 40–1
ACCESS land carbon module (CABLE), 7, 34
aerosols, 15–16, 38, 40–1
aluminium industry, 10, 11
annual science meeting, 53
Antarctic and Climate Ecosystem CRC, 3
Antarctic Circumpolar Current and Southern Ocean Meridional Overturning Circulation, 36
aragonite, 39
archiving of data and publications, 53
Argo program, 4, 20–1
atmospheric carbon dioxide, 13, 26, 38, 49–50
atmospheric chemistry, 40, 41
atmospheric modelling, high resolution, 35–6
atmospheric ozone, 41
Australian Antarctic Division, 3
Australian climate
  changing climate, 5
  climate change projections timeline 1987–2016, 43
  extreme events, 29–30, 49–51
  impact of aerosols, 15–16
  impact of Indian Ocean Dipole, 29–30, 34
  impacts of El Niño Southern Oscillation, 28
  monsoon rainfall projections, 44–5
  simulations, 34–7
  storm formation, southern Australia, 32
  tropical cyclones, 30, 46–8
  variability, 29, 31
  see also Australia's future climate
Australian Climate Change Science Programme
  highlights 2015–16, 3
  legacy, 3, 53–4
  role, 4
Australian Community Climate and Earth System Simulator (ACCESS), 4, 17, 33, 34–8, 40–1
Australian ecosystem carbon uptake, 9
Australian monsoon, 44–5
Australian pressure ridge southward shift, 16
Australian Research Council Centre of Excellence for Climate System Science, 4
Australia's future climate, 5, 42
  climate change impact and projections, 43–51
  publications, 67, 73–4
  research projects, 57
  see also Australian climate

B

benchmarking projects, 36, 37
bottom-up methods, 10
Bureau of Meteorology, 3, 4, 53
bushfire ignition, 50–1 *see also* fire

C

CABLE land surface model, 7, 34
carbon budgets, 6–13
  publications, 60–1, 68–70
  research projects, 55
carbon–climate feedbacks, 39
carbon cycle, 9, 10–13
carbon cycle modelling, 37–9
carbon dioxide
  changes during Little Ice Age, 13
  emissions from global food system, 8
  fertilisation effect on plant growth, 7, 38
  influence on extreme heat event, 49–50
  observed levels, 4
carbon sinks, 8, 18
Centre of Excellence for Climate System Science, 4
climate change projections for Australia, 43–51
climate models *see* Australian Community Climate and Earth System Simulator (ACCESS); Coupled Model Intercomparison Project (CMIP); Intergovernmental Panel on Climate Change (IPCC)
climate snapshot, 4, 5
climate variability, 29–41
  ecosystem response, 18
  modes of, 33–41
  publications, 64–5, 71–2
  research projects, 56
  see also extreme events
cloud feedbacks, 17
CMIP (Coupled Model Intercomparison Project),
Co-ordinated Ocean-ice Reference Experiments (CORE) studies, 36
coastal zone research, 25 *see also* Oceans and coasts observations, processes and projections
collaboration, 4, 58–9
Collaboration for Australian Climate and Weather Research (CAWCR), 54
communication, 54
Community Atmosphere Biosphere Land Exchange (CABLE) model, 7, 34
cooling effect of aerosols, 15–16, 38
Coupled Model Intercomparison Project (CMIP), 29, 31, 32, 36, 37, 40, 46, 49
coupled models, 34, 35, 36 *see also* ACCESS
CSIRO, 4, 53
  Climate Science Centre, 3
cyclones, 30, 46–8

D

data management, 53
decadal climate prediction, 29
deep ocean mixing, 23
Department of the Environment and Energy, 4, 53, 54
deposition, 41
drought, 28, 30
dry lightning, seasonal forecasting, 50–1

E

Earth systems modelling and data integration, 33
  achievements, 34–41
  publications, 65–6, 72–3
  research projects, 56
ecosystems
  Australian ecosystem carbon uptake, 9
  ocean acidification impact on marine ecosystems, 26, 39
  response to increased climate variability, 18
effective radiative forcing (ERF), 40–1
El Niño, 28, 30
El Niño Southern Oscillation (ENSO), 27, 28, 29–30
eREEF project, 26
evapotranspiration, 18
extreme events, 29–30, 49–51 *see also* climate variability

F

feedbacks, 13, 17, 39
fire, 9, 30, 50–1
floods, 30
FluxNet, 4
food production and non-carbon dioxide emissions, 8
funding, 4
future climate *see* Australia's future climate

G

Global and regional carbon budgets, 6
  achievements, 7–13
  publications, 60–1, 68–70
  research projects, 55
Global Carbon Project, 4, 37, 38

Global Climate Observing System (GCOS), 22
global climate snapshot, 4
global flux network and database (FluxNet), 4
global mean sea-level rise, 24 *see also* sea-level change
global ocean climate model benchmarking, 36
Global Ocean Observing System (GOOS), 22
Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), 4, 22–3
GLOMAP-mode, 41
Great Barrier Reef, 26
Greenhouse 2015 conference, Hobart, 54
greenhouse gas emissions, 8 *see also* carbon dioxide; halons; methane; nitrous oxide; ozone; perfluorocarbons
greenhouse gas mitigation, 10

H

Hadley Cells, 31
halons, 10, 12
heat extremes, 18, 49–50
heat lows, 45
high resolution modelling, 34–6
hindcasts, 49
hydrographic surveys of deep ocean, 4, 22–3

I

Indian Ocean Dipole, 29–30, 34
Indo-Pacific climate variability, 29, 30
Indo-Pacific warm pool, 36 *see also* Pacific Ocean
information management, 53
Interdecadal Pacific Oscillation (IPO), 32
Intergovernmental Panel on Climate Change (IPCC) assessment reports, 29, 36, 37, 43

L

La Niña, 28, 30
Land and air observations and processes, 14
- achievements, 14–18
- publications, 61–2, 70
- research projects, 55

land biosphere carbon dioxide uptake, 13, 38
lightning, seasonal forecasting, 50–1
Little Ice Age, 13

M

Madden–Julian Oscillation, 47
management and coordination, 52–3
marine ecosystems, impact of ocean acidification, 26, 39
Marine Observing System (IMOS), 26
Maritime Continent, 35–6
Marsland, Dr Simon, 36
metadata catalogue, 53
methane, 8
Modes of climate variability and change, 27
- achievements, 28–32
- publications, 64–5, 71–2
- research projects, 56

monsoon, 44

N

National Computational Infrastructure facility, 4
National Environmental Science Programme Earth Systems and Climate Change Hub, 3
nitrous oxide, 8
non-carbon dioxide emissions, 8
North Atlantic Ocean, interannual to decadal predictability, 36

O

OASIS3-MCT, 34
ocean acidification, 23, 26, 39
ocean circulation, 23
ocean climate model benchmarking, 36
Ocean Model Intercomparison Project (OMIP), 36
ocean modelling, high resolution, 34–5
ocean uptake of carbon, 37
ocean warming, 20–1, 23 *see also* sea surface temperature
Oceans and coasts observations, processes and projections, 19
- achievements, 20–6
- publications, 62–4, 70–1
- research projects, 55

ozone, 41
ozone hole recovery, 10
Pacific Ocean, 22–3, 30, 32, 36 *see also* El Niño Southern Oscillation

P

palaeo carbon cycle dynamics, 10–13
perfluorocarbons, 10–11
plant growth *see* vegetation
pressure ridge southward shift, 16
publications, 54, 60–74 *see also* research projects

R

radiation (or energy) budget, 40
radiative forcing, 40–1
rainfall
- Australian monsoon, 44
- and ENSO, 28
- modelling, 35–6
- southern Australian winter rainfall, 32
- variability, 29–30

reporting arrangements, 53 *see also* publications
Representative Concentration Pathways (RCP), 32, 39, 48, 51
research partners, 58–9
research projects, 53, 55–7 *see also* publications
role of ACCSP, 4

S

salinity measurement, 20
scientists involved in the programme, 4
sea-level change, 24–5
sea subsurface temperature, 20–1, 29
sea surface temperature, 20–1, 32, 34
South Pacific Convergence Zone, 30
Southern Annular Mode (SAM), 31
Southern Hemisphere climatic conditions, 29, 31
Southern Ocean, 23, 31, 36, 39, 41
storm surges, 25
storms, 32, 50–1
stratosphere, 41
stratospheric ozone layer recovery, 10

T

Tasman Sea temperatures, 29
temperature effects on the carbon cycle, 13
temperature extremes *see* heat extremes
temperature of oceans *see* ocean warming; sea subsurface temperature; sea surface temperature
terrestrial biosphere carbon dioxide uptake, 13, 38
thermal lows, 45
thunderstorms, seasonal forecasting, 50–1
top-down methods, 10
tropical cyclones, 30, 46–8
troposphere, 41

V

vegetation
- carbon dioxide fertilisation effect, 7, 38
- carbon uptake, 7, 8, 9, 13, 18, 38

W

Walker circulation, 36
websites, 54
- archive of ACCSP publications, 53

World Climate Research Programme, 4, 29
- CLIVAR Ocean Model Development Panel, 36

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