Australian Climate Change Science Programme

ANNUAL REPORT 2014–15

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CSIRO

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Bureau of Meteorology

The Australian Climate Change Science Programme – an Australian Government initiative

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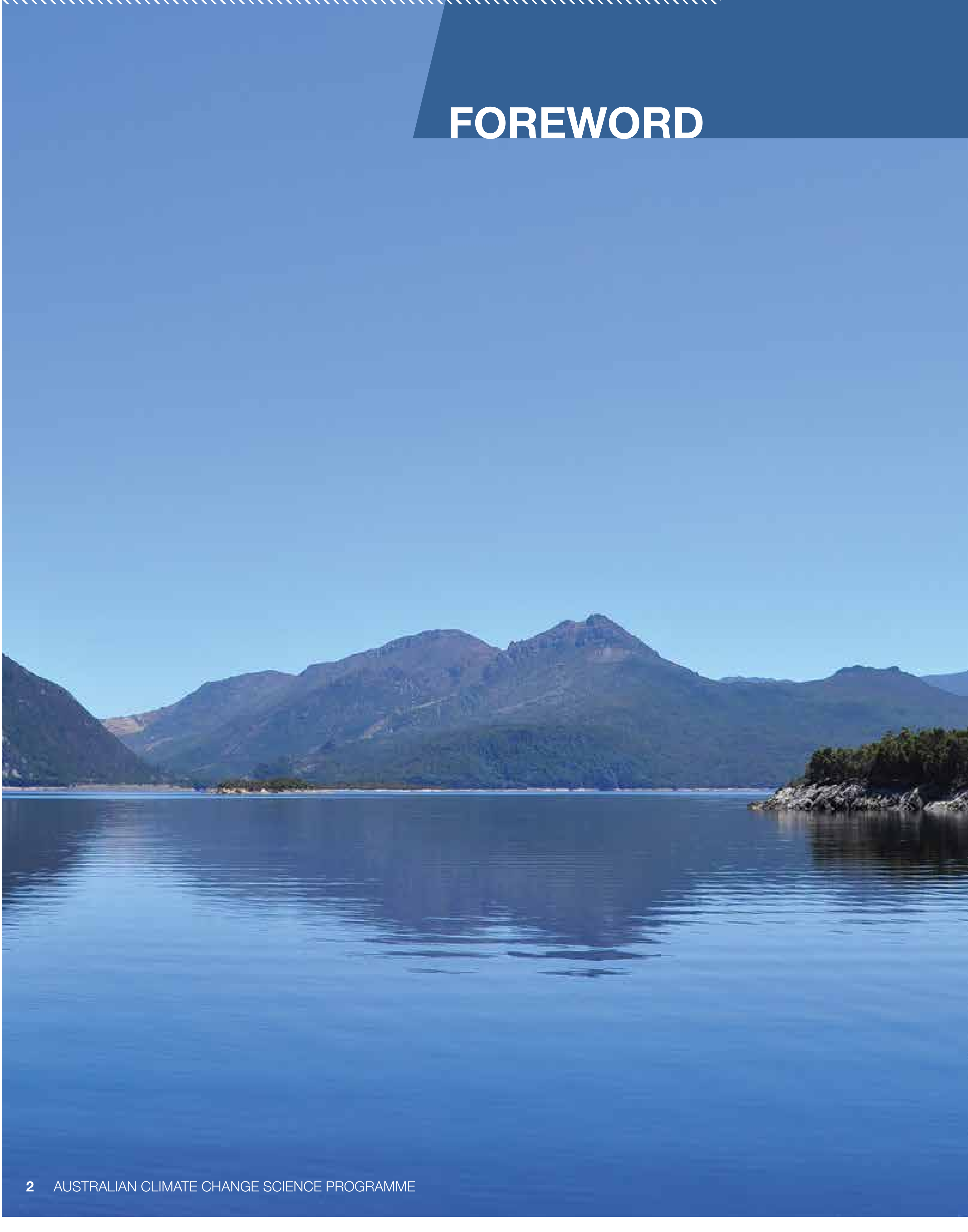

The Australian Climate Change Science Programme (ACCSP) plays a major role in informing Australia's decision makers and improving the understanding of the causes, nature, timing and consequences of climate change.

In 2014–15, more than 100 climate scientists throughout Australia worked on 22 projects across six key research areas that addressed national climate research priorities. The science undertaken by the ACCSP in the reporting year improved our understanding of what changes in the climate system we are seeing now, what changes we are likely to see in the future, and the consequences of a future warmer climate due to greenhouse gas emissions.

We have captured many science highlights in this report.
For example, over the reporting period our researchers:

- determined that global carbon dioxide equivalent emissions from the agricultural sector are bigger than the land carbon dioxide sink
- explained mechanisms causing carbon dioxide changes during the Little Ice Age
- extended the Australian ocean climate record and showed that the oceans continue to warm
- found that increasing carbon dioxide is causing Southern Hemisphere atmospheric circulation change
- demonstrated continued global mean sea-level rise
- found that greenhouse warming leads to increased frequency of extreme La Niña events
- identified the human influence in recent record Australian heat extremes.

This year also saw the release of the most comprehensive national climate projections to date through the *Climate Change in Australia: Projections for Australia's NRM Regions* initiative. These projections, available at **www.climatechangeinaustralia.gov.au**, were underpinned by ACCSP science.

As well as carrying out climate change research, the scientists presented their findings at workshops, conferences and many local and international events. They published their findings in peer-reviewed papers in Australian and international journals and publications for workshops, conferences and other events.

Our achievements would not have been possible without the passion of our scientists and staff. These people are committed to improving Australia's understanding of climate change and the challenges ahead. We would also like to acknowledge the Department of the Environment, which has supported CSIRO and the Bureau of Meteorology as the providers of the climate science undertaken by the ACCSP. The ACCSP plays a key role in helping the Australian Government answer key policy questions and in delivering research to inform the National Science and Research Priority of 'Environmental Change'. It also helps Australia's decision makers understand the impacts of climate change and provides the underpinning science that allows our country to develop ways to adapt to climate change and manage greenhouse gas emissions.

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ABOUT

AUSTRALIA'S CHANGING CLIMATE

The observed climate record indicates that Australian average surface air temperature has increased by 0.9°C since 1910, and many heat-related records have been broken in recent years. Global sea level has risen about 20 cm over the past century.

The Bureau of Meteorology has observed that since the 1970s, northern Australia has become wetter, southern Australia has become drier and the number of extreme fire weather days has increased in many places. Snow depths have declined since the 1950s and cyclone frequency seems to have declined since the 1980s.

Australia's most comprehensive ever climate projections were released in January 2015 as part of the *Climate Change in Australia: Projections for Australia's NRM Regions* initiative. They were compiled by researchers from CSIRO and the Bureau of Meteorology, and are underpinned by science from the ACCSP. The projections were prepared with an emphasis on informing impact assessment and planning in the natural resource management sector. Information has been drawn from simulations from up to 40 global climate models. These projections show that many of the changes observed over recent decades will continue into the future and will be superimposed on significant natural climate variability. These changes include:

- Hot days will become more frequent and hotter.
- Sea levels will rise, oceans will become more acidic.
- Snow depths will decline.
- Extreme rainfall events are likely to become more intense, even where annual-average rainfall is projected to decline.
- Southern and eastern Australia are projected to experience harsher fire weather.
- Tropical cyclones may occur less often, but become more intense.

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

A range of products, including technical reports, summary material and online tools, is available at **www.climatechangeinaustralia.gov.au**.

THE PROGRAMME

The ACCSP is the Australian Government's largest and longest-standing climate change science programme, having been running continuously since 1989. It is a key driver of Australia's climate change research effort, and provides climate research aimed at improving the understanding of the causes, nature, timing and consequences of climate change.

In 2014–15 the ACCSP received funding of

$11 million

through a collaboration between the Department of the Environment, CSIRO and the Bureau of Meteorology.

MORE THAN

100

SCIENTISTS

throughout Australia were involved in the programme, undertaking **22 projects** across six key research areas (see Appendix 1 for a complete project list), and publishing **90 peer-reviewed papers** or articles in Australian and international scientific journals. A further 28 papers were submitted for publishing and 17 others were accepted or in press (see Appendix 3 for a complete publication list).

NATIONAL AND INTERNATIONAL COLLABORATION

The ACCSP is committed to sharing knowledge and ensuring research outputs and outcomes are accessible and relevant for the Australian community. Extensive collaboration and engagement with the Australian Government and Australian and international research agencies helps to ensure our research is stakeholder relevant, effectively leveraged and leading edge.

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

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

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

2014–15 HIGHLIGHTS

1

2014–15 Highlights

Global and regional carbon budgets

Climate change is largely driven by increasing levels of greenhouse gases generated by human activities, such as those from burning fossil fuels. The challenge is to track, understand and predict changes in greenhouse gas levels, and in the stocks and flows of carbon. The ACCSP investigates a range of topics that provide information on changes to greenhouse gas emissions and concentrations, nationally and internationally, and how these affect our environment.

GLOBAL CARBON BUDGETS, ANALYSES AND DELIVERY

Globally carbon dioxide equivalent emissions from the agricultural sector are bigger than the land carbon dioxide sink

The combustion of fossil fuels is the single largest driver of increased greenhouse gases in the atmosphere, specifically of carbon dioxide. However, agriculture is responsible for a large amount of emissions of methane and nitrous oxide, the second and third most important greenhouse gases causing human-driven climate change, with 28 and 265 times larger global warming potential than carbon dioxide.

ACCSP researchers determined that the global warming potential of agricultural methane and nitrous oxide emissions are as large as the entire land carbon dioxide sink, which is responsible for removing more than a quarter of all carbon dioxide emissions from human activities.

If we put together the greenhouse gas emissions attributed to land use change with the ones from the agricultural sector (given that more than 90% of deforestation is driven by the expansion of pastures and croplands) and convert them to carbon dioxide equivalents, emissions related to agriculture are more than double the emissions removed by the land sink (Fig. 1.1). If we move into a low carbon society over the decades to come, with declining global carbon dioxide emissions, the non-carbon dioxide gases from agriculture will become an even larger player, providing a challenge to achieving climate stabilisation while feeding a growing global population.

READ MORE | Canadell & Schulze 2014. Global potential of biospheric carbon management for climate mitigation. *Nature Communications*, 5, 5282, doi:10.1038/ncomms6282.

Carbon dioxide equivalent emissions associated with the production of food are more than double the emissions removed by the land sink.

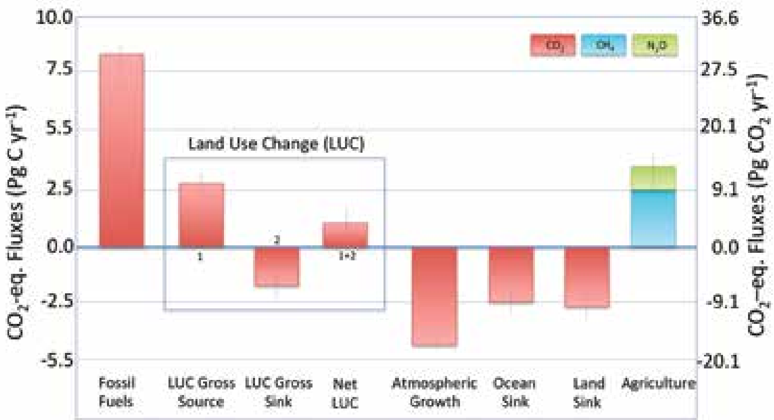


Figure 1.1
Global greenhouse gas emissions associated with human activities. Carbon dioxide equivalent emissions associated with the production of food (net Land Use Change (LUC) and Agriculture) are more than double the emissions removed by the land sink. The left hand scale shows fluxes in Pg of carbon and the right hand in Pg of carbon dioxide. 1 Pg is 10^{12} g or 1 Gigatonne (1 billion tonnes).

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).

2014–15 Highlights

THE AUSTRALIAN TERRESTRIAL CARBON BUDGET: THE ROLE OF VEGETATION DYNAMICS

Woody vegetation dynamics model results extended

Changes in woody biomass storage of carbon in forest and savannah ecosystems are the major component of the terrestrial carbon sink, which currently amounts to around a quarter of anthropogenic emissions, mitigating climate change. However, woody biomass changes are not represented well in Earth system models (ESMs).

CARBON SINKS | A carbon sink removes carbon dioxide from the atmosphere. The terrestrial biosphere (vegetation) has taken up 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 and causing a positive feedback, which amplifies the initial climate response. The future response of the terrestrial biosphere sink to climate change is a large cause of uncertainty in climate projections.

The Populations-Order-Physiology (POP) approach, developed by ACCSP researchers, simulates changes in woody ecosystems, including their response to disturbance. It is suitable for continental to global applications and designed for coupling to the terrestrial ecosystem component of any ESM.

Having already demonstrated the POP approach for savannah in northern Australia, ACCSP researchers successfully extended the application of POP to wide-ranging temperate and boreal forests.

Observations of stem biomass and density were used to calibrate the POP model, which was then coupled to the CABLE land surface model (which is the land surface model in ACCESS). The combined model (CABLE-POP) was evaluated against leaf–stem biomass observations from forest stands ranging in age from 3 to 200 years. In contrast to results from the current generation of Earth system models, CABLE-POP simulations accurately reproduce the observed relationship between leaf and stem biomass. This indicates that structural and functional characteristics are modelled consistently, which is essential for predicting how vegetation responds to changing climate, carbon dioxide and disturbance regimes.

READ MORE | Haverd *et al*. 2014. A stand-alone tree demography and landscape structure module for Earth system models: integration with inventory data from temperate and boreal forests. *Biogeosciences*, 11(15), 4039-4055.

EARTH SYSTEM MODELS | Earth system models incorporate biological and chemical processes and feedbacks into simulations of climate. They take into account influences such as the carbon cycle, aerosols and atmospheric chemistry, as well as atmospheric and ocean circulation and sea ice. By incorporating more elements than general circulation models, they are able to provide more comprehensive simulations of the climate and its feedbacks. Full Earth system models may include human socioeconomic systems as well as the biophysical and biogeochemical systems.

SCIENCE TO INFORM DECISION-MAKING

Understanding how the carbon cycle works – such as the role of vegetation dynamics and changes – helps us develop more accurate climate models.

PALAEO CARBON CYCLE DYNAMICS

Carbon dioxide changes during the Little Ice Age explained

ACCSP researchers measured air extracted from Antarctic ice cores (from Dronning Maud Land and Law Dome, near Australia's Casey Station) and found a decrease in carbon dioxide concentration during the Little Ice Age cool period (1500–1750 AD). A corresponding increase in the carbon-13 isotope of carbon dioxide identified uptake by vegetation as the main cause of this decrease in atmospheric carbon dioxide. Modelling of the simultaneous increase of carbonyl sulphide, an atmospheric tracer of photosynthesis, confirmed that the uptake was due to cooling of the biosphere rather than land use change, which was previously proposed as the cause. Cooling of the terrestrial biosphere reduces respiration (carbon dioxide emission) more than it reduces photosynthesis (carbon dioxide uptake), resulting in a net increase in carbon uptake.

This discovery allowed ACCSP researchers to estimate the sensitivity of the vegetation to temperature change – information that will be used to understand possible changes to the carbon cycle and to test and improve carbon-climate models.

READ MORE | Rubino *et al.* 2015 Atmospheric CO_2 and d13C-CO_2 reconstruction of the Little Ice Age from Antarctic ice cores. *Geophysical Research Abstracts*, 17, EGU2015-9747-2.

Global sources and sinks of methane over the past century quantified

Methane is a powerful greenhouse gas and a compound that is central to many atmospheric chemical processes. It has nearly tripled in concentration over the past 200 years but the relative contributions from its main sources are not well known.

ACCSP researchers used an atmospheric chemical transport model to simulate atmospheric methane concentrations and methane isotopes (carbon-13) and compared them with measurements of air extracted from firn (snow that has not yet been compressed into ice) and ice in Greenland and Antarctica. When emissions from 'bottom-up' inventory databases were used as input to the model, the simulated concentrations differed from the measurements in both hemispheres, overestimating them before 1950 and significantly underestimating them after 1960. The main implication of this result is that the emissions from bottom-up inventory databases are likely to be incorrect. With the additional constraint of the carbon-13 isotope of methane, revised emissions from biomass burning were found to balance the methane budget. The conclusions are that biomass burning generated an increase in methane emissions over the past century, reaching a maximum in the 1980s and decreasing rapidly since then. These changes concur with independent estimates from other 'top-down' atmospheric and ice core studies.

TOP-DOWN & BOTTOM-UP METHODS | 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.

1

2014–15 Highlights

This work reduces uncertainties in methane emissions from biomass burning and their variation over time. It also shows how century-scale measurements can improve our understanding of the methane budget and how it may respond to future potential growth in emissions from sources such as permafrost, hydrates and unconventional gas production.

READ MORE | Ghosh *et al.* 2015. Variations in global methane sources and sinks during 1910–2010, *Atmospheric Chemistry and Physics*, 15, 2595–2612, doi:10.5194/acp-15-2595-2015.

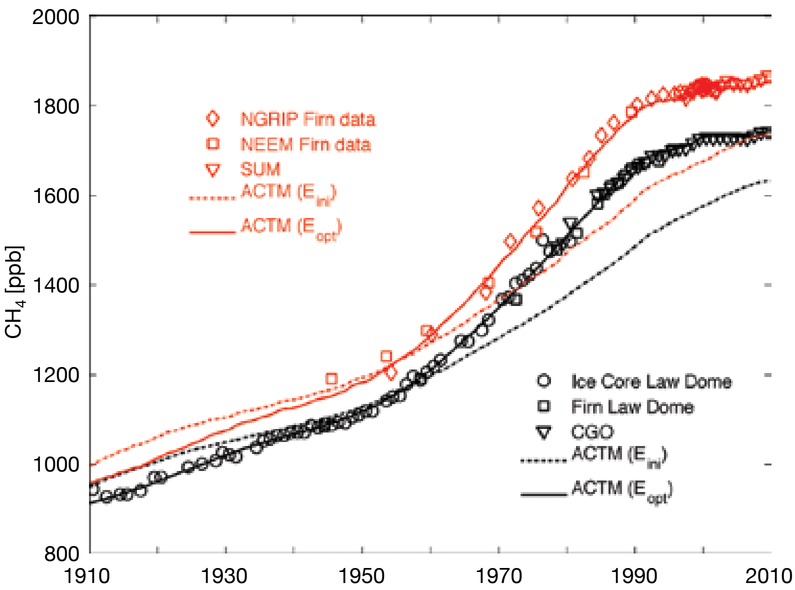


Figure 1.2
Atmospheric methane concentrations in the Northern (red) and Southern (black) Hemispheres simulated by an atmospheric chemistry transport model using initial emissions estimates (dashed line) and emissions optimised to fit observations in firn and from atmospheric stations (symbols). The major part of the difference between initial and optimised emissions is attributed to biomass burning during 1940 to 1990 based on the measured changes in the isotopic composition of methane.

Quantifying long-term atmospheric changes using observation data from ice cores and atmospheric stations helps to improve emissions estimates.

Sampling air and ice from the Antarctic and Greenland ice sheets for measurements of gas concentrations and isotopes for use in century long model simulations of greenhouse gas budgets.

Long-term atmospheric data from ice used to test ACCESS

Recent developments in measuring changes in atmospheric trace gases and their isotopes in ice have provided data from over the past century or more to test climate and Earth system models, including ACCESS. Without these long-term data the models can only be compared with data over the past few decades.

Looking at the longer periods of past centuries to millennia allows the models to be tested for their ability to simulate pre-industrial natural climate variations and the subsequent impact of emissions of gases, aerosols and land use changes caused by human activity.

ACCSP researchers have compared the simulated responses of the land and ocean components of the carbon cycle to temperature change with measurements during the pre-industrial and the last glacial period. Simulations by the recently developed ACCESS chemistry module (see page 39) of changes in key chemical constituents such as carbon monoxide have shown differences to what is recorded by CSIRO's measurements in ice, firn and at atmospheric stations. This is due to a combination of model accuracy and uncertainties in estimates of emissions over the industrial period. This information will help improve the ability of the models to simulate changes over these periods, leading to a better ability to predict atmospheric composition and the resulting climate under a given emissions scenario into the future.

The latest long term CSIRO atmospheric composition data produced in part by ACCSP support will also be used as climate forcing data in the forthcoming CMIP6 climate model comparisons. (See page 16 for more about CMIP – the Coupled Model Intercomparison Project.)

READ MORE | Matear *et al.* 2015. The simulated climate of the Last Glacial Maximum and the insights into the global carbon cycle. *Climate of the Past Discussion*, 11, 1093–1142.

SCIENCE TO INFORM DECISION-MAKING

Testing climate models against measurements from the past is an important way to evaluate climate projections.

2

2014–15 Highlights

Land and air observations and processes

The ACCSP examines atmospheric behaviour and the way in which it is likely to change as concentrations of greenhouse gases rise. Focus areas are 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. An expected decrease in global amounts of human-generated aerosol pollution is likely to accelerate global warming and alter aerosol-induced effects on weather patterns.

AEROSOL AND ITS IMPACT ON AUSTRALIAN CLIMATE

Importance of indirect aerosol effects on future tropical rainfall identified

Aerosols provide an offsetting 'cooling' of the climate, but the strength of that cooling is poorly understood. With aerosol emissions expected to decrease in the future, there will be a decrease in the aerosols in the atmosphere. This will change temperature patterns and affect cloud properties and rainfall but the details and magnitude of these changes remain highly uncertain.

ACCSP researchers compared future tropical temperature and rainfall pattern changes projected by two groups of

climate models – one included only the direct effect of aerosols (i.e. reflecting radiation) and the other included both direct and indirect effects (i.e. effects on clouds). They found when only the direct aerosol effects are considered, projected changes in temperature and rainfall patterns are fairly symmetric around the equator (blue line in Fig. 2.1), but when the indirect effects are also considered warming is strongly skewed to the Northern Hemisphere, increasing tropical Northern Hemisphere rainfall at the expense of Southern Hemisphere tropical rainfall (red line in Fig. 2.1). This skewing is because the aerosol burden being removed occurs predominantly over the Northern Hemisphere, corresponding to the location of industrial aerosol sources.

This work shows that projected changes in tropical rainfall are sensitive to aerosol emissions, and in particular to poorly understood indirect aerosol effects. Under low to moderate emissions scenarios, future aerosol changes are likely to be an important (even dominant) driver of tropical rainfall changes.

READ MORE | Rotstayn *et al.* 2015. Effects of declining aerosols on projections of zonally averaged tropical precipitation, *Environmental Research Letters*, 10, 044018, doi:10.1088/1748-9326/10/4/044018.

AEROSOLS | Aerosols are tiny airborne solid or liquid particles that reside in the atmosphere for hours to weeks. They may be 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).

SCIENCE TO INFORM DECISION-MAKING

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

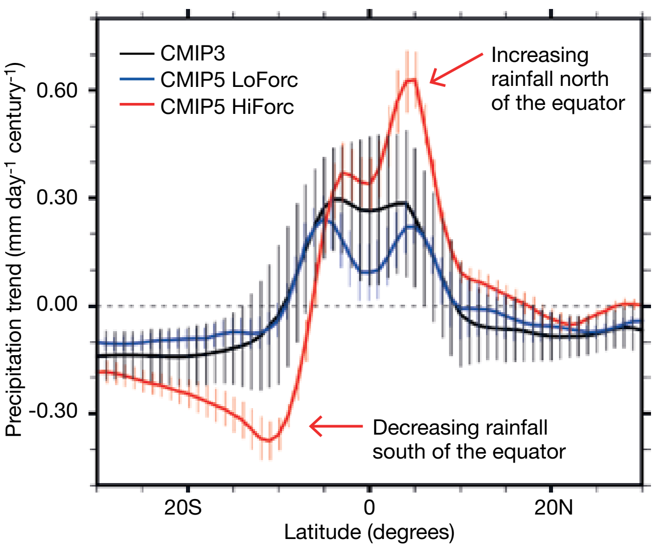


Figure 2.1
Projected, zonal-mean (i.e. averaged around the latitude) trends for rainfall, between 1871 to 2005 and 2006 to 2100 from CMIP5 LoForc ('low aerosol sensitivity', blue line) and CMIP5 HiForc ('high aerosol sensitivity', red line) models. Solid lines show the model average and vertical bars are a measure of model spread (one 'standard deviation'). Also shown are CMIP3 models (black line). These generally had simpler aerosol schemes, without the 'indirect effects' and so respond similarly to the CMIP5 LoForc models.

Projected changes in rainfall are sensitive to aerosol emissions. Under low to moderate emissions scenarios, future aerosol changes are likely to be an important driver for tropical rainfall changes.

2014–15 Highlights

DECLINING AEROSOL EMISSIONS | Although aerosols from human activity are emitted mostly from the industrialised regions of the Northern Hemisphere, their impacts are felt globally. Aerosol emissions increased strongly last century, directly affecting air quality as industrial and combustion-related smog. Since peaking during the 1990s, aerosol emissions have declined globally, and are projected to continue to do so over the coming decades as nations are expected to mandate a decrease in their emissions. A decrease in aerosol emissions rapidly translates to a decrease in the aerosols in the atmosphere because of their short lifespan in the atmosphere – they are relatively quickly 'rained out'.

Aerosol cooling estimated with ACCESS

Anthropogenic (human-generated) aerosol pollution has masked global warming from greenhouse gases during the 20th century, but this cooling effect is slowing down due to reduction in aerosol emissions due to new technologies and policies. Climate models can be used to estimate the amount of aerosol cooling that has already occurred and what to expect in the future.

ACCSP researchers used the ACCESS-1.4 climate model to estimate cooling from aerosols, both globally and over Australia, by simulating the climate from 1850 to 2030 with and without anthropogenic aerosol pollution.

Without anthropogenic aerosols the temperature increase over the 20th century is determined mostly by greenhouse gas emissions. Cooling from aerosols in the ACCESS model increases steadily from 1920, peaks around the year 2000, and then begins declining (Fig. 2.2). 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.

ACCESS | The Australian Community Climate and Earth System Simulator (ACCESS) is Australia's national weather and climate model. Its development was fostered through the ACCSP. See page 32 for more about ACCESS.

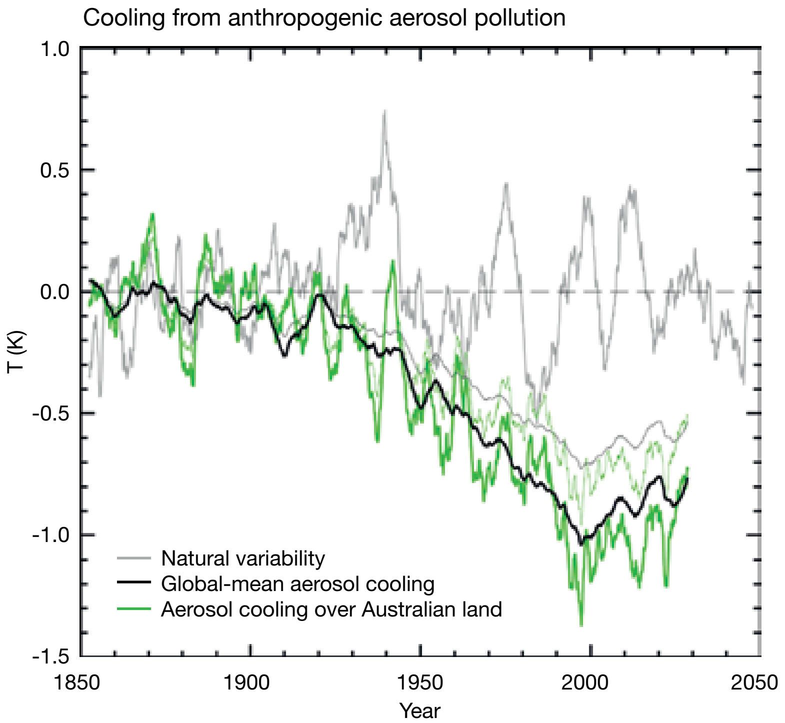


Figure 2.2
Estimated global-mean cooling from anthropogenic aerosols (black) is similar to the average cooling over the Australian continent (green). Thin black and green curves show 70% of the cooling from anthropogenic aerosols (corresponding to the magenta curve in Fig. 2.3). The grey curve is from the pre-industrial control simulation and illustrates the natural variability in Australian-average temperature. Results are based on the ACCESS-1.4 climate model and have been smoothed with 5-year running means.

The cooling effect from aerosol emissions peaked at the end of the 20th century, and is now decreasing. At the same time the warming effect of greenhouse gases continues to rise.

Comparing ACCESS-1.4 model results with observed global mean temperatures suggests that ACCESS-1.4 may overestimate cooling from aerosols. Model results are closer to observations if 70% of the aerosol effect on temperature is used (magenta curve, Fig. 2.3). Further evaluation of aerosol processes in current and future versions of ACCESS will help to improve our understanding of aerosol processes and their role in the climate system and will help to improve the accuracy of ACCESS in estimating aerosol cooling.

SCIENCE TO INFORM DECISION-MAKING

Understanding and evaluating how the ACCESS climate model responds to changing aerosol amounts over the historical period will assist in improving the way aerosols are represented in the model and will increase confidence in future climate projections based on ACCESS.

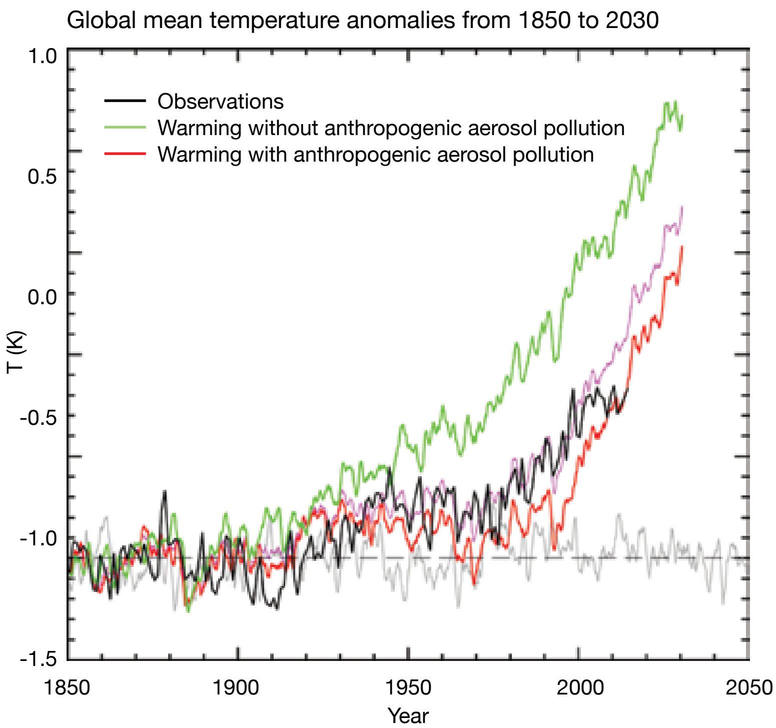


Figure 2.3
Results from the ACCESS-1.4 climate model are compared with observed annual-global-mean temperatures (HadCRUT4, black). Model results are shown with (red) and without (green) anthropogenic aerosols and are based on averages of 3-member ensembles. When all climate forcings are included (red), the modelled temperatures fall below observations. By including 70% of the calculated cooling from anthropogenic aerosols (magenta), the agreement with observed temperatures is greatly improved. The grey curve is from a pre-industrial control simulation and shows the extent of natural variability in the climate system. Model results are 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 high emissions (RCP8.5) scenario. Observations are reported as differences from the 1850–1880 average.

Simulations of combined greenhouse gas and aerosol forcing closely match observations only if 70% of the aerosol effect is used in ACCESS. This suggests aerosol response in the model might be too strong. Work continues to improve our understanding of these aerosol processes and improve the accuracy of ACCESS.

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

FEEDBACKS | 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 arises from cloud changes as the climate warms. Clouds can change in a myriad of ways, including the height, depth, distribution, type and water/ice particle content, which can have positive or negative feedbacks. Because of these uncertainties, cloud feedbacks are the focus of intense international research.

Global feedbacks are similar in strength for many of the processes important for climate change, across a broad range of timescales, however cloud feedback has the greatest uncertainty.

Climate feedbacks in CMIP5 models evaluated

The greatest uncertainty in climate projections for a given emissions scenario is the 'climate sensitivity' of the model, that is, how strong the model's response is to a given increase in greenhouse gases. Climate sensitivity varies by a factor of about two and a half for the CMIP5 models – the most sensitive models produce a temperature increase two and a half times greater than the least sensitive models for a given increase in carbon dioxide. This range in sensitivity is caused by differences in climate model feedbacks, and most importantly from cloud feedback.

ACCSP researchers used 35 CMIP5 models to calculate climate feedbacks for water vapour, lapse rate (vertical temperature structure), surface albedo (snow and sea ice) and clouds. The latter is particularly challenging, as it requires information about all the other feedbacks. They examined a high emissions scenario run (RCP8.5) and a pre-industrial model run, the latter with around 200 years of 'unforced' natural variability. Researchers then evaluated and compared feedbacks from different timescales (seasonal, year to year, decade to decade) by diagnosing the change in global average temperature, then evaluating how changes in water vapour, ice and snow and clouds varied with that temperature. They found that global scale feedbacks show very similar strength, on average, across these very different timescales, with the greatest uncertainty from cloud feedback (shown by the spread of circles on Fig. 2.4).

CMIP5 | 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 latest phase, CMIP5, was used in the IPCC Fifth Assessment Report.

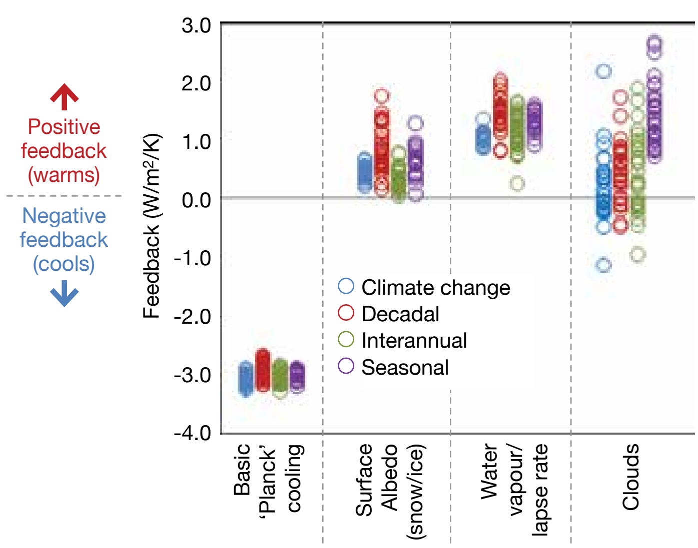


Figure 2.4
Global climate feedbacks evaluated for the CMIP5 models. Each circle represents a model, with the timescale key on the right-hand side. Feedbacks from left to right are (1) the fundamental 'Planck' cooling (i.e. enhancement of the ordinary radiative 'cooling' to space that occurs for the planet); (2) increased absorbed solar radiation from snow and sea-ice retreat; (3) increased radiation trapping from temperature and moisture changes in the atmosphere and (4) cloud changes. The figure shows that global feedbacks are similar in strength for many of the processes important for climate change, across a broad range of timescales of variability (i.e. for seasonal, year-to-year and decadal variability, and for climate change), and that the greatest uncertainty (spread) is in cloud feedback.

New methodology for evaluating and exploring cloud feedbacks in ACCESS

Cloud feedbacks are a critical uncertainty in climate projections. They are also hard to diagnose.

ACCSP researchers have developed a new technique in ACCESS that allows diagnosis of how clouds at particular levels and of particular thicknesses affect the radiation balance at the top of the atmosphere. As temperature changes, so too does the radiation balance. Whether this balance change acts to further reinforce the warming, or to oppose it is called the climate feedback. The new method allows a full three-dimensional picture of how clouds contribute to the feedback in the ACCESS model. Figure 2.5 shows how clouds affect the upwelling long wave radiation from the Earth, which escapes to space.

Ongoing work using this methodology will allow researchers to better understand cloud feedbacks in ACCESS, and the physical processes operating within the model and controlling its climate sensitivity.

Cloud feedback in different regions contributes very differently to warming. On balance globally the value is positive, which means that clouds overall are reinforcing (amplifying) climate change in ACCESS.

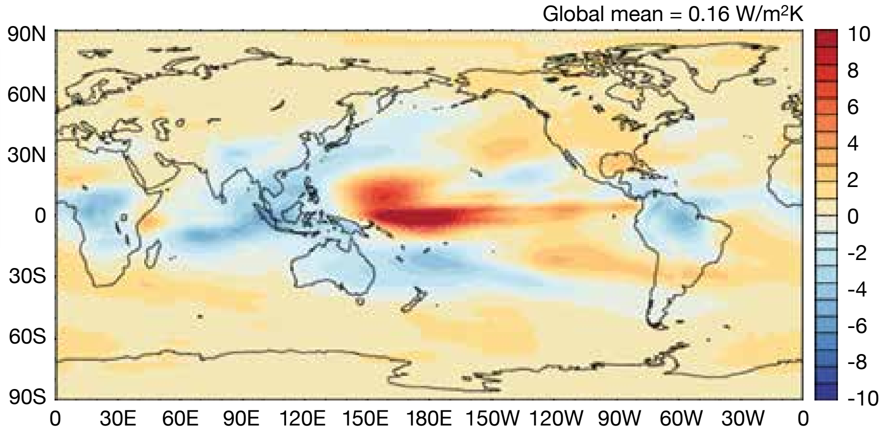


Figure 2.5
Cloud feedback diagnosed for ACCESS1.3, under the warming associated with RCP8.5 by century end. The particular feedback shown is for how clouds affect outgoing terrestrial radiation. Warm colours represent positive feedback, which is predominantly due to increased high cloud. Cool colours represent negative feedback regions. The maximum in the equatorial western Pacific is an area of strongly enhanced rainfall increase, with associated increases in deep convective cloud. Global average feedback (which results from the offsetting positive and negative regions) is a modest, but positive, 0.16W/m²/K.

SCIENCE TO INFORM DECISION-MAKING

Understanding and reducing the range of climate sensitivity in models will give us more confidence in climate projections and better information for adaptation planning and mitigation policies.

2014–15 Highlights

ECOSYSTEM RESPONSE TO INCREASED CLIMATE VARIABILITY

First imagery from unique proximal remote sensing system

ACCSP research is improving our understanding of how vegetation responds to changes in water availability and heat extremes. The vegetation response is one of the largest uncertainties in projecting future climate, carbon sequestration and water resources. Fine temporal and spatial resolution measurements are needed to reduce these uncertainties.

ACCSP researchers have installed a world-first remote sensing system at the Bago State Forest research site near Tumbarumba in south-east New South Wales. The system collects data at high spatial and spectral resolution several times a day. (High spectral resolution data provides detailed information on different wavelengths of light.) These data can be used to observe the efficiency with which the plants use light to assimilate carbon and to detect plant stress (e.g. from heat or insufficient water supply). Researchers are now able to 'see' these stresses, not only at ecosystem level but also how they vary between and within individual trees. These observations, in combination with the other data collected at the site, will greatly enhance knowledge and understanding of the response of vegetation to climate extremes and inform dynamic vegetation enabled land surface models.

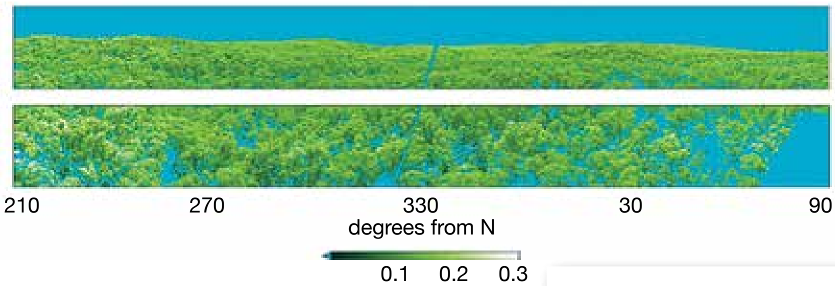


Figure 2.6
TCARI/OSAVI index of imagery captured over Bago State Forest near Tumbarumba, NSW, Australia on 18 November 2014, 11:56 EST, horizontal view (top) and view angle –20 degrees (bottom). Low TCARI/OSAVI (blue and darker green) indicates areas with high chlorophyll content. Areas without vegetation have been masked.

The newly installed remote sensing system in south-east NSW allows scientists to see how ecosystems and individual trees respond to heat or insufficient water supply stressors.

3

2014–15 Highlights

Oceans and coasts observations, processes and projections

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

3

2014–15 Highlights

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

Extended Australian ocean climate record shows continued global warming

The ocean is the dominant heat reservoir of the climate system. By monitoring the heat stored in the ocean, we can 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.

ACCSP researchers extended the ocean climate record around Australia and demonstrated that from 2006–14, global warming has continued, despite an apparent slow-down in the rate of in global surface atmospheric warming. Oceanic warming occurs due to vertical heat movement in the oceans. On interannual timescales, during an El Niño, warm water that usually pools down to 200 m or so in the western Pacific moves eastward and upwards, warming the surface in the central and eastern Pacific. During La Niña, the opposite happens. The vertical heat movement has been measured by the Argo array. Researchers maintained the coverage of the Argo array in the oceans around Australia by deploying around 45 Argo floats in the past year (Fig. 3.1), and assisting international partners deploy 30 floats.

Analysis of Argo data from 2006 to 2014 reveals that the ocean heat content over this period has been rising unabated at a rate of 0.4 W/m^2 global equivalent. Over this period, surface temperatures show little trend but very large year-to-year variability (due to El Niño activity), which is largely compensated at depth (see Fig. 3.2). Over the full 2000 m sampled by Argo, ocean heat content rises relatively smoothly. Most of this heat is being stored in the Southern Hemisphere, much of it around Australia.

The unabated increase in ocean heat content adds great weight to model predictions of ongoing global warming, despite the fact that surface temperatures undergo large swings due to the El Niño cycle.

READ MORE | Roemmich *et al.* 2015. Unabated planetary warming and its anatomy since 2006. *Nature Climate Change*, doi:10.1038/nclimate2513

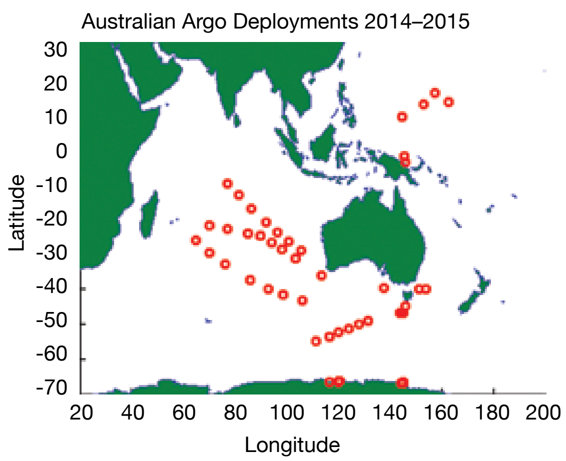


Figure 3.1
Locations of Argo floats deployed this year by Argo Australia. These floats contribute to the global Argo array (**www.argo.net**), which we rely on to track the changing ocean.

Australia deployed 45 Argo floats in 2014-15 to measure ocean temperature and salinity. These data allow us to track changes to our oceans.

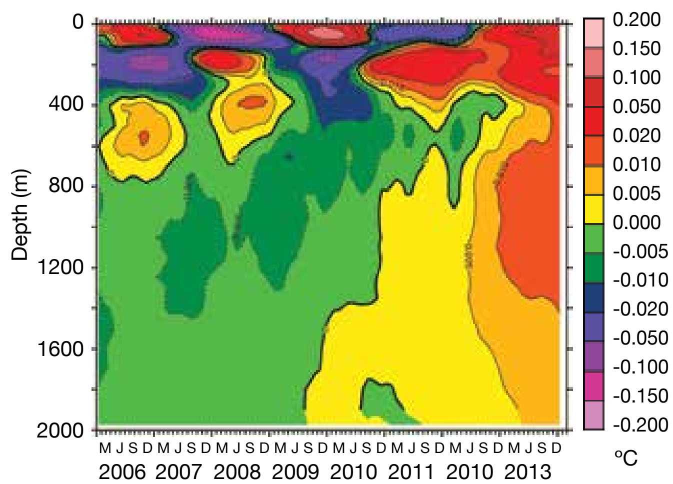
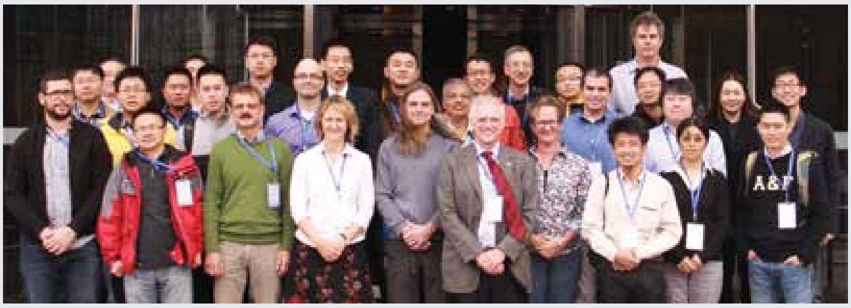


Figure 3.2
Globally averaged temperature anomaly (colour scale) versus depth from Argo (from Roemmich *et al*. 2015).

Argo data shows while year-to-year variability strongly affects ocean surface temperatures, over the full 2000 m of ocean depth measured, ocean heat continues to rise smoothly.



Participants in the 4th XBT Workshop in Beijing.

ARGO | Argo provides high quality, global and deep reaching (2000 m) temperature and salinity measurements across the globe, improving quality and completeness of the ocean data record. Argo reached sufficient global coverage in 2006 to underpin a global heat content estimate. The quality, global reach and depth coverage of Argo is historically unprecedented – never before have we been able to track heat content so accurately and with such confidence. Of particular importance has been the ability to track the vast Southern Hemisphere oceans, where most of the global ocean volume lies. Indeed, in the 2006–2014 period, these oceans are where nearly all of the extra heat has accumulated, with much of it around Australia.

Historical ocean profile data improvements identified

Knowing past rates of ocean warming is important for validating models and for understanding sea-level rise and ecosystem responses, so improving the accuracy of past warming rates and patterns is vital. Current estimates are uncertain due to significant instrumental biases in a large quantity of the historical data collected by free-falling expendable bathythermographs (XBTs, the largest source of upper ocean temperature profiles before Argo data).

ACCSP researchers have led efforts to produce the best international consensus of a corrected data set via international working groups and workshops. The 4th XBT workshop, 'XBT science and the way forward', was held in Beijing on 11–13 November 2014. A major outcome of the workshop was a set of recommendations for application of corrections to historical XBT data. These recommendations have been compiled into a paper, co-authored by ACCSP researchers, and submitted to the *Bulletin of the American Meteorological Society* where it is currently under review.

XBTs and CTDs | XBTs are expendable bathythermographs, single-use probes used to measure the temperature in the ocean. When launched XBTs send temperature measurements back to the ship via thin copper wires. The XBTs fall at a known rate, so their depth can be determined based on the time they've been in the water. Eventually, the wires snap and the XBT falls to the bottom of the ocean. CTDs are large instrument packages used to measure the physical properties of sea water. The CTD (which stands for conductivity, temperature and depth) is lowered from the ship to the sea floor, sending back information via a cable. This device is re-usable and extremely accurate. Collecting CTD and XBT temperature profiles 'side-by-side' from the same ship allows a direct estimate of the error in the lower quality XBT data and the source of the error (whether it is due to a depth bias or a temperature sensor bias).

XBT and CTD pairs were collected off Brisbane on a recent RV *Investigator* voyage. The XBT/CTD pairs will add to our large historical database of pairs and will contribute to assessing ongoing corrections to XBT fall rates and temperature biases. The database is publicly available at **https://data.csiro.au/**. Additionally, XBTs were deployed from varying heights on the RV *Investigator* to assess the effect of deployment height on the initial (in the first 1.5 seconds) fall rate of the XBT.

READ MORE | Cheng *et al.* 2014. Time, probe type and temperature variable bias corrections to historical expendable bathythermograph observations. *Journal of Atmospheric and Oceanic Technology*, 31(8), 1793–1835, doi:10.1175/jtech-d-13-00197.1

SCIENCE TO INFORM DECISION-MAKING

Understanding and reducing the range of climate sensitivity in models will give us more confidence in climate projections and better information for adaptation planning and mitigation policies.

UNDERSTANDING OCEAN DRIVERS OF REGIONAL AND GLOBAL CLIMATE VARIABILITY AND CHANGE

Ocean 'storm tracks' identified and characterised

Much like atmospheric storms, vertical velocity gradients in the oceans generate eddies up to 100 km in diameter. As with mid-latitude atmospheric storm tracks, ocean 'storms' occur in regions where the trade winds and westerlies meet. Oceanic storms occur at depths of between 300 and 500 m.

ACCSP researchers have, for the first time, identified and examined these ocean 'storms' in the subtropical regions of the Southern Hemisphere. Using an ocean general circulation model and a simple potential energy transfer diagnostic, researchers determined the pathways these storms tracks use to communicate information westward from the mid-latitudes to the subtropics (South Pacific Ocean) and from the subtropics to the tropics (Indian Ocean). These pathways have profound implications for understanding decadal variability and predictability, and in particular, the mechanisms by which changes in the oceans of the Southern Hemisphere will determine the large scale atmospheric circulation into the future.

READ MORE | O'Kane *et al.* 2014. Storm tracks in the Southern Hemisphere subtropical oceans. *Journal of Geophysical Research – Oceans*, 119, 6078–6100, doi:10.1002/2014jc009990.

Ocean spiciness initiated the period of strong El Niño events in the 1970s

Changes in ocean spiciness can modify the thermocline (the bottom of the shallow, warm layer at the ocean surface) and regulate how strongly the tropical ocean exchanges heat with the atmosphere. Both positive (warm/salty) and negative (cold/fresh) spiciness anomalies formed in the subtropical south-east Pacific have the potential to modulate the equatorial thermocline. The thermocline changes due to the spiciness anomalies are highly correlated with the thermocline changes characteristic of the El Niño Southern Oscillation (ENSO). However, the complexity of tropical ocean-atmosphere exchanges means that the specific mechanisms by which the equatorial Pacific thermocline adjusts during ENSO remains poorly understood.

ACCSP researchers showed that the arrival of a negative spiciness anomaly in the central tropical Pacific in the late 1970s preceded a period of strong and sustained El Niño events. These anomalies take, on average, seven years to reach the central equatorial Pacific where they may impact on temperature and salinity in the region of the western Pacific warm pool. Positive disturbances at the equator tend to deepen the thermocline, reducing ENSO in model studies, while negative disturbances at the equator are associated with a shoaling (shallowing) of the thermocline and are highly correlated with large El Niño events.

This work establishes a plausible mechanism by which the subtropical oceans may influence Pacific El Niño events on timescales beyond a few months. It has potentially profound implications for our ability to predict climate variations on timescales out to a decade.

READ MORE | O'Kane *et al.* 2014. ENSO regimes and the late 1970's climate shift: The role of synoptic weather and South Pacific ocean spiciness. *Journal of Computational Physics*, 271, 19–38.

OCEAN SPICINESS | Temperature and salinity are two important properties of seawater. They determine the density of the water and, in turn, the stratification (layering) of the ocean. This drives ocean circulation, and so has implications for ocean heat transport.

Changes in temperature or salinity alter the density of the water. In the ocean, the density effect of salinity variations can, on occasion, neutralise the density effect of temperature variations. This can lead to a situation where substantial temperature and salinity changes occur despite no change in density. Warm and salty density compensated disturbances are called 'spicy'.

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

Time of emergence of regional sea-level rise estimated

Regional sea-level rise driven by warming oceans and melting ice is masked by natural variability such as the El Niño, which causes year-to-year changes in sea level of several centimetres. At the same time, human-caused climate change is driving sea level relentlessly higher in most regions, eventually pushing it far outside the bounds of historical variation. But when will the difference become clear?

ACCSP researchers found strong evidence that regional-scale sea-level rise due to anthropogenic climate change will likely exceed the natural variability range within the next two decades. They estimated the time of emergence (ToE, when climate change signal exceeds and thus emerges from natural variability) for sea-level changes relative to the reference period 1986–2005, based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report results and 17 state-of-the-art CMIP5 climate models. These studies are the first to apply the ToE methodology to both sea level and surface air temperature from the same ensemble of CMIP5 climate models.

READ MORE | Lyu *et al.* 2014. Time of emergence for regional sea-level change. *Nature Climate Change*, 4, 1006-1010. doi:10.1038/nclimate2397.

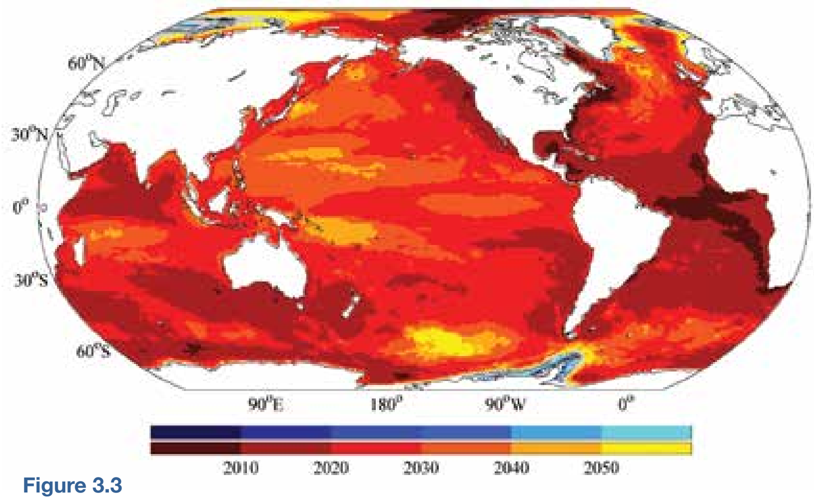


Figure 3.3
The likely time of emergence (year) for regional sea-level change for a business-as-usual scenario. The warm (cold) colours represent rising (falling) sea level.

Regional sea-level rise due to anthropogenic climate change is likely to exceed the natural variability range within the next two decades.

SCIENCE TO INFORM DECISION-MAKING

Coastal communities and industries require information on regional sea-level change to develop strategies for reducing the risk to population, infrastructure and the environment. This work implies that local risk assessment and adaptation planning for sea-level change should be undertaken in anticipation of a sea level that within the next two or three decades is likely to be significantly different to the past two or three decades

3

2014–15 Highlights

Regional sea-level rise projections and allowances for the Australian coastline determined

Regional projections of sea-level rise are important for coastal planning and development but, until now, have not been available for the Australian coastline.

ACCSP researchers have now provided regional coastline projections of sea-level rise from 1996 to 2100. These projections were also compared with available data from the first two decades of this period. The projections were then combined with information on sea-level variability to estimate sea-level 'allowances' at a number of locations around the Australian coastline. These allowances are the height by which coastal property must be raised so that the risk of coastal inundation does not increase.

By 2090, under RCP 4.5 by 2090 allowances will range between 0.50 m and 0.59 m around the coast of Australia (Fig. 3.4). In comparison, under RCP 8.5 by 2090 allowances will range between 0.69 m and 0.84 m.

READ MORE | McInnes *et al.* 2015. Sea-level rise projections for Australia: information for impact and adaptation planning. *Australian Meteorological and Oceanographic Journal* (in press).

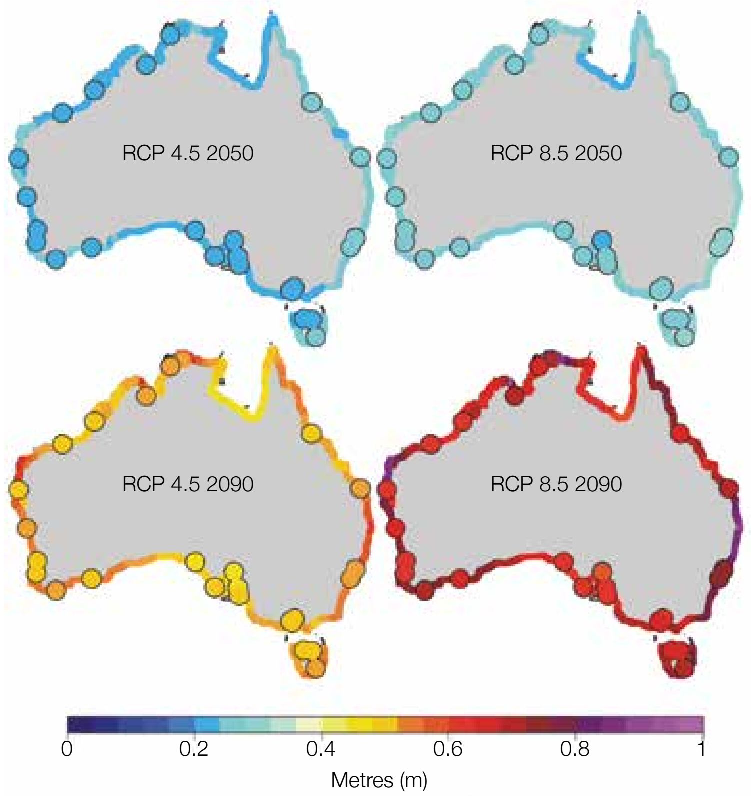


Figure 3.4
Allowances for future periods (2030 and 2090) that an asset needs to be raised under a rising sea level so that the present likelihood of flooding does not increase. The continuous shading around the coastline indicates allowances calculated using extreme sea level properties from model results while the large circles are allowances based on extreme sea level properties from tide gauge data.

By 2090, under RCP 4.5 by 2090 allowances will range between about 0.50 m and 0.60 m around the coast of Australia. In comparison, under RCP 8.5 by 2090 allowances will range between about 0.60 m and 0.90 m.

Global and Australian hydrodynamic and wave climate projections developed

The role of waves is often overlooked in coastal impacts of climate change studies but an international working group study is beginning to provide data to overcome these limitations.

The Coordinated Ocean Wave Climate Project (COWCLIP) is an international working group coordinating and leading efforts to understand wave climate change and variability. It is endorsed under the Joint Commission for Oceanography and Marine Meteorology.

ACCSP researchers coordinated COWCLIP, and organised and chaired the 4th COWCLIP workshop in Paris in September 2014.

Analysis of multi-model ensembles of global wave and Australian hydrodynamic model simulations aims to understand future changes to wave climate, ocean currents and extreme sea levels. So far, this analysis has highlighted coastal regions where future changes in storm surges and waves could lead to large coastal impacts. Future changes include a possible increase in the frequency of extreme sea levels in the Gulf of Carpentaria if the northwest monsoon penetrates further eastward, a small reduction in extreme sea levels (with respect to the rising mean sea level) on the southern coastline due to the southward movement of frontal systems but an overall increase in wave energy reaching this coastline from the southern ocean. Changes in coastal winds may increase coastal upwelling and marine productivity on the south coast and change sediment transport patterns in southeast Victoria.

READ MORE | O'Grady *et al.* 2015. Longshore wind, waves and storm-tide currents: climate and climate projections at Ninety Mile Beach, south-eastern Australia. *International Journal of Climatology*, doi:10.1002/joc.4268.

Continued global mean sea-level rise demonstrated

There has been argument that the rate of sea-level rise during the most recent decade was smaller than the previous decade, principally as a result of storage of water on land.

ACCSP researchers showed that rather than slowing, the rate by contrast has marginally increased. Researchers compared satellite observations of sea level to sea levels measured by coastal tide gauges that had been corrected for estimated vertical land motions. These comparisons were used to estimate any trends in the bias of the satellite observations. They found that the revised estimate of global mean sea-level rise was slightly smaller than previous estimates (ranging from 2.6 ± 0.4 mm/yr to 2.9 ± 0.4 mm/yr, depending on the vertical land motion estimate used), but still larger than the average rate during the 20th century. Researchers also found that the rate of global mean sea level increased slightly (but not statistically significantly) during the 22-year satellite record, consistent with observed increases in ice sheet contributions and the projected increase in the rate of sea-level rise during the early decades of the 21st century.

READ MORE | Watson *et al.* 2015. Unabated global mean sea-level rise over the satellite-era. *Nature Climate Change*, 5, 565–568, doi:10.1038/nclimate2635.

OCEAN ACIDIFICATION

Improved understanding of the Southern Ocean carbon dioxide uptake

The Southern Ocean is one of the most important regions on Earth for removing carbon dioxide from the atmosphere. It is vital that we understand how this sink is changing to help us to understand how the Earth's natural carbon sinks and the global carbon budget are evolving.

ACCSP researchers worked with national and international colleagues to develop the next version of the Surface Ocean CO_2 Atlas and provide new assessments of the global carbon budget. The newest version of the atlas is a major upgrade due for release in late 2016 and incorporates about 10 million measurements collected since the early 1960s. ACCSP researchers chaired the group that compiled the atlas for the Southern Ocean (south of 30°S including coastal waters). This is the main database used to detect trends in carbon dioxide uptake and test ocean carbon cycle models.

As a part of the Southern Ocean focus, ACCSP researchers published more detailed studies of the controls on carbon dioxide uptake in the seasonal sea-ice zone and Integrated Marine Observing System (IMOS) Southern Ocean Time Series site south-west of Tasmania (near 140°E, 47°S). These are regions recognised as significant contributors to ocean carbon dioxide uptake, but have limited observations available to quantify the amounts of uptake and detect trends. The IMOS site, located at the northern boundary of the Southern Ocean, has provided the first high frequency data to determine the seasonal carbon cycle. The research

2014–15 Highlights

is providing key information to aid in the selection of the best global models for this region, which can be used to project future change in the carbon dioxide uptake.

The carbon dioxide uptake is causing ocean acidification, which is predicted to cause widespread disruption to marine ecosystems, including those of the Southern Ocean. ACCSP research is the only Australian effort delivering information on the rate of change of ocean acidification in the ocean around Australia.

SCIENCE TO INFORM DECISION-MAKING

Southern Ocean research provides the foundation data needed to determine ocean acidification that is required for assessments of the likely impact on marine ecosystems. The Southern Ocean will be one of the first regions on Earth to experience ocean acidification impacts on marine ecosystems, due to the amount of carbon dioxide it absorbs.

Diurnal (day-night) variability found in ocean carbon exchange

Changes in the efficiency of the Southern Ocean sink to absorb carbon from the atmosphere would have major consequences for global climate change mitigation strategies. Therefore, understanding and monitoring the Southern Ocean sink behaviour over an extended period and developing tools to identify any changes in this sink is important.

ACCSP researchers analysed the continuous, high-precision atmospheric carbon dioxide data record at Macquarie Island. They refined methods for selecting observations that are representative of the Southern Ocean by removing those that are influenced by the island itself or other landmasses in the Southern Hemisphere. This selected record shows small but consistent day-night and seasonal cycles of atmospheric carbon dioxide, which can be used to improve our understanding of the uptake and release of carbon dioxide from the Southern Ocean, particularly that component related to biological production.

The Macquarie Island data is from an integrated network of Southern Ocean atmospheric observing sites. The network maintains well inter-calibrated, high-precision atmospheric carbon dioxide observing capabilities at Cape Grim (Tasmania), Macquarie Island (Southern Ocean), Baring Head (New Zealand), Casey Station (Antarctica) and Amsterdam Island (southern Indian Ocean). Continuous observations of atmospheric carbon dioxide (and methane, nitrous oxide and carbon monoxide) on-board the new Marine National Facility vessel, RV *Investigator*, have been added to the network this year.

The main purpose of the network is to use high precision atmospheric carbon dioxide data to investigate the changing efficiency of the Southern Ocean carbon dioxide sink. Atmospheric data are influenced by regional ocean-atmosphere exchange, making this an important top-down complement to ocean-based Southern Ocean carbon observation and modelling research.

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 seeks to understand the processes by which these drivers influence Australia's climate, and how these influences will change in a warming climate.

Increasing carbon dioxide caused Southern Annular Mode trend

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 the 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.

Over the past few decades there has been a trend toward the positive phase of the SAM and away from a climate mode known as the hemispheric wave 3 pattern, that tends to block westerly winds and is associated with persistent weather patterns and storms over southern Australia.

Previous studies, focusing on the summertime circulation, have suggested that these changes are driven by ozone depletion; however, significant reductions in storm formation have occurred during the wintertime that cannot be attributed to ozone.

ACCSP researchers analysed atmospheric patterns and observed external radiative forcings over the past five decades and found that increased greenhouse gas concentrations have been the cause of the observed SAM changes and the reduced storm formation over Australia. These results suggest that the recovery of the ozone hole might not delay the signal of global warming as strongly as previously thought.

READ MORE | Franzke *et al.* 2015. Systematic attribution of observed southern hemispheric circulation trends to external forcing and internal variability. *Nonlinear Processes in Geophysics Discussions*, 2, 675–707, doi:10.5194/npgd-2-675-2015.

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

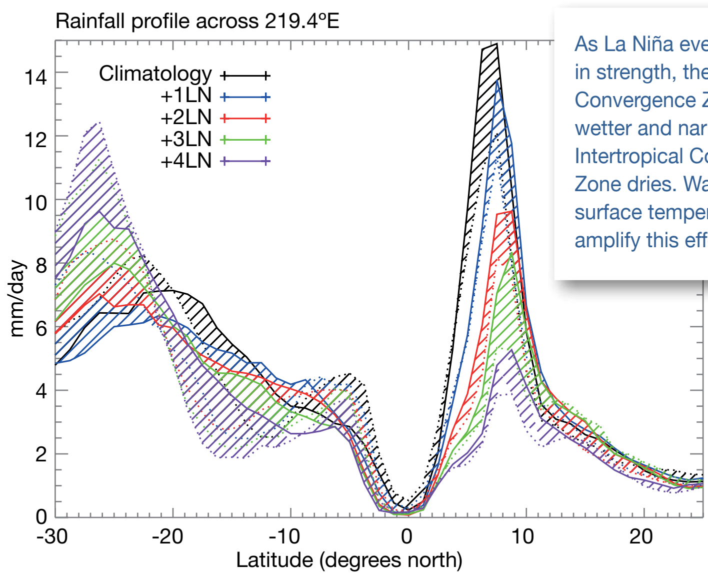
EL NIÑO-SOUTHERN OSCILLATION | The El Niño-Southern Oscillation influences the climate of Australia through its two extremes – El Niño and La Niña events. El Niño events are often associated with drier than normal conditions across eastern and northern Australia, while La Niña events are often associated with wetter than normal conditions in these regions.

Improved understanding of how future La Niña events will affect rainfall over the Pacific Ocean

In the current climate La Niña events have a major impact on rainfall and life in Australia, Pacific island nations, and beyond. It is important that we understand what impact La Niña will have on rainfall over the coming century, as the world warms.

ACCSP researchers conducted experiments using ACCESS and found that global warming reduces rainfall in the Intertropical Convergence Zone (the region of intense rainfall near the equator), but increases it in the South Pacific Convergence Zone (a region of high rainfall extending south eastwards across the western south Pacific), which it also makes much narrower. They also found that these rainfall bands move further away from the equator as the La Niña gets stronger.

READ MORE | Chung & Power 2014. Precipitation response to La Niña and global warming in the Indo-Pacific. *Climate Dynamics*, 43(12), 3293–3307.



As La Niña events increase in strength, the South Pacific Convergence Zone gets wetter and narrower, and the Intertropical Convergence Zone dries. Warming sea surface temperatures amplify this effect.

Figure 4.1
Rainfall along 219.4°E, from 30°S to 25°N, simulated using ACCESS. The response is given for neutral conditions and for increasingly stronger La Niña events. The major peaks correspond to major rainfall bands (the Intertropical Convergence Zone in the Northern Hemisphere and the South Pacific Convergence Zone in the Southern Hemisphere south of 20°S). The dashed lines show what happens if global warming is also added.

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

Pacific warming has emerged from background variability and is due to greenhouse gases

Island nations in the tropical western Pacific are among the most vulnerable to climate change. While a great deal of information on the observed climate change trends and their cause is available for many other regions and for the globe as a whole, much less information has been available specifically for the Pacific.

ACCSP researchers analysed observations which showed that warming over the past 50 years in the western Pacific is evident in the best available temperature records. The warming is so great that Pacific temperature has been expelled beyond the range of previous experience. This warming is primarily due to human-forced increases in greenhouse gases. Further warming in the Pacific over the next few decades is locked in, due to accumulated emissions already present in the atmosphere and further emissions expected over coming years.

READ MORE | Wang, Power and McGree 2015. Unambiguous warming in the western tropical Pacific primarily caused by anthropogenic forcing. *International Journal of Climatology*, doi:10.1002/joc.4395.

READ MORE | Power 2014. Climate science: Expulsion from history. *Nature*, 511(7507), 38–39.

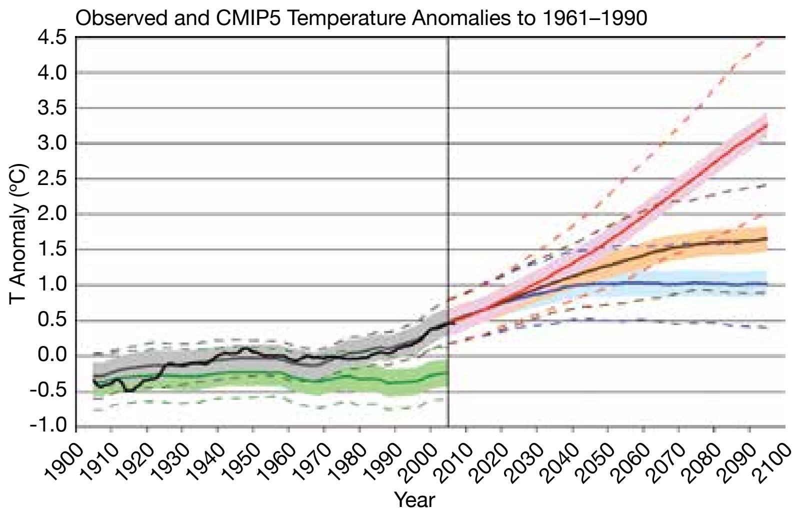


Figure 4.2
Time series of 11-year running mean of surface temperature over the western Pacific (from observations (black solid line) and climate model simulations) for the period 1950–2100. The grey solid line is the multi-model average (MMA) of climate models forced with both anthropogenic and natural forcing. The green line is the MMA of climate models forced with natural forcing only. MMAs of projections under three different future greenhouse gas and aerosols concentrations RCP2.6 (blue solid line), RCP4.5 (brown solid line) and RCP8.5 (red solid line) are shown during 2006–2100. The shading is gives the range of natural internal climate variability. The dashed lines show the range of uncertainty among the models due to both internal climate variability and differences in model sensitivity to the forcing applied.

Warming in the western Pacific is so great that it is beyond the range of previous experiences. Further warming in the Pacific over the next few decades is locked in due to accumulated emissions already present in the atmosphere

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

Greenhouse warming leads to increased frequency of extreme La Niña events

During a typical La Niña event, the central to eastern equatorial Pacific is colder than normal. The associated atmospheric circulation changes generate extreme weather events in many parts of the world, including droughts in the south-western United States, and floods in the western Pacific including north-east Australia. During an extreme La Niña, as in 1998, the impact is far greater.

ACCSP researchers have shown that the frequency of extreme La Niña events could almost double in the future. Analyses were conducted using CMIP5 models that are able to simulate an extreme El Niño (because extreme La Niña events tend to occur after an extreme El Niño). The models were forced with historical anthropogenic and natural forcings from 1900 to 2005, and future greenhouse gas emission scenarios (IPCC's emission scenario RCP8.5) from 2006 to 2100.

Approximately 75% of the increased extreme La Niña events occur in the year following an extreme El Niño, projecting more frequent climatic swings of opposite extremes from one year to the next. This will have profound social and economic implications.

READ MORE | Cai *et al.* 2015. Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change*, doi:10.1038/nclimate2492.

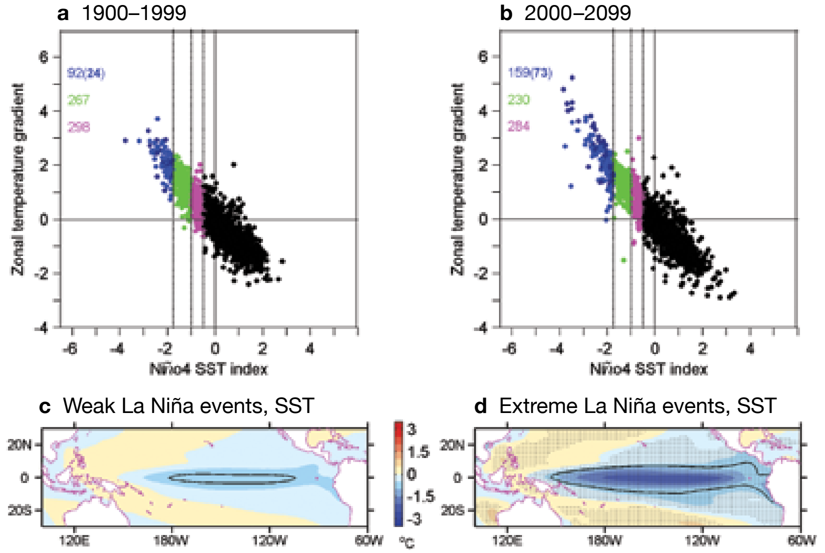


Figure 4.3
Identification of model extreme La Niña events using 21 selected models. An extreme La Niña is defined as Niño4 (a central Pacific sea surface temperature index) amplitude is greater than 1.75 standard deviations (s.d.) (a, b) Relationship of Niño4 with surface temperature gradients between the Maritime region (5°S–5°N, 100°E–125°E) and the central Pacific (5°S–5°N, 160°E–150°W), for the Control and Climate Change period, respectively. Blue, green and purple dots indicate extreme (with |Niño4|>1.75 s.d), moderate (1 s.d.<|Niño4|<1.75 s.d.) and weak (0.5 s.d.<|Niño4|<1.0 s.d.) La Niña. Number of different types of La Niña events is indicated, with thick blue in bracket indicating extreme La Niña events that follow an extreme El Niño. (c, d) Modelled December to February (DJF) composite sea surface temperature anomalies (shading, °C) for weak and extreme La Niña events.

More frequent climatic swings of opposite extremes are projected as approx. 75% of increased extreme La Niña events occur in the year following extreme El Niño events.

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

Climate change signal detected in Australian rainfall variability

Separating the climate change signal from natural variations (the climate 'noise') allows for the attribution of changes in Australian regional climate variations and extremes.

ACCSP researchers have previously shown that in ensembles of climate models it is possible to separate the variability of the climate noise and climate signal. This year they applied the methodology to Australian regions with large rainfall trends: the south-west Western Australia (wintertime) and the monsoonal north-west of Australia (summertime). They found that in the climate signal component, the modelled rainfall pattern matches that of the observed rainfall trend.

This indicates that a component of the observed rainfall change is related to the changes in greenhouse gas concentrations. This is significant, since in many regions, such as the monsoonal north-west, the rainfall measurements may have a large climate noise component, which would hide the underlying climate signal.

CMIP5 projections show that the observed rainfall trend pattern is expected to continue and intensify towards the end of the 21st century with further increases in greenhouse gases.

READ MORE | Frederiksen & Grainger 2015. The role of external forcing in prolonged trends in Australian rainfall. *Climate Dynamics*, doi:10.1007/s00382-015-2482-8.

SCIENCE TO INFORM DECISION-MAKING

By identifying the climate change signal in Australian rainfall, ACCSP research provides guidance to external stakeholders on mitigation of and adaptation to climate change. The increased understanding of Australian climate variability, and its underlying mechanisms, will also give us greater confidence in regional climate change projections.

5

2014–15 Highlights

Earth systems modelling and data integration

The ACCSP supports the development of ACCESS – the Australian Community Climate Earth System Simulator. This sophisticated Earth system model operates on the nation's most powerful supercomputer. A major collaborative undertaking, ACCESS brings together the climate observations, research and modelling capability of the Bureau of Meteorology, CSIRO, Australian universities and international researchers. The result is a national weather climate and Earth system simulation capability that is suited to Australian needs.

The latest version of ACCESS, ACCESS-CM2, is expected to be the Australian contribution to the Coupled Model Intercomparison Project phase 6 (CMIP6).

This will allow for:

- Benchmarking of the model performance against other climate models developed internationally
- Distribution of the model outputs via the Earth System Grid, to ensure they are readily accessible to researchers around Australia and internationally
- Participation in internationally coordinated experiments which are designed to address major problems in climate science, in particular the World Climate Research Program's (WCRP) Grand Challenges of Climate Science (**http://www.wcrp-climate.org/grand-challenges**)
- Australian membership on the WCRP Working Group on Coupled Modelling, where decisions are made on the design and scope of the successive CMIP and subsequent similar projects, which have a major impact on the model simulations available for regional and global climate projections and research
- Use of the modelling results in support of an IPCC 6th Assessment Report.

ACCESS COUPLED CLIMATE MODEL DEVELOPMENT

ACCESS-CM2 successfully configured and run

ACCESS-CM2 is the next-generation coupled climate model, consisting of atmospheric, land surface, oceanic and sea ice component models coupled together by 'coupler' code. The model features a new atmospheric component model (GA6) with improved dynamical processes and more than double the vertical resolution used by the previous coupled model. Under the standard configuration, atmospheric model grid spacing for this initial version of ACCESS-CM2 is roughly 130 km in the horizontal with 85 levels in the vertical (compared with 38 levels in the CMIP5 model versions ACCESS1.0 and 1.3). Ocean model grid spacing is nominally 1 degree latitude and longitude with higher resolution near the equator and the poles.

The higher vertical resolution allows improved representation of near-surface boundary layer processes and also troposphere/stratosphere exchanges of momentum (wind), heat, moisture and other variables. The model also features a new coupler, the OASIS-MCT, which significantly improves computational efficiency of the model.

A 200-year test simulation successfully reproduced a range of features and phenomena important for Australian climate, including the pattern of variability of sea surface temperature in the tropical Pacific Ocean associated with the El Niño Southern Oscillation. This fundamental pattern of variability was typically not well simulated in earlier coupled climate models, including many models in CMIP5, contributing to inadequate simulation of rainfall variability over Australia.

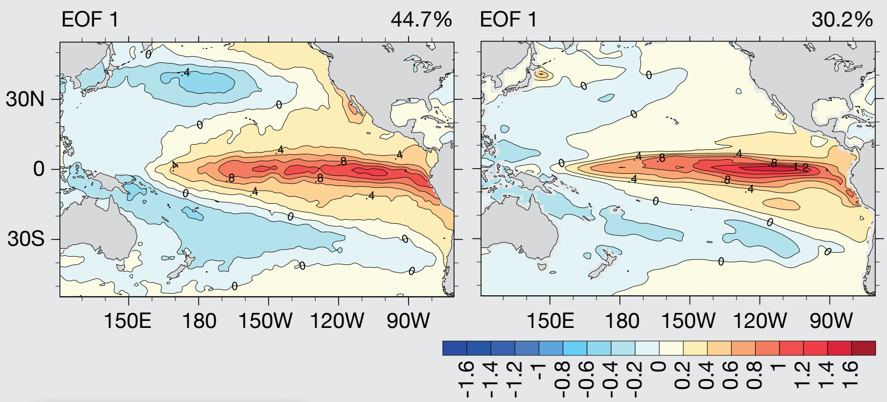


Figure 5.1
Dominant pattern of variability (first empirical orthogonal function) of sea surface temperature (SST) in the Pacific Ocean, from (a) the observations (HadISST, 1950-2013) and (b) the model (years 101-200) using ACCESS-CM2. Units are °C.

ACCESS-CM2 successfully reproduces important Australian climate phenomena.

SCIENCE TO INFORM DECISION-MAKING

Improved representation of Australian climate drivers in ACCESS-CM2 makes the model more useful in support of natural resource management and climate related infrastructure planning, and also in the analysis of carbon cycle/climate feedbacks so as to inform mitigation policy.

5

2014–15 Highlights

ACCESS-CM2 configured with a high horizontal resolution ocean component

ACCESS-CM2 was reconfigured with an oceanic component model of four times the horizontal resolution of the standard configuration (horizontal grid spacing 0.25° latitude by 0.25° longitude). The higher resolution allows for the simulation of oceanic eddies and more realistic simulation of other key ocean processes such as oceanic boundary currents (important currents moving along continental margins).

Evaluation of a test simulation of, so far, 80 years duration has revealed many of the anticipated improvements associated with the higher oceanic resolution. These improvements are illustrated in Figure 5.2, which shows a sample daily sea-surface temperature field from the coupled model simulation. The strong and thin warm coastal currents extending down the West Australian coast (Leeuwin Current) and part of the East Australian coast (East Australian Current) are clearly evident. These currents are important for regional oceanography but poorly simulated in coarser resolution ocean models. Also evident throughout is extensive mesoscale (100–200 km) eddy activity.

The high-resolution ocean modelling has a computational cost about 10 times greater than that of the ACCESS-CM2 model version at standard resolution, so while some testing will continue with this version, focus will be on development and application of the standard resolution version.

This work is in collaboration with the Australian Research Council Centre of Excellence for Climate System Science, who developed the high-resolution ocean component.

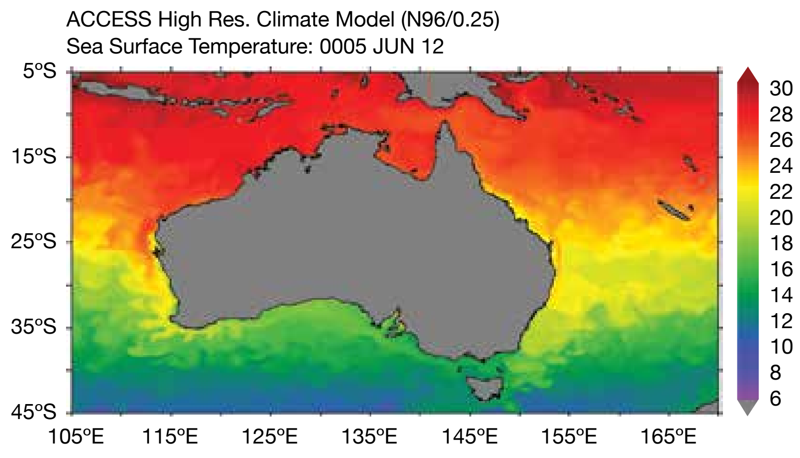


Figure 5.2
Sea surface temperature (SST) pattern for the Australian region on a sample June day from the version of ACCESS-CM2 with high horizontal resolution in the ocean. Units are °C.

High resolution ocean modelling in ACCESS-CM2 successfully reproduces the daily sea-surface temperatures around Australia, including the Leeuwin and East Australian Currents.

PARAMETERISATION | Atmospheric models work by breaking the atmosphere up into many small volumes of space (grid cells), like pixels in a digital photograph. Many important atmospheric processes occur on scales smaller than a grid cell, and the task of relating the impact of these processes back to grid-cell variables is known as 'parameterisation'. Whereas the equations governing the grid cell variables are well known, parameterisation methods are built on a mixture of physical theory and observation, so are continually improving as theories evolve and more detailed observations are made.

Improved cloud-process representation leads to reduced rainfall biases over the Maritime Continent

In earlier ACCESS simulations, in intense convective situations, the model was too cool and dry at heights where the temperature fell to zero (the 'freezing level'). Analysis showed that this was because the model cloud parameterisation melted all the snow at the freezing level. However, recent observational studies show that in the atmosphere liquid and frozen precipitation can co-exist over a relatively deep layer of the atmosphere around the freezing level.

ACCSP researchers incorporated these observational insights into the parameterisation, expanding it to allow liquid and frozen precipitation to co-exist over a range of heights and temperatures – from the freezing level to the freezing level plus 3°C. Trials showed that this effectively removed the excessive model cooling at the freezing level, and led to more rain over warmer surfaces (around 29°C) – with clear implications for improved tropical modelling.

The upper panel of Figure 5.3 shows rainfall biases (differences between model and observed climate) for the baseline model simulation. The spatial distribution around the Maritime Continent (the broad region of ocean and islands in the region to Australia's north), being too dry over land and too wet over the oceans, is common to many climate models. The lower panel shows the difference in simulations between the improved cloud parameterisation and the baseline. The modified parameterisation has reduced model biases in the region, and we now see that there is more rain over land and less over the ocean.

The improved model climatology around the Maritime Continent also improves the eastward-propagation of the Madden-Julian Oscillation (MJO), a phenomena which is difficult to capture in many climate models, but is important for tropical variability on monthly timescales.

READ MORE | Zhu & Hendon 2015. Role of large-scale moisture advection for simulation of the MJO with increased entrainment, *Quarterly Journal of the Royal Meteorological Society*, doi:10.1002/qj.2510.

READ MORE | Jiang *et al.* 2015. Vertical structure and physical processes of the Madden-Julian oscillation: Exploring key model physics in climate simulations. *Journal of Geophysical Research – Atmospheres*, 120, 4718–4748. doi:10.1002/2014jd022375.

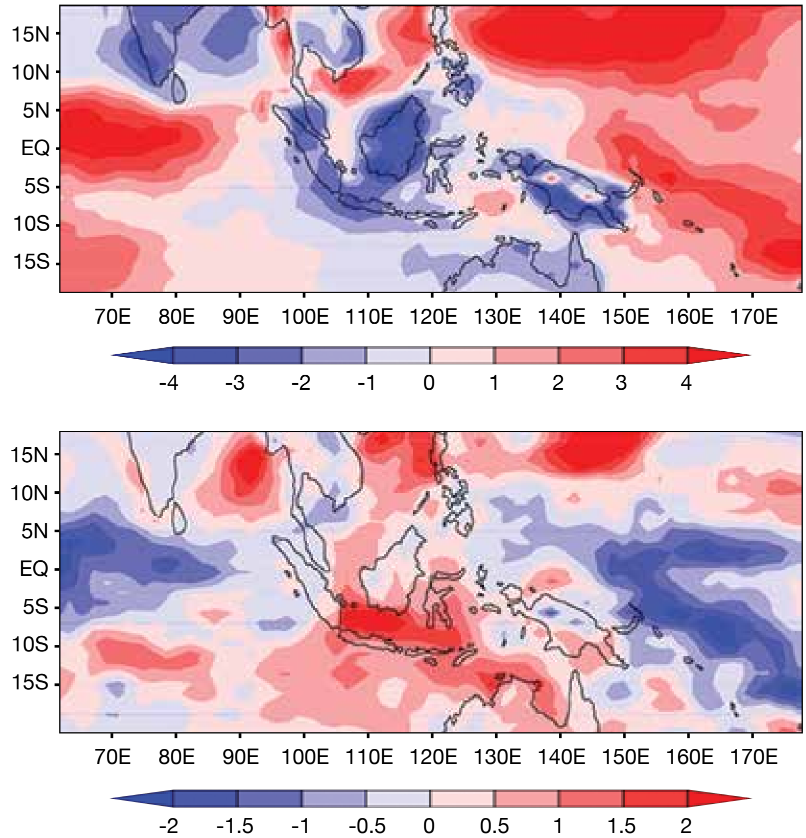


Figure 5.3
Upper panel: model bias (difference between model results and observations, in this case rainfall according to the Global Precipitation Climatology Project satellite-derived data set) for the baseline experiment. Lower panel: Difference in model results between the modified parameterisation and the baseline experiment. For both panels, units are mm/day, and the simulation period was 2006–2009.

ACCESS simulations are too wet over the oceans and too dry over land in the region to the North of Australia. Simulations with improved cloud process representation show more rain over land and less over the oceans – i.e. reduction in these biases.

Improved representation of clouds and precipitation in ACCESS

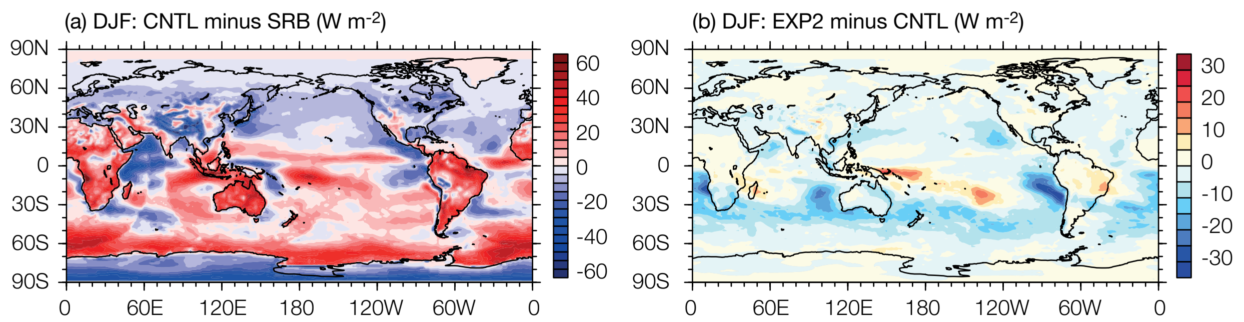
The radiation balance over the Southern Ocean is strongly affected by clouds. Prior work has identified that a lack of cloud liquid water is a key component of the surface radiative flux error in ACCESS, which gives rise to excessively warm sea surface temperatures in the Southern Ocean.

ACCSP researchers developed and implemented an improved representation of cloud microphysical processes in ACCESS. The new 'warm rain' scheme produces clouds, precipitation and radiative fluxes that compare better with satellite observations than the existing scheme in the model. Both the cloud cover and condensate (total cloud liquid and frozen water content) amounts are shown to improve when the new scheme is used, which tends to increase the amount of solar radiation that is reflected back to space. This reduction in the solar radiation that reaches the Earth's surface (see Fig. 5.4) improves the Southern Ocean sea surface temperature simulated by ACCESS by reducing the excessive surface warming.

READ MORE | Franklin 2014. The effects of turbulent collision-coalescence on precipitation formation and precipitation-dynamical feedbacks in simulations of stratocumulus and shallow cumulus convection. *Atmospheric Chemistry and Physics*, 14, 6557–6570, doi:10.5194/acp-14-6557-2014.

READ MORE | Huang *et al*. 2015. Evaluation of boundary layer cloud forecasts over the southern ocean in a limited-area numerical weather prediction system using in-situ space-borne and ground-based observations. *Quarterly Journal of the Royal Meteorological Society*, doi:10.1002/qj.2519.

READ MORE | Mason *et al*. 2015. A hybrid cloud regime methodology used to evaluate Southern Ocean cloud and shortwave radiation errors in ACCESS. *Journal of Climate*, doi:10.1175/jcli-d-14-00846.1.



An improved representation of cloud microphysical processes in ACCESS produces clouds, precipitation and radiative fluxes that better compare with satellite observations.

Figure 5.4
(a) Net surface downward shortwave radiation error from an ACCESS simulation before the improvement, where red (blue) colours denote too much (little) solar radiation reaching the surface. (b) Surface shortwave radiation difference between the control ACCESS1.3 simulation and the simulation using the new warm rain scheme. Blue colours over the Southern Ocean show an improvement in the amount of solar radiation being reflected back to space from clouds and a reduction in the excessive surface warming.

SCIENCE TO INFORM DECISION-MAKING

The Southern Ocean plays a vital role in the global and local energy and water cycles, so improving the representation of clouds in this region will reduce uncertainties in the projection of Australian surface warming and rainfall, as well as Antarctic sea ice loss.

New method for model evaluation and development implemented

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

Figure 5.5 shows how the far faster and cheaper Transpose-AMIP outputs (5-day runs) capture the key model biases as seen in the AMIP simulations (30-year runs) for the GA6 atmospheric model. ACCESS 1.3 experiments also show comparable biases.

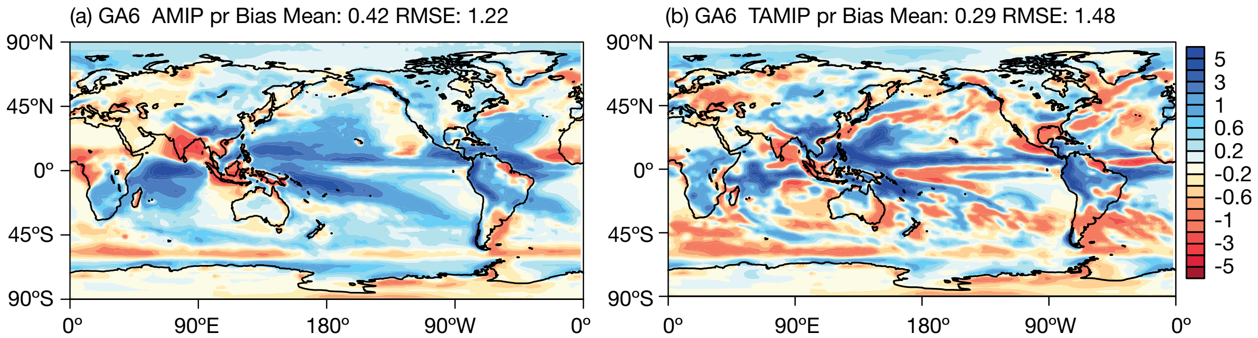


Figure 5.5
Precipitation bias calculated for the GA6 atmospheric model using (a) AMIP and (b) T-AMIP experiments, with bias relative to observed mean precipitation according to the GPCP data set. Units are mm/day.

The far faster and cheaper Transpose-AMIP outputs (5-day runs) capture the key model biases as seen in the slower AMIP simulations (30-year runs).

2014–15 Highlights

ACCESS CARBON CYCLE MODELLING

Successful simulation of the carbon cycle response to increasing atmospheric carbon dioxide

Land and ocean carbon modules have been added to ACCESS to enable simulations of the carbon cycle. Simulations have been run with prescribed pre-industrial and historical carbon dioxide concentrations and a future atmospheric carbon dioxide concentration scenario to see how the exchange of carbon between the atmosphere and land or ocean changes. From 1850 to 2100, carbon uptake by the ocean increases as atmospheric carbon dioxide increases. By contrast, the land biosphere takes up carbon over the historical period but releases carbon back to the atmosphere as atmospheric carbon dioxide continues to increase to 2100 and the climate warms. The land carbon module includes nutrient limitation. For ocean carbon, the ACCESS simulations are comparable to those from other CMIP5 models.

For land carbon, CMIP5 models produce a large range of results depending, in part, on whether land-use change and nutrient limitation are included; ACCESS simulations lie within the range. Test simulations have also been completed in which anthropogenic carbon emissions are input to the model and atmospheric carbon dioxide is simulated rather than prescribed. This will allow the positive feedback between the carbon cycle and climate to be quantified.

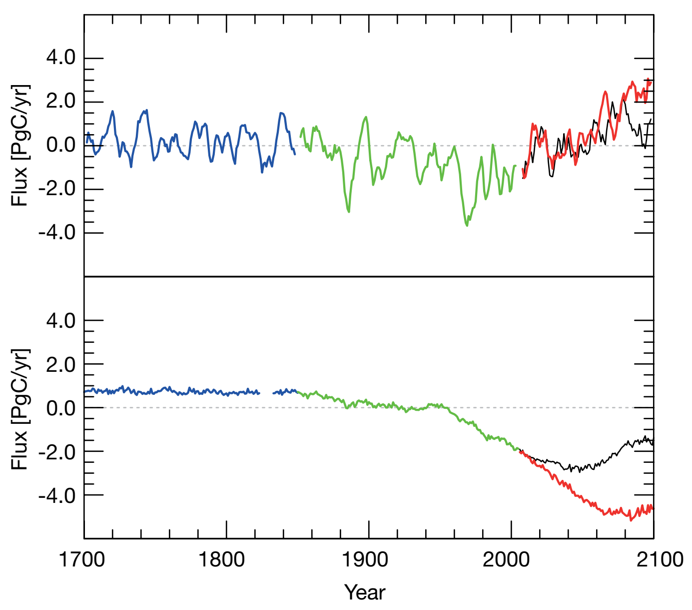


Figure 5.6
Land-to-air (top) and sea-to-air (bottom) carbon flux simulated by ACCESS when atmospheric carbon dioxide concentration is prescribed at the pre-industrial concentration (blue), historical (1850–2005) concentrations (green) and two future (2005–2100) concentration scenarios (RCP4.5 black, RCP8.5 red). The land carbon fluxes are plotted as a 5-year running mean to smooth out large year-to-year variability. Fluxes are in Pg of carbon per year. 1 Pg is 10^{12} g or 1 Gigatonne (1 billion tonnes).

From 1850 to 2100 carbon uptake by the ocean increases as atmospheric carbon dioxide increases. In comparison, the land biosphere initially takes up carbon over this time period but eventually releases carbon dioxide back into the atmosphere as emissions continue to increase and the climate warms.

SCIENCE TO INFORM DECISION-MAKING

ACCSP research has added an important new capability to ACCESS, allowing the interactions of the carbon cycle and climate to be modelled and widening the range of applications for which ACCESS can be used. Examples include regional and global carbon budget assessments, natural resource management and food security, assessing the risk of ocean acidification on Australian and Southern Ocean ecosystems, and linking with observations to better understand the processes of land and ocean carbon exchange. The inclusion of nutrient limitation (both nitrogen and phosphorus) in the ACCESS land carbon module (called CABLE) is important as land carbon uptake is reduced when nutrient availability is accounted for. Very few CMIP5 models included nutrient limitation.

DEVELOPMENT OF THE ACCESS EARTH SYSTEM MODEL FOR AEROSOLS AND CHEMISTRY

Global climate-chemistry-aerosol modelling capability included in ACCESS

Atmospheric chemistry controls the magnitude and distribution of a number of important greenhouse gases (e.g. methane and ozone in the troposphere, and ozone and water vapour in the stratosphere). Changes in aerosol abundance affect climate by changing cloud properties and scattering (reflecting) incoming solar radiation, which changes temperatures. Changes in atmospheric concentrations of aerosols and greenhouse gases are important forcing mechanisms that produce changes in global climate, but to date ACCESS has lacked a climate-chemistry modelling capability.

ACCSP researchers have implemented a new model version of the UK Chemistry and Aerosol (UKCA) model that is able to simulate both the stratospheric and tropospheric chemistry simultaneously and has enhanced aerosol microphysics via a new aerosol scheme called GLOMAP-mode. After evaluating the performance of the new model version for the atmosphere-only ACCESS configuration, researchers can demonstrate that it is now a powerful tool for understanding a plethora of problems involving climate-chemistry-aerosol feedbacks and process understanding.

Evaluation studies and coupling to other ACCESS components such as the carbon cycle and ocean model are among the next anticipated steps.

READ MORE | Uhe & Thatcher 2015. A spectral nudging method for the ACCESS1.3 atmospheric model. *Geoscientific Model Development*, 8, 1645–1658. doi:10.5194/gmd-8-1645-2015.

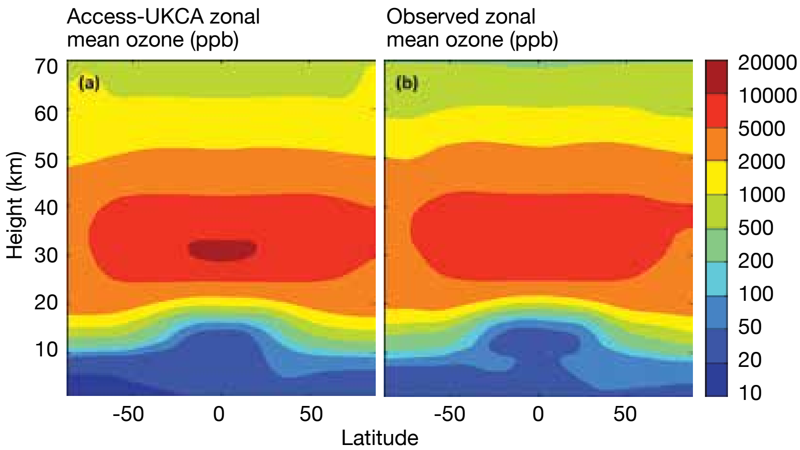


Figure 5.7
Zonal mean (latitude average) ozone concentration (ppb) as a function of height, averaged over the years 2001–2007: (a) simulated using ACCESS-UKCA, and (b) based on satellite and ozonesonde observations. The lower vertical region is the troposphere which extends to 10 km at the poles and to about 15 km at the Equator. The overlying region is the stratosphere with high ozone concentrations in the middle. The model is able to simulate the overall observed ozone distribution, but with some model underestimation in the troposphere, for example south of 50°S, and overestimation in the tropics at a height of 30 km.

The new chemistry-aerosol modelling capability in ACCESS simulates the overall observed ozone distribution well. There is some underestimation in the troposphere and some overestimation in the topics.

SCIENCE TO INFORM DECISION-MAKING

Reactive gases (such as methane and ozone) and aerosols are important climate drivers. Including their atmospheric chemistry in ACCESS contributes to making it a world-class Earth system model. This will improve our understanding of key climate feedbacks and associated uncertainties, and our ability to provide model simulations of Earth's climate at global and national scales. This work, coupled with a global emissions database, represents Australia's first climate-chemistry-aerosol modelling capability. It will serve as a platform for expanded collaboration with national and international institutions.

Multi-decadal reactive gas and aerosol emissions database developed for climate-chemistry-aerosol simulations

Emissions of reactive gases and aerosols are a critical input to a climate-chemistry model since they determine the atmospheric abundance of chemical precursors and products that influence radiative forcing.

ACCSP researchers developed a global, annually varying, gridded emissions database for gaseous and aerosol sources, both anthropogenic and natural, for the years 1900–2100 for ACCESS-UKCA climate-chemistry simulations (Fig. 5.8 gives an example). The gaseous species include reactive oxides of nitrogen, carbon monoxide, formaldehyde, acetaldehyde, methane, ethane, propane, acetone, and isoprene. The aerosol precursors and components include sulphur dioxide, and black and organic carbon.

The emissions evaluation methodology contains a number of steps, including the derivation of a realistic vertical distribution of wildfire emissions to account for the rise of fire plumes. The pre-2000 anthropogenic and biomass-burning emissions were acquired from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) while the post-2000 emissions were taken from Representation Concentration Pathways (RCP) based ACCMIP scenarios. For natural emissions, various emission databases were analysed to include the biogenic, soil, and oceanic components. Anthropogenic emissions were validated using the National Greenhouse Gas Inventory data for Australia.

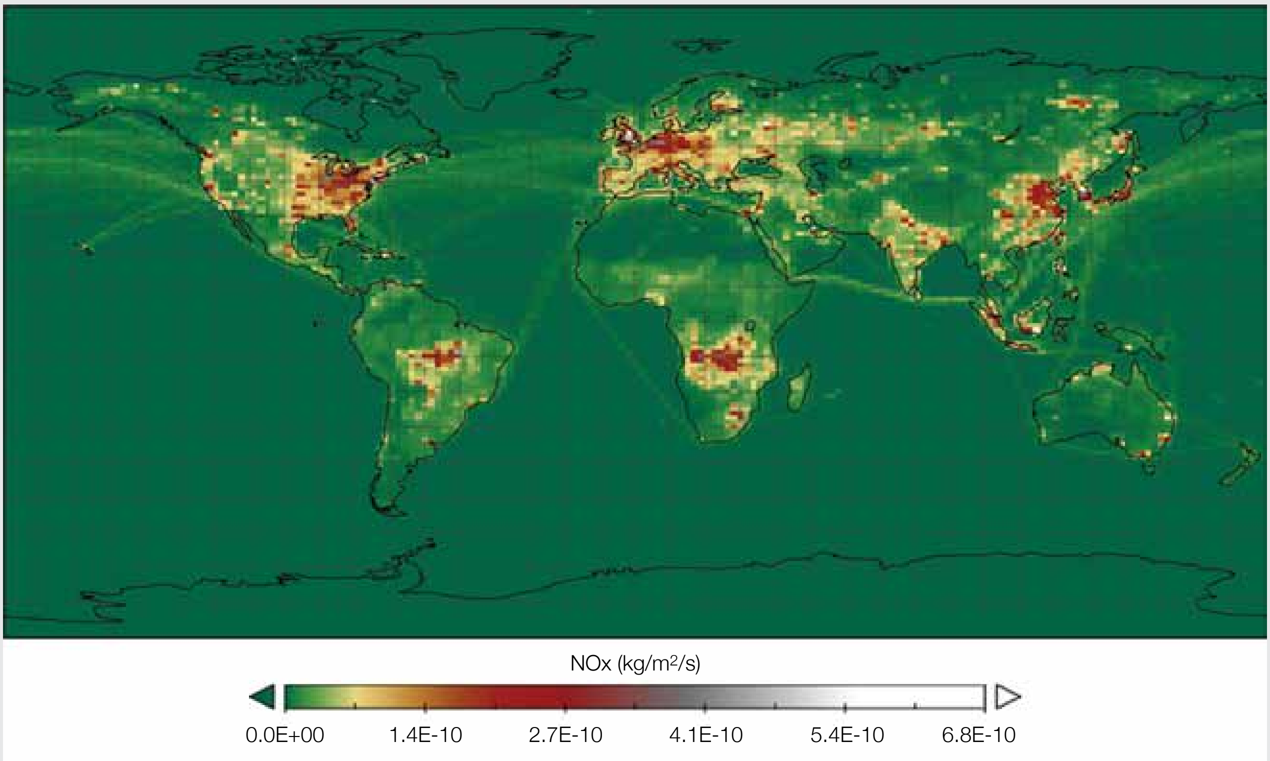


Figure 5.8
Global distribution of total surface emissions of reactive oxides of nitrogen (as NO_2, kg m^{-2} s^{-1}) for August 2000, which include both anthropogenic and natural components. Shipping emissions over the oceans are noticeable as continuous lines. Aircraft emissions are excluded, as they are not surface emissions, but they are accounted for in the model.

In this plot of total surface emissions of reactive oxides of nitrogen, shipping emissions are noticeable as continuous lines.

This work has provided a computational methodology and resulting databases that can be used to investigate the impact of various emission scenarios on climate feedbacks and parameters.

Role of atmospheric aerosols quantified in ACCESS

Aerosols represent a significant uncertainty in our current understanding of the climate system. ACCSP researchers compared observed aerosol optical depth seasonal climatologies with different versions of the ACCESS model and evaluated the representation of biomass-burning emissions over northern Australia. Updated aerosol radiative forcing simulations were completed for CMIP5 (1.0, 1.3) and post CMIP5 (1.4) versions of ACCESS and analysis of these runs commenced. Work was also done to assess aerosol distributions in more recent versions of the ACCESS model, which are being developed in preparation for the upcoming CMIP6 climate model evaluation. Evaluating the role of aerosols in the ACCESS model and understanding their impact on present-day and future climate is crucial for providing more reliable climate projections for the Australian region.

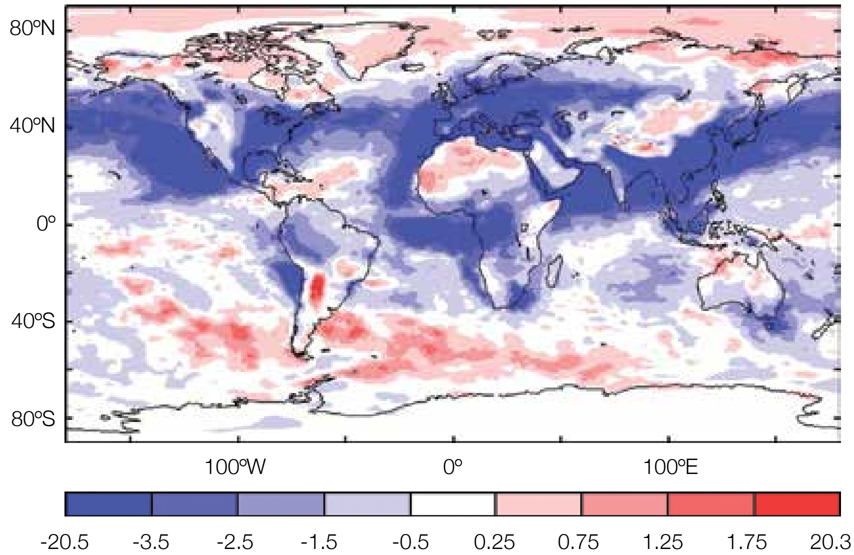


Figure 5.9
Global distribution of annual mean effective radiative forcing (ERF) (W/m^2) due to anthropogenic aerosol changes since pre-industrial times for the ACCESS1.4 model. Negative ERF values indicate cooling and positive ERF indicates warming. Overall, there is net global cooling (ERF = –1.5 W/m^2) due to anthropogenic aerosols, largely as a result of sulphate aerosols and related cloud changes over, and downwind from, industrial regions. The distribution shown compares well with those obtained by other global models, although the sensitivity to aerosols is towards the upper (most negative) end of the 5-95% uncertainty range –0.1 to –1.9 W/m^2 reported in IPCC AR5.

Overall there is net global cooling due to anthropogenic aerosols. ACCESS reproduces this cooling moderately well compared with other climate models.

6

2014–15 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. Climate change projections for Australia were released in January 2015, supported by the *NRM Planning for Climate Change Fund* and co-investment from CSIRO and the Bureau of Meteorology. This work was partly underpinned by contributions from the ACCSP. The projections provide important information for decision-makers about our future climate.

REGIONAL CLIMATE PROJECTIONS SCIENCE

Underpinning science and methods for the new national climate projections

The latest national climate projections, *Climate Change in Australia* (**www.climatechangeinaustralia.gov.au**), use the very latest tools, knowledge and methods to produce regional climate change projections for regions of Australia.

ACCSP researchers worked on various aspects of the regional climate change science that informs and guides much of the methodology and content in the new national projections. For example, ACCSP research into regionalisation methods, such as downscaling and the potential for 'added value' that downscaling provides, informed the strategy to include downscaling into the projections, and many of the regional insights that were reported.

Other work from ACCSP informed the confidence rating system and final ratings for various regional projections by providing physical reasoning and information about model consistency on projected change.

SCIENCE TO INFORM DECISION-MAKING

Sound research about the confidence in regional projections, including the regional signal from downscaling, are crucial components of credible and useful regional projections. These projections are used by researchers and managers from a wide range of sectors for informing and motivating greenhouse gas mitigation efforts and developing adaptation plans.

2014–15 Highlights

UNDERSTANDING AND NARROWING UNCERTAINTIES IN TROPICAL AUSTRALIAN RAINFALL PROJECTIONS

Model representation of large-scale drivers linked to uncertainty in monsoon onset projections

ACCSP researchers used daily data from CMIP5 models, to investigate the 'onset' (i.e. annual commencement) of the Australian monsoon in the historic and future climate simulations using defined atmospheric circulation and moisture conditions.

They found that Indian and Pacific Ocean tropical sea-surface temperatures provided important conditions for the onset of the Australian monsoon, but that under global warming the influence of these conditions are highly variable and model dependent. A large part of the uncertainty in projected rainfall change for Australian tropics can be explained through these different responses within each model: how strongly each model's atmosphere is connected to each ocean basin and how the impact for tropical Australian rainfall will change under future warming.

This work shows that it is important not to just look at overall mean changes from the large model ensemble but to understand the processes involved in driving changes to rainfall within each model.

READ MORE | Zhang *et al.* 2015. Uncertainty in CMIP5 model-projected changes in the onset/retreat of the Australian summer monsoon. *Climate Dynamics*, doi:10.1007/s00382-015-2707-x.

New method for determining skill of tropical rainfall projections

ACCSP researchers developed a methodology for determining how CMIP5 models simulate changes in different components of Australian tropical rainfall.

They decomposed changes in Australian tropical rainfall for each CMIP5 model into five components (changes in the temperature of the atmosphere, relative humidity, the strength of the atmospheric circulation, the spatial shifts in circulation and a nonlinear term), then studied the processes driving the changes using two sub-sets of models (those projecting either dryer or wetter future conditions across the top end of Australia). Based on this methodology, statements can be made on how skilfully these processes are simulated and how this affects confidence in projected changes from each of the models.

SCIENCE TO INFORM DECISION-MAKING

The Australian monsoon is a critical feature for northern Australian climate. Its seasonal cycle in winds and rainfall has a major influence on agriculture, ecosystems and society.

Major uncertainties remain in climate model projections of changes to tropical Australian rainfall and its variability under global warming. The causes of this spread and the implications for regional climate change projections, however, remain largely unknown.

Understanding the processes behind projected changes to the Australian monsoon can help reduce this uncertainty and therefore lead to increased confidence in future rainfall projections.

EVALUATION OF TROPICAL CYCLONE DEVELOPMENT IN THE AUSTRALIAN REGION

Regional variability in favourable tropical cyclone formation conditions

Tropical cyclones develop from tropical depressions, but not all tropical depressions develop into tropical cyclones. Understanding why this is so can help us to better identify the conditions for tropical cyclone formation and to more accurately represent tropical cyclones in climate models.

ACCSP researchers examined observational data for the period 1979–2013 and determined the fraction of tropical depressions that do not become tropical cyclones (the 'failure' rate). They found considerable regional variation, with higher tropical cyclone failure poleward of 15° of latitude, especially in the south Pacific (Fig. 6.1, yellow box), in stark contrast to the lowest value globally in the South Indian basin (Fig. 6.1, blue box). This highlights strong regional differences in favourable conditions for tropical cyclone formation across the broader Australian region.

TROPICAL DEPRESSIONS AND TROPICAL CYCLONES | A tropical depression is a region of organised deep, moist convection (multiple, persistent thunderstorms) embedded in a region of relatively low pressure, with winds rotating in an approximately closed circulation. The system does not yet have an eye and the wind speeds are less than tropical cyclone intensity (34 knots). Each thunderstorm in the tropical depression contains very buoyant air that accelerates upwards to the tropopause where it decelerates and spreads outwards. This amounts to a large and persistent upward 'mass flux' across the many thunderstorms within the tropical depression. Air must be drawn inwards to replace the air accelerating upwards, which in an already rotating environment must rotate faster and faster to conserve angular momentum (like water flowing towards a plug hole). In this way, the large tropical depression circulation gradually spins up with time. Once the average winds in the storm reach 34 knots, it is considered to have become a tropical cyclone.

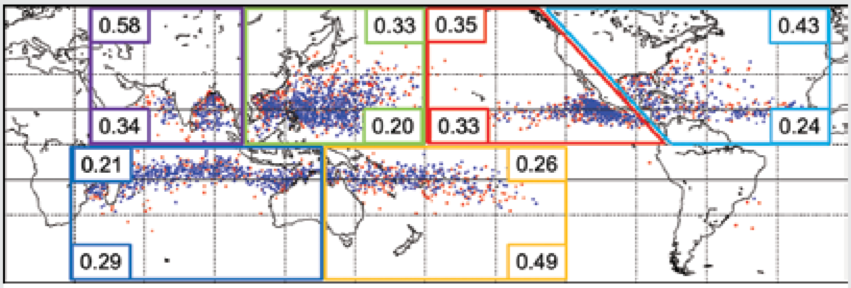


Figure 6.1
Global distribution of tropical cyclones (blue dots) and 'failed' tropical cyclones (red dots) 1979 to 2013. Coloured boxes show the tropical cyclone basin regions. Two failure rates are given for each basin – one for regions equatorward of 15° latitude and one for regions poleward of 15° latitude.

There are strong regional differences in favourable conditions for tropical cyclone formation across the broader Australian region.

6

2014–15 Highlights

ATTRIBUTION OF EXTREME EVENTS: MECHANISMS AND METHODS

Human influence in recent record Australian heat extremes

2013 was Australia's warmest year since reliable instrumental records began in 1910 and the Australian summer of 2012/13, spring 2013 and September 2013 also broke records for warmth. In 2014 Australian temperature records were again broken, with a significant heatwave in January, a prolonged warm spell in autumn and the warmest spring on record (Fig. 6.2).

Building on their investigation of September 2013's record warmth, ACCSP researchers investigated the causes of the 2014 record springtime warmth using statistical analysis and sensitivity experiments with the Bureau of Meteorology's seasonal prediction system. They found that the record warm Australian spring of 2014 would likely not have occurred without the increases in carbon dioxide over the past 50 years. The unusual weather event was caused by an anomalous circulation in the upper level of the atmosphere, associated with high rainfall in the tropical Indian Ocean, which worked in concert with human-induced carbon dioxide increases to amplify temperatures over Australia.

Recent record Australian rainfall extremes due to long-term Pacific warming

In spring 2010, Australia experienced record high rainfall, priming the soil for major floods in the following months.

ACCSP researchers examining the cause of this record rainfall found that a strong La Niña event contributed to the extreme rainfall. Modelling experiments with the Australian Bureau of Meteorology coupled model seasonal forecast system showed that the long-term warming of tropical ocean temperatures amplified the rainfall response over Australia.

READ MORE | Arblaster *et al*. 2014. Understanding Australia's hottest September on record. *Bulletin of the American Meteorological Society*, 95(9), S37–S41.

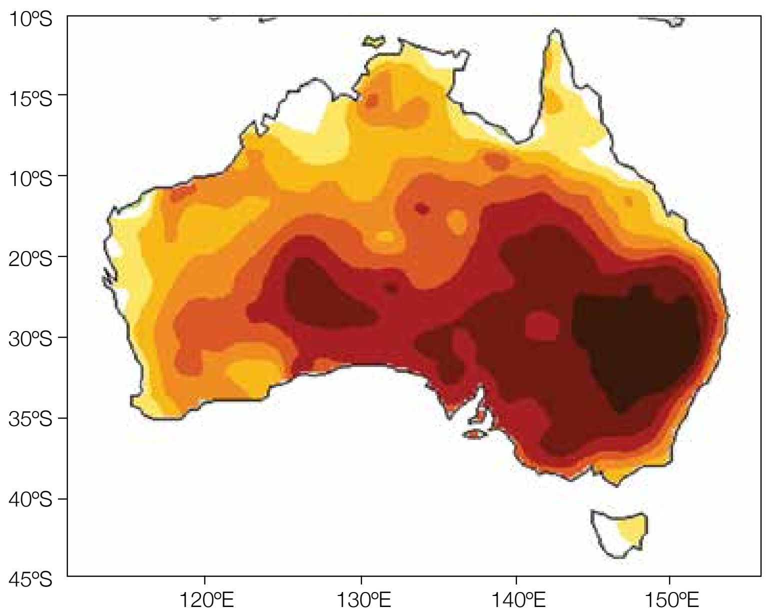
SCIENCE TO INFORM DECISION-MAKING

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.

Figure 6.2
Observed Australian late-spring 2014 maximum temperatures (expressed as anomalies relative to the 1961–1990 long-term average).

°C
-3.9 -2.7 -1.5 -0.3 0.9 2.1 3.3

The record warm Australian spring of 2014 would likely not have occurred without the increases in carbon dioxide over the past 50 years.



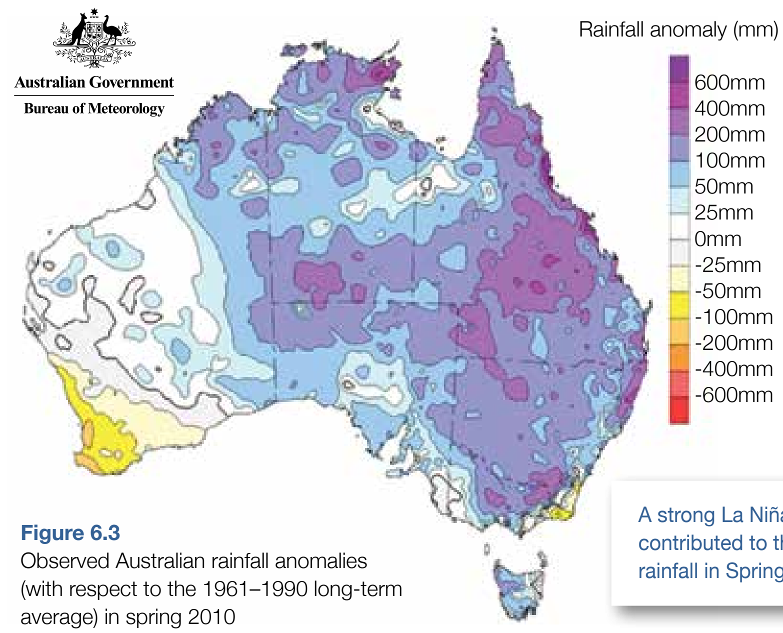


Figure 6.3
Observed Australian rainfall anomalies (with respect to the 1961–1990 long-term average) in spring 2010

A strong La Niña event contributed to the record rainfall in Spring 2010.

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

Better understanding of lightning variability

Lightning is responsible for a significant proportion of the area burnt by bushfires. It is important to understand lightning and fire weather conditions, so we can be better prepared now and learn how they may change in the future.

ACCSP researchers developed a large-scale method for examining conditions favourable to dry-lightning occurrence, suitable for application to global climate models. They also produced a data set of fire weather conditions, including three different measures of fuel moisture, of importance to the chance of fire ignition from lightning. The data set of fuel moisture conditions provides measures of moisture for fine or surface fuels, as well as fuels of moderate depth or size and fuels of large size or depth. This is important as previous work has shown that the different classes of fuel moisture have differing influences on the chance of fire per lightning stroke. Existing fire danger measures such as the McArthur FFDI (forest fire danger index) do not provide such information.

Researchers also developed a seasonal forecasting method for thunderstorms and lightning. These forecasts are important for improved preparedness for the extreme weather often associated with thunderstorm activity, including hail, tornados, extreme rainfall, winds and lightning-ignited fires.

First examination of long-term lightning trends

ACCSP researchers undertook the first ever examination of long-term lightning activity trends in Australia. They found a decreasing trend in lightning activity in southern Australia, particularly during the cooler months of the year, with relatively little observed change in other seasons or regions of Australia. This work is important to our understanding of long-term changes in the risk of fire ignition, as well as our understanding of changes in thunderstorm and convection in general (which can be responsible for a range of associated extreme weather events).

7

2014–15 Highlights

Management, coordination and communication

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

MANAGEMENT AND COORDINATION

A joint management team comprising senior representatives from the Department of the Environment, CSIRO and the Bureau oversees the ACCSP. The team is responsible for day-to-day management, progress reporting and finances, and meets 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) summarise key achievements of the Programme throughout the year.

Annual Review Meeting

Each year an annual review meeting is convened where researchers share and discuss key research findings with the Department of the Environment. The 2014–15 ACCSP Annual Review Meeting was held at Melbourne Airport in June 2015, and attended by ACCSP science and management representation from CSIRO, the Bureau of Meteorology and Department of the Environment. The meeting featured presentations from all Programme component leaders, and from representative early career scientists, across the full scope of the ACCSP project portfolio.

COMMUNICATION

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

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

As Australia's largest climate change science programme, the ACCSP undertakes nationally and internationally acclaimed work. The Programme directly supports and organises scientific workshops and conferences, and ACCSP scientists regularly make presentations at national and international conferences and workshops to communicate research findings to a broad audience of stakeholders.

Publications

In 2014–15, ACCSP researchers published 90 peer-reviewed papers or articles in Australian and international scientific publications. A further 28 papers were submitted for publishing and 17 others were accepted by the publisher but not published at the time of the Annual Report.

In addition to peer-reviewed, technical and conference papers produced by researchers, the ACCSP develops information papers for non-technical audiences on key climate issues. This year two brochures were published:

- Weather extremes and climate change: the science behind the attribution of climatic events
- What is ocean acidification and how will it impact on marine life?

The 2013–14 ACCSP Annual Report published in 2014 not only noted Programme achievements for 2013–14, but also highlighted the contributions the ACCSP has made to our understanding of Australia's climate over the past 25 years.

These publications are available at **www.cawcr.gov.au/projects/climatechange/resources**.

Refer to Appendix 3 for a comprehensive list of ACCSP publications.

Websites

The ACCSP maintains an online presence to inform a wide audience about the science undertaken though the Programme.

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

There is also information about the ACCSP on the Department of the Environment website at **http://www.environment.gov.au/climate-change/climate-science/australian-climate-change-science-program**.

GREENHOUSE 2015

A feature of the ACCSP communication strategy is the biennial GREENHOUSE conference. 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.

During 2014–15, preparations began for GREENHOUSE 2015, the latest conference in this influential series delivered by the ACCSP. GREENHOUSE 2015 will be held in Hobart in October 2015. Taking advantage of the strength of Southern Hemisphere climate change science in Tasmania, the theme of the conference is 'Atmosphere, oceans and ice'.

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)	Globally carbon dioxide equivalent emissions from the agricultural sector are bigger than the land carbon dioxide sink (p. 7)
1.2 The Australian terrestrial carbon budget: The role of vegetation dynamics	Vanessa Haverd (CSIRO Pep Canadell (CSIRO)	Woody vegetation dynamics model results extended (p. 8)
1.3 Palaeo carbon cycle dynamics	David Etheridge (CSIRO) Cathy Trudinger (CSIRO) Richard Matear (CSIRO)	Carbon dioxide changes during the Little Ice Age explained (p. 9) Global sources and sinks of methane over the past century quantified (p. 9) Long-term atmospheric data from ice used to test ACCESS (p. 9)

2 LAND AND AIR OBSERVATIONS AND PROCESSES		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
2.1 Aerosol and its impact on Australian climate	Leon Rotstayn (CSIRO)	Importance of indirect aerosol effects on future tropical rainfall identified (p. 13) Aerosol cooling estimated with ACCESS (p. 14)
2.2 Reducing uncertainties in climate projections by understanding, evaluating and intercomparing climate change feedbacks	Robert Colman (Bureau of Meteorology)	Climate feedbacks in CMIP5 models evaluated (p. 16) New methodology for evaluating and exploring cloud feedbacks in ACCESS (p. 17)
2.3 Ecosystem response to increased climate variability	Eva van Gorsel (CSIRO)	First imagery from unique proximal remote sensing system (p. 18)

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) Ann Thresher(CSIRO) Ken Ridgway (CSIRO)	Extended Australian ocean climate record shows continued global warming (p. 20) Historical ocean profile data improvements identified (p. 21)
3.2 Understanding ocean drivers of regional and global climate variability and change	Bernadette Sloyan (CSIRO) Steve Rintoul (CSIRO) Terry O'Kane (CSIRO) Susan Wijffels (CSIRO)	Ocean 'storm tracks' identified and characterised (p. 22) Increasing carbon dioxide caused Southern Annular Mode trend (p. 28) Ocean spiciness initiated the period of strong El Niño events in the 1970s (p. 22)
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)	Time of emergence of regional sea-level rise estimated (p. 23) Regional sea-level rise projections and allowances for the Australian coastline determined (p. 24) Global and Australian hydrodynamic and wave climate projections developed (p. 25) Continued global mean sea-rise demonstrated (p. 25)
3.4 Ocean acidification	Bronte Tilbrook (CSIRO) Marcel van der Schoot (CSIRO)	Improved understanding of the Southern Ocean carbon dioxide uptake (p. 25) Diurnal variability found in ocean carbon exchange (p. 26)

4 MODES OF CLIMATE VARIABILITY AND CHANGE		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
4.1 The El Niño-Southern Oscillation and its impacts on Australasia in the 21st century	Scott Power (Bureau of Meteorology)	Improved understanding of how future La Niña events will affect rainfall over the Pacific Ocean (p. 28)
4.2 Decadal variability in Australian and Indo-Pacific climate: predictability and prediction	Scott Power (Bureau of Meteorology)	Pacific warming has emerged from background variability and is due to greenhouse gases (p. 29)
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) Tim Cowan (CSIRO)	Greenhouse warming leads to increased frequency of extreme La Niña events (p. 30)
4.4 Attribution, projection and mechanisms of climatic extremes and change, modes of variability and regional weather systems.	Carsten Frederiksen (Bureau of Meteorology) Jorgen Frederiksen (CSIRO)	Climate change signal detected in Australian rainfall variability (p. 31)

5 EARTH SYSTEMS MODELLING AND DATA INTEGRATION		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
5.1 ACCESS coupled climate model development	Kamal Puri (Bureau of Meteorology) Tony Hirst (CSIRO) Gary Dietachmayer (Bureau of Meteorology)	ACCESS-CM2 successfully configured and run (p. 33) ACCESS-CM2 configured with a high horizontal resolution ocean component (p. 34) Improved cloud-process representation leads to reduced rainfall biases over the Maritime Continent (p. 34) Improved representation of clouds and precipitation in ACCESS (p. 36) New method for model evaluation and development implemented (p. 37)
5.2 ACCESS carbon cycle modelling	Rachel Law (CSIRO) Richard Matear (CSIRO)	Successful simulation of the carbon cycle response to increasing atmospheric carbon dioxide (p. 38)
5.3 Development of the ACCESS Earth System Model for aerosol and chemistry	Ashok Luhar (CSIRO) Peter Vohralik (CSIRO)	Global climate-chemistry-aerosol modelling capability included in ACCESS (p. 39) Multi-decadal reactive gas and aerosol emissions database developed for climate-chemistry-aerosol simulations (p. 40) Role of atmospheric aerosols quantified in ACCESS (p. 41)

6 AUSTRALIA'S FUTURE CLIMATE		
PROJECT TITLE	**PRINCIPAL INVESTIGATORS**	**HIGHLIGHTS**
6.1 Regional climate projections science	Penny Whetton (CSIRO)	Underpinning science and methods for the new national climate projections (p. 43)
6.2 Understanding and narrowing uncertainties in tropical Australian rainfall projections	Aurel Moise (Bureau of Meteorology) Huqiang Zhang (Bureau of Meteorology)	Model representation of large-scale drivers linked to uncertainty in monsoon onset projections (p. 44) New method for determining skill of tropical rainfall projections (p. 44)
6.3 Evaluation of tropical cyclone development in the Australian region	Kevin Tory (Bureau of Meteorology) Sally Lavender (CSIRO) Tony Rafter (CSIRO)	Regional variability in favourable tropical cyclone formation conditions (p. 45)
6.4 Attribution of extreme events: mechanisms and methods	Julie Arblaster (Bureau of Meteorology) Pandora Hope (Bureau of Meteorology)	Human influence in recent record Australian heat extremes (p. 46) Recent record Australian rainfall extremes due to long-term Pacific warming (p. 46)
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)	Better understanding of lightning variability (p. 47) First examination of long-term lightning trends (p. 47)

APPENDIX 2 Partners and collaborators

AUSTRALIA

- Antarctic Climate and Ecosystems Cooperative Research Centre
- ARC Centre of Excellence for Climate System Science
- Australian Antarctic Division
- Australian Institute of Marine Science
- Australian National University
- Australian Nuclear Science and Technology Organisation
- Charles Darwin University
- Integrated Marine Observing System
- James Cook University
- Macquarie University
- Monash University
- National Computational Infrastructure
- Queensland Government Department of Science, Information Technology, Innovation and the Arts
- Queensland University of Technology
- Royal Australian Navy
- Southern Cross University
- Swinburne University
- The Goyder Institute
- University of Adelaide
- University of Melbourne
- University of New South Wales
- University of Queensland
- University of South Australia
- University of Sydney
- University of Tasmania
- University of Technology, Sydney
- University of Western Australia
- University of Wollongong

AUSTRIA

- University of Innsbruck

BRAZIL

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

CANADA

- Environment Canada, Toronto
- University of Alberta
- University of Lethbridge, Alberta

CHINA

- College for Global Change and Earth System Science, Beijing Normal University
- Institute of Atmospheric Physics, Chinese Academy of Sciences
- Institute of Oceanology, Chinese Academy of Sciences
- State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology
- Third Institute of Oceanography, State Oceanic Administration

COOK ISLANDS

- Meteorological Service

DENMARK

- Centre for Ice and Climate, University of Copenhagen

FRANCE

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

GERMANY

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

INDIA

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

JAPAN

- Department of Geophysics, Graduate School of Science, Tohoku University, Sendai
- Disaster Prevention Research Institute, Kyoto University
- Japan Agency for Marine-Earth Science and Technology
- Low Temperature Research Laboratory
- National Institute for Environmental Studies

THE NETHERLANDS

- Institute for Marine and Atmospheric Research Utrecht, Utrecht University

NEW ZEALAND

- National Institute for Water and Atmosphere
- University of Auckland

NORWAY

- Center for International Climate and Environmental Research

PORTUGAL

- Escola Naval, CINAV, Lisbon

SOUTH KOREA

- School of Earth and Environmental Sciences, Seoul National University

SPAIN

- Universitat de València

SWEDEN

- Department of Earth Sciences, Uppsala University
- Lund University

SWITZERLAND

- Empa – Laboratory for Air Pollution and Environmental Technology

UK

- British Antarctic Survey
- Department of Statistical Science, University College London
- MetOffice
- School of Environmental Sciences, University of East Anglia
- Swansea University
- Tyndall Center
- University of Cambridge
- University of Exeter
- University of Leeds
- University of Reading

USA

- Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration
- California Institute of Technology
- Carbon Dioxide Information and Analysis Center
- Department of Earth and Environmental Sciences, University of Rochester
- Department of Earth System Science, University of California
- Department of Physical Oceanography, Woods Hole Oceanographic Institution
- Departments of Earth & Planetary Science and of Chemistry, University of California
- Duke University
- Geophysical Fluid Dynamics Laboratory
- Institute of Arctic and Alpine Research, University of Colorado
- International Pacific Research Center, Hawaii
- Lamont Doherty Earth Observatory
- NASA Goddard Institute for Space Studies
- NASA Goddard Space Flight Center
- National Center for Atmospheric Research
- National Oceanic and Atmospheric Administration
- National Oceanographic Data Center
- Oregon State University
- Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration
- Princeton University
- Scripps Institution of Oceanography, University of California
- University of Hawaii

INTERNATIONAL

- Global Carbon Project
- International Argo Project (more than 15 countries – see **www.argo.net**)
- International Geosphere-Biosphere Programme
- World Climate Research Programme
- World Meteorological Organization Global Atmosphere Watch

APPENDIX 3 Publications

PEER-REVIEWED PUBLICATIONS

In 2014–15, ACCSP researchers published 90 peer-reviewed papers or articles in Australian and international scientific journals. A further 28 papers were submitted for publishing and 17 others were accepted by the publisher but not published at the time of the 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

Canadell JG, Schulze ED. 2014. Global potential of biospheric carbon management for climate mitigation. *Nature Communications*, 5, 5282, doi:10.1038/ncomms6282.

Fogwill C, Turney C, Golledge N, Etheridge D, Rubino M, Woodward J, Reid K, van Ommen T, Moy A, Curran M, Thornton D, Rootes C, Rivera A. 2015. Direct evidence for significant deglaciation across the Weddell Sea embayment during MeltWater Pulse-1B. *Geophysical Research Abstracts*, 17, EGU2015-2572-1.

Ghosh A, Patra PK, Ishijima K, Umezawa T, Ito A, Etheridge DM, Sugawara S, Kawamura K, Miller JB, Dlugokencky EJ, Krummel PB, Fraser PJ, Steele LP, Langenfelds RL, Trudinger CM, White JWC, Vaughn B, Saeki T, Aoki S, Nakazawa T. 2015. Variations in global methane sources and sinks during 1910–2010, *Atmospheric Chemistry and Physics*, 15, 2595-2612, doi:10.5194/acp-15-2595-2015.

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Hirsch AL, Kala J, Pitman AJ, Carouge C, Evans JP, Haverd V, Mocko D. 2014. Impact of land surface initialisation on sub-seasonal forecast skill: a regional analysis in the Southern Hemisphere. *Journal of Hydrometeorology*, 15, 300-319.

Loh ZM, Law RM, Haynes KD, Krummel PB, Steele LP, Fraser PJ, Chambers SD, Williams AG. 2015. Simulations of atmospheric methane for Cape Grim, Tasmania, to constrain South East Australian methane emissions, *Atmospheric Chemistry and Physics*, 15, 305-317, doi:10.5194/acp-15-305-2015.

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Naudts K, Ryder J, McGrath MJ, Otto J, Chen Y, Valade A, Bellasen V, Berhongaray G, Bönisch G, Campioli M, Ghattas J, De Groote T, Haverd V, Kattge J, MacBean N, Maignan F, Merilä P, Penuelas J, Peylin P, Pinty B, Pretzsch H, Schulze ED, Solyga D, Vuichard N, Yan Y, Luyssaert S. 2014. A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes. *Geoscientific Model Development Discussion*, 7(6), 8565-8647.

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Rubino M, Etheridge D, Trudinger C, Allison C, Rayner P, Mulvaney R, Steele P, Langenfeld R, Sturges W, Curran M, Smith A. 2015. Atmospheric CO_2 and d13C-CO_2 reconstruction of the Little Ice Age from Antarctic ice cores. *Geophysical Research Abstracts,* 17, EGU2015-9747-2.

Ryder J, Polcher J, Peylin P, Ottlé C, Chen Y, van Gorsel E, Haverd V, McGrath MJ, Naudts K, Otto J, Valade A, Luyssaert S. 2014. A multi-layer land surface energy budget model for implicit coupling with global atmospheric simulations. *Geoscientific Model Development Discussion*, 7(6), 8649-8701.

Sapart CJ, Martinerie P, Witrant E, Monteil G, Banda N, Houweling S, Krol M, Chappellaz J, van de Wal R, Sperlich P, van der Veen C, Sturges W, Blunier T, Schwander J, Etheridge E, Röckmann T. 2015. Reconstructing the recent methane atmospheric budget using firn air methane stable isotope analyses. *Geophysical Research Abstracts*, 17, EGU2015-6936.

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Barraza V, Grings F, Ferrazzoli P, Huete A, Restrepo-Coupe N, Beringer J, van Gorsel E, Karszenbaum H. 2014. Behaviour of multitemporal and multisensor passive microwave indices in Southern Hemisphere ecosystems. *Journal of Geophysical Research – Biogeosciences*, 2231–2244. doi:10.1002/2014JG002626.

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Colman RA. 2015. Climate radiative feedbacks and adjustments at the Earth's surface. *Journal of Geophysical Research*, 120, doi:10.1002/2014JD022896.

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OCEANS AND COASTS OBSERVATIONS, PROCESSES AND PROJECTIONS

Almar R, Kestenare E, Reyns J, Jouanno J, Anthony EJ, Laibi R, Hemer M, Du Penhoat Y, Ranasinghe R. 2015. Wave climate variability and trends in the Gulf of Guinea, West Africa, and consequences for longshore sediment transport. *Continental Shelf Research* (submitted).

Bakker DCE, Pfeil B, Smith K, Hankin S, Olsen A, Alin SR, Cosca C, Harasawa S, Kozyr A, Nojiri Y, O'Brien KM, Schuster U, Telszewski M, Tilbrook B, Wada C, Akl J, Barbero L, Bates N, Boutin J, Cai W-J, Castle RD, Chavez FP, Chen L, Chierici M, Currie K, De Baar HJW, Evans W, Feely RA, Fransson A, Gao Z, Hales B, Hardman-Mountford N, Hoppema M, Huang W-J, Hunt CW, Huss B, Ichikawa T, Johannessen T, Jones EM, Jones S, Jutterstrøm S, Kitidis V, Körtzinger A, Lauvset SK, Lefèvre N, Manke AB, Mathis JT, Merlivat L, Metzl N, Murata A, Newberger T, Ono T, Park G-H, Paterson K, Pierrot D, Ríos AF, Sabine CL, Saito S, Salisbury J, Sarma VVSS, Schlitzer R, Sieger R, Skjelvan I, Steinhoff T, Sullivan K, Sun H, Sutton AJ, Suzuki T, Sweeney C, Takahashi T, Tjiputra J, Tsurushima N, van Heuven SMAC, Vandemark D, Vlahos P, Wallace DWR, Wanninkhof R, Watson AJ. 2014. An update to the Surface Ocean CO_2 Atlas (SOCAT version 2). *Earth System Science Data*, 6(1), 69–90, doi:10.5194/essd-6-69-2014.

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Durack PJ, Wijffels SE, Gleckler PJ. 2014. Long-term sea-level change revisited: the role of salinity. *Environmental Research Letters*, 9, 11407, doi:10.1088/1748-9326/9/11/114017.

Franzke CLE, O'Kane TJ, Berner J, Williams PD, Lucarini V. 2014. Stochastic climate theory and modelling, *WIREs Climate Change*, doi:10.1002/wcc.318.

Freitas ACV, Frederiksen JS, Whelan J, O'Kane TJ, Ambrizzi T. 2015. Observed and simulated inter-decadal changes in the structure of Southern Hemisphere large-scale circulation, *Climate Dynamics*, doi:10.1007/s00382-015-2519-z.

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