Australian ClimateChange ScienceProgramme

ACHIEVEMENTS REPORT

Australian Government
Department of the Environment and Energy

CSIRO

Australian Government
Bureau of Meteorology

The Australian Climate Change Science Programme – an Australian Government initiative

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Photo: Lea Walpole

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ABOUT

The Australian Climate Change Science Programme (ACCSP) was Australia's largest and longest standing programme studying the causes, nature, timing and consequences of climate change.

The Programme began in 1989 when the Australian Government funded CSIRO and the Bureau of Meteorology to establish a national climate change research programme.

The person largely responsible for the establishment of the ACCSP is former chief of CSIRO's Atmospheric Research division, Dr Graeme Pearman. Recognising the potential wide-ranging impacts of a changing climate, Dr Pearman saw the need for a science programme that would not only provide for long-term monitoring of greenhouse gases in the atmosphere but that would also broaden our understanding of the climate system and how changes might impact on Australia. This vision was realised when, following GREENHOUSE 87, Dr Pearman headed to Canberra and worked with Government officials to produce a strategic plan to invest additional funds in climate science, and the Climate Change Research Programme was established.

Over the years the Programme was known as the National Greenhouse Science Programme, the Australian Greenhouse Science Programme, and then the ACCSP. Regardless of the name, the Programme remained both a key driver of Australia's climate change research effort and a leader in Southern Hemisphere climate science.

During the life of ACCSP, scientists and managers across many institutions drew on the support and outputs from the ACCSP to tackle diverse climate research challenges, for example, seasonal climate services at the Bureau of Meteorology, and impacts, adaptation and mitigation research at CSIRO. The Australian Research Council Centre of Excellence for Climate System Science, the Australian Antarctic Division, Antarctic Climate & Ecosystems Cooperative Research Centre and the National Climate Change Adaptation Research Facility are examples of other institutions that used ACCSP science.

The ACCSP has underpinned Australia's climate change research effort. It provided core capabilities including observations of atmospheric greenhouse gases, ocean and land carbon budgets and the Southern Hemisphere oceans, and modelling capability such as the development of our national climate and weather models, including most recently the Australian Community Climate and Earth System Simulator, ACCESS. These capabilities enabled much science and many applications such that the ACCSP made a significant contribution to the national climate change research effort beyond the size of its budget, by:

- acting as a catalyst for a larger effort within the participating research organisations
- facilitating collaboration among scientists from a range of institutions and disciplines
- feeding back into planning for the research effort at the national level
- helping to respond to policy needs for up-to-date, evidence-based information on climate matters.

With the advent of the Australian Government's National Environmental Science Programme, the ACCSP concluded in June 2016.

The legacy of the ACCSP is clear and positive. In the process of providing policy-relevant climate science for Australia, the ACCSP built the national climate science capability, supported the increasing international reach of Australian climate science, and expanded our understanding of the climate system, both global and regional.

This report highlights some of the Programme's achievements, with a particular focus on the last decade. The achievements have been drawn from a range of publications, which are available on the ACCSP legacy website at www.nespclimate.com.au/accsp.

ACCSP timeline

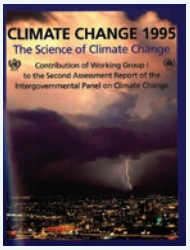
1976 — Carbon dioxide concentrations approach 350 parts per million

1987 — World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) establish the Intergovernmental Panel on Climate Change (IPCC)

1988 — IPCC publish their first assessment report

1989 — United Nations Framework Convention on Climate Change (UNFCCC) established

1990 — IPCC publish their second assessment report



1991 — GREENHOUSE 1994 conference held in Wellington, New Zealand

1992 — CSIRO publish their first climate projections for Australia

1993 — CSIRO establish the only Southern Hemisphere calibration site for global satellite sea-level monitoring in Bass Strait

1994 — Australia launched the first floats in the Argo network

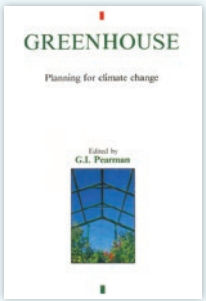
1995 — National Greenhouse Science Programme renamed Australian Greenhouse Science Programme

1996 — CSIRO publish updated climate projections for Australia

1997 — [mid-1990s] Climate Change Research Programme renamed National Greenhouse Science Programme

1998 — **Commonwealth Government grant CSIRO and the Bureau of Meteorology funds to research Australia's changing climate – Climate Change Research Programme begins**

1999

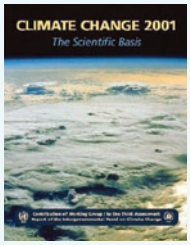


First GREENHOUSE conference held in Melbourne, Victoria

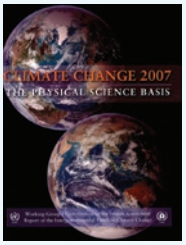
CSIRO opens the Global Atmospheric Sampling Laboratory (GASLAB) in Melbourne

Cape Grim Baseline Air Pollution Station established in Tasmania

IPCC publish their third assessment report



IPCC publish their fourth assessment report



IPCC publish their fifth assessment report

Carbon dioxide concentrations reach 400 parts per million

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016

ACCSP concludes 30 June

CSIRO and Bureau of Meteorology publish *Climate Change in Australia*, the most comprehensive assessment of Australia's future climate to date • GREENHOUSE 2015 conference held in Hobart, Tasmania

Bureau of Meteorology, CSIRO and universities join forces to develop the Australian Community Climate Earth System Simulator (ACCESS) model • GREENHOUSE 2005 conference held in Melbourne, Victoria

GREENHOUSE 2013 conference held in Adelaide, South Australia

Australian Greenhouse Science Programme renamed Australian Climate Change Science Programme

ACCESS submission to CMIP5

External review of the Australian Greenhouse Science Programme by Roy Green and Don McRae

GREENHOUSE 2011 conference held in Cairns, Queensland

CSIRO publish updated climate projections for Australia

CSIRO established Australia's network of deep ocean repeat sections (which eventually merged in to GO-SHIP) to monitor ocean change from Australian research vessels

GREEHOUSE 2009 conference held in Perth, Western Australia

CSIRO builds a 70-metre high tower at Tumbarumba in New South Wales to measure the exchange of water vapour, carbon dioxide and heat between the land and air

CSIRO and the Bureau of Meteorology publish new climate projections for Australia • GREENHOUSE 2007 in Sydney, New South Wales • External review of the ACCSP by Susan Solomon and Will Steffen

Achievements

DELIVERING SCIENCE FOR POLICY AND DECISION MAKING

ACCSP science was undertaken in close collaboration with Government priorities, providing the information needed to understand and plan for the impacts of climate, climate variability and climate change in Australia.

With a focus on the Southern Hemisphere, ACCSP research examined the atmosphere, land, ocean and large-scale climate processes that shape and affect Australia's climate, in order to provide information about policy-relevant issues including water resources, disaster management and greenhouse gas emissions.

ACCSP researchers also actively raised the profile of climate science in government circles and ensured that the latest climate science was accessible to decision makers.

Fact sheets, FAQs, information papers and summary reports were among the key publications produced through the ACCSP, on topics ranging from learning about our climate through palaeo-science, to climate variability and the El Niño–Southern Oscillation, to ocean acidification. These publications were supplemented by annual reports, technical reports and papers published in peer-reviewed journals.

Briefings, workshops and meetings all afforded face-to-face opportunities for delivery of policy-relevant ACCSP science. The GREENHOUSE conference series was key among these. GREENHOUSE conferences provided a unique opportunity for scientists and stakeholders from government and industry to come together to discuss the latest climate change science. The ACCSP was established after the first of these events, GREENHOUSE 87 in Melbourne. This was followed by GREENHOUSE 94 in Wellington, New Zealand. The next conference wasn't held until 2005 in Melbourne, then followed a series of five biennial events – in Sydney (2007), Perth (2009), Cairns (2011), Adelaide (2013) and Hobart (2015).

From a policy perspective, bringing together all of these threads of information and being able to communicate it to politicians, managers and the community has been its greatest achievement.

ANTONIO MOZQUEIRA
ACT Government Environment and Planning Directorate

A selection of the publications produced through the ACCSP


GREENHOUSE 2013
GREENHOUSE 2013


AUSTRALIAN
CLIMATE CHANGE
SCIENCE PROGRAMME
MAJOR ACHIEVEMENTS
1989–2004


AUSTRALIAN
CLIMATE CHANGE
SCIENCE PROGRAMME
STRATEGIC RESEARCH AGENDA
2004–2008


CLIMATE CHANGE SCIENCE
FREQUENTLY ASKED QUESTIONS


CSIRO

Achievements

EXTENDING THE INTERNATIONAL REACH OF AUSTRALIAN CLIMATE SCIENCE

The ACCSP enabled Australian researchers to be active participants and leaders in the international climate science community, enhancing the global reputation of Australian science and scientists, and leveraging international research for Australia's benefit.

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

ACCSP researchers played leading roles in international bodies such as the International Geosphere-Biosphere Programme and the Global Carbon Project. Australia's contribution to the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP) – developed under ACCSP projects – meant that Australia was able to be an informed user and reviewer of modelling outputs produced by teams around the world.

The ACCSP also supported Australia's participation in global observation programs such as the International Argo Project, the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), Global Atmospheric Watch (GAW), the Global Ocean Acidification Observation Network and the global flux network and database (FluxNet).

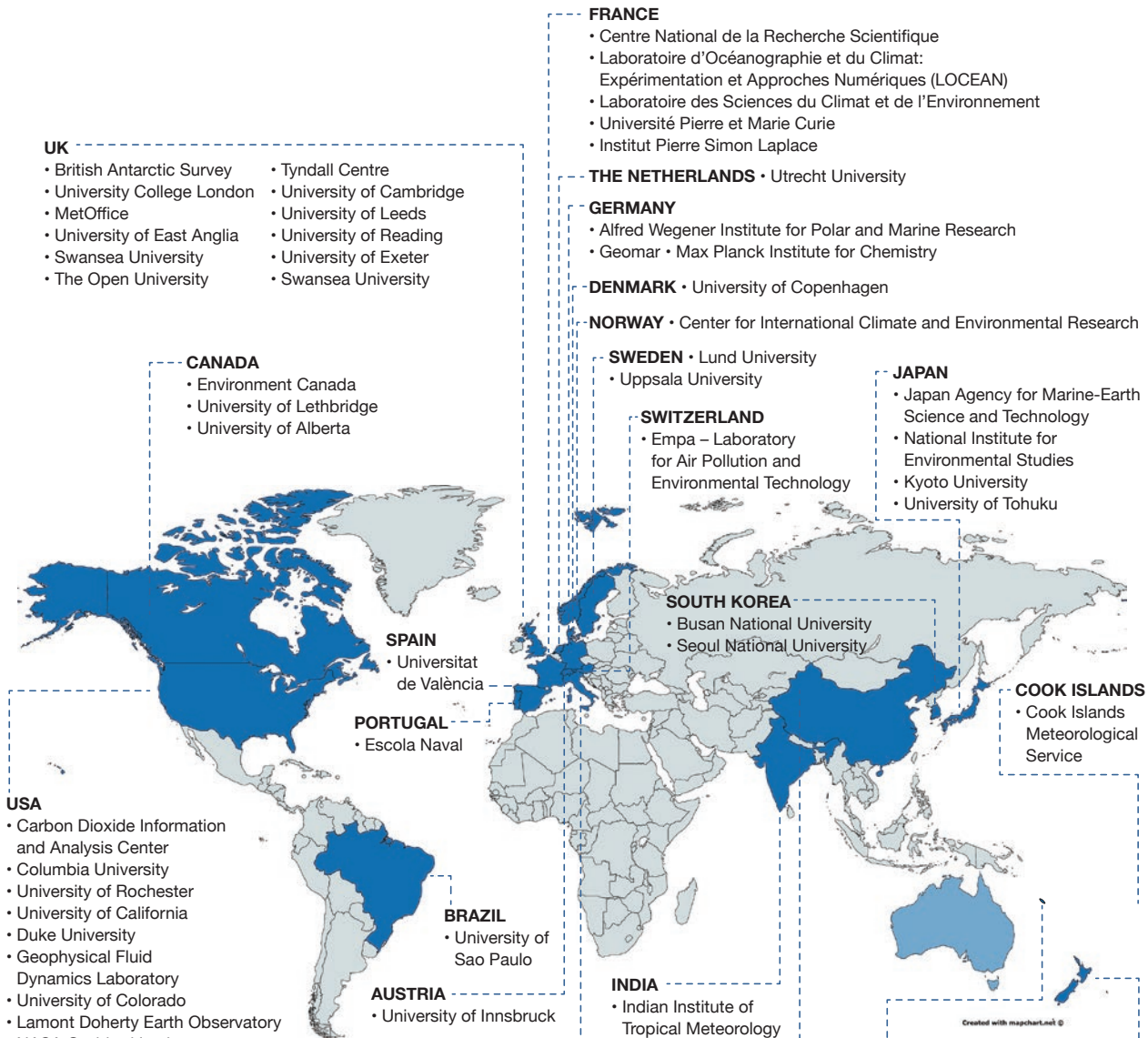
ACCSP researchers contributed to the Intergovernmental Panel on Climate Change (IPCC) as authors of assessment reports and through dozens of cited publications. As with earlier IPCC assessments, the Fifth Assessment Report includes extensive citations of ACCSP research in the Working Group I and II reports. Seven ACCSP researchers contributed as either coordinating lead authors or lead authors, and many other ACCSP researchers contributed to the report's content and review.

The knowledge that Australian scientists and government funding contribute to global science makes us proud. It would be an embarrassment if that ongoing contribution isn't there. We're part of the world team.

GEOFF WITHYCOMBE
Sydney Coastal Councils Group Inc.

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

SOME OF OUR INTERNATIONAL COLLABORATORS



Achievements

BUILDING NATIONAL CLIMATE CHANGE SCIENCE CAPABILITY

The ACCSP helped develop a climate research capability in Australia by funding critical infrastructure, helping build the climate research community, and paving the way for climate change science outside of the Programme.

Infrastructure

With the establishment of the ACCSP in 1989, funding was available to set up CSIRO's world-class GASLAB/ICELAB facility at Aspendale, south of Melbourne. GASLAB (Global Atmosphere Sampling laboratory) contains sensitive, state-of-the-art equipment that detects oxygen, carbon dioxide, nitrous oxide, methane, carbon monoxide, hydrogen and chlorofluorocarbons in air samples collected at the Cape Grim Baseline Air Pollution Station in Tasmania, and from around the world. The work carried out in this lab is critical for calibration and quality control across the entire CSIRO greenhouse gas network. Across the hall, in the ICELAB (Ice Core Extraction laboratory) air samples are recovered from polar ice cores, then analysed in GASLAB.

The ACCSP supported the maintenance and operation of two flux stations as part of OzFlux, the Australian flux network. These stations – one in a cool, temperate tall eucalypt forest in south-eastern New South Wales, and the other in a tropical wet/dry savanna in northern Queensland – continuously measure the exchange of carbon dioxide, as well as water and heat, between the atmosphere and the terrestrial surface. The results have improved our understanding of the interactions between climate, hydrology and carbon cycling in Australian ecosystems and their variability. This has, in turn, informed the development of better biosphere-climate models and provided key information for managing water and carbon resources in a variable and changing climate.

These were profoundly enabling programs – the basic infrastructure around observations and modelling are irreplaceable and important contributions from the ACCSP.

ANDY PITMAN
ARC Centre of Excellence for Climate System Science

Research community

The ACCSP facilitated conversations on the climate system, climate change science and regional adaptation, building a strong climate research community over many years.

As well as serving as a conduit for collaboration, the ACCSP provided training and a local path for career development that enabled graduate students to contribute to increasing Australian research capability. A number of these young researchers are now recognised leaders in their fields.

What the ACCSP did, in my view, was to build a community and resource a research backbone that actively fostered cross-linkages that made the whole much greater than a sum of parts.

TAS VAN OMMEN
Australian Antarctic Division

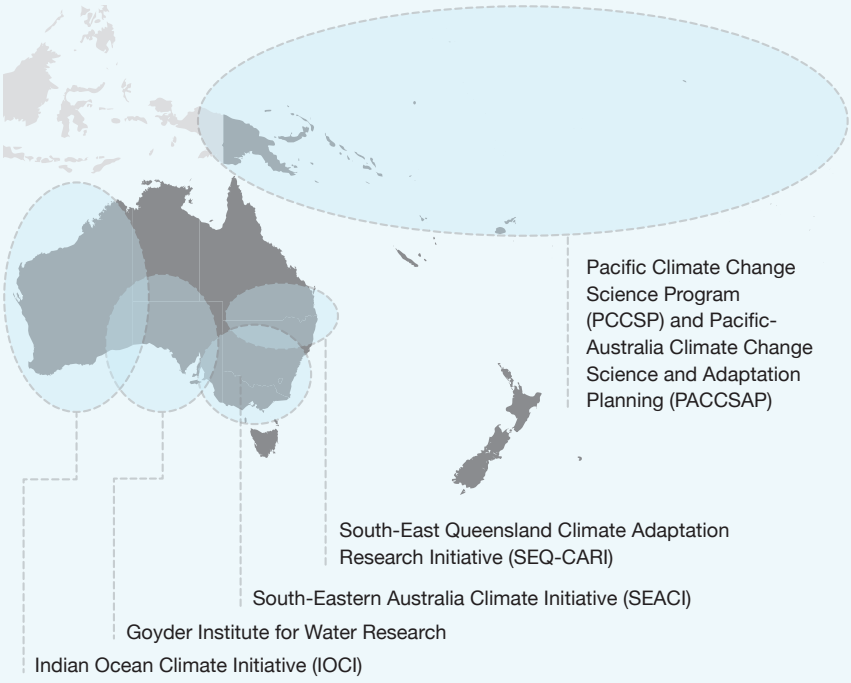
Regional programmes

The climate research capability developed in the ACCSP paved the way for, and facilitated the development of a host of regional programmes that have increased our understanding of climate change. These include:

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

ACCSP funding also provided leverage for CSIRO and the Bureau of Meteorology to conduct climate research beyond that directly funded through the Programme. This had flow-on effects to other bodies, such as the Antarctic Climate & Ecosystems Cooperative Research Centre (ACE CRC) and the National Climate Change Adaptation Research Facility (NCCARF), which were able to take advantage of consequent research results and collaborative research opportunities.

RESEARCH PROGRAMMES BUILT ON ACCSP FOUNDATIONS



Achievements

DEVELOPING A NATIONAL CLIMATE MODELLING CAPABILITY

The ACCSP supported the improvement of Australia's climate models, culminating in the development of the Australian Community Climate and Earth System Simulator (ACCESS), our national climate model.

At the time that the ACCSP was established, Australia's climate modelling capability was limited – mirroring the relatively primitive status of global climate modelling at the time. These early models were very coarse in their resolution, and included relatively few climate system processes. Moreover, most global climate models had been developed in the Northern Hemisphere and so did not reflect conditions and processes in the Southern Hemisphere very well. Models also tended to only focus on one component of the climate system—such as the atmosphere or ocean—even though in the real world these components are strongly coupled with each other.

ACCSP funding has been crucially important in developing global climate models that better represent the features of the climate system, particularly for the Australian region. This has been achieved by the development of coupled models, as well as by gaining better understanding of natural systems and processes, and translating this knowledge and information into models.

A significant advance in this area, strongly underpinned with ACCSP resources has been the development of ACCESS since 2005. Bringing together the climate observations, research and modelling capability of the Bureau of Meteorology, CSIRO, Australian universities and international researchers, ACCESS is a national weather, climate and Earth system simulation capability that is suited to Australian needs.

What are the top scientific achievements? ACCESS, ACCESS, ACCESS.

MARK GIBBS
Queensland University of Technology

Two configurations of the ACCESS global coupled model (ACCESS 1.0 and ACCESS 1.3) were Australia's primary submission to the Coupled Model Intercomparison Project phase 5 (CMIP5), where they were shown to be among the top performing models across a range of metrics, including those of greatest relevance to climate in the Australasian region. CMIP5 simulations were used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

The ACCESS Earth system model (ACCESS-ESM1) is the first version of ACCESS to include carbon cycling, so can simulate changes in land and ocean productivity due to different emissions and mitigation strategies. This allows simulations exploring what the impacts and feedbacks may be on key sectors of the Australian economy. Evaluation of a fully interactive atmospheric chemistry module within ACCESS has further extended ACCESS's capability.

Development of the ACCESS global climate and Earth system models continues, in preparation for the Australian modelling contribution to the IPCC Sixth Assessment Report, and the associated CMIP6 international modelling project.

The ACCSP also supported the development of downscaling techniques. These techniques allow us to 'zoom in' on regional climate change from the relatively coarse resolution of global climate model output, by including the effect of local climate processes such as coastal and mountain effects. Downscaling provides more detailed information about the changes likely to be experienced at a community level.

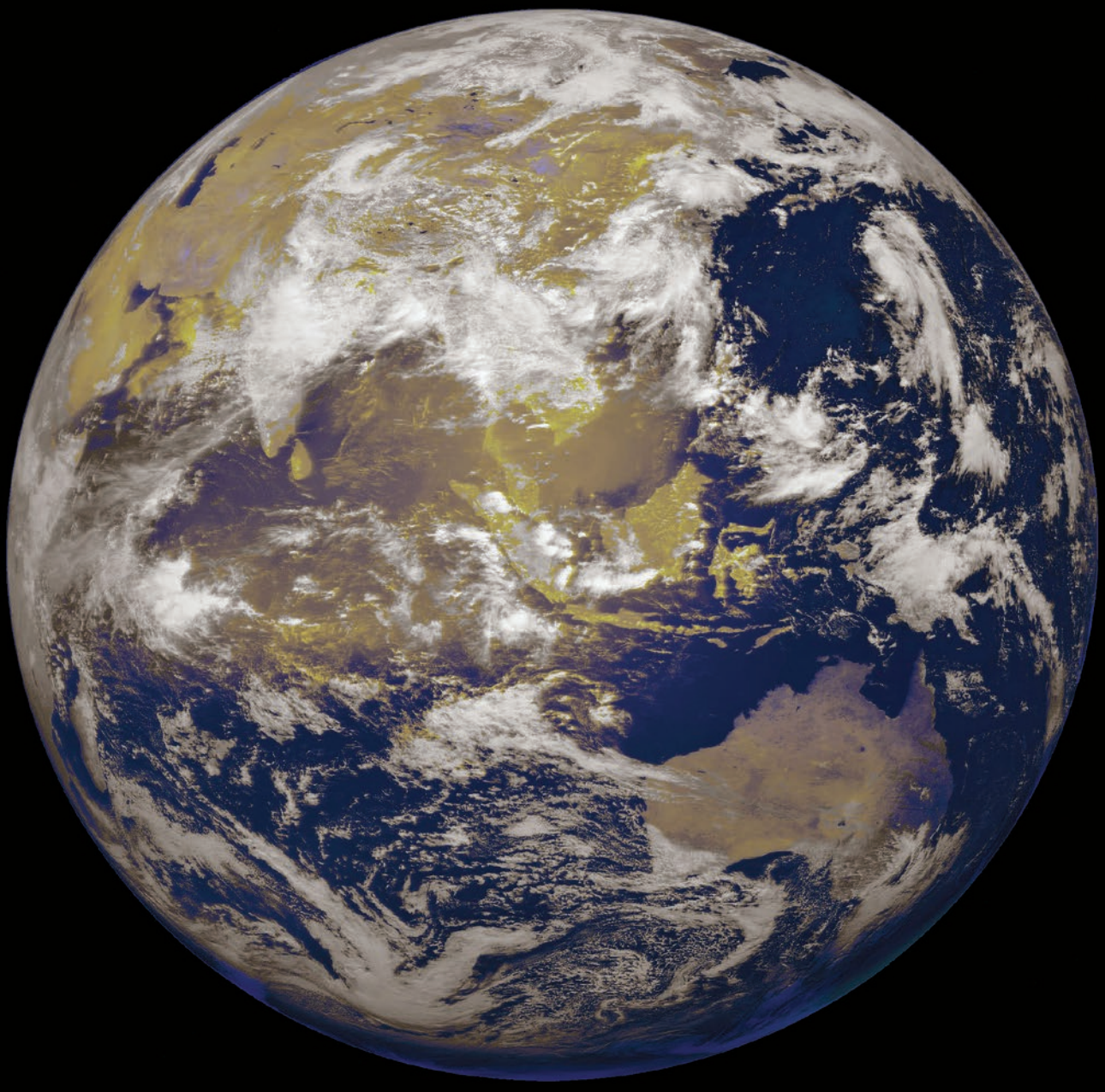


Image: Bureau of Meterology

Achievements

ENABLING CLIMATE PROJECTIONS FOR AUSTRALIA

ACCSP investment has allowed the generation of climate projections that are used by governments, industry and communities to plan for and adapt to our changing climate.

Advances in our understanding of climate processes and the climate system, and our evaluation of the strengths and weaknesses of climate models resulting from ACCSP research, allowed the development of national climate projections capability for Australia. This includes the science, the approaches and the projections themselves. This has been very important in building the nation's preparedness for climate change and information needed for regional adaptation plans.

Through the ACCSP, researchers in CSIRO's climate impact group developed the first climate change scenarios for Australia in 1992, with updated scenarios released in 1996, 2001 and, in collaboration with the Bureau of Meteorology, in 2007.

ACCSP science underpinned the 2015 climate projections prepared by CSIRO and the Bureau of Meteorology, that were funded through the Regional Natural Resource Management Planning for Climate Change Fund. These projections, which draw on improvements in climate models and our understanding of climate processes, are the most comprehensive to date and include more climate variables and greater regional information that earlier projections.

The ongoing development of national climate projections would not have been possible without ACCSP research on projections science and methodologies, model evaluation, downscaling and regional projections. This science has resulted in robust, credible projections to inform adaptation activities and mitigation policy.

The 2015 climate change projections, as well as earlier ACCSP projections in 1990, 1992, 2007, have allowed for improved understanding of climate impacts, and outreach to stakeholders who need the information for decision making.

DAVID KAROLY
University of Melbourne

Climate Change in Australia
(2015 projections)
www.climatechangeinaustralia.gov.au

ADVANCING OUR UNDERSTANDING OF THE CLIMATE SYSTEM: **GREENHOUSE GASES AND CARBON**

ACCSP research provided information on changes to greenhouse gas emissions and concentrations, and how these affect our environment, as well as improving our understanding of the global and regional carbon cycles.

Carbon budget

Through the Global Carbon Project, the ACCSP has supported the production of the annual carbon budget (since 2005) and the development of the online global carbon atlas (in 2013). Both are important tools for understanding and communicating the global carbon budget – including trends in global carbon emissions and emission intensities, what this means for future climate change, and for informing decisions about mitigation.

Global Carbon Project
www.globalcarbonproject.org
Global Carbon Atlas
www.globalcarbonatlas.org

The capacity of the terrestrial carbon sink was demonstrated in ACCSP-supported research that found that, despite widespread droughts and increasing global temperatures, globally, land is greener today that it has been over the past three decades ago due to the carbon dioxide fertilisation effect on plant growth.

ACCSP research provided insights into the Australian carbon budget. Through ACCSP funding, the first comprehensive full carbon balance for the Australian continent was produced in 2013. This showed that on a unit-area basis, the Australian terrestrial carbon sink operates at only 40 per cent of the strength of the global average sink.

Southern Ocean carbon sink

The Southern Ocean is one of the most important regions on Earth for removing carbon dioxide from the atmosphere. ACCSP research improved our understanding of the role of the Southern Ocean in the uptake of carbon dioxide and its effect on the global carbon budget.

Researchers found evidence of a small reduction in the efficiency of the ocean carbon dioxide uptake in winter months, consistent with a weakening of the Southern Ocean carbon sink. Related work also identified how physical processes, including ocean currents and winds, combine to produce regions in the Southern Ocean where water containing carbon dioxide produced by humans is carried into the deep ocean.

ACCSP supported Australia's participation in the initial development and updating of the surface ocean carbon dioxide atlas—this is the major database for detecting changes in the ocean carbon sink and for testing ocean carbon cycle models.

Surface Ocean CO_2 Atlas
www.socat.info

Examining past climate

ACCSP researchers used air measurements from ice cores, firn (the upper layer of ice sheets), air archives and direct atmospheric observations to prepare long-term greenhouse gas concentration data for driving model simulations of climate, carbon and chemistry.

Ice core studies have not only extended our records of the concentration of carbon dioxide in our atmosphere, but also offered insights into past impacts of changing carbon dioxide concentrations. ACCSP-supported research showed that the land ecosystem was responsible for the carbon dioxide reduction during the Little Ice Age, a period from the 15th to 19th centuries of modest cooling – less than 1 °C relative to late 20th century levels – of the northern hemisphere. Air extracted from Antarctic ice cores also showed a positive feedback between climate and the carbon cycle: warming results in more carbon dioxide in the atmosphere, which results in further warming.

Non-carbon dioxide greenhouse gases

ACCSP-supported research found that non-carbon dioxide emissions from global food production are becoming bigger players in climate change. Emissions from the global food system (methane, nitrous oxide and carbon dioxide) are equivalent to more than half of the emissions from fossil fuels.

Ice core studies supported by the ACCSP extended our records of the concentration of other important gases in the atmosphere, including nitrous oxide, methane, and halons and perfluorocarbons. This work provided new insights into changes in atmospheric composition.

ADVANCING OUR UNDERSTANDING OF THE CLIMATE SYSTEM: **LAND AND AIR**

The ACCSP investigated terrestrial and atmospheric climate processes so we can better understand their influences, and how they may change in a changing climate.

Terrestrial ecosystems

Data collected through the OzFlux network (see page 10) has provided important information about interactions between terrestrial carbon and water cycles and the climate in Australian ecosystems, and improved the modelling of these processes.

ACCSP researchers studying flows of carbon, energy and water into and out of Australian ecosystems found that Australia's plant carbon uptake is highly variable and changes considerably in response to short-term climate fluctuations. For example, the normally strong carbon uptake in the productive eucalyptus forests of south-east Australia was found to reverse, to become a carbon source, during the 2012/13 summer (with high temperatures and low rainfall). This forest recovered after rains and started sequestering carbon again. ACCSP researchers also found that in Australia, the savannas (grassy woodlands and grasslands) in the east of the continent make the greatest contribution to variability in net carbon uptake. This variability, due to variations in productivity of the eastern savanna, is linked to variable rainfall, driven predominantly by the El Niño–Southern Oscillation.

Information for understanding the flows, reservoirs, and interactions of carbon and water in the Australian landscape is available through the Carbon Water Observatory, an online portal developed with the support of the ACCSP. The ACCSP also supported the development of the modelling system that underpins the portal and provides our key infrastructure for understanding the coupled carbon and water cycles in the Australian landscape.

Carbon Water Observatory
http://carbonwaterobservatory.csiro.au

The ACCSP supported research at the OzFACE facility in north-eastern Queensland, which was established to examine the impacts of carbon dioxide and climate change on tropical savannas. A free-air carbon dioxide enrichment (FACE) system was set up to allow researchers to manipulate carbon dioxide levels over unenclosed plots of savannah. Monitoring the growth of vegetation under different treatments, researchers concluded that rising carbon dioxide levels are likely to favour the establishment and growth of woody plants, at the expense of grass production, in Australian savannahs.

Aerosols

Aerosols are fine particles suspended in the atmosphere, which tend to exert a cooling effect on the climate. They occur naturally from volcanoes, dust storms and pollen, and are also generated by humans from industry, motor vehicles and vegetation burning. Soot, dust, smoke, sulfates and other pollutants are all aerosols.

ACCSP research helped us to better understand the behaviour of aerosols and how they influence our climate. For example, circulation systems that are important for Australia's climate – such as the subtropical jet – are sensitive to changes in aerosol emissions from the northern hemisphere, as are projected changes in rainfall.

Researchers found that aerosols offset the effects of increasing greenhouse gases, which would otherwise be causing a decrease in rainfall in north Western Australia. They also found that aerosols partly offset the southward shift of the southern mid-latitude pressure ridge due to greenhouse warming, reducing the change in the prevailing westerly winds and associated rainfall patterns.

In general, aerosols offset around a third of global warming. With aerosols projected to reduce from current levels, this 'cooling' effect will decline.

Understanding climate feedbacks

Climate feedbacks are responsible for around half the uncertainty in climate change projections at global scales. A climate feedback is a change to a large-scale climate feature, such as the amount and distribution of water vapour, snow, sea ice or clouds, which increases or reduces the climate response to any changes in greenhouse gases generated by humans.

Research supported by ACCSP showed that feedbacks associated with natural climate variability are of similar strength to those operating under climate change, opening the potential for evaluation of feedbacks from observations.

Cloud feedbacks were a particular area of ACCSP research. Clouds play a very important role in the climate system and, depending on their altitude, can have either a positive or negative feedback on the system. High altitude clouds reflect more heat back to Earth, warming it (positive feedback) while low altitude clouds reflect solar radiation back into space, cooling the Earth's surface (negative feedback). ACCSP researchers improved our understanding of cloud feedbacks and how they may change in the future, which helps us to understand the range in climate projections.

ACCSP research has improved our understanding of the relationship between aerosol production and cloud formation. Observations over the Southern Ocean have shown that the presence of aerosols altered the optical properties and lifespan of clouds in the region.

ADVANCING OUR UNDERSTANDING OF THE CLIMATE SYSTEM: **OCEANS AND COASTS**

ACCSP research has resulted in substantial progress in understanding the behaviour of the oceans surrounding our continent and their role in the climate system.

Monitoring and data collection

The ACCSP supported Australia's involvement in the Argo Project, a major international collaboration to observe the world's oceans. Argo consists of a global array of robotic floats that drift at depths of between one and two kilometres, regularly measuring temperature and salinity. Argo has now collected over a million profiles of ocean temperature and salinity.

International Argo Project
www.argo.net

Argo temperature data showed that global ocean warming continued over the period 2006–14, despite an apparent slow-down in the rate of global surface atmospheric warming.

Analysis of changing salinity patterns in the oceans during the past 50 years indicates that global rainfall and evaporation – the water cycle – has changed: oceanic dry regions have become drier and wet regions have become wetter in response to global warming.

The ACCSP also supported Australia's participation in the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), a coordinated global program to collect ship-based observations. Data collected in this program is used to benchmark data that is collected autonomously, such as from the Argo program. As a result of GO-SHIP participation, we have a long-term record of ocean heat and carbon content at the western boundary of the Pacific, along a survey line extending from the ice edge to the equator. This record is critical for tracking deep ocean changes.

GO-SHIP www.go-ship.org

Ocean processes and currents

The ACCSP supported investigations of ocean processes and currents, which advance our understanding of how the oceans, particularly in the Southern Hemisphere, store and transport heat and carbon.

ACCSP research showed how the Southern Ocean links the circulation of the major ocean basins, connects the surface and deep ocean as part of the 'ocean conveyor belt' and absorbs vast amounts of carbon dioxide, strongly influencing global circulation patterns and climate. Researchers also determined the strength of the Southern Ocean overturning circulation (the circulation of seawater driven by changes in the heat and water density) and highlighted the sensitivity of this circulation to climate change.

Oceanographers supported by the ACCSP have measured the strength of the Antarctic Circumpolar Current and the Indonesian Throughflow, a movement of warm, low salinity waters from the tropical Western Pacific through the Indonesian seas into the Indian Ocean. They have also observed changes to ocean currents, extending deep below the ocean surface. Profiles of the East Australian Current, the Leeuwin Current in Western Australia, and the Southern Ocean help us understand what these changes are and what they mean for marine ecosystems, coastal populations and climate.

Sea-level rise

ACCSP collaborative international research found that the two largest contributions to observed sea-level rise since 1972 came from ocean thermal expansion (about 40 per cent) and glacier melting (another 35 per cent). The remaining sea-level rise comes from changes in the ice sheets and land storage in reservoirs and extraction of groundwater from aquifers.

ACCSP research demonstrated continuing global mean sea level rise and determined that the larger rate of sea-level rise since 1993 is largely a result of changes in natural forcing of climate and ongoing anthropogenic greenhouse gas emissions. Regional sea-level rise due to climate change is likely to exceed the natural variability range within the next two decades.

Coasts

ACCSP researchers provided regional projections of sea-level rise from 1996 to 2100 for the Australian coastline, and determined sea-level allowances, the height by which coastal property must be raised so that the risk of coastal inundation does not increase.

Researchers found that changes to extreme sea levels and coastal currents are likely to be greatest where large changes in wind speed and direction are projected to occur.

The ACCSP supported the extension of the CSIRO global dynamical CMIP5-derived wind-wave climate model to enable uncertainty in wave climate studies to be investigated. ACCSP researchers led an international working group that led efforts to understand wave climate change and variability, and developed global and Australian hydrodynamic and wave climate projections.

Ocean acidification

Carbon dioxide uptake (see page 16) is causing ocean acidification, which is predicted to cause widespread disruption to marine ecosystems, including in the Southern Ocean and the Great Barrier Reef. Modelling by ACCSP researchers using ACCESS has shown that in little more than 50 years, it is likely that much of the ocean around Australia will no longer be suitable for coral formation due to increasing acidification.

ACCSP ocean research has provided key data for assessing acidification change, the associated risk to ecosystems in our region, and for testing models used to predict ocean carbon dioxide uptake. In fact, in 2014/15, ACCSP research was the only Australian effort delivering information on the rate of change of ocean acidification in the ocean around Australia. Without this research, the first estimates of ocean acidification change around Australia and through the Great Barrier Reef would not have been possible.

ADVANCING OUR UNDERSTANDING OF THE CLIMATE SYSTEM: **CLIMATE DRIVERS, VARIABILITY AND EXTREMES**

ACCSP research transformed our understanding of the drivers of Australian climate variability and their causes, and how they may change in a changing climate.

El Niño–Southern Oscillation

The El Niño–Southern Oscillation (ENSO) 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. However, a 1000-year climate simulation by ACCSP researchers showed that the Australian impacts of El Niño/La Niña events vary over time.

ACCSP research showed that La Niña affects low-pressure systems, providing a possible explanation for two extreme flooding periods in January 1974 and January 2011.

ENSO's influence over southern Australia was shown to be conducted through the Indian Ocean via large scale atmospheric waves. Prior to this ACCSP research, the process whereby an El Niño causes the drier conditions was not well understood.

ACCSP researchers also showed that the Walker circulation, one of the world's largest and most important wind systems, which profoundly influences climate in Australasia and beyond, weakened markedly over the 20th century. Internally-generated climate variability caused approximately half of the weakening, with the remainder from a combination of human activities, volcanoes and solar radiation changes. In recent decades there has been a re-strengthening of the circulation that is at least partially driven by the Interdecadal Pacific Oscillation, but further research is needed to understand this.

ACCSP researchers investigating the 2011 marine heatwave that caused the first recorded coral bleaching event in Western Australia's Ningaloo Reef found that these 'Ningaloo Niño' events occur in strong La Niña years. Using coral proxy records, researchers also determined that the 2011 Ningaloo Niño was unprecedented in 200 years.

In a warming climate, the impact of El Niño on tropical rainfall is likely to intensify, and the frequency of extreme El Niño events will increase. Greenhouse warming also leads to more frequent extreme La Niña events, and to more frequent consecutive extreme climate events (an extreme El Niño preceded by an extreme positive Indian Ocean Dipole event and followed by an extreme La Niña).

Indian Ocean Dipole

At the outset of the ACCSP, we did not know about the Indian Ocean Dipole, a cycle in which the region of peak sea-surface temperature swings back and forth between the eastern and western Indian Ocean. During the positive phase of this cycle, warmer than normal waters in the western Indian Ocean change the path of weather systems coming from Australia's west. As a result, parts of Australia experience less rainfall and higher temperatures during winter and spring.

Drawing on observations and climate model simulations, ACCSP researchers showed that the positive Indian Ocean Dipole affects bushfire risk and severe droughts over south-east Australia. They also showed that the frequency of extreme Indian Ocean Dipole events is expected to increase over the 21st century in response to high greenhouse gas emissions.

Australian monsoon

The pronounced seasonal rainfall cycle of the Australian monsoon is a critical feature for northern Australian climate. ACCSP research found that El Niño–Southern Oscillation changes and warming over the Indian Ocean may lead to delay in the onset of the Australian monsoon in the future. Research also determined that the Australian monsoon system could become more variable from year-to-year by the end of this century due to increasing greenhouse gas emissions.

Extreme climate events

ACCSP research on east coast lows showed that these weather systems are the sole cause of waves that are seven metres high or higher along the central and southern parts of Australia's east coast. Researchers also showed that under high greenhouse gas emissions, there will be up to 25 per cent fewer east coast lows by the end of the century.

Lightning is responsible for a significant proportion of the area burnt by bushfires. ACCSP researchers developed a method for examining conditions favourable to dry lightning which, when applied to a global climate model, allowed them to examine the changes in

these conditions in the future. They found that the changes are variable between seasons and regions.

ACCSP has improved our understanding of tropical cyclone formation. Researchers found strong regional differences in favourable conditions for tropical cyclone formation across the broader Australian region and, further to this, developed a method to identify the geographic boundaries for regions where tropical cyclones can and cannot form. Tropical cyclone projections using this method show a strong decrease in tropical cyclone numbers in the west, but a possible increase or little change in the east towards the end of the century.

Attribution

Understanding the underlying mechanisms of climate drivers, climate extremes, climate change and regional weather systems is important in order to understand whether any trends in rainfall and weather systems throughout Australia are predominantly ongoing or random.

ACCSP research has shown that human activity is changing the weather: Southern Hemisphere winter circulation changes have been driven by temperature deviations from the long-term average that are largely due to increasing greenhouse gases, and the prolonged trends in rainfall over south-west Western Australia in winter and north-west Australia in summer are likely the result of external influences such as changes in greenhouse gases, ozone and aerosols.

The Southern Annular Mode 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. ACCSP research showed that its recent trend toward the positive phase, when it is contracted towards Antarctica, is due to increasing carbon dioxide in the atmosphere.

ACCSP researchers also detected a climate change signal in Australian rainfall variability, and Pacific warming.

Attributing the causes of single weather or climate events is difficult because each event is unique; however, ACCSP researchers have been at the forefront in developing methodologies for the determination of extreme weather attribution. For example, ACCSP research determined that an extreme heat event in October–November 2014 was due to the influence of carbon dioxide, while the record Australian temperatures in September 2013 were the result of a combination of a highly unusual atmospheric circulation pattern, background warming caused by increasing greenhouse gas emissions, and the preceding dry and warm land-surface conditions.

THE NEXT PHASE OF AUSTRALIAN CLIMATE CHANGE SCIENCE

The ACCSP laid a solid foundation for Australia's climate science research in the 21st century.

The Earth Systems and Climate Change Hub was established in 2015, and began its research program in July 2016, at the conclusion of the ACCSP.

The Hub is a partnership of Australia's leading Earth systems and climate change research institutions:

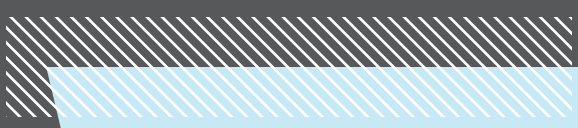
- CSIRO
- Bureau of Meteorology
- University of New South Wales
- Australian National University
- Monash University
- University of Melbourne
- University of Tasmania.

Hosted by CSIRO, the Earth Systems and Climate Change Hub is one of six hubs supported by funding through the National Environmental Science Programme, the Australian Government's long-term commitment to environment and climate research.

The Hub will develop our understanding of Australia's past, present and future climate to help address major challenges that the changing climate poses for Australia. These challenges encompass water, food, natural resources and the environment, coasts, natural disasters and greenhouse gases.

Like the ACCSP before it, the Hub will forge close ties with the Australian and global research community, to ensure that Australia's policies and management decisions are effectively informed by Earth systems and climate change science, now and into the future.

Earth Systems and Climate Change Hub www.nespclimate.com.au



Australian Climate Change Science Programme (ACCSP)
www.nespclimate.com.au/accsp