AUSTRALIAN CLIMATE CHANGE SCIENCE PROGRAMME

MAJOR ACHIEVEMENTS

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MINISTER'S FOREWORD

Australian scientists are at the forefront of building understanding of climate change, particularly as it affects Australia and the surrounding region.

Research work funded by the Australian Government and carried out by our leading climate change scientists over the past 15 years has proven a great investment. Today, climate change science demonstrates conclusively that human activity is changing the Earth's climate system.

This publication documents the achievements of our scientists since 1989. This in turn has increased Australia's capacity to both respond to climate change locally and to contribute soundly to the ongoing international climate change efforts.

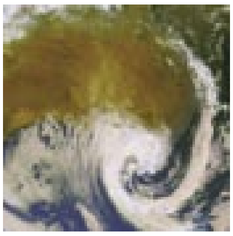
The Australian Government recognises the world class contribution made by Australian scientists in progressing our understanding of climate change and its impacts on the southern hemisphere.

This publication is designed to complement its partner publication Australian Climate Change Science Programme – Strategic Research Agenda 2004-2008.

I am delighted to recommend these publications to you as valuable resources in both documenting the significant progress made so far in Australian scientific research and also charting the way forward as we face the challenges of climate change in our region in coming years.

Senator the Hon. Ian Campbell

Australian Minister for the Environment and Heritage



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PREFACE

The Australian Climate Change Science Programme

This document outlines the major achievements of Australia's Climate Change Science Programme – a key science investment of the Australian Government since 1989.

The Programme is funded through, and administered by, the Australian Greenhouse Office in the Department of the Environment and Heritage. Major science providers and co-investors in the Programme are the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Bureau of Meteorology Research Centre (BMRC). The Australian Academy of Science participates by providing links to key international programmes.

The Australian Climate Change Science Programme is the critical core and driver of climate change science in Australia. The research effort has significantly advanced our understanding of the climate system and the processes that affect global and regional climate. This vital information has enhanced the capacity of governments, business and the community to respond to climate change and has underpinned Australia's international negotiating strength and domestic policies and measures.

The Programme contributes to the delivery of Australia's National Research Priorities for An Environmentally Sustainable Australia.

An independent evaluation in 2003 assessed the Programme as "highly effective and efficient and observed that it exerts substantial domestic funding leverage, particularly from the research partners". Importantly, the Programme has influenced the national research activity by priority setting and consequent leveraging of both the direction and allocation of resources by government agencies, universities and cooperative research centres.

The evaluation noted that, although modest in scale, the Programme has supported a strong level of engagement in the international research effort. Australia has derived measurable benefits from contributing to international climate change science forums that greatly exceed the dollar value of Australian input. The credibility achieved by our scientists, world-leading in several areas, has enabled Australia to influence the priorities for greenhouse research at the global scale and leverage research input from other countries to our benefit. For example, the high quality and prominence of Australia's Southern Ocean research has attracted more than US$5m of overseas investment in experiments in the Australian sector in recent years.

Through the Programme, Australia demonstrates leadership and expertise in southern hemisphere climate research.

1. INTRODUCTION

1.1 The climate system

A key question for the world is no longer “Will the climate change?” but rather “How will it change?”

Climate has shaped our world - our environment, economy and our way of life. Changes in climate, whatever the cause, have significant implications for our region and the global community. The climate of the world, and Australia, has always varied, both year-to-year and over millions of years. Our climate will continue to change in the future.

Our capacity to provide scientifically-based forewarning as to the nature and probability of climate change is essential for sound risk assessment and strategic planning. This is not an easy task. Climate is the result of the complex interaction of many processes and interactions between the oceans, atmosphere, biosphere and cryosphere (ice, snow and permafrost) which generate variations on year-to-year, inter-decadal and century timescales (Figure 1). Increasingly sophisticated computer models are required to investigate and understand this complexity, the feedbacks between these climate components, and their vulnerability to disturbance and change.

It can be argued that there is much to be gained from progressing this understanding for the management of natural variations in the climate system, especially in Australia. However, we are now aware that the most probable and influential climate variation this century is one that we are generating ourselves - through our impact on the composition of the global atmosphere resulting from greenhouse gas emissions associated with human activities. Thus there is an even greater urgency for the development of understanding and incorporation of this understanding into policy development.

All regions of the world will be impacted in some way by both the direct effects of a changed climate, and the indirect effects arising from the range of institutional, legal, social, and economic responses different countries will need to make to minimise the risks associated with climate change.

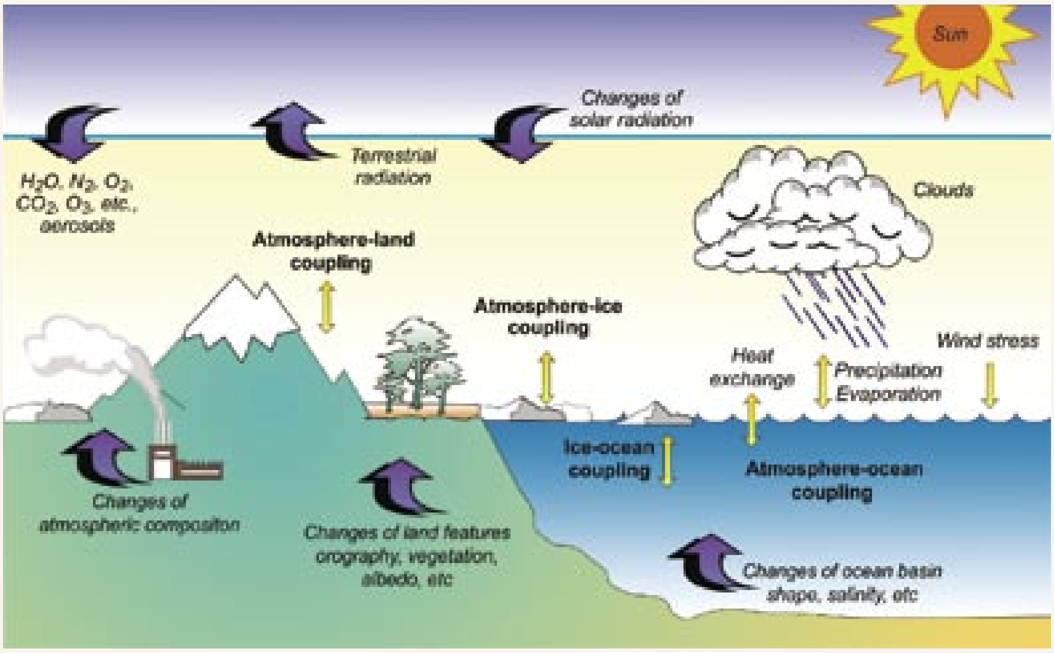
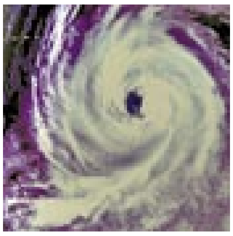
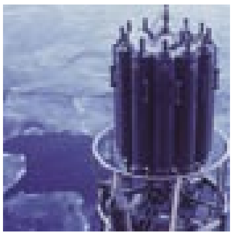


Figure 1: The global climate system (CSIRO).





1.2 Climate change assessment

The presence of certain gases in the atmosphere trap heat and cause the planet to be about 30°C warmer than it would otherwise be. This natural phenomenon is referred to as the 'greenhouse effect' and the gases (for example carbon dioxide) as 'greenhouse gases'. The influence of atmospheric carbon dioxide as a greenhouse gas was recognised as early as 1896. During the 1930s it was suggested that concentrations of carbon dioxide might be increasing due to the burning of fossil fuels. In the late 1950s, systematic measurements showed this to be the case. Climate change due to increases in greenhouse gases is referred to as the 'enhanced greenhouse effect'.

In the mid-1980s two major international reports on the possible impacts of rising atmospheric carbon dioxide (from a committee of the International Council of Scientific Unions and the Villach conference, WMO 1986), led to the establishment in 1992 of the United Nations Framework Convention on Climate Change (UNFCCC). In 1988, the World Meteorological Organisation and the United Nations Environment Programme set up the Intergovernmental Panel on Climate Change (IPCC) to underpin the deliberations of the signatories to the Convention with respect to the rapidly developing science.

The IPCC provides a very important bridge between scientists and governments, involving several thousand experts from around the world (see www.ipcc.ch). Its purpose is to assess scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation. The IPCC has issued three major Assessment Reports (published in 1990, 1995 and 2001).

The Third Assessment Report was published in 2001, with its main conclusions remaining valid and in many cases strengthened by more recent research. It concluded that:

- global warming has taken place over the last century, and that new and stronger evidence suggests that most of the warming over the last 50 years is attributable to the increase in greenhouse gas concentrations resulting from human activities;
- the atmospheric concentration of carbon dioxide has increased by 32 per cent since 1750. The present concentration (about 380 ppm) has not been exceeded during the past 420,000 years and likely not during the past 20 million years. The current rate of increase is unprecedented during at least the past 20,000 years; and
- the 1990s was the warmest decade in the last 1000 years, at least in the northern hemisphere. Other observations are consistent with this observed warming, including a rise in global average sea level (10 to 20 cm in the 20th century) and ocean heat content, and decreases in snow cover and ice extent, both in mountain glaciers and Arctic sea ice.

With respect to the future, the IPCC stated that it is likely there will be:

- higher maximum temperatures and heat indices over many land areas, and reduced frequency of low temperatures, including frosts;
- more intense precipitation events over many mid-to-high latitude land areas;
- increased summer continental drying and associated risk of drought in mid-latitudes;
- more intense tropical cyclones with higher peak winds and rainfall intensities; and
- changes in the frequency and intensity of other patterns of climate variability, including the El Niño-Southern Oscillation (ENSO).

The IPCC Third Assessment Report notes several possibly interacting anthropogenic causes for climate change, including greenhouse gas concentrations, the direct and indirect effects of anthropogenic particulates (aerosols), and

Anthropogenic and natural forcing of the climate for the year 2000 relative to 1750.

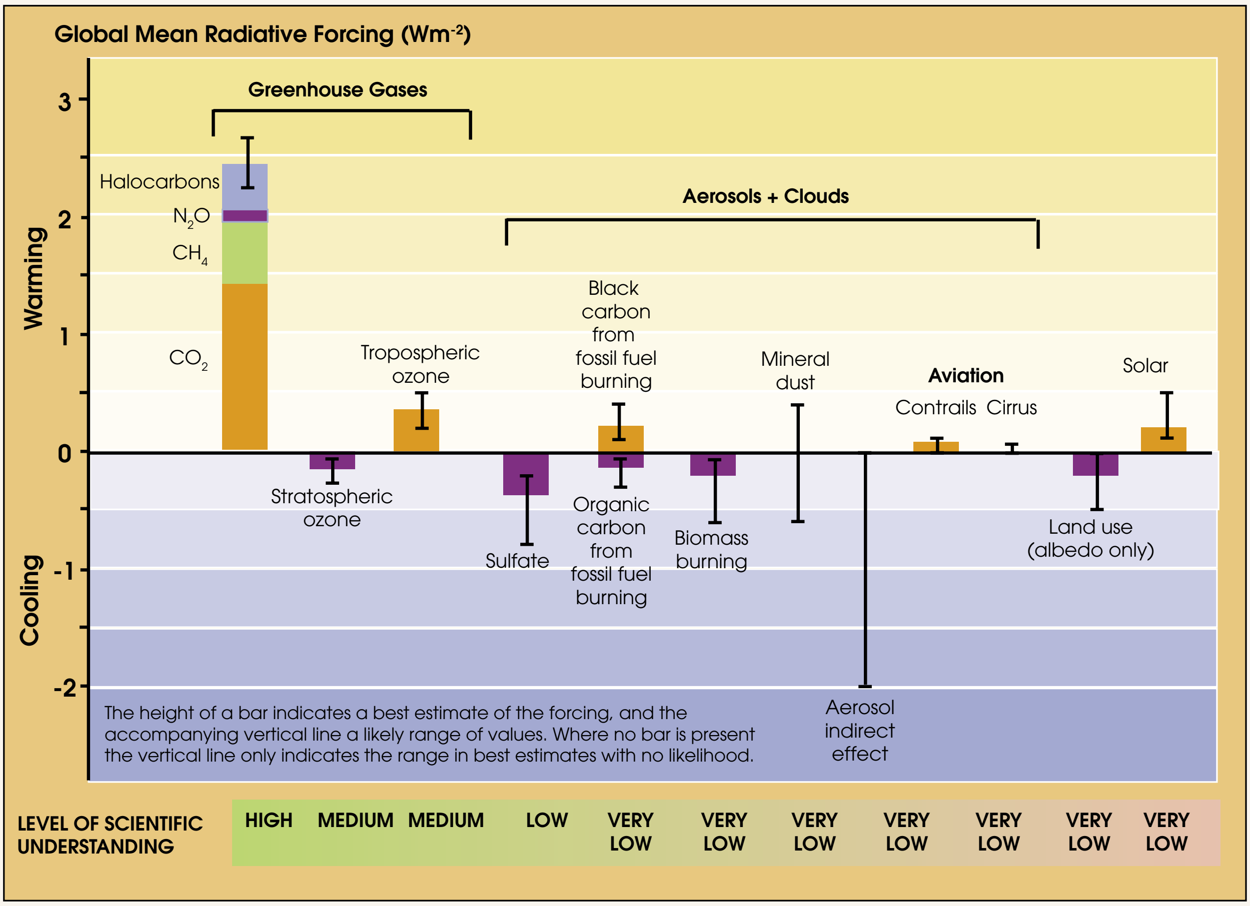


Figure 2: Comparison of the contribution various anthropogenic factors make to climate change due to their influence on the radiative budget of the Earth (IPCC 2001).

stratospheric ozone depletion. Greenhouse gases are clearly the largest driver of global warming. The relative contributions of factors that influence climate are shown in Figure 2.

More recent research suggests that increasing greenhouse gas concentrations and stratospheric ozone depletion may both be contributing to a strengthening of the polar wind vortex in both hemispheres, with a polewards movement of the mid-latitude westerly winds, and associated effects on regional climates. In the southern hemisphere, research suggests that strengthening of the westerly wind vortex is pulling rainfall southward, away from the Australian land mass. The Fourth Assessment Report, due to be released in 2007, will summarise this and other research findings since 2001.

1.3 Australia's vulnerability to climate change

The conclusions of the IPCC Third Assessment Report published in 2001 had a major influence on our understanding and acceptance of evidence for human-induced climate change. The Australian Government accepts the findings of the Third Assessment Report – that "global warming has taken place over the last century and there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities."

The changes in climate projected for Australia are highly significant. Because we already have extensive arid and semi-arid areas, experience pronounced climate variability, and live with existing pressures on water supplies in many areas, areas of Australia are highly vulnerable to the changes in temperature and rainfall projected for the next 50 to 100 years.

Vulnerability also arises because of high fire risk and ecosystems that are sensitive to change. Natural systems most at risk from climate change include alpine regions, coral reefs, freshwater wetlands across northern Australia, native forests and woodlands and riverine systems (Figure 3). Coastal communities and infrastructure are at risk through likely increased storm intensity, sea level rise and flooding.

(Roger Good)

Figures 3a and 3b: Coral reefs and alpine areas are vulnerable to climate change.

2. AUSTRALIAN CLIMATE CHANGE SCIENCE PROGRAMME – DRIVING THE RESEARCH AGENDA

The Australian Climate Change Science Programme is the critical core and driver for climate change science in Australia

While research into climate change and greenhouse has a 30-year long history in Australia, special government funding for a climate change science programme commenced in 1989. Since then, Australia has built national capability in climate change science recognised to be of world standard.

Through its climate change strategy announced in 2004, the Australian Government is currently investing $30.7 million between 2004 and 2008 in the Australian Climate Change Science Programme (ACCSP).

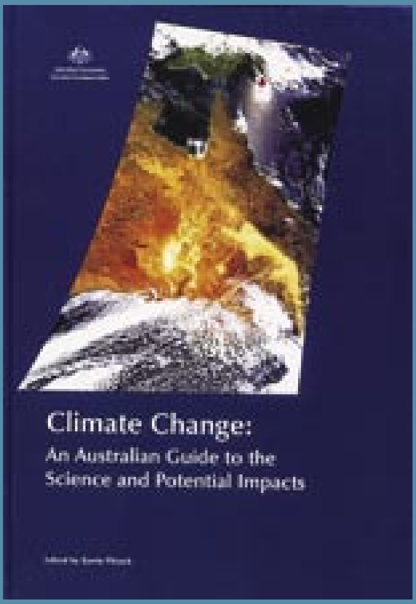
The Programme is focusing its research efforts on areas of strategic and scientific importance to Australia, improving our understanding of significant climate processes in our region and addressing key questions that are unlikely to be addressed by northern hemisphere research. Because of major differences in ocean and polar influences on climate, together with uniquely Australian hydrological systems, fire regimes, soils and ecosystems, southern hemisphere climate processes differ significantly from those in the northern hemisphere. This focus has been considerably refined for the research programme for 2004-2008 (see Australian Climate Change Science Programme: Strategic Research Agenda 2004-08).

Box 1: Showcase – Australian Climate Change Science

In 2003 the Australian Greenhouse Office published the first major climate change science book with a focus on Australia – Climate Change Science: An Australian Guide to the Science and Potential Impacts (Pittock ed. 2003). The book was launched in December 2003 at the UNFCCC 9th Conference of the Parties in Milan, Italy.

The Science Guide:

- Compiles the most recent global and regional climate science studies regarding the impacts of climate change in Australia.
- Presents new information on key regional issues, such as the declining rainfall in southern Australia and the influence of southern hemisphere climate phenomena on this trend.
- Demonstrates the high calibre of Australian science and the contribution that our scientists are making to the body of global knowledge.



An independent evaluation of the Programme undertaken in 2003 concluded that, within the bounds of available funding, the Programme had been extremely effective. The Programme has made a significant contribution to our understanding of the climate system and the likely effects of climate change on our environment, our economy and our society.

The evaluation describes the Programme as the critical core and driver for climate change research in Australia, and notes that it exerts substantial domestic funding leverage, particularly from research partners. The Programme has influenced national research activity by stimulating priority setting and consequent leveraging of both the direction and allocation of resources by government agencies, universities and cooperative research centres.

The Programme supports considerable international leveraging, and Australia has derived measurable benefits from contributing to international science forums that greatly exceed the dollar value of Australian input. The credibility achieved by our scientists, world-leading in several areas, has enabled Australia to influence the priorities for climate change research at the global scale and leverage research input from other countries to our benefit.

Elements of Australian climate change science have led the global research effort in many important areas such as Southern Ocean science, global carbon budgeting, and high precision monitoring of the changing composition of the atmosphere. There has also been great national progress in:

- understanding of the **ocean circulation and processes** around Australia that influence our climate;
- advancing knowledge of the **processes in the atmosphere**, such as cloud formation, that contribute to the way the Australian and global climate functions;
- understanding the contribution and response of **Australia's unique biosphere** to climate change;
- combining current knowledge into **computer models** that represent the climate system, models that can be verified and used for the projection of future climate change and its impacts; and
- development of 'downscaling' techniques to provide **regional climate assessment**.

This booklet highlights a few of the wide range of outcomes achieved by the Programme and its many contributors.

2.1 Australian leadership in oceanic research

Prior to the Programme, Australia did not carry out any research on the role of oceans in climate – we are now a leader in the field

The oceans of the world play a fundamental role in the climate system. Oceans transport large quantities of heat from one location to another; they are the source of water in the hydrological cycle. They are also the main long-term sink for atmospheric carbon dioxide and play an important role in controlling the rate at which carbon dioxide is increasing in the atmosphere.

Heat absorbed by the ocean in one location may be carried thousands of kilometres before being released into the atmosphere. This release of heat drives motions in the atmosphere that determine the temperature and rainfall patterns that make up our climate.

The ACCSP has been a driving force for observational studies in the oceanic regions around Australia (Figure 4) and in increasing our understanding of ocean processes and their influence on climate. Prior to the Programme, these regions were poorly studied and, despite an increased research effort, the Southern Ocean is still the most poorly sampled ocean in the world. Fifteen years ago, Australian oceanographic research focused primarily on waters over the continental shelf and slope – the dynamics of the deep ocean were virtually unknown.

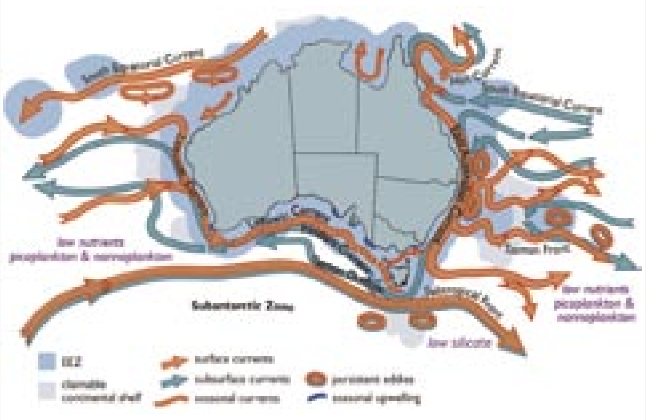


Figure 4: Schematic of ocean currents around Australia (CSIRO).

Over the last decade, Australian researchers have made substantial progress in understanding the processes of the oceans surrounding the continent and their role in the climate system. These advances have been based on new observations from ships, moorings, drifting robotic floats (see Box 4) and satellites; and advances in our ability to simulate the interactions between the atmosphere, ocean, sea ice and biogeochemistry using climate models. Importantly, Australian oceans research has captured the interest of international scientists and has brought scientists and research ships into these waters, substantially enhancing the scale of what has been achieved.

The ACCSP has placed special emphasis on regions that have significant influences on our climate, and are not covered by other countries – namely the Indian, the South Pacific and Southern Oceans. Key areas of research on oceanic processes and circulations in the Australian regions include:

- the **Southern Ocean** – a major component of oceanic heat transport, overturning circulation and carbon sink (see Box 2);
- the Antarctic coastal region, where deep ocean water – **Antarctic Bottom Water** – is formed as a result of the formation of cold and saline water (see Box 2);
- **Antarctic Circumpolar Current** that connects all of the major ocean basins to the south of Australia;
- the **Indonesian Throughflow** – warm water that flows through the Indonesian archipelago from the Pacific Ocean into the Indian Ocean which is closely linked to Australian climate variability; and
- the ocean-atmosphere linkage that causes the **El Niño-Southern Oscillation** annual variations that so greatly affect Australian climate variability (see section 2.4).

2.1.1 The Southern Ocean – a key role in global circulation and carbon storage

The Southern Ocean is a key component of the global climate system. By linking the circulation of the major ocean basins, by connecting the surface and deep ocean as part of a global 'ocean conveyor belt' and by absorbing carbon dioxide, the Southern Ocean strongly influences global circulation patterns and climate.

Over the last decade, Australian researchers have led global research in understanding the Southern Ocean and its role in the climate system. It is now known that interactions between the ocean, atmosphere and sea ice in the Southern Ocean produce water masses that spread north to occupy about half the volume of the world ocean. These water masses sequester heat and carbon dioxide in the deep ocean. About one-third of the carbon dioxide produced by human activities is accumulating in the ocean, slowing the rate of climate change due to the enhanced greenhouse effect.

> Approximately 40 per cent of the ocean storage of anthropogenic carbon dioxide is found in the Southern Ocean, south of 30°S

The Southern Ocean is the location of a major part of the overturning circulation or ocean 'conveyor belt' which is a global three-dimensional system of currents that transport heat around all the world's oceans and significantly influence global climate. The Antarctic Circumpolar Current carries water around Antarctica and is linked with other currents that carry water towards and away from the continent, at different depths and in different directions (see Box 2). Importantly, the water mass transformations taking place in the Southern Ocean play a critical role in this overturning circulation by connecting the shallow and deep limbs of this global-scale 'conveyor belt.'

While the importance of the Southern Ocean overturning circulation to global climate has been recognised for many years, the strength of the circulation was unknown until recently. Because ocean currents influence the overlying atmosphere, changes in the strength of the current may in turn drive further changes in the climate. Programme scientists have recently determined the strength of the Southern Ocean overturning by investigating water mass formation processes and vertical circulation. The study is an important baseline from which changes in strength can be monitored and causes studied.

The CSIRO coupled ocean-climate model, developed with support from the Programme, suggests the Southern Ocean overturning circulation is sensitive to climate change. Most international models show similar results. In particular, density changes arising from global warming and the inflow of fresh water could slow this circulation. This is likely to increase the rate of carbon dioxide accumulation in the atmosphere (rather than the ocean) and hinder the oxygenation of the deep oceans.

A slow-down or change to the overturning circulation could lead to major changes to the present climate, with widespread, but uncertain impacts. Gaining a greater understanding of the dynamics of the overturning circulation in the Southern Ocean is a key focus of research in the ongoing Programme (see Australian Climate Change Science Programme – Strategic Research Agenda 2004-08).

As noted in Box 2, Antarctic Bottom Water is important to the overturning circulation of the world oceans and consequently to the uptake of carbon dioxide from the atmosphere and the oxygenation of the deep ocean. Programme scientists have shown that the Antarctic coastline south of Tasmania is a significant source of Antarctic Bottom Water, accounting for 25 per cent of the total inventory. Previous estimates of the global inventory of Antarctic Bottom Water attributed only 0.5 per cent to sources in the Australian-Antarctic basin.

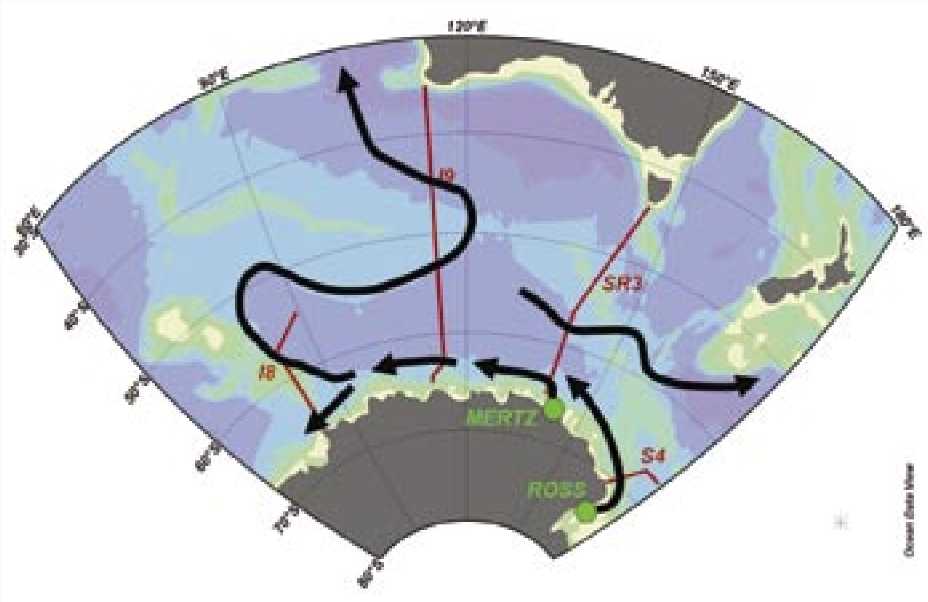
Subsequent studies by the Programme and the Antarctic Cooperative Research Centre showed conclusively that the Mertz Glacier Polynya (Figure 5) was a globally significant source of bottom water. A polynya is a region within the sea ice pack that remains ice-free in winter, usually due to strong winds blowing ice offshore. A major field programme, the first such expedition to an Antarctic coastal polynya in mid-winter, confirmed the region was a sea ice 'factory' and a potent source of bottom water (Figure 6).

Ocean sampling in early 2005 revealed that the deep waters in the basin between Australia and Antarctica were cooler and less salty than they were 10 years ago. This suggests that the movement of water between the warm surface layers of the ocean and the cool deep layers is changing. Understanding why this is happening and why it is happening so quickly is a major focus of ongoing research in the Programme.

With a relatively small research community and a vast ocean area, Australia's overall Southern Ocean research effort has been significantly enhanced through collaboration between the Programme and CSIRO, the Antarctic Climate and Ecosystems CRC, the Australian National Antarctic Research Expeditions, and vital international partnerships. Further leveraging and support has come from complementary research by the Bureau of Meteorology and the University of Tasmania.

Figure 5: The Mertz Glacier Tongue, Antarctica. The area of open water in the lee of the glacier tongue, known as a polynya, is a region of intense ocean-air-ice interaction producing large amounts of Antarctic Bottom Water (V. Lytle).

Figure 6: Circulation path of Antarctic Bottom Water arising from the Mertz Glacier Polyna and the Ross Ice Shelf (CSIRO).



Box 2: The Southern Ocean: a window to the deep sea

Throughout most of the world's oceans, warm water floats on top of cold deep waters. In a few regions like the Southern Ocean, however, the cold layers rise towards the surface. Here the water characteristics are modified by intense interactions between the atmosphere, ocean and sea ice. Some of the upwelled water is warmed by the atmosphere and freshened by rainfall and melting sea ice. The modified waters spread north to supply the intermediate depths of the world ocean. Water that upwells closer to Antarctica is cooled by cold air blowing off the continent and its salinity is increased by brine released during sea ice formation. These processes create the densest water in the world ocean, known as Antarctic Bottom Water, which sinks near Antarctica and spreads north near the sea floor.

The water masses formed in the Southern Ocean carry oxygen into the deep sea. In the absence of dense, oxygen-rich water sinking near Antarctica, the deep ocean would have much lower oxygen levels. In this sense, the Southern Ocean acts as a 'window' to the deep sea, ventilating the waters beneath the sea surface.

Climate models suggest this circulation is sensitive to climate change, and may slow down sometime this century or even halt further into the future. A key issue for future research is to determine the likelihood and impact of a slow-down of the Southern Ocean overturning circulation.

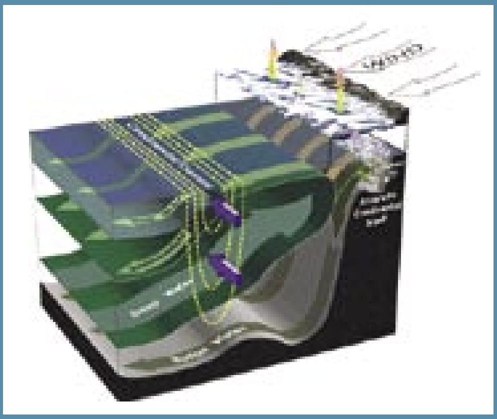


Figure 7: A schematic view of a north-south slice across the Southern Ocean, illustrating the currents involved in the overturning circulation (CSIRO).

2.1.2 The Antarctic Circumpolar Current

> Prior to the Australian Climate Change Science Programme, there were no measurements south of Australia with sufficient resolution to determine how much water, heat and salt are carried from the Indian Ocean to the Pacific by the Antarctic Circumpolar Current

The Antarctic Circumpolar Current (ACC) is the largest current in the world and the most important current in the Southern Ocean. The mean transport of the ACC is estimated to be 147±10 million cubic metres of water per second - **equivalent to moving the volume of Sydney Harbour every 3-4 seconds**. The current is so vast it carries 150 times more water around Antarctica than the flow of all the world's rivers combined.

The ACC is the only current that flows completely around the globe without being blocked by land – connecting the Atlantic, Pacific and Indian oceans to form a global network of currents that redistributes heat around the world and influences the climate of much of the Earth (see Figure 8).

In 1991, Programme scientists initiated a series of repeat transects to determine how much water, heat and salt the ACC carries from the Indian Ocean to the Pacific. These studies are maintained to the present day. As a result, the Australian sector is now better measured and understood than any other region of the Southern Ocean, with the exception of Drake Passage on the southern tip of South America. This provides valuable information to help scientists determine how transport of the current varies today in response to winds and cooling by the atmosphere; understand the interaction between the current and global

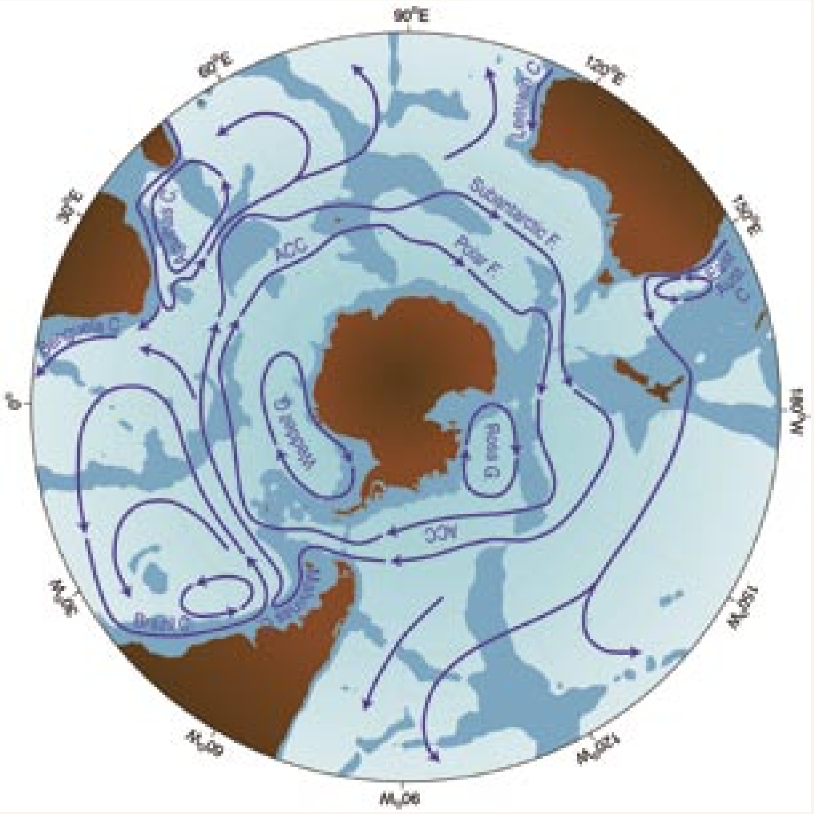


Figure 8: Schematic of the Antarctic Circumpolar Current (CSIRO).

climate; and predict the impact of future warming on the current.

Australian scientists also developed a new technique to monitor changes in the strength of the Current. Programme scientists have used ship-based observations, in combination with satellite data, to estimate the transport of the ACC every 10 days for the last 10 years. **This study was the first to use satellite altimeter data to determine full-depth transports in the Southern Ocean**. Satellite altimeters measure the height of the sea surface with an accuracy of a few centimetres. Because ocean currents cause the sea surface to slope (the sea surface is about a metre higher near Tasmania than it is near Antarctica), the altimeter provides a means of monitoring ocean currents from space. The near-continuous record of transports is providing new insights into how the circumpolar current responds to, and drives changes in the overlying atmosphere.

Box 3: Highlights of Southern Ocean research

Programme scientists have:

- Determined the strength of the Southern Ocean overturning circulation and highlighted the sensitivity of the overturning circulation to climate change.
- Demonstrated how the Southern Ocean links the shallow and deep limbs of the ocean `conveyor belt,' and so plays a key role in the heat engine that influences global climate patterns.
- Measured the transport variability of the Antarctic Circumpolar Current south of Australia, providing new insights into how the circumpolar current responds to, and drives changes in the overlying atmosphere.
- Showed that the Adelie Land coast of Antarctica produces about 25 per cent of the global volume of the dense Antarctic Bottom Water that `ventilates' the deep ocean with oxygen.
- Showed that the Southern Ocean absorbs carbon dioxide from the atmosphere and presently stores about 40 per cent of the anthropogenic carbon dioxide that has accumulated in the ocean.
- Provided new insights into the complex interactions between physics, biology and chemistry that together determine levels of biological productivity and the amount of carbon dioxide absorbed by the Southern Ocean, e.g.:
    - o resolved the seasonal changes in carbon dioxide in the surface water of the Southern Ocean for the first time, providing more accurate estimates of air-sea exchange of carbon dioxide.
- Detected decreasing oxygen concentrations in the Southern Ocean and changes in seawater properties that suggest precipitation has increased at high southern latitudes.

Box 4: Robots in the Southern Ocean - Argo floats

The oceans store and transport vast amounts of heat. The top three metres of ocean have the same heat capacity as the entire atmosphere, and thus the ocean plays a large role in climate changes on seasonal (drought/floods) and longer time periods (climate change). Australia is a founding contributor to Argo, a novel method of collecting information from the upper ocean using robotic floats. The floats are the only means to collect the many subsurface observations needed to provide year-round, near real time information on ocean conditions

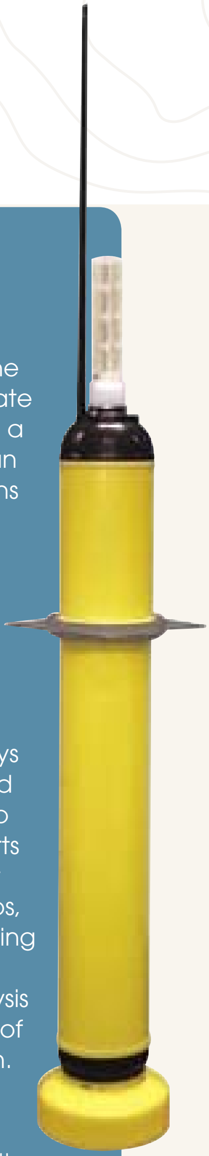


Figure 9: Launching an Argo float into the Southern Ocean (CSIRO).

The floats drift at depths between 1000 and 2000 metres measuring temperature and salinity. Every 10 days each float ascends to the surface and transmits these data and its position to satellites. The float then dives and starts a new cycle. Argo data complement other observations obtained from ships, moored instruments and earth observing satellites. Argo data are used in operational ocean and climate analysis and forecasting and in a wide range of oceanographic and climate research.

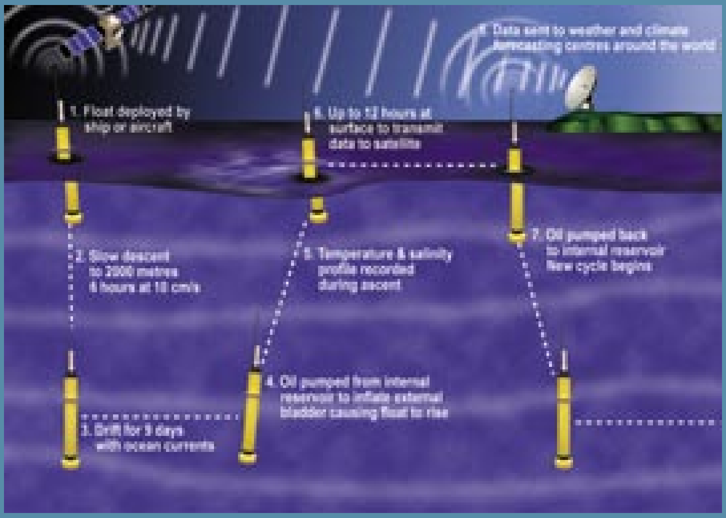


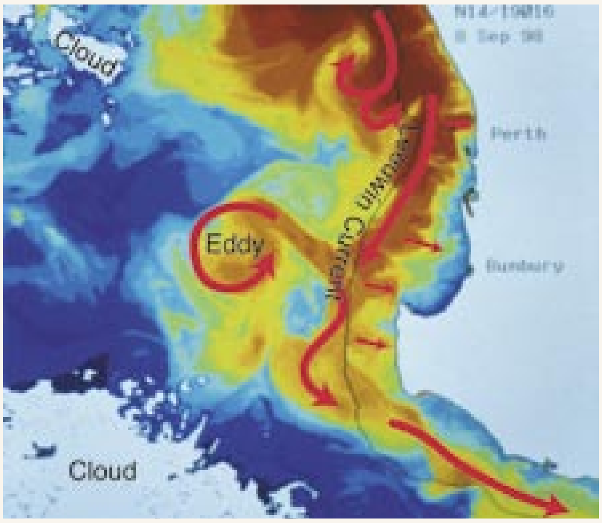
Figure 10: Schematic showing the cycle of an Argo float (CSIRO).

The first 10 Argo floats launched in 1999 were Australian. By July 2003, when the First Earth Observations Summit was held, 815 floats were delivering data. Today around 2000 are in place and the array should be complete in 2007. Australia has deployed 51 floats in the Indian, Pacific and Southern oceans, with funds to deploy 30 per year in the near term. To maintain coverage around Australia about 60 floats per year are needed.

2.1.3 Indonesian Throughflow - linking the Pacific and Indian Oceans

The Indonesian Throughflow comprises a series of currents that transfer warm, low salinity waters from the tropical Western Pacific Ocean through the Indonesian seas into the South Indian Ocean (Figure 11). The Throughflow is a critical element in the global climate system because the heat it transfers from the tropical Pacific to the Indian Ocean increases energy available to the Asian and Australian Monsoons and other atmospheric circulations. These monsoons bring regular rainfall to much of northern Australia.

Most of the Throughflow water feeds the South Equatorial Current, the dominant flow across the South Indian Ocean, with a shallow component flowing back eastward to feed the Leeuwin Current. The Leeuwin Current transports warm water south along the Western Australian coastline, profoundly impacting ocean conditions and coastal climate.

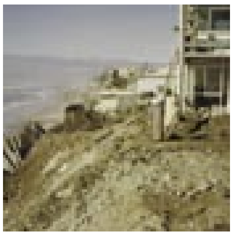


(CSIRO)

Figure 11: The Indonesian Throughflow and Leeuwin Current (CSIRO).

A 15-year record of the volume and temperatures of the upper ocean waters flowing between the Pacific and Indian Oceans through the Indonesian archipelago has been obtained. Recent results from these data demonstrate that seasonal anomalies of ocean variability in the Indonesian region and off Western Australia are largely driven by the remote winds along the equators of the Pacific and Indian Oceans, and that local winds have a much weaker effect. This research has provided the most accurate estimate to date of the mean volume, heat and freshwater flux between the Pacific and Indian Oceans.

The relevance of this research is the degree to which ocean currents in the Pacific and Indian oceans influence regional sea surface temperatures and rainfall. The way the upper ocean and atmosphere react is the key to predicting variations in rainfall and climate.



2.2 Sea level rise

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

Figure 12: Australian sea level gauge (National Tidal Centre).

There are two causes for present day sea level rise. Firstly, the oceans warm as heat from the atmosphere is carried into the ocean depth by ocean currents and mixing. Just as 'thermal expansion' causes the height of liquid in a thermometer to rise, warming of the ocean causes the sea level to rise. Secondly, an increase in the mass of the oceans from an influx of water from glaciers, ice caps and ice sheets causes sea level to rise. The contribution from water stored on land (for example, in aquifers) is still uncertain.

The Earth's climate has oscillated between glacial and interglacial conditions several times over the past half million years. During these oscillations sea level has changed by more than 100 metres. Since the end of the last glacial cycle (about 10,000 years ago), the rate of sea level rise has been relatively slow. However, the rate of sea level rise during the 20th century was an order of magnitude faster than the average over the past 3000 years.

To estimate the rate of sea level rise around Australia, the ACCSP has implemented a sea level monitoring network around the continent - the Australian Baseline Monitoring Array (see Figure 12). This dedicated system is part of a global network of observations, supported by satellite observations to provide global and regional observations of sea level change. These data have also been used to test the ability of models to accurately represent past sea level rise.

In the last IPCC report, researchers did not have an accurate quantitative estimate or an adequate explanation for observed 20th century sea level

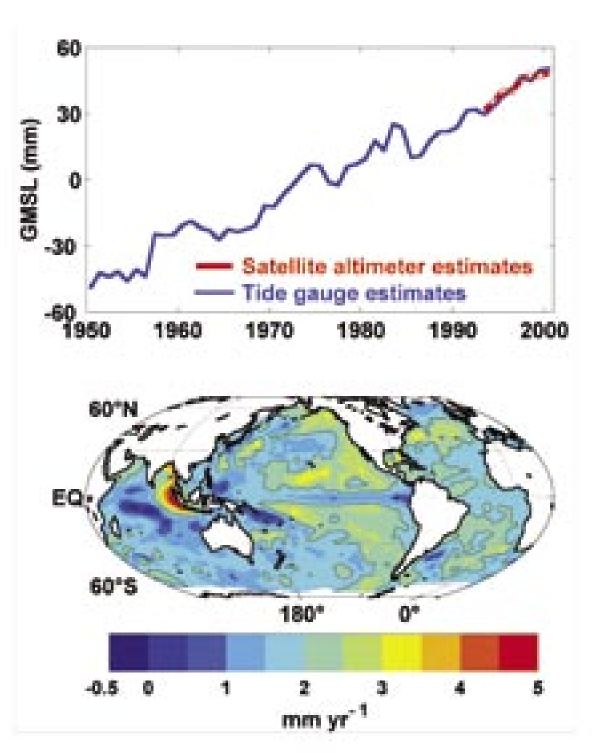


Figure 13a and 13b: Global averaged sea level change between January 1950 and December 2000 are shown in the top panel. This estimate of sea level rise agrees well with estimates from recent satellite data. The estimated regional distribution of sea level rise between January 1950 and December 2000 is shown in the bottom panel. The solid line is 2.0 mm yr $^{-1}$ and the contour interval 0.5 mm yr $^{-1}$ (CSIRO).

rise. By combining Australian and international sea level observations together with satellite observations, Programme scientists have estimated that global average sea level rose at the rate of 1.8 ± 0.3 mm per year during the second half of the 20th century (Figure 13a).

For the Australian coastline, the estimated rate of relative sea level rise for the period 1920 to 2000 is 1.2 mm per year. Analysis of the two longest Australian records (Fremantle and Sydney) shows the shift in mean sea level during the 20th century has brought about a significant increase in the frequency of extreme sea levels of a given value (by a factor of between 2 and 3).

Programme scientists have also produced the first regional estimates of sea level rise across the globe. The different rates of rise between regions had puzzled analysts for some years, and the Australian results for the first time reconcile and substantiate the earlier, apparently inconsistent, estimates of regional variations in sea level rise (Figure 13b).

> "How fast is sea level rising?" "What are the causes?" and "What are the implications for the future?" are questions requiring urgent answers

New research shows that volcanoes have a significant influence on sea level rise. Volcanic eruptions inject particles and gases which reflect solar radiation and thus rapidly cool the ocean. This cooling causes the water to contract and hence lowers the global mean sea level. The initial fall in sea level is followed by a slow increase lasting for a decade or more as levels return towards the pre-eruption state. For example, simulations indicate that the Mt Pinatubo eruption in 1991 produced a fall in sea level of approximately 6 millimetres in about a year, followed by a slow rise of about 0.5 millimetres per year over a decade or more.

The research also indicates that a series of major eruptions between 1960 and 2000 masked some of the anthropogenic sea level rise that would otherwise be expected.

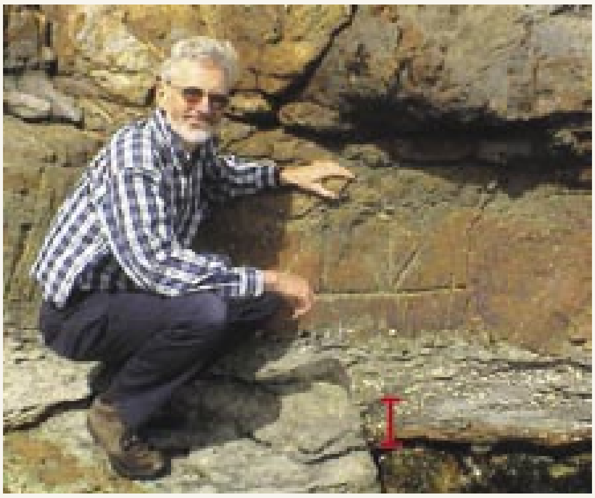


Figure 14: The sea level benchmark on the Isle of the Dead, Port Arthur, Tasmania, which was struck on 1 July 1841. Sea level measurements at that time and at the end of the 20th century have indicated a relative rise in mean sea level of 13.5 cm, as shown by the red bar superimposed below the benchmark (ACE CRC).

Figure 15: Mt Redoubt eruption1989 Alaska. Hot ash rises in an updraft over a pyroclastic flow (J.Clacus).

2.3 Understanding atmospheric processes and composition

Atmospheric concentrations of carbon dioxide are now at a level that is unprecedented during the past 420,000 years

As with the ocean, the atmosphere is a complex system that impacts greatly on our climate. Many simultaneously active and interactive processes within the atmosphere ultimately determine the climate state and its response to greenhouse gases. Australian scientists are contributing to the global effort to better measure, understand and model these processes - both separately and within fully coupled atmosphere-ocean-biosphere climate models.

Prior to industrialisation, natural exchange of carbon dioxide between the atmosphere, oceans and biosphere of the Earth maintained atmospheric concentrations at about 280 parts per million by volume (ppmv). Industrialisation and the expansion of agriculture have altered this balance, with carbon dioxide levels now at about 380 ppmv. The present concentration has not been exceeded during the past 420,000 years and likely not during the past 20 million years. Levels are continuing to increase at about 0.4 per cent per year, which is faster than any time in the past 20,000 years.

The increase is the net result of a combination of direct inputs to, and responses of, the global carbon cycle. We need to understand these responses to be able to project future carbon dioxide concentrations, and thus climate change, for given future greenhouse gas emissions.

2.3.1 Cape Grim – Australia's own 'air bank'

Since the early 1970s, Australia has contributed to the monitoring of changes in the background composition of the atmosphere. Aircraft have been used to monitor carbon dioxide levels, and in 1976 the Australian Government established the Cape Grim Baseline Air Pollution Station in Tasmania (Figure 16). Cape Grim plays a vital role in a global network that monitors constituents of the global atmosphere. At Cape Grim scientists collect what is probably the most pristine air in the world. Like bottled spring water, the air samples are sealed at the source in flasks, and the composition of the atmosphere analysed for greenhouse gases (Figure 17) and other pollutants. The measurements are so sensitive that emissions from a ship on a far horizon can be detected. This provides valuable information on how and why concentrations of greenhouse gases have increased over recent decades.

Figure 16: The Cape Grim Observatory, north-west Tasmania (Bureau of Meteorology and CSIRO).

Australian scientists have played a key role and often led internationally in developing current understanding of the global carbon budget. This has been achieved by deducing the location and mechanisms of sources and uptake of carbon dioxide using:

- precise time/spatial observations of variations of both concentrations and isotopic ratios of atmospheric carbon dioxide over the Earth;
- coupling of these observations to understanding of atmospheric and oceanic transport processes;
- high precision measurements of the changes of oxygen in the atmosphere; and
- measurement of the distribution of carbon in the oceans.

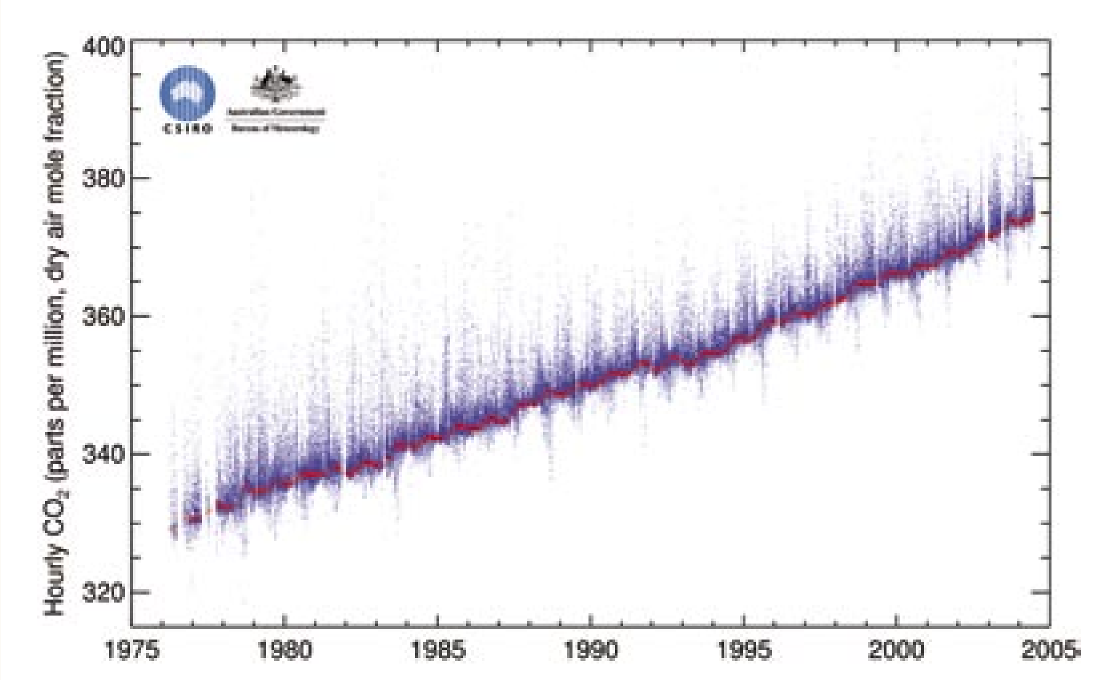


Figure 17: Hourly mean carbon dioxide concentrations at Cape Grim, Tasmania (The station is funded and managed by the Bureau of Meteorology, and jointly supervised by CSIRO).

2.3.2 Impacts of aerosols and clouds on climate

Airborne particles (aerosols) and clouds can alter atmospheric circulation and rainfall patterns

Major sources of uncertainty in predicting climate change are the feedbacks between climate, aerosols (airborne particles such as carbon, dust and sea salt) and clouds. We know that clouds play a very important role in the climate system. They are the result of the transport of water from the Earth's surface into the atmosphere, where they can either trap or reflect heat and complex physical processes cause the formation of droplets that may or may not fall as rain or snow. This condensation releases energy that further drives atmospheric mixing.

Given the importance of clouds to the climate system, we need to better understand the way in which they form and interact with the system as a whole, and how these complex processes themselves may be changed as greenhouse warming continues. This will be a focus of future work under the ACCSP (see Australian Climate Change Science Programme – Strategic Research Agenda 2004-08).

Major aerosols in Australia are mineral dust generated by wind on arid soils and carbonaceous particles from burning vegetation. Recent work in the ACCSP and elsewhere has shown that aerosols may have more potent effects on climate than previously understood. These effects are complex given that aerosols:

- can have a direct effect on the transmission of sunlight through the Earth's atmosphere;
- can indirectly cause the optical properties of clouds to vary depending on the abundance of aerosol particles;
- can indirectly change the lifetime of individual clouds and their propensity to deliver rain; and

Box 5: Key achievements in understanding the composition of the atmosphere

Atmospheric carbon dioxide levels have increased by more than 30 per cent since pre-industrial times. This current level is unprecedented during the past 420,000 years.

The Programme has had many successes including:

- Identifying the importance of oceans as a carbon dioxide sink – **oceans currently remove about 2000 million tonnes of carbon from the atmosphere each year.**
- Improving our understanding of the role of the Southern Ocean in the uptake of carbon dioxide and its effect on the global carbon budget.
- Measurements of the distribution of carbon in the oceans to further understand the role of the oceans in removing carbon from the atmosphere.
- Australia's own 'air bank' - samples of captured air at Cape Grim - have enabled us to measure changes of atmospheric composition over time, increasing our understanding of how and why concentrations have increased over recent decades and centuries (Figure 18).
- High precision measurements of both concentrations and isotopic ratios of atmospheric carbon dioxide over the Earth have improved our understanding of atmospheric and oceanic transport processes.
- Development of methods to calculate what exchanges of gases take place at the Earth's surface leading to better understanding of how the atmosphere and oceans mix.
- Development of LoFlo™ – a precision instrument that measures carbon dioxide (Figure 19). The analysers can fill gaps in the current observation network over land, and detect subtle changes in carbon dioxide sources and sinks from remote locations around the Southern Ocean. LoFlo™ allows detection of these changes over years rather than decades.

Figure 18: Air bank (CSIRO).

Figure 19: LoFlo (CSIRO).

- vary in physical/chemical composition and spatial/temporal distribution.

For example, field observations of atmospheric aerosols and cloud optical properties off the coast of Tasmania have confirmed that seasonal changes in the biological processes in the ocean surface waters cause seasonal changes in the number of cloud condensation nuclei. These biological processes release sulfur compounds that become sulfate aerosols onto which cloud droplets are formed. More aerosols are released in summer, resulting in clouds with more droplets. As a result, clouds in summer are relatively more reflective (whiter) than those in winter. This has been confirmed by observations of these clouds from satellites. Further, these studies show that when more cloud droplets occur, there is a lesser tendency for precipitation to fall, and the clouds persist longer.

The net result of changes in aerosol amounts can be an alteration to atmospheric circulation and rainfall patterns, especially in the Tropics. In addition, satellite observations have suggested that local suppression of precipitation due to aerosol effects on clouds may be climatically significant.

Studies using CSIRO's climate model show that the indirect effects of sulfate aerosol from industrial sources (primarily over Europe) may have had far-reaching effects on atmospheric circulation and rainfall patterns. These included a general southward shift of the tropical rainfall belt.

This suggests that aerosols may have contributed to the devastating droughts experienced in the Sahel region in Africa since the 1970s (Figure 20). The direct and indirect effects of aerosols

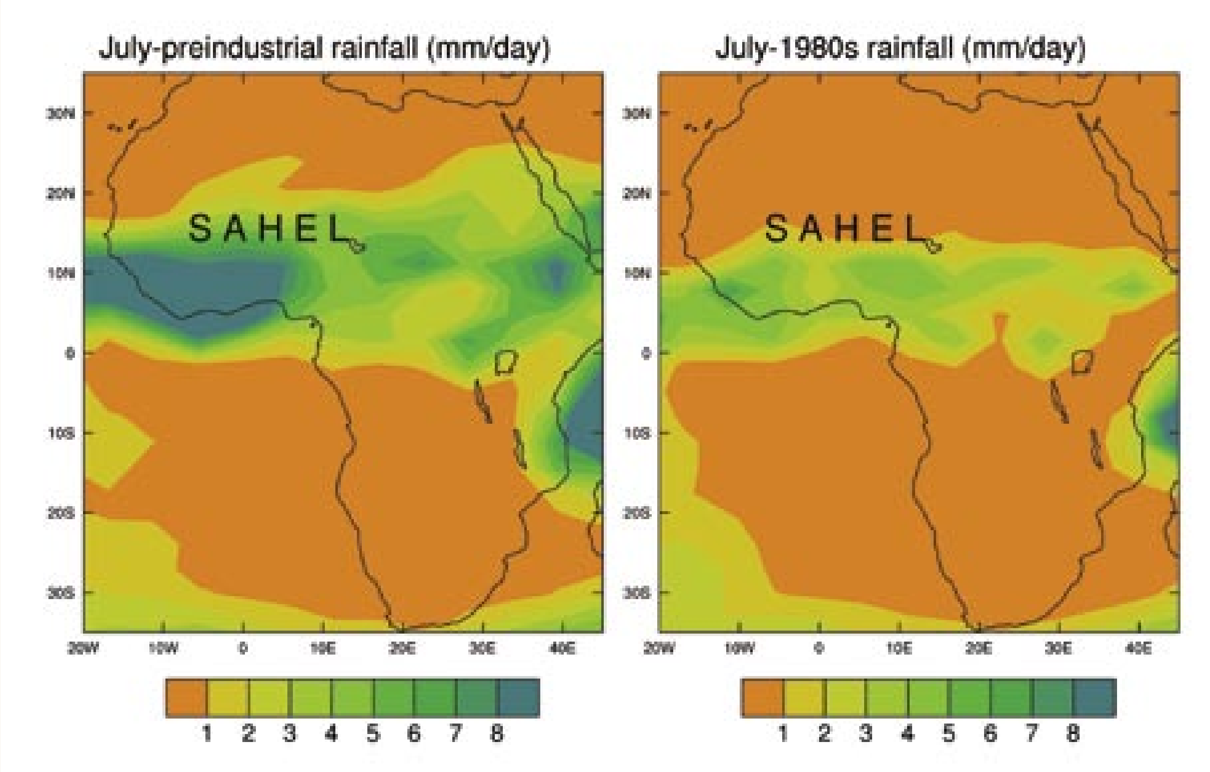
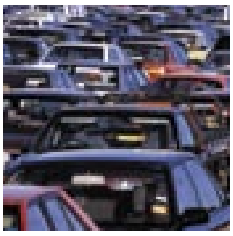


Figure 20: Rainfall simulated by the CSIRO climate model for the month of July (wet season in the Sahel region of Africa) for (a) pre-industrial, and (b) present-day levels of sulfate aerosol showing the very significant loss of rain resulting from these changes (CSIRO).

(both sulfate and non-sulfate) may also have important climatic effects, in addition to the effect of aerosols on the pattern of temperature change.

The phenomenon known as 'solar dimming' is likely to be at least partly related to aerosols. In certain parts of the world (developing parts of Asia, and probably also Europe since the 1950s), observations have shown that the amount of solar radiation reaching the Earth's surface has been decreasing as a result of rising levels of aerosols in the atmosphere. The degree to which this is impacting global temperatures and the climate systems is debatable.

(Bill Slattery)

Box 6: Key achievements in understanding atmospheric processes

Recent work by the Australian Climate Change Science Programme has shown that aerosols may have a more potent effect on climate than previously understood.

The Programme has had many successes including:

- Observations in the Southern Ocean have shown that the presence of aerosols altered the optical properties and lifespan of clouds in the region, improving our understanding the relationship between aerosol production and cloud formation.
- Representation of aerosols in the latest climate models has helped understand their impact on the global and Australian climate.
- Identification of the impact of aerosols on the droughts experienced in sub-Saharan Africa since the 1970s (see Figure 20).
- Development of climate models that represent the impact of aerosols including black carbon, organic carbon, dust and sea salt.

2.4 Understanding El Niño

Australian scientists have played major roles in understanding the nature of the ENSO and predicting its impact on the climate

The El Niño-Southern Oscillation (ENSO) is the result of a cyclic warming and cooling of the surface ocean in the central and eastern Pacific. This in turn influences the moisture content and circulation of the atmosphere. El Niño events occur at intervals of between three to seven years, hindering the formation of monsoon seasons in countries near the equator. Some South American countries experience heavy rainfall, and there are severe droughts in eastern Australia. During the opposite phase (La Niña), the eastern Pacific cools, often bringing widespread rain and flooding.

Australian scientists have played major roles in understanding the coupled ocean-atmosphere nature of the ENSO and in developing systems for predicting its impact on the climate. CSIRO and the Bureau of Meteorology Research Centre (BMRC) have jointly developed a world-class computer model for the prediction of the El Niño, and other oceanic climate phenomena, and their climate impacts. Today's climate models generate year-to-year variables in Australia's climate that reflect observed variations (see Box 10).

The representation of ENSO in a computer-based mathematical model of the Earth's climate, developed by the BMRC, produces rainfall changes over Australia that are generally consistent with documented observational changes – i.e. dry/hot conditions occur more frequently during El Niño years and wet/mild conditions occur more frequently during La Niña years.

Collaborative research involving scientists in BMRC and at the University of East Anglia in the United Kingdom has discovered that the relationship between ENSO and Australian rainfall is asymmetric - a large La Niña sea surface temperature (SST) anomaly results in a large Australian response (i.e. Australia usually becomes much wetter), whereas the magnitude of an El Niño SST anomaly is not a good indicator of how

Box 7: Discovering El Niño

As early as 1877–78 when India was in a severe drought, the Indian Government meteorologist contacted other meteorologists around the world, enquiring about their meteorological situation. Charles Todd (Figure 21), the South Australian government meteorologist (and the builder of the overland telegraph between Darwin and Adelaide) noticed that Australia was often in drought at the same time as India.

In the early decades of the 20th century, Australian meteorologist, E. T. Quayle, recognised that tropical pressures (specifically at Darwin) could be used to make seasonal climate forecasts for south-east Australia. Scepticism about such findings meant that Quayle's work did not lead to operational climate forecasts at that time.

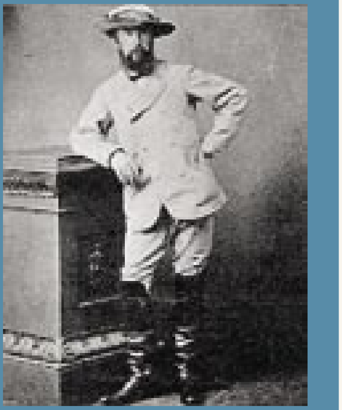


Figure 21:
In 1877-78 Charles Todd first noticed that Australia was often in drought at the same time as India (Bureau of Meteorology).

dry Australia will actually become. Australia tends to dry out during El Niño events but the degree of drying is not tightly linked to the magnitude of the El Niño SST anomaly.

Generally, the more intense the El Niño, the more intense and longer the Australian droughts, although this was not the case during the 2002 drought – understanding this phenomenon is a major challenge being tackled by the research programme for 2004-2008 (see Australian Climate Change Science: Strategic Research Agenda 2004-08).

Scientists have also examined longer term variations of temperature and pressure in the Pacific Ocean, a region known to influence Australia's climate. This has shown substantial variations from decade to decade, which influence the cycle of ENSO. A model has been developed which is able to reproduce this variability, helping us to understand these long-term climate variations.

A major challenge now is to determine how the El Niño phenomenon and its impacts and predictability may change in a changing climate.

One of the goals of the ACCSP is to develop models capable of answering this question (see Australian Climate Change Science Programme: Strategic Research Agenda 2004-08).

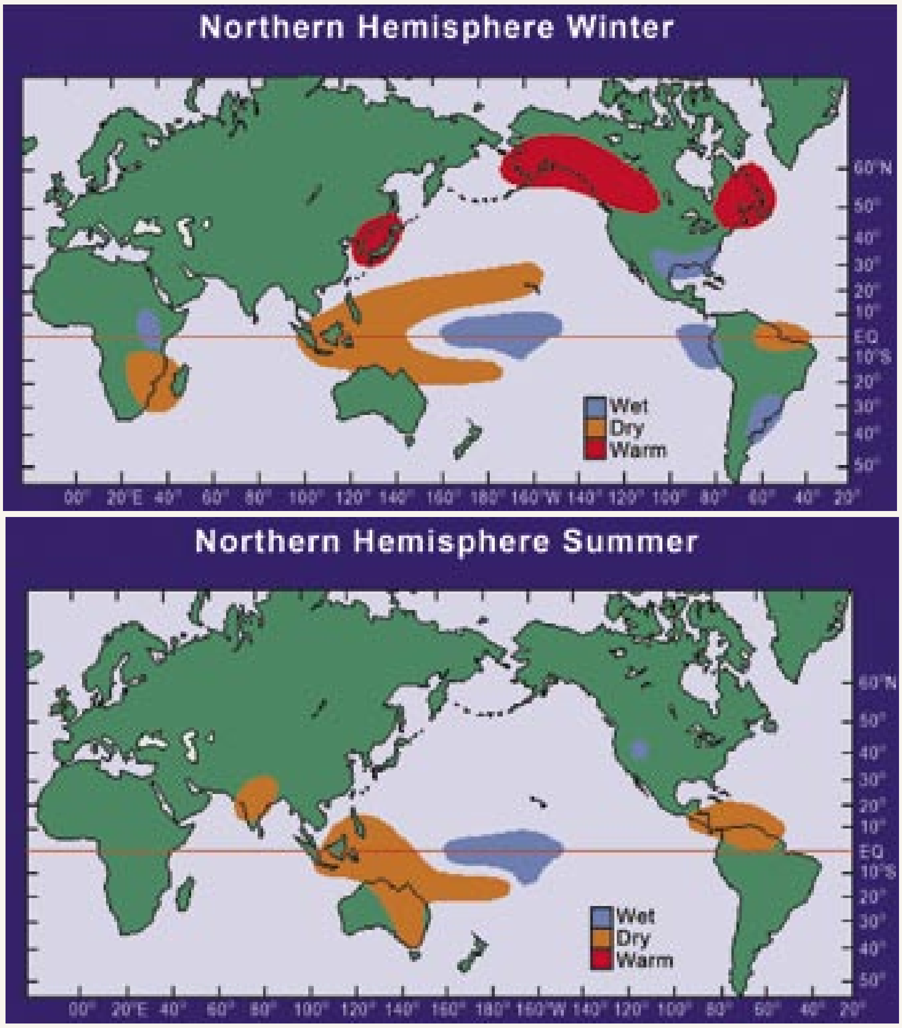


Figure 22: Impacts of ENSO on different regions of the world (NOAA, http://www.pmel.noaa.gov/tao/elnino/).

2.5 Australia's unique biosphere

The terrestrial biosphere is an important component of the global carbon cycle, having taken up one-third of total carbon dioxide emissions since the start of the industrial revolution. Vegetation and soils also affect climate and weather, both locally and globally, through the partitioning of the sun's energy into heating the air and evaporating moisture.

Australia's terrestrial ecosystems are unique. As a result of climatic and geological factors, and the dominant role of fire, our ecosystems are markedly different from those in North America and Europe. This poses particular scientific challenges, such as:

- Currently no climate models include Australia-specific vegetation types in their land surface specifications.
- Terrestrial biogeochemical models developed overseas may not adequately represent the cycling of carbon, water and nutrients in Australian ecosystems or their responses to climate variability.
- Locally developed algorithms that represent Australian vegetation are needed if the impact of vegetation on regional climate, water resources and productivity are to be modelled.
- There are important climate-biosphere feedbacks in Australia as demonstrated by the link between climate (low rainfall and drought) and the frequency of bushfires and dust storms. Both are important sources of aerosols (see section 2.3.2) in Australia and bushfires are an important source of greenhouse gases.

Major challenges for future research include understanding the patterns of sources and sinks of carbon across Australia, how vulnerable they are to land management, disturbance and climate change, and using this information to develop an interactive carbon-climate model (see Australian Climate Change Science Programme: Strategic Research Agenda 2004-08).

2.5.1 Measuring carbon dioxide in terrestrial systems

> The Programme supported the first multi-annual carbon dioxide flux measurements in Australian ecosystems

Australia is part of a global network of over 250 flux stations that has been established to study biogeochemical cycles in ecosystems and to provide the data and process understanding necessary to develop and test biosphere-climate models (Figure 23).

The ACCSP has supported the operation and maintenance of two flux stations as part of the Australian flux network (Ozflux). One is in a cool temperate, tall eucalypt forest in south-eastern New South Wales (Tumbarumba) Figure 24; and the other in a tropical wet/dry savanna in northern Queensland (Virginia Park).

These stations continuously measure the exchange of carbon dioxide, as well as water and heat, from the atmosphere with the terrestrial surface. The aim

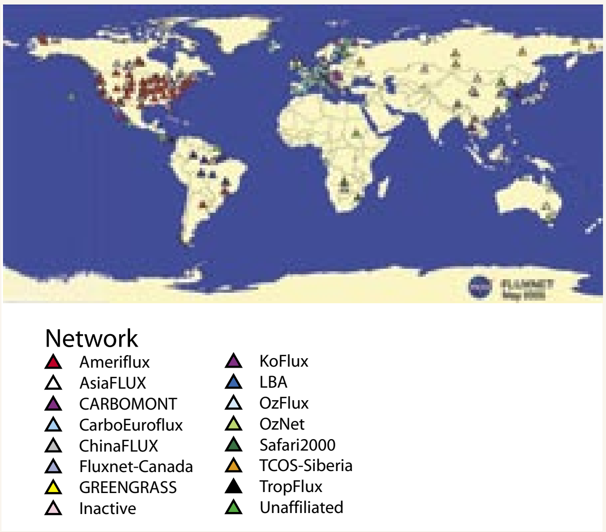


Figure 23: Spatial distribution of FLUXNET sites and their sponsoring countries or regions (http://www-eosdis.ornl.gov/FLUXNET/).

is to improve our understanding of the interactions between climate, hydrology and carbon cycling in Australian ecosystems – especially the climatic and biotic factors that determine the daily and seasonal variations in carbon dioxide exchanges.

The results of this research are highlighted in Box 8.

Box 8: Australia's unique biosphere – flux tower results

Results from the flux towers indicate that rainfall (timing and amount) and atmospheric humidity are key drivers on the seasonal variation in net ecosystem productivity. For example, the savanna site became a net source of CO_2 in those years when the wet season failed (2002-03 and 2003-04) and large humidity deficits limited photosynthetic uptake in the Tumbarumba forest more than the near-freezing winter temperatures.

The large variability in seasonal and annual rainfall is reflected in the large year-to-year variability in net ecosystem productivity in both ecosystems. While the evaporation closely balances the rainfall input at the savanna site, water use by the temperate eucalypt forest was much less variable from year-to-year, because of deeper soils that provide a large water store.

Another important finding is that the annual average net primary production and net ecosystem production (production less loss from decomposition) for Australia is very low and highly variable from year-to-year, compared with the global average for a continent of Australia's size (Figure 25).

Figure 24: Measurements being taken above the tree line from a flux tower in Tumbarumba, New South Wales (CSIRO).

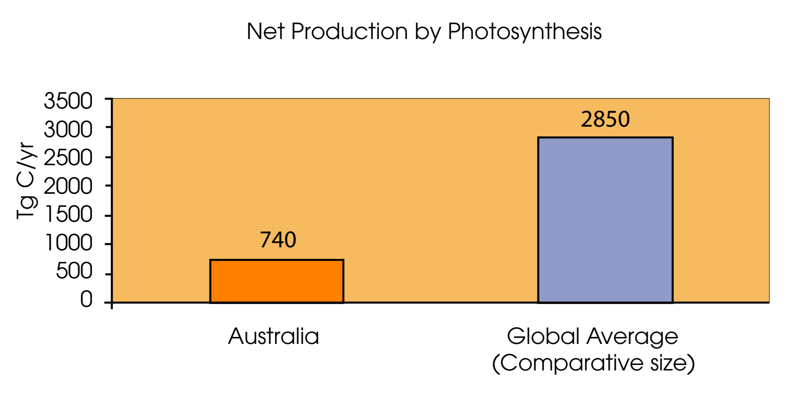


Figure 25: Difference between global average and Australian net ecosystem productivity can be seen by comparing the annual average net production by photosynthesis for Australia with the global average for a continent of Australia's size (CSIRO).

2.5.2 Measuring the effect of enhanced carbon dioxide on vegetation

In the Australian ecosystem any major positive effect of elevated carbon dioxide may be offset by a limited supply of water and nutrients

In addition to the impact of temperature, rainfall and soil moisture changes on the growth of vegetation, it is expected in a 'greenhouse' world, that increased atmospheric concentrations of carbon dioxide will also influence growth. Indeed these factors will interact in a complex and unpredictable way.

The ACCSP supports a free air carbon enrichment experiment – OzFACE. This is an experimental system established through the collaboration of CSIRO and an industry partner, Queensland Nickel Pty Ltd. The purpose is to measure ecosystem responses to enhanced levels of atmospheric carbon dioxide manipulated to expected 2050 levels to obtain a clearer view of the net impacts.

Results thus far show that seedling growth of two tree species is enhanced by elevated carbon dioxide, with a stronger response in the nitrogen-fixer (Acacia holosericea) than the non-nitrogen fixer (Corymbia tessallaris). This suggests that an adequate source of nitrogen can enhance the fertilisation effect of carbon dioxide (Figure 26).

Growth responses of tropical grasses to elevated carbon dioxide have not been as consistent as those observed for woody plants with no appreciable response seen except during the first year of study. This may be related to the enhanced water use efficiency of tropical grasses at higher carbon dioxide levels, a benefit that might be most strongly expressed only in growth periods where moisture is moderately limiting.

However, it is extremely difficult to disentangle the effects of elevated carbon dioxide from the effects of climate change (and from other environmental factors) which bring their own set of considerable uncertainties and gaps in understanding. In the Australian ecosystem, any positive effect is likely to be offset by a limited supply of water and nutrients. This research raises the question – in what conditions is the carbon dioxide fertilisation effect likely to be important and how can land management be adapted to take best advantage of it? This highlights the need for more research on a larger spatial and longer time scale.

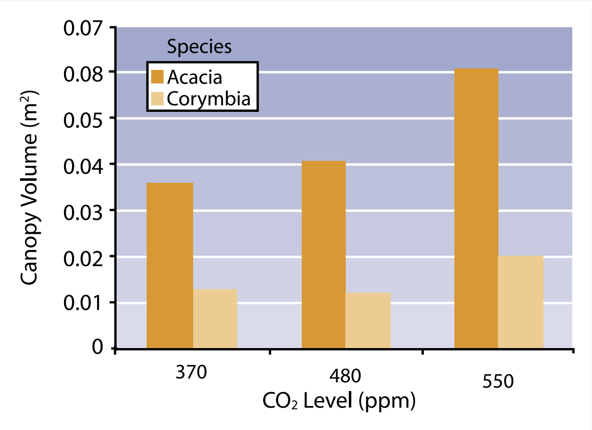
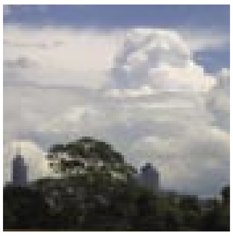
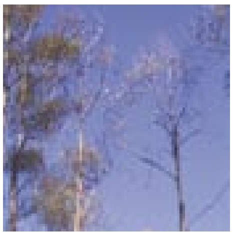


Figure 26: Field trials using 'free air carbon enrichment' to study the impact of enhanced carbon dioxide on a mature savanna ecosystem (CSIRO).





Box 9: Key achievements in studies of the biosphere

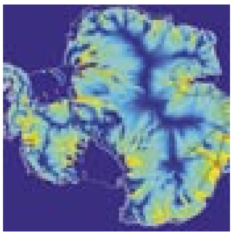
What we have learnt about Australian systems

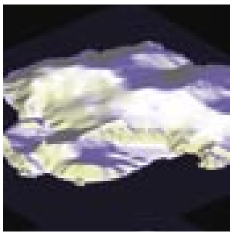
- While experiments show that increasing carbon dioxide levels can lead to an enhancement of plant photosynthetic activity and growth - in the Australian ecosystem any positive effect is likely to be offset by a limited supply of water and nutrients.
- Carbon models have shown that the terrestrial carbon cycle of Australia, due to a unique combination of flora, climate and soils, behaves differently from elsewhere in the world. This highlights the need for the development of climate models that accurately represent our unique ecosystems. For example:
  - unlike regions of the northern hemisphere, variation and trends in rainfall have a stronger influence on net terrestrial exchanges of carbon dioxide;
  - turnover of carbon in surface soil layers of Australia's tropical savannas is longer than elsewhere probably because of the high clay contents of these soils, the high fire incidence and charcoal production, and greater aridity in Australian ecosystems; and
  - the Australian continental net primary production is extremely low compared to other areas of the world.

Australia's contribution to biosphere science

- Australia has contributed to science showing that since pre-industrial times the terrestrial biosphere has switched from an annual net source of carbon to become a carbon sink. During the 1980s and 1990s the biosphere absorbed about 39 ±18 thousand million tonnes of carbon from the atmosphere.
- Through the first multi-annual flux measurements in Australian ecosystems, we have new insight and understanding of the interactions between climate, hydrology and carbon cycling in Australian ecosystems providing an important dataset for testing and constraining terrestrial biogeochemical models.
- New mathematical techniques have been developed to use information from a range of sources, including flux towers and remote sensing observations, to improve predictions by carbon cycle models.
- Our science has revealed that annual climate variation in Australia is a major driver of variation in net primary production leading to annual net ecosystem production (production less loss from decomposition) ranging from a source to the atmosphere of 80 million tonnes per year to a sink of 120 million tonnes per year (about 4 per cent of global variation).
- Modelling of emissions from biomass burning for Australia shows that due to climate variation, emissions range from about 80 to 130 million tonnes of carbon per year (between 8 and 21 per cent of continental net primary production).

2.6 Climate modelling





The ACCSP has enabled Australian climate models to reach international standards

Most scientific experiments involve changing a variable and comparing the observed changes to a baseline or control. As there is only one Earth, climate scientists have to rely on developing computer models to represent the climate system. As we learn more about the components of the system, the models are better able to simulate the real world.

These models are then used to obtain insight as to the effect particular changes to greenhouse gases in the atmosphere will have on the magnitude of the global warming, and the way this translates into regional climatic changes.

Prior to the ACCSP Australia did not have a global climate change modelling capacity. In 15 years, with Programme support, Australia's models have been recognised as world-class and have contributed to our influence in the international climate change science community. Australian models were among those that performed well in analyses for the IPCC Third Assessment Report.

There has been a continuing research focus within the ACCSP, and elsewhere, aimed at reducing the uncertainties in climate models.

Research has greatly improved the way in which climate models represent the real climate, in terms of day-to-day, month-to-month and decade-to-decade variability of temporal and spatial patterns of the climate (Figure 27). The modelling work entails comparison of model outputs with observations and that of other models internationally. Such studies have been useful in demonstrating that current shortcomings in the representation of the physics and dynamics of the

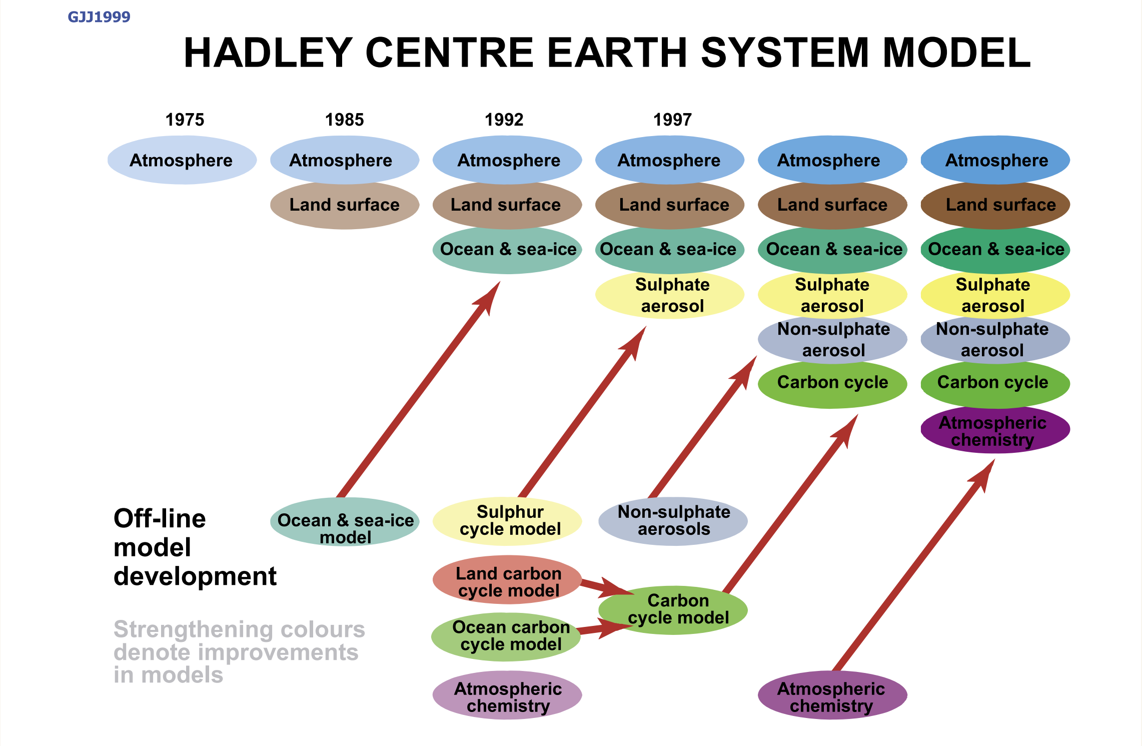


Figure 27: Development of climate models - a schematic history of the development of some of the modules that comprise the Hadley Centre climate modelling system. The different components are first developed separately and later coupled into comprehensive climate models (V. Pope, Hadley Centre, UK).

systems do not invalidate the overall conclusions concerning the connection between greenhouse gases and climate change.

Figure 28 shows how well the warming of the last century is modelled by a group of these global models.

An example of Australian leadership in climate system modelling is the representation of the role of eddies in the dynamics of the ocean current and the overturning circulation. Eddies or 'turbulence' transport heat and momentum from one place to another in the oceans. Oceanographers knew for decades that the way that ocean eddies were incorporated into their models led to some undesirable features such as unwanted vertical mixing. Scientists had no way of quantifying the error these crude representations of eddies introduced into the simulations.

This new representation of ocean eddies in climate models, developed and implemented by Programme scientists, led to dramatic improvements in the ability of the models to simulate the response of the ocean to enhanced greenhouse warming. With the new eddy-parameterisation, excessively deep mixed layers are avoided, the sea surface temperature is closer to reality, and the fluxes of heat between the ocean and atmosphere are greatly improved.

This approach is now standard in climate models world-wide.

The challenge ahead for Australian climate change science is to develop our modelling system further to meet our own needs and to maintain a world-class standard that enables us to contribute state-of-the-art climate projections and scenarios to future IPCC assessments. This will involve developing a fully coupled carbon cycle model covering terrestrial, ocean and atmosphere systems and incorporating a dynamic vegetation model.

This challenge is much more demanding than any one institution can address and through the ACCSP a strong collaboration between the Bureau of Meteorology Research Centre and CSIRO has been formed. The aim is to develop an Australian Community Climate Earth System Simulator (ACCESS) – a coupled climate and earth system simulator – to ensure the maintenance of our world-class climate modelling capability. A key objective of this system is to inform policy development aimed at national and international application on the implications of climate change and climate variability at global, national, regional and local scales (see Australian Climate Change Science Programme: Strategic Research Agenda 2004-08).

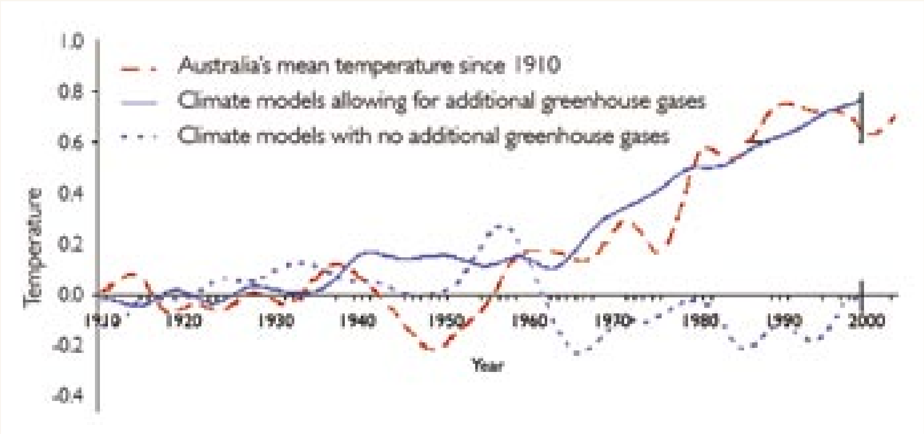


Figure 28: Comparison of the change of average temperature of Australia over the past century as observed with that calculated by eight of the world's best climate models (including Australia), showing the agreement between observations and calculation of the impact of greenhouse gases (Monash University).

Box 10: Key achievements in global climate modelling

- Most Australian versions of the global climate system models successfully represent many of the detailed features of the real climate system – particularly for the Australian region.
- The development of coupled models – models that bring together atmospheric, oceanic, land surface and sea ice components in a single global climate model. Coupling of these components has led to a better understanding of the Earth's response to greenhouse forcing, through better representation of links between the carbon cycle and physical climate system (Figure 29).
- Significant improvements in the realistic representation of the inter-annual climate variation driven by El Niño, cyclone formation, rainfall distributions, frontal patterns, seasonality, and agreement between observed regional warming and that simulated for the past century.
- Improved capacity to use versions of these models for seasonal forecasting – vital for Australia because of our highly variable climate.
- New representation of ocean eddies in climate models led to dramatic improvements in the ability of the models to simulate the response of the ocean to enhanced greenhouse warming.
- Recognition of tropical aerosol as a significant climate forcing agent that needs to be better represented in climate models. Aerosols can alter atmospheric circulation and rainfall patterns, especially in tropical Australia (see Australian Climate Change Science Programme: Strategic Research Agenda 2004-08).
- Global warming simulations of the ocean have shown that dissolved oxygen in the ocean is a sensitive indicator of changes in ocean circulation. Model simulated multi-decadal changes in dissolved oxygen in the Southern Ocean are in good agreement with observed changes. Investigations in the Pacific Ocean have also documented substantial changes in dissolved oxygen. Understanding the causes of these oceanic changes in dissolved oxygen provides insight into how global warming is affecting ocean circulation and the Earth's climate.
- Investigations of the character and predictability of natural decadal variability of the southern hemisphere climate have identified links between changes in the overturning circulation and southern Australian climate, and highly predictable decadal changes in the subsurface Pacific Ocean.

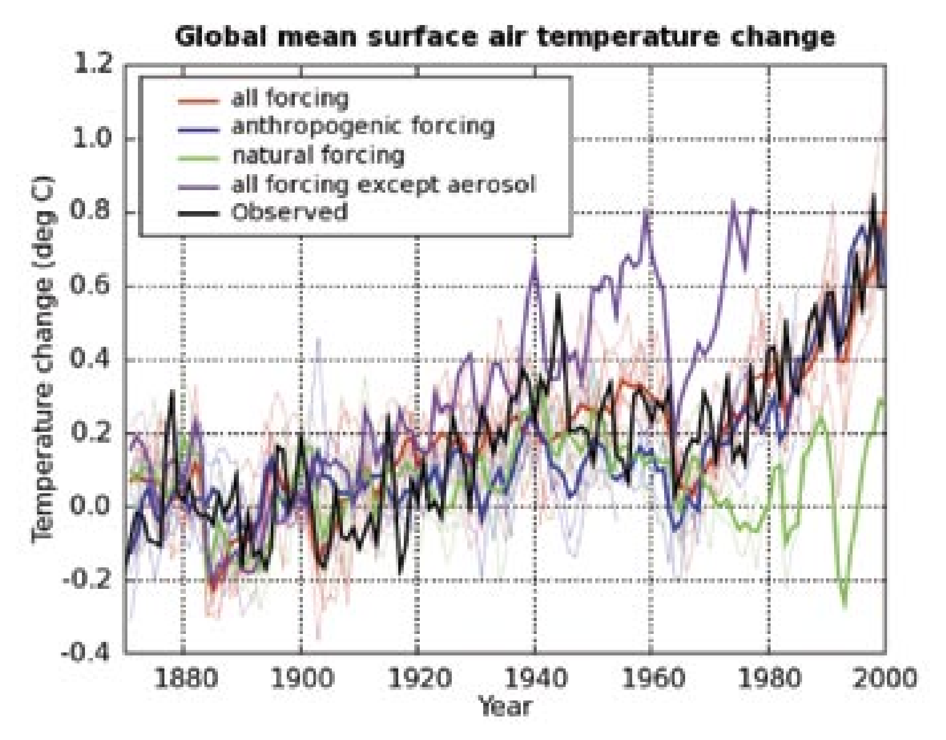


Figure 29: The ability of models to accurately represent observed temperature changes is shown. The anthropogenic forcing (blue line) represents models that include greenhouse gas emissions from human activity. This aligns well with observed temperature change (black line). The 'natural forcing' (green line), which represents models that include only solar and volcanic effects, does not capture the observed warming of the late 20th century. This suggests that the observed warming is inconsistent with natural variability (CSIRO).

Box 11: Key achievements in regional climate modelling

The impact that climate has on our lives is a result of very localised influences such as mountains and proximity to the ocean. It is important to be able to express climate changes at these levels. However, accurately representing the complexity of the climate system demands very sophisticated modelling tools. This, together with existing computing capacity, limits the level of spatial resolution that can be represented in global models. Therefore a gap exists between what climate models can predict about future climate change and the information relevant to our daily life.

- Australia is at the forefront of approaches to fill this gap by reducing the scale of model outputs to give more accurate regional information. This is known as 'downscaling'. The two main strategies used to achieve such an outcome are the nesting of higher resolution models within lower resolution global models (dynamical downscaling) and the development of a statistical relationship between regional climatological characteristics and point locations (statistical downscaling).
- Australia has developed an innovative modelling tool that enable global models with different levels of computational detail to be run at different locations over the Earth's surface (Figure 30). This work has enabled Australian scientists to look more specifically at particular regions of Australia and in Southeast Asia and the western Pacific. The advantage of this approach is that it provides a full range of information which is physically consistent with large-scale features but with a much finer resolution. However, this approach is limited in term of spatial resolution and is also incredibly computer intensive.
- In order to provide even smaller scale information, statistical techniques have been utilised. This approach involves using observations data to establish a linkage between large-scale atmospheric variables that are reliably predicted by climate models and local scale climate variables relevant to our daily life (Figure 31). These approaches have a very low computational cost and are a flexible tool for studying a range of very important issues such as the uncertainties associated with climate change projections or the predicted changes in extreme events. However, such a method can only be developed where a long record of climate information exists and for the variables that are routinely observed. This obviously limits the information that can be provided.

By investing in these two types of approaches, Australia is well equipped to provide a large range of climate change information relevant at a regional and at a local scale. In particular, it is now possible to combine the two approaches to develop 'hybrid' statistical-dynamical downscaling techniques to benefit from the advantages of the two approaches. These techniques are critical to provide detailed information relevant to the study of local impacts of our changing climate on day-to-day activities and our natural environment.

Figure 30: The Cubic-Conformal Atmospheric Model (C-CAM) which uses an innovative 'stretched grid' pattern in which the greatest climatic detail is determined for the area of finest resolution. Typical model resolution is 60 km, with some highly detailed simulations using 14 km grid spacing (CSIRO).

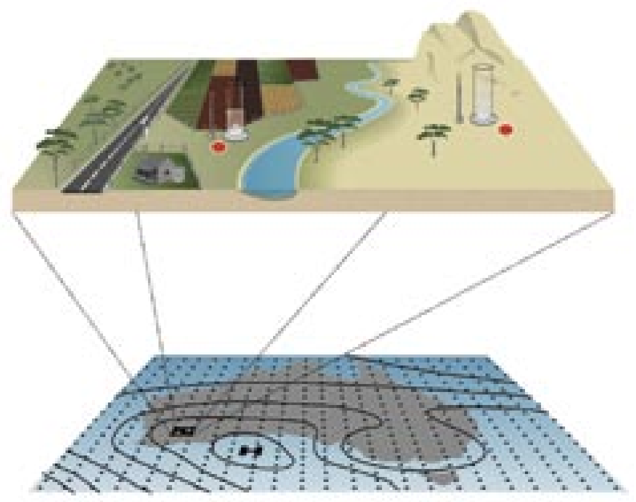


Figure 31: A statistical downscaling approach uses climate model predictions for large-scale atmospheric patterns such as atmospheric pressure (lower part), which drive the local climate alongside small-scale features (upper part), which are taken, into account via the statistical linkage created (Bureau of Meteorology).

2.7 Regional climate change assessment

Climate projections produced through the Programme have underpinned a number of climate change impacts studies

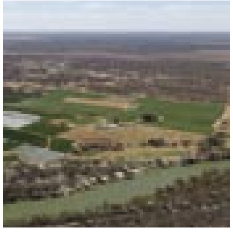
From a national perspective, the real drive behind this science is to understand our own national vulnerabilities to climate change (and climate variability) especially on a regional scale.

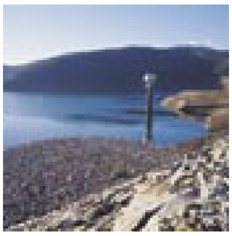
This is a very challenging task scientifically, as regional to local climate depends on extremely fine balances between atmospheric and ocean circulations. Small meridional or latitudinal shifts in location can have a huge influence. The challenge also relates to the representation of these locally important components in the framework of the global system that drives the coarser features.

Regional projections have been periodically released by CSIRO for use by the wider research and policy community (www.csiro.au). These projections based on numerous climate models are driven by a range of greenhouse gas and sulfate aerosol emission scenarios which reflect alternative futures for global energy use. The emission scenarios are based on scenarios used in the IPCC Third Assessment Report released in 2001.

Climate projections produced through the Programme have been used in a number of climate change impacts studies, some of which have been supported by the AGO, CSIRO and State governments. Many studies have been performed on the potential impact of climate change on specific sectors of the Australian community. Such sectors include forestry, agriculture, water resources, health, natural resources, energy. CSIRO has also undertaken a wide range of studies to provide State governments with the best available indications of what a 'greenhouse' world will look like within their borders.

(Arthur Mostead, Murray-Darling Basin Commission)





Box 12: Regional climate scenarios – an integrated study of the Macquarie River Valley Catchment

For this project two regional climate change scenarios, developed by CSIRO, were adopted and used as the input to assess future river flow, water availability, as well as the economic and ecological effect of climate change on the region. Both scenarios were based on patterns of regional climate change from a single simulation (from a high resolution nested climate model), but differ markedly in the assumptions that are made about the future rate of emission of greenhouse gases and the sensitivity of the global climate system (assumptions relevant to the rate of global warming) (Figure 32).

The scenarios were presented as plausible possibilities, rather than predictions, of what the climate may look like in 2030 and were used as input to a Macquarie River Model to produce river flow scenarios. The effects on water availability for both irrigation and flows into the Macquarie Marshes were also calculated, assuming that the 1997 water allocation rules were followed.

The climatic effects on the economy of the region were then assessed. These effects included both negative factors (lower irrigation water diversions, lower rainfall and higher evaporation) as well as assumed beneficial factors (higher temperature and higher CO_2 levels) that can lead to higher plant growth. Taking both positive and negative factors into account, the potential effect on the local economy was calculated to be a loss in Gross Revenue of between $38 million and $152 million dollars per year (6 to 22 per cent) under the High and Low scenarios, respectively. Under these scenarios, it is suggested that livestock industries, given their scale and that negative factors far outweigh positive factors, would be the worst affected.

The NSW National Parks and Wildlife Service assessed the effects of the lower water flow into the Macquarie Marshes. The potential effects included: a reduction of both semi-permanent and ephemeral wetland vegetation by 20 per cent to 40 per cent of their original area by 2030, less frequent breeding events for the colonial nesting bird species and, depending on what effects these climate changes have elsewhere on the species, the occurrence of local, regional and global extinctions.

The information collected formed the basis for suggested future wetland management plans, allowing for uncertainty, including a range of suggested adaptive and avoidance strategies.

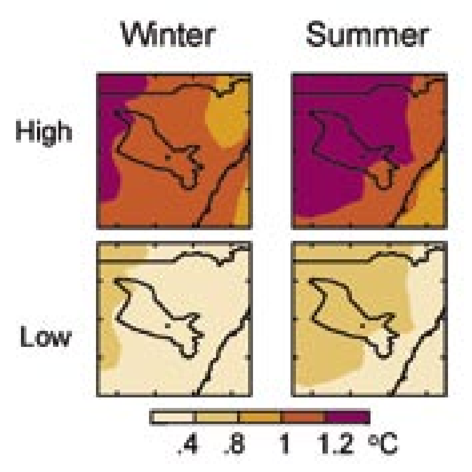
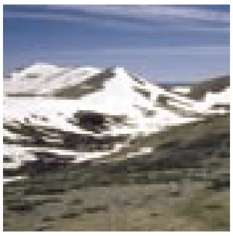


Figure 32: High and Low scenarios for seasonal mean temperature change in 2030 for the Macquarie River Valley Catchment. Units in degrees Celsius (CSIRO).



3. THE CHALLENGES FOR CLIMATE CHANGE SCIENCE

Profound progress has been made since the commencement of the Australian Climate Change Science Programme in 1989, in both our observation and understanding of the climate system, and of the drivers of change. This has led to improved projections of climate change through development of more sophisticated and representative climate models.

Australia's climate modeling capacity has been recognised as world class, for example through its use in global assessments reported by the Intergovernmental Panel on Climate Change. Selection of models for use in these global assessments is based on how well the model simulates the mean seasonal climate for a number of variables, and on the ability of the model to describe climate variability over a range of time-scales. Importantly, model performance is assessed against observed data. Australia's climate models provide credible simulations of the present climate, including seasonal cycles, and can reproduce the observed warming trend in the 20th century.

The body of evidence of climate change has also grown substantially in recent years. Satellites and oceanic Argo floats have massively increased the number of observations of the climate system, and Australia's flux towers and tidal measurement gauges are providing high precision data not previously available.

There is now no doubt that climate change is occurring and that present levels of greenhouse gases in the atmosphere, as a result of human activity, will lead to some unavoidable impacts.

However, given the complexity of the climate system and the intricate interconnections of land, oceans and atmosphere, there remain a number of unresolved issues in our current knowledge of climate change science. Further work is required to improve the ability to detect, attribute and understand climate change, particularly at regional scales, to reduce uncertainties, and to project future climate changes. This will require additional systematic observations, modelling and process studies.

One challenge faced by Australian climate change science is that in many instances our needs will not be served by northern hemisphere research. Critical differences in the productivity and functioning of vegetation and in the sources of aerosols between Australia and global averages will at times prevent the application of research results from Europe and the United States.

Australia also has a stake in addressing key global knowledge gaps, such as:

- the behaviour of the Southern Ocean overturning circulation and likelihood of any disruption;

- changes in the capacity of the Southern Ocean to absorb anthropogenic carbon dioxide;
- the role of aerosols and clouds on our climate system;
- the respective roles of greenhouse gases and ozone depletion in changed rainfall patterns over southern Australia; and
- the potential for positive climate feedbacks, including the likelihood of abrupt changes in climate and their likely consequences.

A major challenge for Australia in contributing to these science questions is simply the vast size of the Southern Ocean, and the fact that there are very few countries in the southern hemisphere with the research capacity to assist.

Through its climate change strategy announced in 2004, the Australian Government is currently investing $30.7 million between 2004 and 2008 in the Australian Climate Change Science Programme.

The 2004-2008 research agenda has been designed to advance our understanding of these challenging areas of climate change science, and respond to stakeholder requests for better projections of the impacts of climate change on industry sectors, regions and the community. Future directions of the Programme are highlighted in the accompanying document Australian Climate Change Science Programme: Strategic Research Agenda 2004-08.

Importantly, this Programme concentrates upon policy-relevant research and aims to provide the best possible information to support decision-making on climate-related issues. The Programme underpins the capacity of governments, business and industry, and the community to understand and respond to climate change. Advances in understanding of climate change and its likely impacts will be vital to the preparedness of Australia to respond and adapt.

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(Roger Good)

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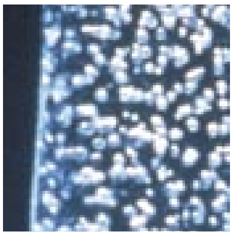

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