Australian Climate Change Science Program

Annual report 2009–10

A summary of climate change science undertaken by CSIRO and the Bureau of Meteorology under the ACCSP, prepared for the Department of Climate Change and Energy Efficiency.

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Summary of major achievements

The Australian Climate Change Science Program (ACCSP) continues to improve our understanding of the causes, nature, timing and consequences of climate change so that industry, community and government decisions are better informed. The program has been running continuously since 1989 and is a key driver of Australia's climate change research effort.

Significant progress has been made in research on climate change in Australia in 2009-2010. The ACCSP has addressed a range of climate change research needs. The program continues to demonstrate that human-induced changes are taking place in our atmosphere, oceans and biosphere. For example, oceans are warming, greenhouse gas concentrations are rising and we are experiencing some impacts of climate change through extreme events. Our researchers are establishing how these changes are happening and what we may expect in the future.

The ACCSP program has delivered:

- Improved observations, data management and modelling
- An enhanced understanding of climate and weather systems, particularly for the Australian region
- Improved tracking of atmospheric carbon concentrations, and
- Updated projections of climate change for Australia.

Environmental observations

The ACCSP supports the vast array of global observations used to monitor our climate and to underpin climate projections. Some significant observations include:

Sea-level rise
The National Tidal Centre continues to monitor sea-level around Australia. The precise extent of sea-level rise varies from place to place and year to year because of fluctuations associated with climate variation. Since 1992 global sea-level has risen by 3.2 ± 0.4 mm/yr, nearly twice the average rate (1.7 mm per year) experienced during the 20th century as a whole and at a rate near the upper end of the Intergovernmental Panel on Climate Change projections.

Ocean temperature
Heat from the atmosphere is penetrating into the oceans. The surface ocean and the deep ocean have both warmed, contributing significantly to the Earth's global energy budget and to sea-level rise.

Ocean acidification
Areas of the ocean surrounding the Great Barrier Reef are becoming more acidic due to increasing concentrations of carbon dioxide. Ocean acidification adds stress to reefs and the ecosystems that rely upon them. For example, acidification makes it more difficult for corals and other organisms to maintain their carbonate structures, which form the basis of reefs and shells).

Ocean salinity
ACCSP researchers have observed that changing rainfall patterns are affecting the salinity of the oceans. Some regions in the ocean that receive low rainfall are becoming saltier, and regions with

high rainfall are becoming less salty. These changes indicate that the global water cycle is intensifying, implying that arid regions over land and sea will become drier and high rainfall areas wetter.

Climate modelling

Significant progress has been made in developing Australia's climate modelling capability and in improving data sourcing and management.

The ACCSP supports Australia's new global climate model, the Australian Community Climate and Earth-System Simulator (ACCESS). ACCESS represents a major advance over earlier, simpler climate models. It sources a wealth of data from earth-observing satellites and other climate sensors, including atmosphere, ocean, sea-ice, and land-surface information. The model can skilfully simulate many parts of the global climate system. This will help provide Australian's with better tools and information needed to make effective future decisions about climate change.

A number of tests indicate that the model will soon enable Australia to contribute to future Intergovernmental Panel on Climate Change (IPCC) assessments, and participate in international model comparisons. Improvements include:

- Numerous 100 year simulations performed to test differences in atmospheric, oceanic and sea ice settings;
- Evaluation of the accuracy of climate simulations and the ability of the model to simulate important climate patterns such as the El Niño Southern Oscillation (ENSO); and
- Tests of land surface, atmosphere and ocean/sea-ice simulations.

The capacity to undertake downscaled modelling for regionally specific information is also being improved. Downscaling offers the advantage of presenting information at a resolution sufficiently high to assist with regional decision making, for example helping inform adaptation needs on sea-level rise and coastal inundation.

- A statistical downscaling model has been developed to provide downscaled climate projections. These are available to a resolution of approximately 5 km over the entire Australian continent.
- The emphasis of work in 2009–10 has been on adapting the model to accommodate climate observations (for rainfall, maximum and minimum temperature) and evaluating the downscaled projections in comparison to the high quality observation network.

Climate and weather systems

ACCSP researchers are investigating differences in climate change and climate variability. Climate change refers to long term trends (decades or longer) in climate averages and the frequency, duration and severity of extreme events. Climate variability indicates daily, seasonal, annual or multi-year events or variations in climate, such as fluctuations in ENSO.

A number of climatic drivers influence Australian weather systems, including ENSO, the Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD). The ACCSP has made major discoveries about the way in which these drivers influence rainfall in various regions of Australia. Analysis of their behaviour improves our understanding of how they will affect rainfall and extreme events.

For example, observations show that of the 16 positive IOD events since 1950, 11 were followed by major bushfires including the Ash Wednesday (February 1983) and Black Saturday (February 2009) disasters. Climate models, forced with and without climate change, show that the frequency of positive IOD events increased by 17% under a climate change scenario. This model result is largely caused by faster warming over land than over the ocean.

Superimposed onto climatic variability are longer-term changes to rainfall. Large areas of eastern and south-eastern Australia have experienced a drying trend over recent decades, as has the south-west of Western Australia. Conversely, north-western Australia has become considerably wetter.

Measuring the carbon cycle

Human activities have considerably altered the concentration of greenhouse gases in our atmosphere. The Global Carbon Project (GCP) aims to develop a complete picture of the global carbon cycle, including both biophysical and human dimensions. The ACCSP supports key research in the GCP to improve international understanding of the carbon cycle, and establish a knowledge base to support policy that affects atmospheric greenhouse gases concentrations.

Recent research on the carbon cycle shows:

- Human activities have released 500 billion tonnes of carbon dioxide into the atmosphere since the beginning of the Industrial Revolution, around 1750.
- Atmospheric carbon dioxide has increased 38% since 1750 and contributed 63% of all anthropogenic radiative forcing to date.
- In 2008, human activities added almost 10 billion tonnes of carbon to the atmosphere (this is equivalent to about 30 billion tonnes of carbon dioxide). This included 8.7 billion tonnes carbon from fossil fuel combustion and industrial activities, and the rest from net land use change.
- The dominant carbon dioxide emissions contribution from fossil fuels has accelerated in recent years, increasing at an average growth rate of 3.4% per year during 2000–2008, compared to 1.1% per year during the 1990s and an average of 2% per year since 1970.
- In 2008, developing countries emitted more fossil fuel carbon dioxide (55% of the total) than the developed world (45%); however, per capita emissions remained much higher in developed countries.
- The global financial crisis that began in 2008 is expected to lower global fossil-fuel carbon dioxide emissions, but will hardly effect the growth of the concentration of atmospheric carbon dioxide because of the large year-to-year variability in natural carbon dioxide sinks.

Science highlights

UNDERSTANDING THE KEY DRIVERS OF CLIMATE CHANGE IN THE AUSTRALIAN REGION

Atmospheric greenhouse gases and aerosol

Southern Ocean carbon dioxide sink

- Development of the Southern Ocean CO_2 observation network took another step forward when a research plan was formulated with French collaborators Laboratoire des Sciences du Climat et l'Environnement (LSCE) to integrate CO_2, CO_2 isotope and O_2/N_2 data set records at Amsterdam Island with the CSIRO network sites. This included establishing a protocol for a high precision Inter-Calibration Program (ICP) to be developed for the Southern Ocean CO_2 network (France-Australia-New Zealand).

Carbon-climate feedbacks in the palaeo record

- Ice core and firn air samples were collected in Greenland and analysed at CSIRO GASLAB for the full range of greenhouse and ozone depleting gases.
- The Mk3L climate model is being coupled with carbon cycle modules in order to assess the role of greenhouse gases in forcing climate change.

Aerosols and Australian climate change

- Researchers have published a decadal time series of aerosol loading over an Australian Outback ground station.
- Modelled change in global-mean temperature for the period 1851–2005 shows that simulated warming that includes the masking effect of aerosols is substantially smaller than that simulated when aerosol effects are omitted, a result consistent with previous modelling studies.

Terrestrial water and carbon cycle

Biogeochemical cycles and climate for Australian landscapes

- An improved soil module that couples fluxes of heat, water and stable isotopes and includes a litter layer was developed for the CABLE land surface model.
- Key parameters for south-eastern Australia in CABLE were estimated. It was shown that the inclusion of multiple data types (soil moisture, stream flow and fluxes from flux towers) in the training data set improves model performance against independent validation data.

- Field equipment was installed at three grassland sites in northern Australia for the study of savanna phenology. The sites will be valuable for validating both remote sensing products and modelling from CABLE.
- A database containing biomass and NPP observations from the published literature and existing databases was prepared. It includes approximately 2200 geo-referenced, site-based observations of vegetation carbon, and approximately 1700 observations of NPP.

Ocean chemistry

Ocean acidification and carbon cycle

- A new hydrographic section database containing Atlantic and Southern Ocean data has been publically released as CARINA, and is available at <http://cdiac.ornl.gov/oceans/CARINA/about_carina.html>.
- Researchers deployed the first ocean acidification mooring in Australian waters on the Great Barrier Reef (in collaboration with NOAA, USA).
- Researchers found that a geoengineering option for enhancing oceanic uptake of atmospheric CO_2 by artificial upwelling of nutrient-rich deep waters has only a small impact on CO_2 uptake.

Ocean processes

Ocean data partnership through IMOS

- Argo Australia deployed 54 floats in our region, bringing the Argo Australia fleet to 263 active floats. Argo Australia delivered approximately 9000 profiles to the global Argo data system (up from approximately 7500 from last year).
- A 20-year time series of the volume transport associated with each of the main inflows and outflows within the South Pacific boundary current system shows that at a 1–5 year time scale the flow through the Auckland–Fiji section is predominantly balanced by that exiting through the Brisbane–Fiji section.
- Researchers deployed the first deep ocean glider in the southern hemisphere, and assessed its suitability for measuring the Eastern Australian Current.

Ocean climate and rates of change

- Analysis revealed that climate models simulate deep ocean change but they poorly represent the rate of change and its spatial distribution.
- Robust deep ocean warming and freshening was found in the western Pacific Ocean, particularly in the southern basins that are directly connected to the Southern Ocean, but also extending as far north as the equator.

- The deep boundary current adjacent to the Kerguelen Plateau is a major pathway of the deep overturning circulation of the Southern Ocean. Similar measurements on the Antarctic continental shelf provided the first direct measurements of the rate at which dense water sinks to the deep ocean to supply new Antarctic Bottom Water.

- An array of five current meter moorings was successfully deployed in December 2009 off the coast of Antarctica as a part of a joint Australian–US experiment aiming to test the hypothesis of a very energetic, largely barotropic, gyre in the Australian-Antarctic Basin and to provide detailed measurements of the deep boundary current exporting Antarctic Bottom Water.

- The processes that result in the formation of Subantarctic Mode Water in the south-east Pacific Ocean were determined, particularly the importance of wind-induced mixing on the development of winter deep mixed layers upstream of Drake Passage.

- A new approach for studying the Antarctic Circumpolar Current using satellite and ship data was developed, allowing the structure and variability of the current to be examined in detail for the first time.

- The Antarctic Circumpolar Current was found to consist of multiple filaments along the entire 20,000-km long path circling Antarctica.

- Argo float data was used to quantify the rate at which surface waters (and therefore heat and carbon) are subducted into the ocean interior for the first time, revealing unexpected ‘hot spots’ of subduction and showing that eddies made an important contribution.

- Researchers assessed the sensitivity of mode and intermediate water formation to climate change, and found that the subduction rate was reduced and the water masses migrated to lower densities. This suggests a smaller volume of the ocean will be ventilated in the future.

- The interaction of the fronts of the Antarctic Circumpolar Current and topography was investigated in a previously poorly studied region near the Kerguelen Plateau.

- Studies of surface and subsurface ocean salinity change over the past 50 years revealed a strengthening of the mean salinity pattern, consistent with an amplification of the global hydrological cycle over the past 50 years. Subsurface ocean water mass changes largely result from the subduction into the ocean interior of a broad scale warming and its subsequent advection by the global ocean circulation.

The response of Indo-Pacific Ocean variability to climate change and its impact on Australian rainfall

- Of the 16 positive Indian Ocean Dipole (IOD) events since 1950, 11 were followed by major bushfires including the Ash Wednesday (February 1983) and Black Saturday (February 2009) disasters.

- No systematic linkage between ENSO amplitude and ENSO–IOD coherence was identified, meaning that the IOD is not always triggered by ENSO events.

- In the presence of climate change, the frequency of positive Indian Ocean Dipole events increased by 17%, consistent with a weakening tropical circulation with a shallowing Indo–Pacific thermocline and enhanced Asia–Australia monsoon, supported by a robust faster warming over land than over the ocean.

- Anthropogenic aerosols are responsible for driving the observed subsurface cooling of the southern Indian Ocean in recent decades.

Understanding, evaluating and intercomparing climate change feedbacks

- Analysis of climate feedbacks in the AR4 models revealed the low latitude 'dominance' of water vapour feedback (i.e. that the tropics are responsible for the vast bulk feedback strength), the effect of clouds in partially 'masking' that feedback (especially in the heavily cloud covered equatorial region), and that the tropics was the major source of feedback disagreements between models.

- Code has been developed to perform year-to-year feedback calculations in the AR4 models. This code development is a significant advance on previous analysis techniques, permitting feedback estimates, as well as measures of their uncertainty from the analysis technique itself.

- A number of important aspects of what are generally understood to be 'feedbacks', particularly in cloud responses, may in fact be the result of relatively rapid adjustment to stability changes caused by greenhouse gases (such as CO_2 increases).

Sea level rise

Global and regional sea-level rise: Reducing uncertainty and improving projections

- Updated estimates of global averaged sea-level rise (both globally and around Australia) and ocean thermal expansion have been made available at <http://www.cmar.csiro.au/sealevel/>.

- Researchers have collected the first set of data to enable estimates of the surface wave effects (sea-state bias) on satellite sea-level measurements.

- An extended and improved sea-level budget up to the end of 2008 has been drafted.

Detection and attribution of climate change

Attribution and projection of climate variability and changing weather systems

- Researchers found significant decreases in the winter growth rates of blocking modes, as well as storm track modes, significant increases in the growth rates of the north-west cloud band and intraseasonal oscillations crossing Australia, little change in Antarctic teleconnection patterns and moderate increases in growth rates of African easterly waves since the mid-1970s.

- Inverse modelling methods were developed for attribution of anomalous thermodynamical and dynamical forcing associated with the changes in the mean climate of the southern hemisphere circulation.

- New methodologies were developed to investigate changes in large-scale atmospheric variability in CMIP3 models under climate change, and to study the relationship between the large scale atmospheric variability and Australian rainfall. The latter method allows both the internally and externally forced coupled modes between Australian rainfall and the pressure field to be identified.

IMPROVED CLIMATE SYSTEM AND CHANGE MODELLING

Development of the ACCESS coupled climate modelling system

- In preparation for the ACCESS coupled model contribution of modelling results to the IPCC fifth assessment report (AR5) six principal test simulations, each of 100 years duration, were conducted. Many key climate processes were simulated to a degree of realism that lies well within the range anticipated to be displayed by the other participating models. The conclusion is that ACCESS is getting close to being ready for the IPCC AR5 simulations, but needs some more work especially on mitigation of some regional biases.

CLIMATE CHANGE, CLIMATE VARIABILITY AND EXTREME EVENTS

Development of high quality historical tropical cyclone data in the Australian region

- The tropical cyclone database has been purged of gross errors and loaded onto the expanded ADAM database and checked for transfer errors. The development of a user-friendly interface is well advanced.

Climate change – climate diagnostic

- A series of diagnostics developed for fine resolution numerical weather predictions models were adapted to coarser resolution climate models. The diagnostics evaluate the large-scale conditions that are favourable to the formation of east coast lows.

Tropical processes affecting Australia – climate simulations and projections of the Australian monsoon, ENSO and the Walker Circulation

- The Australian monsoon is strongly affected by the phase of ENSO. During El Niño events, the total rainfall amounts for the entire wet season are less than during La Niña years, but during the onset period (the first few weeks after the onset date) there is not much difference. The main difference lies in the rainfall at least one month after the onset, with significantly more rainfall during La Niña years.

- Researchers found evidence for a slight prolonging of the monsoon season in climate change projections. There was no significant change in the average monsoon onset date, but a slight intensification in the low level westerlies during the wet season across tropical Australia.

REGIONAL CLIMATE CHANGE PROJECTIONS

Projecting future climate and its extremes

- Projections for annual average number of days (and 3–5 day heatwaves) with Tmax over 30–45°C, Tmin over 20–30°C and Tmin under 0–10°C for present (1970–2000), 2030, 2050 and 2070, including changes in daily variability, provide clear evidence for an increase in hot days and a decrease in cold days. In areas that become drier, the increase in hot days is larger and the reduction in cold days is smaller.

- Projections indicating the percentage change in intensity of 1-day and 3-day events with return periods of 10, 20 and 50 years for 2055 and 2090 for 11 models over 11 regions have been developed. Extreme rainfall tends to become more intense in most models and regions, even in regions that on average become drier.

- The mean significant wave height along the eastern Australian coast is projected to decrease slightly in future (~1 cm/decade), particularly during autumn and winter. Spring and summer wave heights are relatively unchanged.

- Fewer tropical cyclones are likely in the future near Australia, but there is likely to be an increased percentage of severe (Category 3-5) events.

- A web-based tool has been developed which simplifies communication of projections and has proved popular in workshops. More development is necessary before ‘Climate futures’ is made public.

Extremes research supporting adaptation for infrastructure planning

- Researchers demonstrated proof-in-principle use of a new method for selecting a sparse subset of variables from a much larger ensemble of potential predictors.

Enhancement of the Bureau of Meteorology statistical downscaling model

- The statistical downscaling model (BoM-SDM) has been adapted to provide downscaled climate projections onto a 0.05 degree grid over the entire Australian continent.

Uncertainty in future climate projections and water resources assessment

- In an effort to improve modelling of future water availability, four downscaling models were assessed. All can generally reproduce the observed historical rainfall characteristics. The rainfall-runoff modelling using downscaled rainfall also reproduces the observed historical runoff characteristics. The future simulations are most similar between the daily scaling, analogue and NHMM models, all of them simulating a drier future. The GLIMCLIM and CCAM models simulate a smaller decrease in future rainfall.

INTERNATIONAL RESEARCH COLLABORATION

Global Carbon Project: regional and global carbon trends, budgets and drivers, and carbon-climate feedbacks

- Human activities have released 500 billion tonnes of carbon to the atmosphere in the form of CO_2 since the beginning of the Industrial Revolution around 1750. These emissions have led to an increase of 38% in atmospheric CO_2, from 280 ppm in 1750 to 387 ppm in 2009, and contributed 63% of all anthropogenic radiative forcing to date. Currently, CO_2 emissions are responsible for 80% of the growth of anthropogenic radiative forcing.

- The total CO_2 emission flux from human activities was almost 10 billion tonnes of carbon per year in 2008, made up of 8.7 billion tonnes from fossil fuel combustion and industrial activities, and the rest from net land use change.

- The dominant CO_2 emissions contribution from fossil fuels has accelerated in recent years, increasing at an average growth rate of 3.4%/year during 2000–2008, compared to 1.1%/year during the 1990s and an average of 2%/year since 1970.

- In 2008, developing countries emitted more fossil fuel CO_2 (55% of the total) than the developed world (45%); however, per capita emissions remained much higher in developed countries. The global financial crisis that began in 2008 is expected to have a discernable impact on global fossil-fuel CO_2 emissions, but a scarcely detectable effect on the growth of the concentration of atmospheric CO_2 because of the large year-to-year variability in natural CO_2 sinks.

- Emissions from tropical peatlands have been estimated for the first time. CO_2 emission caused by decomposition of drained peatlands was between 355 and 855 million tonnes per year in 2006, of which 82% came from Indonesia, largely Sumatra and Kalimantan. At a global scale, CO_2 emission from peatland drainage in Southeast Asia is contributing the equivalent of 1.3% to 3.1% of current global CO_2 emissions from the combustion of fossil fuel.

MANAGEMENT AND COMMUNICATION

Project management and communication

- CSIRO Marine and Atmospheric Research hosted a workshop on carbon cycle science to determine priority research areas. They were past and future global budgets of CO_2 and methane, the Australian carbon budget, and human impacts on the land carbon budget.

- The Bureau of Meteorology hosted a national workshop on climatic extremes led by the Department of Climate Change and Energy Efficiency in May.

- The ACCSP convened a workshop at for CSIRO and Bureau of Meteorology communicators, climate scientists and social scientists involved in the communication of climate change. The meeting was a chance to share resources and ideas on better communicating the science and the need for adaptation and mitigation.

- Planning for projects for 2010-11 began with a one-day meeting in November 2009, in which researchers presented on progress in their disciplines and identified future needs and collaboration opportunities.

- The ACCSP annual meeting was held at CSIRO’s Aspendale laboratories on 18–19 May 2010, with presentations and discussions reviewing progress in all components during 2009–10.

- Selected presentations from the GREENHOUSE 2009 conference, held in March 2009 and organised through the ACCSP, have been published as the book ‘Managing Climate Change’, available through CSIRO Publishing.

1. Understanding the key drivers of climate change in the Australian region

Atmospheric greenhouse gases and aerosol

1.1 Southern Ocean carbon dioxide sink[1]

Recent studies suggest that the efficiency of carbon dioxide (CO_2) uptake by the Southern Ocean may be decreasing. However, there is some debate about this in the literature. ACCSP researchers are attempting to clarify this important issue by establishing a well inter-calibrated, high-precision observation network for measurement of CO_2 and oxygen/nitrogen (O_2/N_2) in the Southern Ocean. Network sites are at Cape Grim, Macquarie Island, Amsterdam Island (part of the Territory of the French Southern and Antarctic Lands) and possibly an Antarctic site (Figure 1).

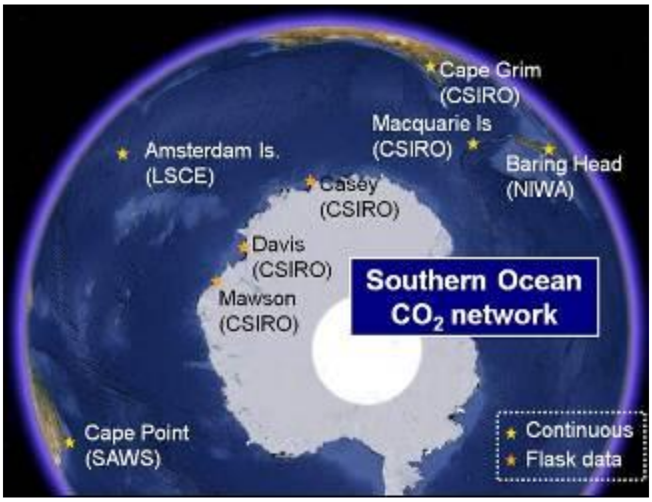

Figure 1: Southern Ocean region collaborative CO_2 observation network

The high-quality data collected through this network will form the basis of the most comprehensive, precise and accurate data set for CO_2, CO_2 isotopes and O_2/N_2 over the Southern Ocean region. The network data will be compiled and analysed for site calibration biases. The data set will then be used to construct a modelling framework for determining the most accurate estimate of the current magnitude of the Southern Ocean CO_2 sink using an ocean-atmospheric inversion model.

Following successful meetings with French collaborators Laboratoire des Sciences du Climat et l'Environnement (LSCE) in September 2009, a research plan was formulated to integrate dataset records at Amsterdam Island with the CSIRO network sites. Importantly, this included establishing a

[1] Heading numbers throughout refer to relevant ACCSP project numbers

protocol for a high precision Inter-Calibration Program (ICP) to be developed for the Southern Ocean CO_2 network (France-Australia-New Zealand). ICP measurements have been made at three sites so far.

Ongoing work will:

- reprocess the Macquarie Island and Cape Grim high precision in-situ CO_2 LoFlo data sets and compile them onto a known common calibration scale. Inter-site calibration uncertainties will also be defined;

- construct a modelling framework for determining potential changes in the Southern Ocean sink using this high precision (0.01 ppm) in-situ integrated data set within an ocean-atmospheric inversion model;

- improve CCAM simulations of synoptic variations in CO_2, then model CO_2 at Macquarie Island over the same period as the current continuous data record (2005–present), incorporating ocean fluxes; and

- develop inverse modelling capability using the continuous in-situ data from multiple Southern Ocean network sites.

1.2 Carbon-climate feedbacks in the palaeo record

Future climate forcing by trace gases depends largely on how the natural sources and sinks of CO_2 and methane (CH_4) will behave. The behaviour will be in turn affected by climate. Understanding how greenhouse gas-climate feedbacks operate will reduce one of the largest uncertainties in model predictions of climate, both globally and in the Australian region.

Climate models rely on observational data from the past and current climate, however the period of direct measurements of climate and atmospheric composition and other drivers is short compared to their variability and trends. Evidence of atmospheric changes over a longer time scale can be found in the palaeo record, mainly from ice cores. The pre-industrial period is of particular interest because it is before the overwhelming anthropogenic influence but at a time when factors such as sea level and solar irradiance were similar to what we expect over the next 50 years or more when warming will increase.

ACCSP researchers collected ice core samples and samples of firn air (air extracted directly from the ~50 m deep compressed snow layer atop ice sheets) during participation in the international North Greenland Eemian Ice Drilling (NEEM) and Centre for Ice and Climate (CIC) ice core programs at the Greenland NEEM site.

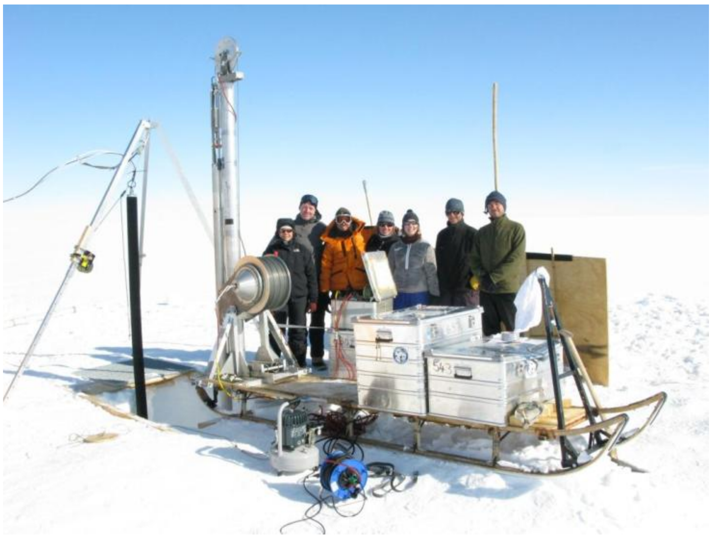

Figure 2: Drilling team at NEEM international ice core project

The firn air samples have been analysed for the full range of greenhouse and ozone depleting gases at CSIRO GASLAB. These records complement our measurements from Antarctic sites by providing a northern hemisphere record. Carbon-14 in CO_2 (measured in collaboration with the Australian Nuclear Science and Technology Organisation) revealed the 'bomb pulse' and provides a powerful tracer for dating the firn and ice core air (Figure 3).

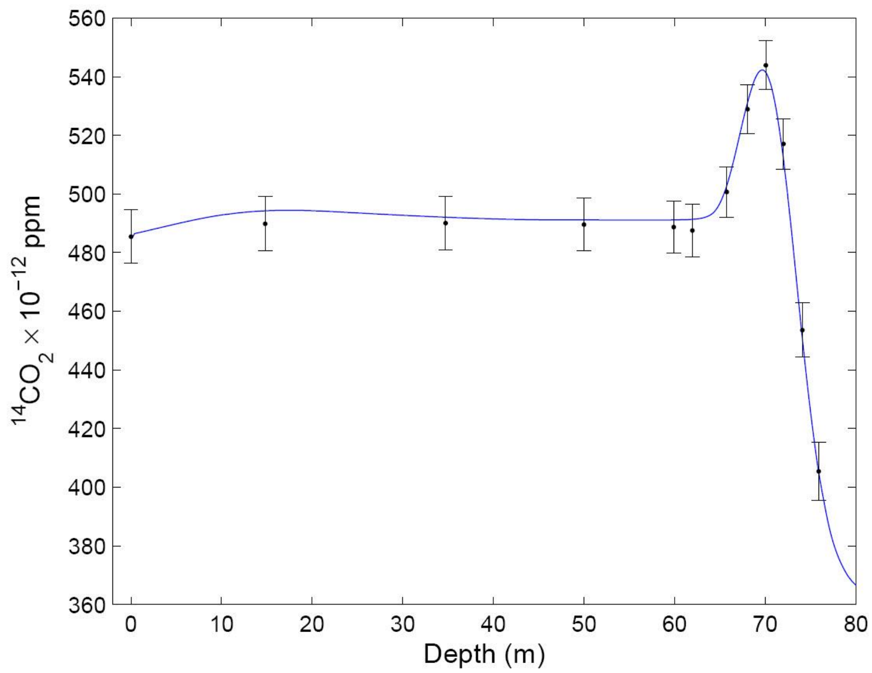

Figure 3: 'Nuclear bomb pulse' of $^{14}CO_2$ measured in NEEM firn air (Greenland) and model prediction, to use as dating constraint

Preliminary modelling of the firn records using the CSIRO firn air diffusion model has tuned the NEEM site so that records of atmospheric composition can be derived from the measured vertical profiles.

The CO_2 concentration and isotopes measured in the NEEM firn air showed only minor influence of contamination from impurities, a feature that has limited reconstructions of past atmospheric CO_2 from Greenland ice. This provides some hope that the firn layer, and possibly recent ice core material from the NEEM project, will provide useful material for CO_2 as well as other greenhouse gases and their isotopes.

New ice core measurements have been made on Antarctic samples using improved analysis procedures, particularly focussing on CO_2 isotopes. Greenhouse gas concentrations have the required precision to investigate the significant natural variations during the pre-industrial period, such as the Little Ice Age. Measurements of the carbon-13 isotope of CO2 are lower than the previously published benchmark.

Climate simulations for the past millennia, forced by the ice core greenhouse gas changes and orbital changes, have been made using the CSIRO Mk3L model. The simulated Little Ice Age cooling is apparent but smaller than observed, confirming the role of other factors such as volcanic aerosols and solar variations. Mk3L has been equipped with a coupled ocean biochemistry scheme to help partition the roles of the land and ocean carbon budgets in the CO2 changes. The model is now expected to be ready to simulate the changes emerging from measurements of CO2 and CO2 isotopes.

Ongoing work will:

- continue measuring CO_2 and $\delta^{13}CO_2$ through the periods of pre-industrial changes. Newly drilled cores from Law Dome will be compared with those used in earlier surveys to test for sample deterioration. Samples from three locations in Greenland will be measured for in situ CO_2 production and used to conclude whether Greenland ice can provide complementary atmospheric information.

- use the CSIRO Mk3L model (and possibly similar models of collaborators at the University of Exeter and University of Copenhagen) with coupled ocean and land carbon schemes, forced by the latest palaeo climatic proxies, to simulate the periods measured to help understand the land and ocean carbon responses.

1.3 Aerosols and Australian climate change

A large component of uncertainty in modelled climate projections is due to gaps in our knowledge regarding aerosol properties. ACCSP researchers are responding by taking aerosol measurements over the Australian region. These measurements are being used to evaluate the performance of global climate model (GCM) aerosol modules, and to investigate possible aerosol influence on Australian climate, including rainfall.

A highlight of the observational work over 2009–10 was the publication of the decadal time series of aerosol loading over the Tinga Tingana ground station in north-east South Australia (Mitchell et al. 2010) showing a significant increase in aerosol loading over the period 1997 to 2007. Further analysis shows a very strong increase in dust storm frequency and intensity following the onset of the drought in 2002 affecting much of eastern and central Australia. The increasing trend in aerosol loading and its relation to the regional rainfall anomaly, particularly to the 2002 drought, is apparent in Figure 4. This result raises the question of how such a change might feed back into Australian climate, given previous studies showing that the USA 'dustbowl' drought of the 1930s was exacerbated by the increased dust load.

Modelling analysis of the effect of dust on Australian climate (particularly rainfall) has already begun and will continue in subsequent cycles.

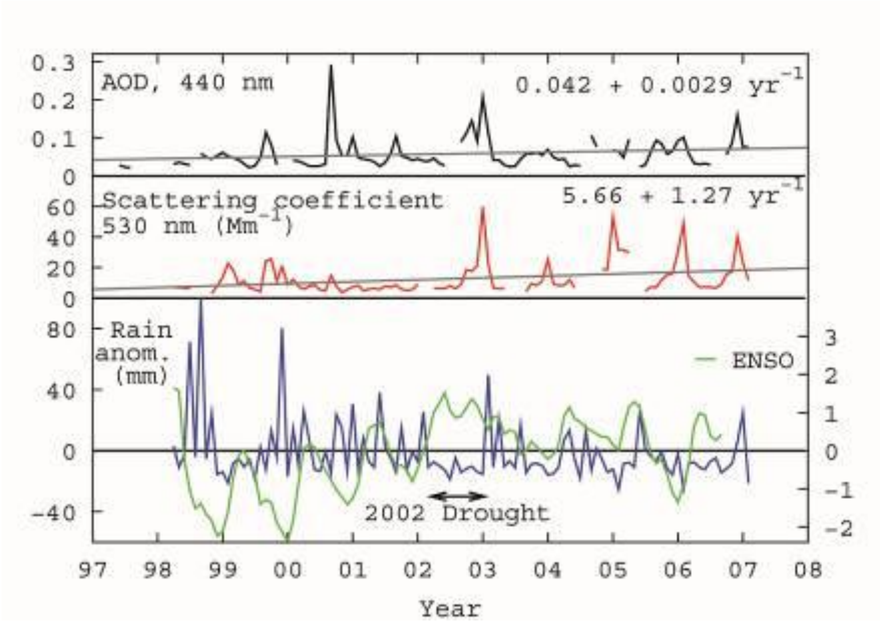

Figure 4: Monthly mean time series obtained from the CSIRO aerosol ground station at Tinga Tingana, South Australia, from 1997 to 2007. The top panel shows a measure of aerosol loading through the entire atmospheric column (aerosol optical depth at 440 nm). The middle panel shows aerosol scattering coefficient at 530 nm, indicative of near-surface aerosol, showing increased dust activity following the onset of the 2002 drought. The lower panel shows rainfall anomaly and the El Niño–Southern Oscillation (ENSO) index Niño 3.4 sea-surface temperature.

Terrestrial water and carbon cycle

1.4 Biogeochemical cycles and climate for Australian landscapes

Improving land surface modelling in CABLE

Accurate representation of the land surface in GCMs is an essential and challenging task for climate science. CABLE, the land surface scheme in ACCESS, simulates and projects radiation, heat, carbon, water and nutrient budgets of terrestrial ecosystems at multiple space and time scales. Such simulations require data to estimate model parameters and to evaluate model predictions. Several kinds of data are available:

1. direct flux measurements from flux towers
2. ecosystem data, especially changes in carbon and nutrient stocks estimated using biometric techniques
3. stream flow data (water balance)
4. remotely sensed data on leaf area dynamics, surface temperature other surface properties.

ACCSP researchers have developed a modelling and evaluation framework, called CABLE-Dyn, to test CABLE against all these data. They have also developed an improved soil module for CABLE that couples fluxes of heat, water and stable isotopes and includes a litter layer. They have tested the model against soil moisture data, eddy flux data and stream flow from ungauged catchments in south-eastern Australia.

ACCSP researchers have estimated key parameters in CABLE for south-eastern Australia, and showed that including multiple data types (soil moisture, stream flow and fluxes from flux towers) in the training data set improves model performance against independent validation data, relative to using a single data type.

Examining the phenology of Australia’s savannas

ACCSP researchers are examining the role of climate, vegetation, and fire on the phenology (the study of the timing of life cycle events in plants and animals) of Australia’s savannas using remote sensing. They are also assessing the effect of fire on productivity. The phenology of Australian savannas is affected strongly by fire because the trees are generally evergreen, and fire leads to defoliation. If the phenology response and recovery to fire is relatively simple, an algorithm in a model such as CABLE can be implemented.

Field equipment has been installed at three grassland sites in northern Australia. The sites will be valuable for validating both remote sensing products and modelling from CABLE. The savanna phenology will also provide input for policy makers and decision makers on questions of fire management.

Measuring volatile organic carbon emissions

Plants release numerous volatile organic compounds (VOCs) into the atmosphere. VOC emissions play a significant role the global radiation budget due to their role in the formation of tropospheric ozone and secondary aerosols. The factors controlling the in-canopy emission, chemistry and aerosol formation prior to transport into the lower troposphere are currently poorly quantified, significantly limiting our ability to robustly model future climate change.

Emissions of biogenic VOCs (along with biogenic and anthropogenic emissions of NOx) have multiple impacts on atmospheric composition, including enhanced ozone formation rates, decreased oxidising capacity of the global troposphere and substantial contribution to tropospheric aerosol abundances in continental regions.

ACCSP researchers measuring VOC emissions at the Tumbarumba flux station (in the Bago State forest in south-eastern New South Wales) have found that disturbance has a significant impact on all scalar fluxes. Drought and insect attacks have significantly affected the carbon and water balance at Tumbarumba and logging announced for September 2010, presents a major disturbance to the ecosystem. ACCSP researchers will continue to measure the fluxes of carbon and water vapour and their drivers before and after the logging to quantify the effect of the disturbance on VOC emissions, and in the process will derive a unique dataset for testing biogeochemical models.

Modelling carbon, nitrogen and phosphorus fluxes

CASACNP is a global ecosystem model of the linked carbon (C), nitrogen (N) and phosphorus (P) biogeochemistry cycles that is complemented by the CABLE model through describing the link between the vegetated land surface and the atmosphere. CABLE and CASACNP are being integrated into the ACCESS framework to link the atmosphere-land surface interactions with the stocks and fluxes of ecosystem C, N and P.

As part of this integration process, CASACNP has been modified for use in ACCESS, and an initial run performed at the global scale. Although the CASACNP model generates many specific predictions involving the stocks and fluxes of C, N and P, evaluating the robustness of such predictions at the global scale is problematic. For example, many of the processes involving the flows of C, N and P through ecosystems, and how these change across global scales, are poorly understood; the data available against which to compare model performance is often limited.

Two of the ecosystem attributes that have the broadest global distribution of observations are the standing biomass of vegetation carbon, and the net rate at which carbon is fixed by vegetation (Net Primary Production (NPP)). A major activity during 2009–10 has been retrieving biomass and NPP observations from the published literature and existing databases, and re-organising that data into a form suitable for comparison with the CASACNP outputs. The final database includes approximately 2200 geo-referenced, site-based observations of vegetation carbon, and approximately 1700 observations of NPP.

At the level of global-scale vegetation complexes, the model predictions of ecosystem C density match the empirical database well (Figure 5a). Variability increases at the scale of smaller regions or individual sites (Figure 5b), with some indication that the sites containing the highest biomass are under-predicted by the model (above approximately 20,000 gC/m^2). The comparison of NPP observations with CASACNP predictions shows a similar under-estimation of productivity at the most productive sites (above approximately 1000 gC/m^2/yr) (Figure). This pattern of model under-prediction in regions of highest productivity has also been noted in other global biogeochemical models.

The observational database may also contain some bias if the observations do not adequately represent the underlying spatial and temporal environmental and vegetation variability. Understanding the apparent bias in Figure 5 and Figure 6 will therefore require both an examination of the underlying CASACNP model structure and parameters and a closer examination of the representativeness of the empirical database.

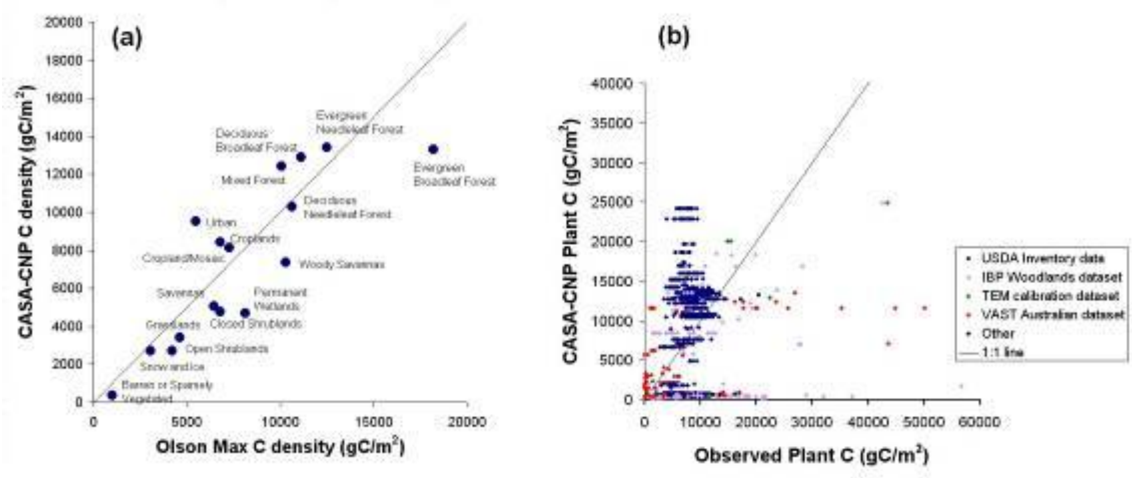

Figure 5: (a) Biome-averaged comparison of empirically-based vegetation + litter C estimates ('Olson Max C') with the equivalent CASACNP predictions. (b) Site-based comparison of observed vs. predicted estimates of total living vegetation carbon (above+below ground).

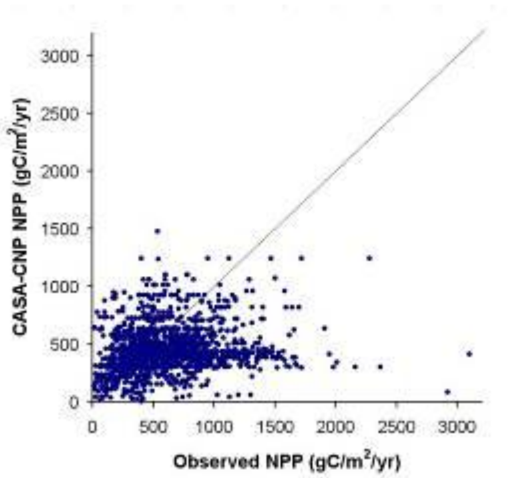

Figure 6: Observed vs predicted estimates of Net Primary Productivity (NPP)

The empirical database and the results of the model-data comparisons conducted as part of this project have been provided to the ACCESS development team to assist with the future development and validation of the CABLE-CASACNP.

Developing Australia's terrestrial carbon budget

The improved CABLE model will be used in a new project to assess Australia's terrestrial carbon budget. The project will establish the mean carbon balance of the Australian continent for the period 1990–2008, including its component sink and source fluxes. It will be achieved by using a combination of bottom-up and top-down measurements and models outputs from Australian and global analyses.

Ongoing work on biogeochemical cycles in the Australian landscape that will contribute to this project includes:

- introducing additional features to the CABLE model, namely lateral flow and variable soil depth, in order to improve the dynamics of stream-flow predictions.

- using the validated CABLE model with improved parameter estimates to evaluate climate sensitivity of the south-east Australian water balance and hence to attribute the dramatic decline in run-off in the Murray–Darling Basin observed in the 2000–08 drought period.

Ocean chemistry

1.5 Ocean acidification and carbon cycle

The ocean removes about 25% of the CO_2 emitted each year by human activities, with the Southern Ocean and waters on its northern boundary acting as one of the largest sink regions on Earth. The ocean uptake provides a huge benefit by reducing the rate of increase of atmospheric CO_2. However, it is also the cause of ocean acidification, which is a serious threat to the health and sustainability of key marine ecosystems like the Great Barrier Reef. Sustained observations and process studies by ACCSP researchers are a key to understanding the uptake and acidification in our region and how they will change in future. The research effort is integrated with international efforts in other ocean basins, with Australia taking the lead in our own region and the critical Southern Ocean through this project.

Carbon measurements made on hydrographic sections are the only way to detect changes in ocean carbon storage. The first comprehensive and quality controlled database for carbon and related biogeochemical tracers of the carbon cycle, GLODAP, was released in 2004 with the project delivering a significant amount of Southern Ocean data.

In September 2009, new hydrographic section data collected between 2000 and 2007 from the Atlantic and Southern Oceans has been quality-controlled and publicly released under theCARINA project (CARbon dioxide IN the Atlantic

Ocean)<http://cdiac.ornl.gov/oceans/CARINA/about_carina.html>. ACCSP researchers collected the database's Australian section data.

A Surface Ocean CO_2 Atlas (SOCAT) is being developed for surface CO_2 measurements that are used to detect change in the air-sea flux of carbon for all ocean basins. The unified database will provide the foundation for assessing variability and decadal change in surface carbon. An international meeting was held 16–18 June 2010 in Hobart to finalise the Southern and Indian Ocean data sets. The meeting, sponsored by UNESCO, IGBP and CSIRO, was attended by scientists from seven countries (Figure). The database quality control is planned to be completed by October 2010 and public release is anticipated in May 2011. Data synthesis efforts using the new database are being planned by the international community for delivery of new assessments on the ocean uptake of CO_2 to the IPCC Fifth Assessment Report, with project personnel leading the Southern Ocean effort.

Figure 7: Participants at the ocean carbon meeting held in Hobart in June 2010.

In October 2009, the first ocean acidification mooring in Australian waters was deployed on the Great Barrier Reef (GBR) in collaboration with NOAA, USA. The mooring delivers high frequency CO_2 data and is the foundation of a modelling and observational effort to use Heron Island as a test bed for assessing how waters are acidifying in the southern GBR and the impact on reef calcification/production. This work is being undertaken in collaboration with the Australian Institute of Marine Science and the University of Queensland. The GBR research was complemented by the first evaluation of the carbonate chemistry of the waters offshore of Ningaloo Reef, which was sampled on a research voyage in collaboration with University of Western Australia researchers in May 2010.

ACCSP researchers examined the controls on the seasonality and regional variability in CO_2 uptake for the Subantarctic Zone (SAZ). The influence of the supply of the limiting nutrient iron from dust and shelf sediments in controlling high biomass in surface waters was determined near Tasmania using a combination of models and observations. The results show mechanisms related to the delivery of iron to the SAZ through shelf-water interactions of the East Australia Current and through dust events that may both alter under climate change and influence biomass and CO_2 uptake for the region.

Ocean processes

1.6 Ocean data partnership through IMOS

High quality ocean data sets are a prerequisite for the detection, attribution, model validation/process improvement and real-time tracking of the global climate system response. ACCSP researchers are working with the National Collaborative Research Infrastructure Strategy (NCRIS's) Integrated Marine Observing System (IMOS) and the international community to expand the ocean climate observing system. They are also improving the quality of both IMOS and historical data and providing scientific oversight and data quality analysis for the IMOS Argo/ship-of-opportunity program. Researchers are also exploring the next generation of observing system through the pilot use of offshore glider technology in Australian waters.

Argo

Despite global deployments being reduced by half, coverage by the Argo array in oceans around Australia remained high, largely due to Australian deployments. Argo Australia deployed 54 floats in our region (Figure 8), bringing the active Argo Australia fleet to 263 active floats. Argo Australia delivered approximately 9000 profiles to the global Argo data system, increased from approximately 7500 from last year (Figure 9).

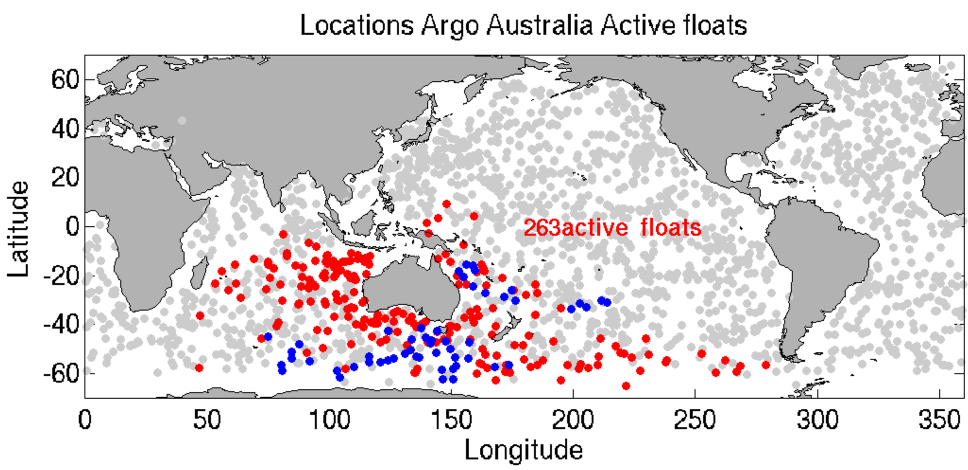

Figure 8: Locations of active Argo floats (grey), with Argo Australia floats in red and blue, the latter being floats deployed this fiscal year

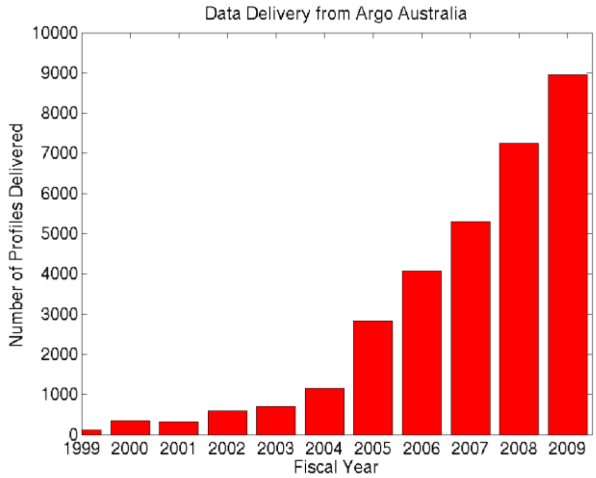

Figure 9: Number of ocean profiles delivered to the Australian and international research community by Argo Australia per fiscal year.

Processing of Argo data to the high quality needed for climate science made great strides, with the majority of eligible data delivered in delayed-mode and well-documented (see <http://www.cmar.csiro.au/argo/dmqc/index.html>). The global Argo data set was carefully screened and corrected for subtle pressure sensor biases. This bias-free data set is the basis of new sea level and global heat trend analyses being undertaken by ACCSP researchers.

Researchers began an analysis of the technological prospects and requirements to extend the Argo core mission to include the seasonal ice zones. The program also piloted direct deployments into the Antarctic sea ice zone with ice-capable floats.

Maintaining Argo design coverage by targeting gaps and thin parts of the array in the Australian region remains the highest priority. ACCSP researchers will continue to improve the Australian and global data set through auditing for uncorrected pressure biases (particularly problematic for the climate change use of Argo data) and collaborating with international Argo data centres to build their quality control capacity.

Sea gliders

Sustained, high-resolution measurements of the total transports of the East Australian Current (EAC) and other boundary currents are vital to improving our understanding of the variability and impacts of these major deep-ocean influences on the Australian shelf/slope systems. Boundary current systems are energetic and narrow and cannot be adequately sampled with broad scale networks (e.g. Argo); very fine scales are necessary to measure heat and freshwater transport. Their high current speeds make them inherently non-linear, producing internally-generated variability that demands sustained sampling. Deepwater gliders provide an alternative and relatively new technology for monitoring these boundary currents. However, the most efficient mode of deployment of these instruments within the highly variable boundary currents is still to be determined.

Figure 50: Glider on deck ready for initial launch. This was the first deep ocean glider deployment in the southern hemisphere.

ACCSP researchers have assessed the capacity of the sea gliders using results from three deployments off eastern Tasmania, a Southern Ocean deployment and several deployments within the EAC eddy system off eastern Australia. The gliders are provided by the IMOS data facility, Australian National Facility for Ocean Gliders (ANFOG).

1.7 Ocean climate and rates of change

Deep ocean heat and freshwater changes in Australian region oceans

Despite numerous technological advances over the last several decades, ship-based surveys remain the only method for obtaining high-quality observations of a suite of physical, chemical, and biological parameters over the full water column, especially for the deep ocean below 2 km (52% of global ocean volume).

To assess the deep ocean property changes, ACCSP researchers have compared observations from the repeat hydrographic sections in the western Pacific and eastern Indian Oceans to determine the decadal temperature, salinity and carbon changes. The observed temperature and salinity changes below 3500 m have been compared to climate model simulation of the deep ocean property changes. This has shown that the climate models do simulate deep ocean change but the rate of change and its spatial distribution are poorly represented.

The deep ocean is a significant component of the Earth’s climate system. The world’s abyssal ocean properties reflect the formation processes of dense water masses of the high latitude Southern and North Atlantic Oceans. The deep oceans play a crucial role in setting the rate and nature of global climate change and variability through their moderation of the planetary heat, freshwater and carbon budgets.

Accurate estimates of the total sea level budget must include all components of the earth system that contribute to sea level rise. The deep ocean component (below the 2000 m sampling depth of Argo) of the observed sea level budget is highly uncertain. Comparison of repeat hydrographic sections has revealed statistically significant warming of the abyssal oceans. While the sparse data makes quantification of these changes difficult, they do appear large enough to be significant contributors to global heat, and sea level budgets. Accurate simulation of the abyssal ocean properties and circulation in climate models will enable us to use models to explore the processes governing the deep ocean warming, freshening, and carbon sequestration needed to provide reliable projections of global and regional carbon and sea level budgets.

Robust deep ocean (below 3500 m) warming and freshening has been found in the western Pacific Ocean from the comparison of three repeat hydrographic sections. The largest warming and freshening is found in the southern basins that are directly connected to the Southern Ocean, but the changes extend as far north as the equator. Working with international colleagues, ACCSP researchers are beginning to assess climate model simulations of the global changes in deep ocean heat content (Figure 61).

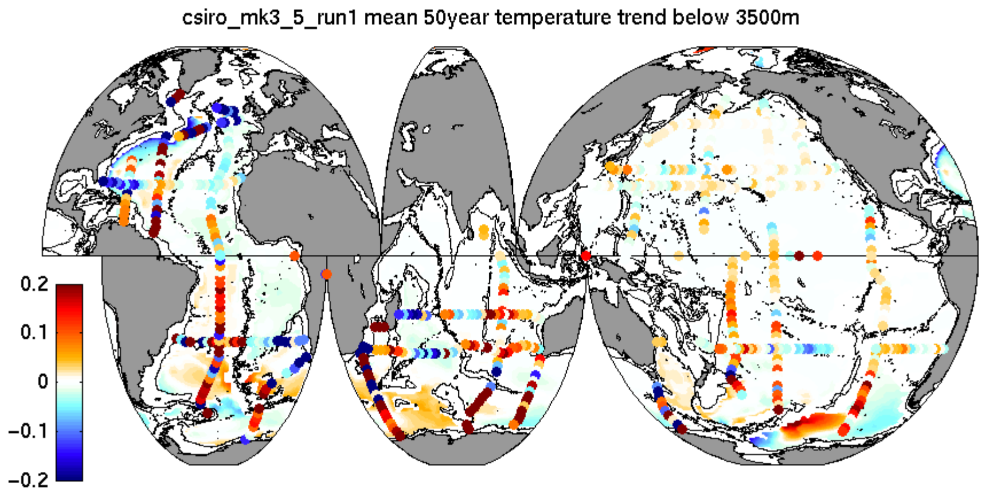

Figure 61: Comparison of the 50 year temperature trend between a global climate model (colour contour) and observations (colour dots) below 3500 m

ACCSP research provided new insights into the formation of Antarctic Bottom Water and the system of deep currents carrying this water northward to ventilate the abyssal layers of the global ocean. Current meter data were used to show that the deep boundary current adjacent to the Kerguelen Plateau is a major pathway of the deep overturning circulation of the Southern Ocean. Similar measurements on the Antarctic continental shelf provided the first direct measurements of the rate at which dense water sinks to the deep ocean to supply new Antarctic Bottom Water. Ongoing work is using temperature profiles collected by elephant seals to identify locations where relatively warm waters may cause melting of the Antarctic ice sheet where it enters the ocean, a process recently recognised as important to the stability of the ice sheet and sea-level rise.

An array of five current meter moorings was successfully deployed in December 2009 off the coast of Antarctica as a part of a joint Australian–US experiment with substantial funding from the National Science Foundation (US$2.1M). The array includes a large number of current meters and conductivity, temperature and depth (CTD) sensors that move up and down the mooring wire to collect profiles of temperature and salinity. The aim of the experiment is two-fold: to test the hypothesis of a very energetic, largely barotropic, gyre in the Australian-Antarctic Basin and to provide detailed measurements of the deep boundary current exporting Antarctic Bottom Water.

Working with US colleagues ACCSP researchers have determined the processes that result in the formation of Subantarctic Mode Water in the south-east Pacific Ocean. They found that wind-induced mixing is important on the development of winter deep mixed layers upstream of Drake Passage. Further, they have shown that frontal meanders are quasi-stationary, and therefore the deep mixed layers maintain their position to the front on seasonal time scales. Researchers also developed a new technique that will enable the community to use standard ocean profile observation to determine the large scale distribution of horizontal and vertical mixing. Understanding the ocean processes that drive water mass formation and the spatial variability of mixing will improve our understanding of the ability of the ocean to store heat and carbon in the climate system.

Finally, a successful international workshop of more than 30 Australian and international climate scientists – Deep Ocean Workshop: Observed and model-simulated property changes in the Deep Ocean of the Southern Hemisphere – was held in Hobart from 21-23 June 2010.The workshop provided the opportunity for the international community to present and consider the diverse research begin undertaken in the southern hemisphere deep oceans. The meeting clearly showed that the global deep ocean has warmed and that this warming is dominated by changes in the Southern Ocean and adjoining basins. A workshop report is being completed and will be distributed locally and internationally.

Improved understanding of frontal processes in the Antarctic Circumpolar Current

The Antarctic Circumpolar Current (ACC) is the largest current in the world ocean. By connecting the ocean basins, the current has a profound influence on the global ocean circulation and climate. Despite its importance, the current remains poorly understood. In particular, the lack of in situ observations has made it difficult to determine how and why the current varies in time. This is important because changes in the current may influence regional climate by changing the amount of heat, carbon and other properties carried between the basins and because shifts in the current systems can cause regional changes in sea level.

ACCSP researchers have described the mean structure of the ACC, showing that it consists of multiple filaments along the entire 20,000 km long path circling Antarctica. This result extends earlier work south of Australia and helps reconcile a long-standing discrepancy between ship-based studies and results from high resolution models and dynamical theory.

Researchers also showed how the ‘fronts’ evolved between 1992 and 2007. They found an overall southward shift of the current, associated with an increase in sea level. This pattern is not uniform around the Southern Ocean, with stronger southward shifts of the currents resulting in enhanced rates of sea-level rise in the Australian sector of the Southern Ocean.

Also in 2009–10:

- Argo float data was used to quantify the rate at which surface waters (and therefore heat and carbon) are subducted into the ocean interior for the first time. The study revealed unexpected “hot spots” of subduction and showed that eddies made an important contribution.

- Float data was also used in a study of the ocean surface mixed layer to changes in winds associated with the Southern Annular Mode. The response of the ocean was found to be strong and surprisingly asymmetric.

- A regional study south of Tasmania showed that eddies spawned from the ACC and EAC drive strong variability in water properties in the upper ocean. This result demonstrates that the eddy contribution must be considered when analysing time series for evidence of trends related to greenhouse warming.

- The sensitivity of mode and intermediate water formation to climate change was assessed with the CSIRO climate model. The subduction rate was reduced and the water masses migrated to lower densities, suggesting a smaller volume of the ocean will be ventilated in the future.

- The interaction of the fronts of the ACC and topography was investigated in a previously poorly studied region near the Kerguelen Plateau.

ACCSP researchers will continue to use a variety of observational data sets and model output to investigate the dynamics of the ACC and the upper limb of the Southern Ocean overturning circulation. A topic of uncertainty at the moment is how the Southern Ocean circulation responds to changes in forcing (e.g. changes in winds). Understanding this response is critical to assess the potential for the Southern Ocean to take up heat and carbon in the future and thereby influence the rate of climate change.

Improved ocean warming and salinity data

The oceans play a crucial role in setting the rate and nature of global climate change and variability through their moderation of the planetary heat budget. Ocean processes also control the regional pattern of sea level rise. Past observational estimates of ocean change and its regional patterns are affected by data bias and inaccurate mapping techniques.

ACCSP researchers are increasing our understanding of ocean change over the last 50 years by exploiting newly acquired Argo data and improving historic observational data sets to quantify the observed rate and causes of ocean change, and to identify the key ocean processes involved. They are benchmarking models against global and regional data sets to gain confidence in model projections and to help improve their simulation of climate variability by informing the development of ACCESS.

In 2009–10, researchers quantified and described the kinematics of both surface and subsurface ocean salinity change over the past 50 years. Exploiting ACCSP Data Partnership data from both Argo and hydrographic lines, this analysis revealed that surface salinity changes are largely a strengthening of the mean salinity pattern, consistent with an amplification of the global hydrological cycle over the past 50 years, comprising the clearest observation evidence to date of this change which has long been expected from both theoretical and coupled model work. Subsurface ocean water mass changes are shown to largely result from the subduction into the ocean interior of a broad scale warming and its subsequent advection by the global ocean circulation.

Comparison of coupled-climate model (CMIP3) 20C responses in surface salinity and the hydrological cycle reveals a strength of response largely controlled by their degree of warming – cold models (where aerosol cooling effects are large) are less realistic in their salinity responses than warm models (where greenhouse gas forcing dominates). This suggests that in some models over-cooling compared to the observations occurs due to potentially overactive aerosol schemes.

This global hydrographic/Argo analysis is also the basis of new analysis of regional patterns of sea level rise, whereby the temperature-driven and salinity-driven components can be clearly distinguished.

The causes and corrections for biases in the historically dominant XBT data remain controversial with conflicting explanations appearing in the literature. These bias-corrections remain the largest source of uncertainty in our understanding of both past and modern planetary energy budget. To more clearly address this, a database of historical side-by-side deployments of XBTs and high quality CTD data have been assembled. To date approximately 1500 pairs have been assembled (in collaboration with US and Japanese colleagues). Preliminary results show that XBTs appear to have a constant temperature bias and time-variable depth bias.

1.8 The response of Indo-Pacific Ocean variability to climate change and its impact on Australian rainfall

The Indian Ocean Dipole (IOD) strongly influences rainfall variability across southern and south-east Australia (SEA) in the winter and spring seasons, with drier and warmer than normal conditions associated with positive IOD (pIOD) events. Recently, the Indian Ocean has been trending towards a more pIOD-like state, with significant implications.

ACCSP researchers are working to determine if current climate models simulate this increased pIOD frequency and the associated impacts, and if there linkages to the El Niño–Southern Oscillation (ENSO) and Southern Annular Mode (SAM). They are also investigating the change that climate change will have on the IOD.

The occurrences of pIOD events typically lay the foundation for dry conditions to emerge across SEA in the seasons leading up to summer. Research over 2009–10 has showed that of the 16 pIOD events since 1950, 11 were followed by major bushfires including the Ash Wednesday (February 1983) and Black Saturday (February 2009) disasters.

Given the observed linkage of the IOD with ENSO and with the SAM, ACCSP researchers looked at whether climate models can simulate ENSO, its impact on Australian rainfall, and the ENSO–IOD relationship. They found that there is no systematic linkage between ENSO amplitude and ENSO–IOD coherence. Most models simulate a weaker ENSO–IOD coherence than is observed, and model results suggest that the IOD is not always triggered by ENSO events.

Over 2009–10 the role of climate change in driving the trend towards more pIOD occurrences (reported in 2008–09) was assessed by examining outputs from 24 CMIP3 climate models. The results showed that in the presence of climate change the frequency of pIOD increases by 17%. The increasing frequency is consistent with a weakening tropical circulation with a shallowing Indo–Pacific thermocline (particularly in the West Pacific and eastern Indian Ocean) and enhanced Asia–Australia monsoon, supported by a robust faster warming over land than over the ocean.

The greatest change in ocean warming to a depth of 2000 m in recent decades has occurred in the mid-latitude oceans of the southern hemisphere, where a subsurface cooling has been observed in the southern Indian Ocean. ACCSP researchers have shown that anthropogenic aerosols are responsible for driving this observed subsurface cooling and contribute to the mid-latitude warming (Figure 12).

Further, the reported linkage between the increasing north-west Australia (NWA) rainfall and increasing aerosols simulated in CSIRO Mk3A is a consequence of an unrealistic IOD operating in austral summer. ACCSP research shows that none of the CMIP3 model ensembles with the direct or indirect effect of aerosols included simulates the observed summer NWA rainfall increase over the past 50 years. This is because climate models are unable to simulate the relationship between Indo–Pacific sea surface temperature and NWA rainfall, upon which aerosols' impact projects; climate models suffer from too strong an ENSO–NWA rainfall teleconnection, resulting from the Pacific warm pool bias that extends too far west into the eastern Indian Ocean. This generates a summer ENSO-rainfall relationship that is strongest over NWA, rather than over north-east Australia as is observed.

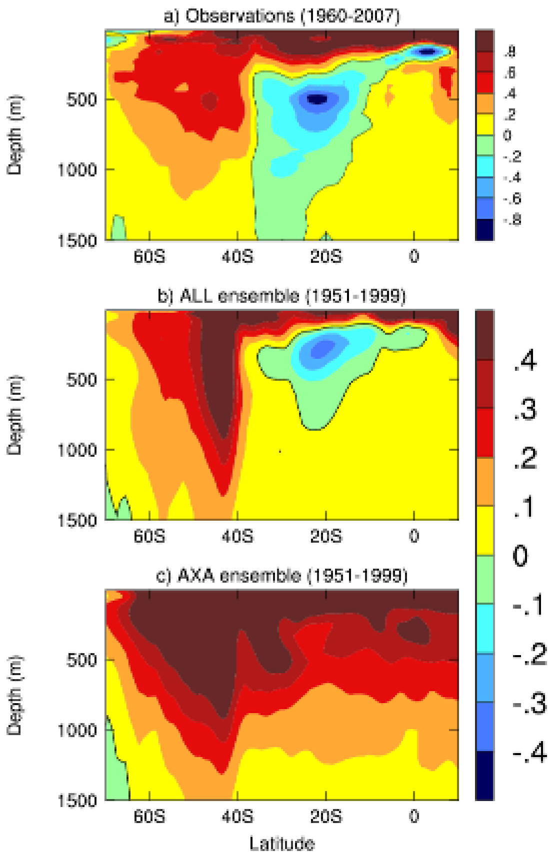

Figure 12: Trends of zonally averaged temperature for the southern hemisphere from surface to 2000 m based on (a) observations (1960-2007), and a two-model ensemble (1951-1999) forced with (b) all forcings including anthropogenic aerosols (ALL) and (c) all forcings except for anthropogenic aerosols (AXA). Units are ($\times10^{-2}$) °C per year.

1.9 Understanding, evaluating and intercomparing climate change feedbacks

Differences in model feedbacks are directly responsible for around half the uncertainty in future climate projections, so understanding climate feedback (in particular from water vapour, surface albedo, lapse rate or clouds) is fundamental to understanding, quantifying and ultimately reducing projection uncertainties.

ACCSP researchers are evaluating the structure of individual feedbacks found across all models used in the IPCC fourth assessment report (AR4). By understanding how feedbacks vary in strength we can understand the source of much of the range of climate 'sensitivity' present in climate models. Further, by examining how the structure of these feedbacks varies (for example, in their strength at different latitudes) we can identify critical regions and processes producing these feedbacks, and identify regions of most significant disagreement between models. Understanding how feedbacks vary at different timescales (for example, from year-to-year variability compared with secular climate change) provides insights into important feedback processes, and potentially powerful techniques for evaluating feedbacks from 'short' timescale observations. An analysis of how feedbacks vary at the very short timescales (for example, from initial rapid cloud adjustment to radiative forcing) is also important for understanding what processes are truly driven by global surface temperature changes (i.e. are truly feedbacks), and which are simply rapid responses to a given forcing.

In 2009–10, ACCSP researchers built on earlier work to determine and compare the structure of transient timescale climate feedbacks in the AR4 models. Their analysis revealed that the tropics are responsible for the vast bulk of water vapour feedback strength; that clouds partially ‘mask’ that feedback (especially in the heavily cloud covered equatorial region); and that the tropics was the major source of feedback disagreements between models (see Figure 13).

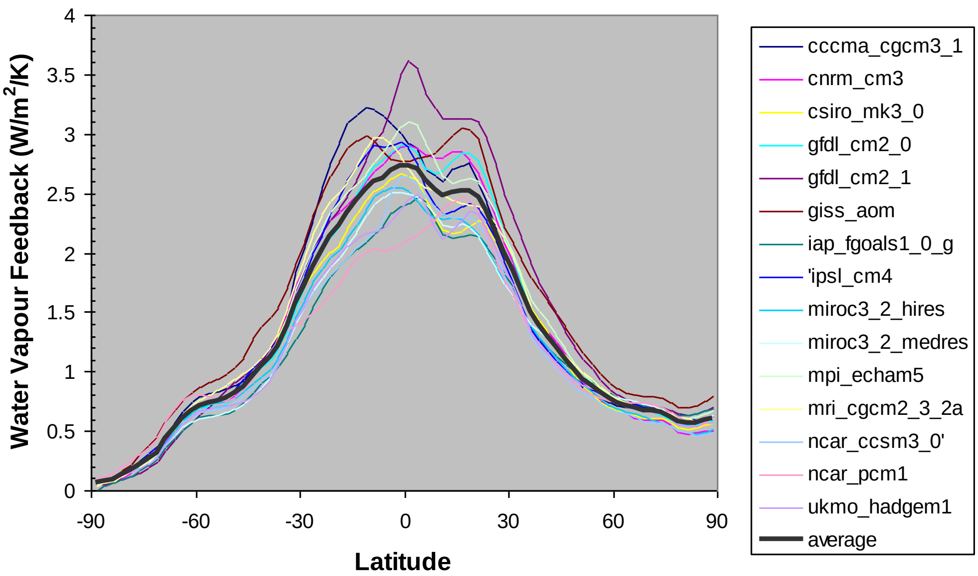

Figure 73: Structure of water vapour feedbacks in a range of the AR4 models as a function of latitude. Feedback units are watts/square metre per Kelvin of global warming. Also shown is the average of all the models (heavy black line). This plot shows that both the magnitude of the water vapour feedback and the differences in feedback strength between models is dominated by the tropics (i.e. to roughly 30° north and south). Models also show differences in their latitude of maximum feedback, and a tendency to have more than a single low latitude ‘peak’. Further analysis shows this to be due to the effect of cloud ‘shielding’ on water vapour feedback.

Code has been developed to perform year-to-year feedback calculations in the AR4 models using the so-called radiative ‘kernel’ approach. This code development is a significant advance on previous analysis techniques, permitting feedback estimates, as well as measures of their uncertainty from the analysis technique itself.

A preliminary examination of year-to-year versus transient timescale global water vapour feedback found no obvious relationship between the two. This suggests there is no obvious connection between the two timescales. However, the approach is a promising one and relationships may exist for other feedbacks, or for other regions (such as tropics, or oceans only). Other timescales (e.g. decadal) may also provide better analogues.

ACCSP research also revealed that a number of important aspects of what are generally understood to be ‘feedbacks’, particularly in cloud responses, may in fact be the result of relatively rapid adjustment to stability changes caused by greenhouse gases (such as CO_2 increases). Whilst this does not change our estimates or range of uncertainties of climate projections, it provides insights into physical processes important for cloud feedback, for example. In particular, changes in low clouds (affecting the cloud ‘feedback’ for reflected solar radiation) are partly a result of rapid stability changes, whereas water vapour feedback is little affected.

The examination of year-to-year feedback was a preliminary one, considering global values and a single feedback – water vapour only. An important extension is to consider other feedbacks and other regions (such as the tropics or extra tropics). The effect of clouds on other year-to-year and transient feedbacks also needs to be examined, along with other timescales, such as decadal.

Sea level rise

1.10 Global and regional sea-level rise: reducing uncertainty and improving projections

Sea-level rise, the result of thermal expansion of the world’s oceans and of melting glaciers and ice sheets, contributes to coastal erosion and the inundation of low-lying coastal regions, particularly during extreme events. With more than 80% of Australia’s population living in coastal regions society is heavily affected by extreme sea level events and these are expected to have a greater impact as sea level rises. Detecting changes in extreme events and estimating how they might change in future is the first step to adapting to change.

Figure 14: Queensland’s Gold Coast, one of the fastest growing regions in Australia

ACCSP researchers have updated estimates of global averaged sea-level rise (both globally and around Australia) and ocean thermal expansion. These are available at

<http://www.cmar.csiro.au/sealevel/>. Updated estimates of ocean heat content have also been calculated.

Researchers have also:

- collected data to enable estimates of the surface wave effects (sea-state bias) on satellite sea-level measurements. Preliminary analysis indicates good quality.
- drafted an extended and improved sea-level budget up to the end of 2008. Preliminary work has also been done on extending the budget back prior to 1960.
- compared observed and modelled ocean thermal expansion and glacier contributions. These comparisons were presented in a poster at the recent IPCC Sea-level Rise and Ice-sheet Instability Workshop.

Researchers at the National Tidal Centre have reassessed the rates of mean sea level rise for all the conventional tide gauge sites that have more than 25 years of hourly data on the Australian sea level database, as well as for SEAFRAMEs (Sea Level Fine Resolution Acoustic Measuring Equipment).

Detection and attribution of climate change

1.11 Attribution and projection of climate variability and changing weather systems

ACCSP researchers have evaluated how well climate models simulate the southern hemisphere circulation shifts and changes in the major weather systems during the 20th century, as well the major modes of climate variability, including the SAM and ENSO. Based on this evaluation, they have selected and used suitable models to investigate projected future changes in the weather systems and modes of variability, and their impact on Australian climate.

Over 2009–10 ACCSP researchers:

- found significant decreases in the winter growth rates of blocking modes, as well as storm track modes, significant increases in the growth rates of north-west cloud band and intraseasonal oscillations crossing Australia, little change in Antarctic teleconnection patterns and moderate increases in growth rates of African easterly waves since the mid-1970s. These findings are consistent with the observed reductions in winter rainfall over southern Australia and the increases over northern Australia.
- examined coupled CMIP3 and atmosphere only C20C models to see whether they are capable of reproducing observed 20th century changes and trends in the winter southern hemisphere atmospheric circulation and rainfall. Results indicate that there is a component of decadal variability in the CMIP3 model results that is dependent on the base period chosen in the pre-industrial runs.

- considered the impact of further increases in CO_2 concentrations using the B1, A1B and A2 scenarios in CMIP3 models that were found to reproduce observed 20th century changes. These models show further reductions in rainfall over southern Australia, and in a subtropical band throughout the hemisphere. Reductions from the pre-industrial over the south-west and south-east of Australia can be as much as twice those seen at the end of the 20th century.

- developed a new methodology to investigate changes in large-scale atmospheric variability in CMIP3 models under climate change. This allows the identification of changes in 'intraseasonal' (related to blocking and intraseasonal oscillations), 'slow-internal' (related to slow internal dynamics and boundary forcing by sea-surface temperature (SST)) and 'slow-external' (related to external forcings by greenhouse gases) large-scale atmospheric modes. Largest changes in the 21st century are seen in the 'slow-external' modes.

- developed a new methodology to study the relationship between the large scale atmospheric variability and Australian rainfall. The method allows both the 'intraseasonal' and 'slow' (internally and externally forced) coupled modes between Australian rainfall and the pressure field to be identified.

- evaluated CMIP3 and C20C (atmosphere only) models for their ability to reproduce 'intraseasonal' and 'slow' modes of year-to-year variation in the large scale atmospheric circulation. Regional features of the model atmospheric circulation modes appear to affect the ability of the models to reproduce the observed rainfall variability. Further investigation is underway.

2. Improved climate system and change modelling

2.1 Development of the ACCESS coupled modelling system

The Australian Community Climate and Earth System Simulator (ACCESS) is the next generation of climate and earth system modelling capability in Australia. It is being developed through a partnership between CSIRO, the Bureau of Meteorology and Australian universities.

ACCESS is a modelling system that meets a variety of needs over a range of space and time scales, from numerical weather prediction to climate change simulation. The ACCSP supports development of those aspects of ACCESS particularly relevant to climate change simulation.

The core components of the ACCESS coupled model include the UK Met Office Unified Model (UM) (atmosphere), the Australian Climate Ocean Model (AusCOM) (ocean/sea ice) and the CABLE Australian community land surface model. The development of ACCESS as a full earth systems model (ESM) will include the addition of components for atmospheric chemistry, soil carbon and nutrient storage and cycling, oceanic biogeochemistry, and dynamic vegetation.

Preparations for IPCC fifth assessment report contributions

A major focus of the work in 2009–10 was preparation of the ACCESS coupled model for contribution of modelling results to the IPCC fifth assessment report (AR5). Six principal test simulations, each of 100 years duration, have been conducted. These differ from one another in terms of ocean/atmosphere coupling frequency, number of vertical levels in the ocean, treatment of sea ice albedo (reflectivity) and treatment of certain cloud processes. There has been considerable progress in improving the simulation, with many key climate processes simulated to a degree of realism that lies well within the range anticipated to be displayed by the other participating models.

A key aspect of climate variability affecting the Australian region is ENSO. Figure 15 shows a time series of equatorial central Pacific SST anomaly (over the “Nino3.4” region) for the last 60 years of the most recent 100-year simulation, compared to sections from the observed record. The model displays strong ENSO-like behaviour with a peak in the spectrum at 4-5 years. These features are broadly realistic, with the variability slightly stronger than observed. However, the model ENSO differs from the observed in some features of the spatial pattern. The SST anomaly extends too far westward, and there are problems with the ocean-atmosphere feedbacks. Nevertheless, the overall behaviour of the model ENSO will likely be well within the range displayed by other IPCC AR5 models.

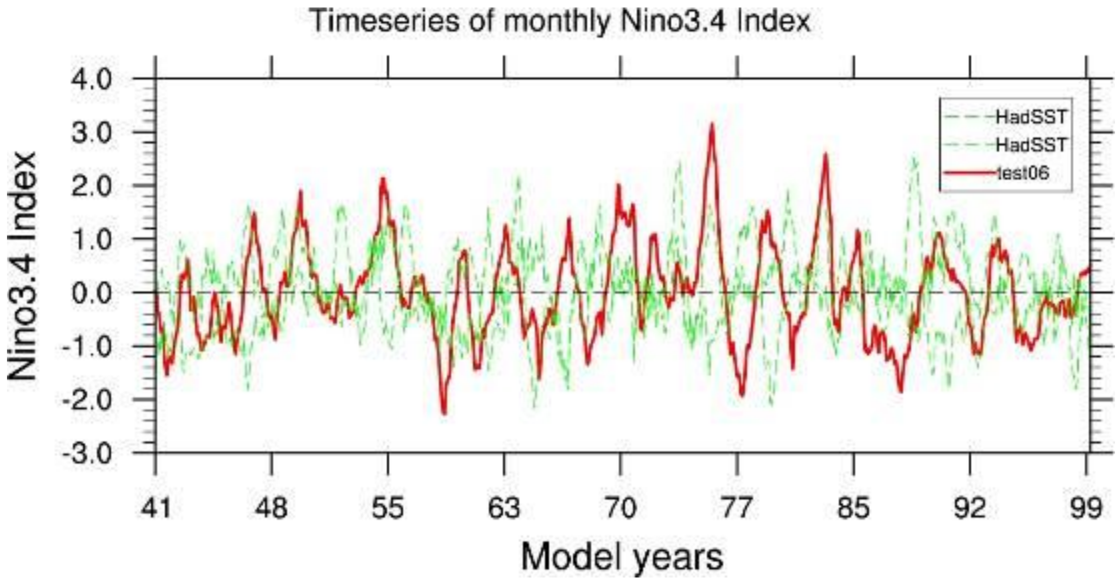

Figure 85: Time series of sea surface temperature anomaly in the Nino3.4 area (5º N–5º S; 120º W–165º W) for years 41-100 of ACCESS Test 6 (red) and observed according to two representative time slices from the HadSST data set (green).

Figure 96 shows the difference between the observed and modelled annual mean SST, both averaged over 30-year periods. Differences are mostly fairly small (less than 1.5º C). There are more substantial differences in the equatorial Pacific (where the strip of excessively cold surface water may play a role in the causing the imperfections noted above for the model ENSO) and in the high latitude North Atlantic. The latter is associated with excessive Arctic sea ice. Mitigation of both these regional biases is a focus of current work.

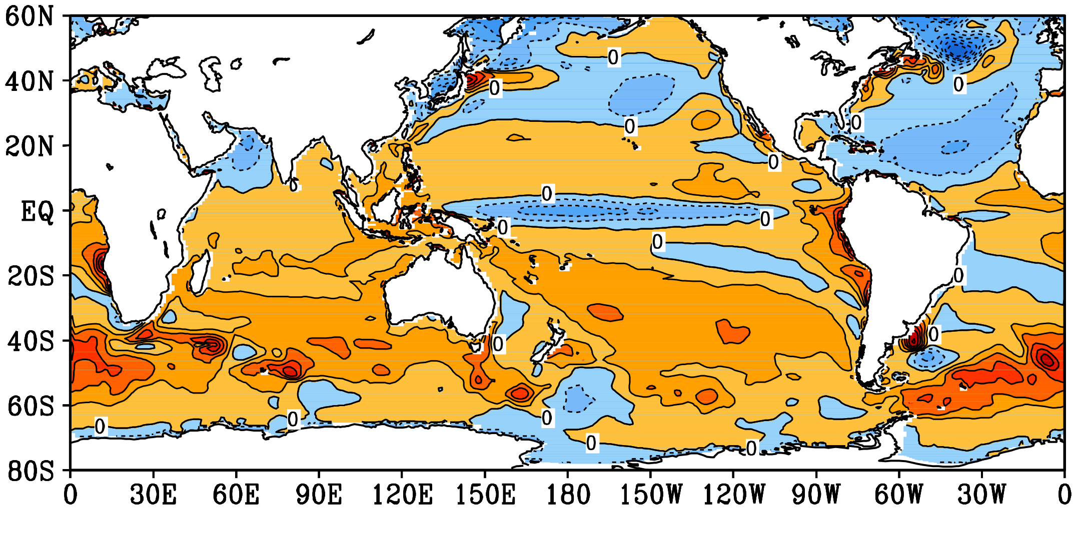

Figure 96: Difference in sea surface temperature between model (years 71–100 of Expt. 5) and observations (according to HadSST data set).

Overall, ACCESS is close to being ready for the IPCC AR5 simulations, but needs some more work especially on mitigation of some regional biases. The revised timelines for Working Group 1 of the IPCC AR5 allow more time for this work to be carried out. Submission of the 'core' simulations for the IPCC AR5 should be completed during the first third of 2011, well in time for the bulk of the IPCC analysis which is likely to occur during later 2011 and first half 2012.

This coupled model work was performed on the National Computational Infrastructure National Facility (NCI NF) machines at the Australian National University (ANU). The commissioning of the new peak NCI machine 'Vayu' in February 2010 has been a major benefit to the model development, with the capability now of performing several coupled model simulations simultaneously at an acceptable 3–4 model years per day. Another major benefit of performing the simulations at NCI is that NCI will host the Australian node of the Earth Systems Grid (ESG), which will house the ACCESS contribution to the IPCC AR5. The ESG is an international network which will connect institutional repositories of model output data for the IPCC AR5 and beyond in a distributed system, with the chief hub and coordination by PCMDI at Lawrence Livermore National Laboratory, California. The ESG node at NCI is currently in test phase, using climate model output for the testing.

Model evaluation

The coupled modelling development is being also supported by application of a framework for model evaluation. As a basis for this framework, a number of climate observational time series datasets have been collected, transformed into a standardised data format and used to generate monthly climatologies. In its initial form, the framework is being used to routinely generate figures for successive model versions, and has proven very useful in tracking coupled model progress. It its more advanced form, the (pilot) objective climate model evaluation framework takes into account the observational uncertainty and uses metric sets designed to evaluate fitness of purpose has been developed and tested on a number of climate model runs for a test metric set. The ACCESS model evaluation work was presented at the US National Climatic Data Center and at the American Meteorological Society Annual Meeting in January 2010.

New techniques are being developed to evaluate the ability of models to simulate the major remote drivers of Australian rainfall variability. In Figure 107 the pattern of influence of four remote drivers of rainfall variability in spring in a 30-year simulation of the ACCESS atmospheric model is compared to observations. In this case, a fairly realistic pattern is evident, with variability over much of northern Australian dominated by ENSO and over much of south-eastern Australia dominated by blocking variability.

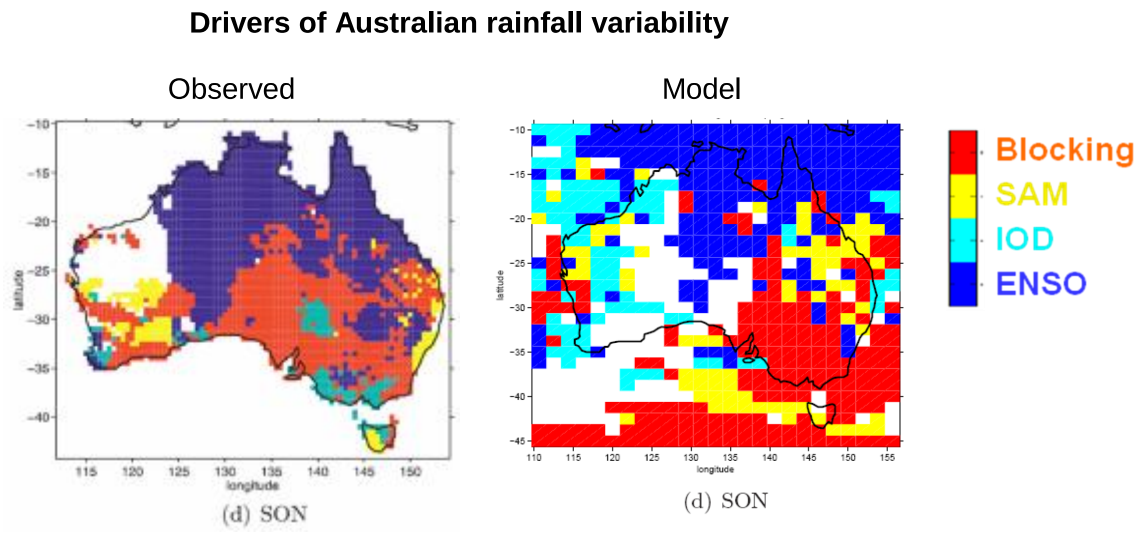

Figure 107: Patterns of influence of four remote drivers of Australian rainfall (blocking over the southern Tasman Sea, the Southern Annular Model (SAM), Indian Ocean Dipole (IOD) and ENSO). Colours on maps indicate the dominant driver (in terms of strongest correlation) at each location. Model result is from an ACCESS atmospheric model simulation over the years 1979–2008.

Component model improvement

Substantial work has been done to improve the separate component models. This is partly to explore model sensitivity to parameter changes in order to feed improvements into the full coupled model, and partly to prepare the component models for wider usage in the Australian research community.

Atmospheric model

The atmospheric model code has been upgraded from the UM6.6 and UM7.1 code versions to the UM7.3. This later versions feature improvements in code structure and in model physics options. UM7.3 is now the standard code basis for both atmosphere-only and coupled model simulations.

In a substantial delivery for ACCESS, the development of our new SES2 (Sun-Edwards-Slingo-2) radiation scheme has matured to the point where it has now been accepted as an option in the main trunk of the UM source code.

Atmosphere-only simulations for the period 1979–2008 performed both locally and at the UK Met Office have been evaluated with particular emphasis on accuracy of model processes in the tropics. In an examination of the tropical relationship between precipitation-rate and radiative-forcing, model configurations with a recently developed PC2 prognostic cloud scheme (namely the local simulation HadGEM1-PC2 and Met Office simulation HadGEM3) has better tropical cloud/radiation properties than the (Met Office simulation) HadGEM2 configuration which uses the standard, less sophisticated, cloud scheme (Figure 18). This work is an example of mutual benefit of the collaboration between the Centre for Australian Weather and Climate Research and the Met Office involving ACCESS.

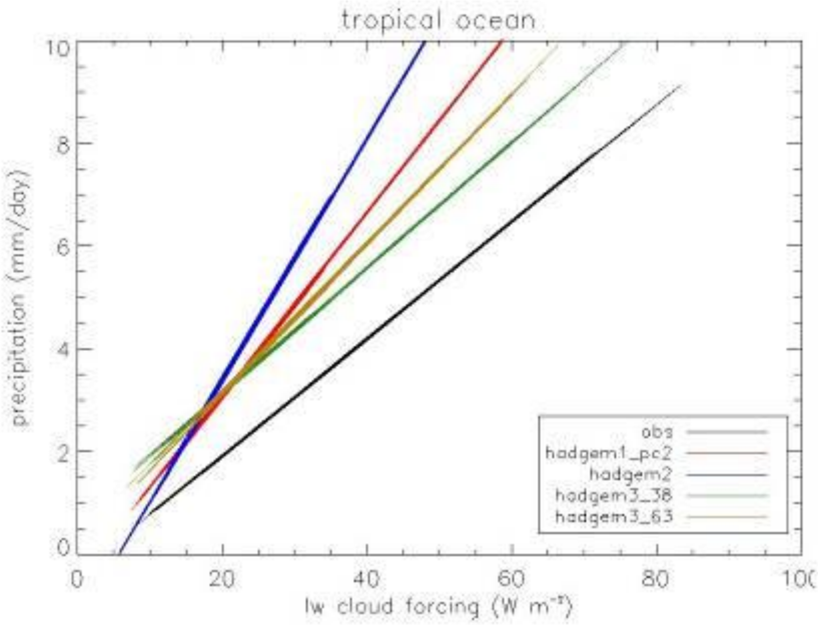

Figure 118: Relationship between long wave cloud-forcing and precipitation-rates over tropical-ocean points. Black – observations, Red – HadGEM1+PC2, Blue – HadGEM2, Green – HadGEM3 38 Levels, Brown – HadGEM3 63 Levels.

Experiments using the single-column model remain an active area of research. Recent examples include evaluation of model cloud behaviour against that observed in the TWP-ICE observational program based in the region to the north of Darwin (where the use of the PC2 cloud scheme was shown to produce a better representation of the diurnal cycle in both active and suppressed periods) and contribution of modelled cloud fields to the CFMIP/GCSS intercomparison study in joint work with the UK Met Office.

Work examining the impact of the treatment of tropical convection on the accuracy of ACCESS climate simulations continues, with an example being the impact of convective momentum transport (CMT). Four-year simulations with the global atmospheric model have been carried out with CMT enabled and disabled. There was significant impact on the model’s representation of the intraseasonal Madden-Julian Oscillation (MJO), with the no-CMT experiment exhibiting improved simulation of the MJO in particular with the observed eastward-propagation of the MJO lacking in the experiment with CMT.

There are known significant deficiencies of the UM boundary layer scheme in low-wind environments, which has the potential to adversely affect coupled model behaviour. A new surface-momentum scaling scheme was introduced into the UM and tested inside both the single-column-model form of the UM, and the full three-dimensional model. Following on from work with the single column model, researchers have this year completed the first set of three-year global simulations using the new scheme. The impact of the new scheme on the overall climate simulation was less clear than anticipated. This contrasts with the positive impact found in the very short-time-scale experiments. More extensive climate experimentation is planned, with longer simulation periods and/or the use of ensembles to attempt to more clearly identify the parameterisation-impact-signal.

Ocean/sea ice model

The ACCESS ocean/sea ice model (AusCOM) has been significantly developed, including an increase in the vertical resolution, especially at the depth of the tropical thermocline (50–200 m). Figure 1912 compares the temperature variability in the upper ocean along the equator between the observed and two model simulations, one with the former, lower, resolution at thermocline depth and one with the new, higher resolution. In both simulations, the ocean model was forced with observed winds over the period 1978 to present. The simulation with the higher vertical resolution at thermocline depth displays a much increased and more realistic degree of variance that that with the lower resolution. The higher resolution (together with other model improvements) has been implemented in the full coupled model, and has contributed to the much stronger ENSO behaviour in the recent 100-year simulations of the coupled model.

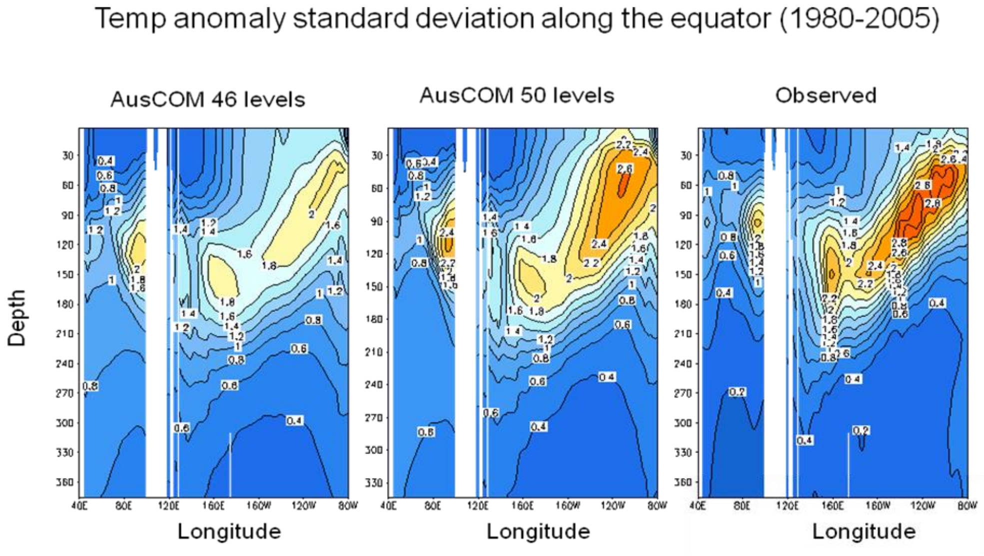

Figure 1912: Comparison of standard deviation of temperature anomaly along equator from 40ºE to 80ºW over the period 1980 to 2005 of AusCOM model with the previously standard lower resolution over the depth range 50-200 m (left), AusCOM model with higher resolution over that depth range (centre), and observations (right). Units are ºC.

Tropospheric chemistry/aerosols

A fundamental goal of ACCESS is to develop the coupled model into a full earth systems model, including atmospheric chemistry and the biogeochemical cycles. A step towards that goal was the successful implementation of new tropospheric chemistry and aerosols modules in the ACCESS system, and the performance of a two-year model simulation to evaluate science processes and model system performance. A longer (12-year) model simulation to assess climate model performance, including an initial evaluation of gas species accumulation and feedbacks and of shorter-lived gas and aerosols species is under way. Initial model evaluation against surface observation networks and global reanalysis products has yielded promising results. Work is under way on evaluating surface fluxes of gases and aerosols, including dry deposition processes and anthropogenic emissions. A further step in this area will be the implementation of a new stratospheric chemistry module into ACCESS, in collaboration with Melbourne University.

Terrestrial biogeochemistry

The terrestrial biogeochemical cycle model CASACNP has been further developed for incorporation into the ACCESS coupled model. CASACNP has been calibrated offline for 17 vegetation types globally using the output from CABLE. In the process, researchers have derived the first-ever global nutrient limitation map for the present conditions.

CASACNP has also been applied to a range of science problems offline. A total of nine publications are related to this work in 2009–10. Work on the nitrogen constraint on carbon uptake on land and the projected future warming due to carbon-climate feedback was highlighted in *Nature*.

Land surface

Improvements continue to be made to the ACCESS land surface model CABLE as coupled to the UM. A comparison of the performance of CABLE and the Met Office land surface scheme MOSES found that the performance of CABLE is significantly better than MOSES for surface temperature and rainfall for Australia under present conditions. This is important to ensure that the physical climate as simulated by ACCESS with CABLE for IPCC AR5 is realistic.

The full CABLE modelling structure (17 vegetation types and six soil layers) has now been successfully coupled with the UM. In doing this, researchers have resolved many unexpected technical difficulties, some of which are related to UM rather than CABLE.

Ocean biogeochemistry

The CSIRO ocean biogeochemical model will be a key component of ACCESS. The model has been used to examine the importance of iron deposition in the oceanic region around Australia. Several multi-century runs with and without iron have been performed to explore different parameterisations. In collaboration with colleagues at Griffith University, an improved dust deposition dataset will be produced for our region. This will be used in future simulations.

In further work using the CSIRO ocean biogeochemical model and AusCOM, researchers will perform an experiment with interannually varying surface meteorological forcing to assess the year-to-year variability in carbon fluxes. Previous work has identified the freshwater flux as a key process driving the CO_2 flux variability in the Southern Ocean. This idea will be explored further with ACCESS ocean model simulations.

3. Climate change, climate variability and extreme events

3.1 Development of high quality historical tropical cyclone data in the Australian region

There is much debate in the scientific community on the expected trends in tropical cyclone activity as a consequence of global warming. A large number of factors affect cyclone development in terms of intensity and the spatial range of impact. Climate models suggest multiple scenarios; however to ascertain the most likely correct scenario, trends in existing activity in a warming climate need to be evaluated.

The pre-existing tropical cyclone database was tainted with errors and unknown biases introduced by possible calibration problems in satellite data and earlier assumptions used by the analysts of the day, compromising the use of this data for climate trend analysis and prognoses. ACCSP researchers are working to minimise the systematic biases so the real trends can be detected.

Over 2009-10 ACCSP researchers:

- loaded the database (which had been purged of gross errors) onto the expanded ADAM database and checked for transfer errors. The development of the user-friendly interfaces is well advanced. Prototypes (see Figure 20) were demonstrated at the Pacific Climate Change Science Program (PCCSP) workshop in Darwin (31 May–4 June 2010) and the AGU Western Pacific Geophysics Meeting in Taipei (22–25 June 2010). The final implementation is expected in the coming months.

- completed evaluation of the satellite data. While some calibration issues were detected, these problems were relatively small. Blind trial analyses of a number of historical cyclones showed that the historical data is not significantly tainted by instrument bias. This knowledge simplifies the remainder of the database repair process. The satellite data is now available on the McIDAS system.

- finalised the pressure-maximum wind relation equations and evaluated them with respect to data available from US hurricanes. It has now been accepted as a standard equation in Australia.

Figure 130: Prototype web interface for the tropical cyclone database

3.2 Climate change – climate diagnostic

East coast lows (ECLs) are responsible for the most damaging extreme weather events in Australia, predominantly affecting the most populated areas of the country. ECLs are not properly captured by coarse resolution climate models so the reliability of rainfall projections from GCMs is questionable for that part of the Australian continent. In addition, all along eastern Australia, rainfall projections produced by climate models are very uncertain.

In 2009–10, ACCSP researchers adapted a series of diagnostics developed for fine resolution numerical weather predictions models to coarser resolution climate models. The diagnostics evaluate the large-scale conditions that favourable to the formation of ECLs. As well as offering the possibility for diagnosing these extreme events, this work provides a process-based understanding of rainfall projections from GCMs.

Three simple diagnostics were calculated and assessed. The assessment revealed that the 90th percentile of each diagnostic, calculated for the period 1989–2006, provided a reasonable hit rate and false alarm rate of observed ECL cases. There is a qualitatively good agreement between maxima in the diagnostic quantities and the ECL events.

3.3 Tropical processes affecting Australia - climate simulations and projections of the Australian monsoon, ENSO and the Walker Circulation

The Australian monsoon system provides most of the rainfall across the top end of Australia. Changes in the timing, positioning and intensity of the rainfall systems associated with the monsoon due to increased greenhouse gases will affect the economy, infrastructure and social fabric. At present, there is substantial uncertainty in the tropical rainfall projections from the CMIP3 model simulations.

Researchers are addressing the issues associated with this uncertainty in the newest generation of GCMs.

The large scale features of the Australian monsoon are simulated with some skill, but there remain large uncertainties in summer rainfall. ACCSP researchers analysed different rainfall amounts in different convective regimes within the models, and found that models are reproducing sufficient rain for medium convective regimes, but are somewhat deficient in producing correct rainfall amounts for deep convective regimes over tropical Australia.

The Australian monsoon is strongly affected by the phase of ENSO. During El Niño events, the total rainfall amounts for the entire wet season are less than during La Niña years, but during the onset period (the first few weeks after the onset date) there is not much difference. The main difference lies in the rainfall at least one month after the onset, with significantly more rainfall during La Niña years.

The year-to-year rainfall variability across tropical Australia is not very well simulated with most models showing deficient variability. This contributes to the somewhat unrealistic ENSO teleconnections in most models, represented by the correlation of tropical rainfall to SST in the equatorial Pacific Ocean (Nino3.4 region). The main contribution to this deficiency is the so-called cold tongue problem within CMIP3 models, whereby western equatorial Pacific SSTs are too cold.

On average, summer rainfall across tropical Australia does not show significant changes even following the high emission A2 scenario. Large uncertainties surround this result and, given the deficiencies seen in some of the models, a case for model selection and weighting can be made. Researchers have found evidence for a slight prolonging of the monsoon season with the monsoon ‘shear line’ (the boundary demarking the change from trade easterlies to monsoon westerlies) remaining across the top end for longer during the A2 scenario. There was no significant change in the average monsoon onset date, but a slight intensification in the low level westerlies during the wet season across tropical Australia.

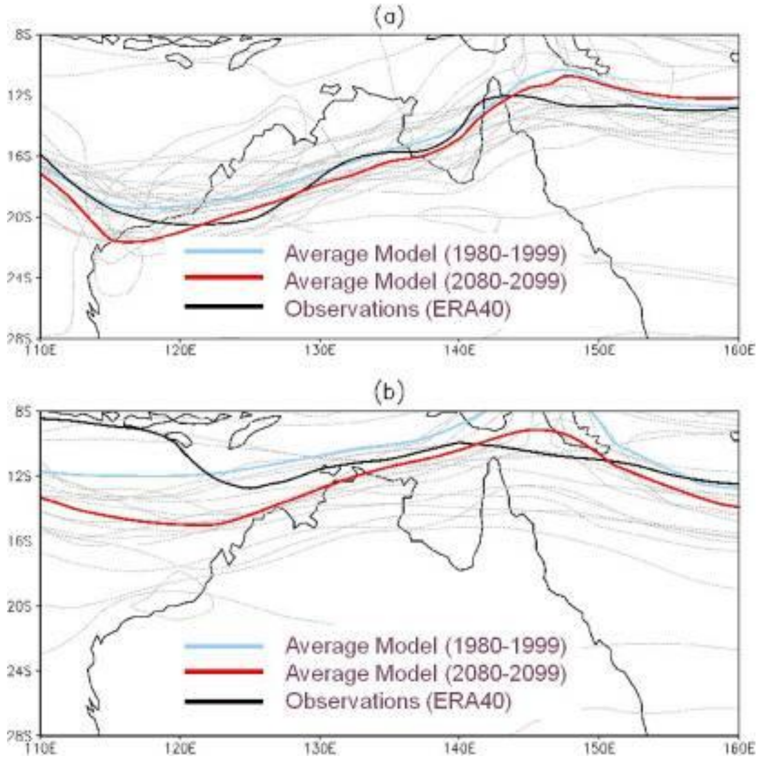

Figure 141: Monsoon 'shearline' during the 1980–1999 period (OBS and CMIP3 ensemble mean) and during the 2080–2099 period (CMIP3 ensemble mean). Shown are January (a) and March means (b).

4. Regional climate change projections

4.1 Projecting future climate and its extremes

The most recent climate change projections for Australia, published by CSIRO and the Bureau of Meteorology in October 2007, have been used in many risk assessments. However, there is a need to do a more rigorous assessment of model reliability to inform the selection and weighting of models for use in projections. There is also a need to meet the demand for probabilistic projections for some applications and reduced complexity for other applications. Many risk assessments require detailed information about projected changes in extreme events, such as heatwaves, heavy rain and tropical cyclones, since these tend to cause the largest impacts. There is significant uncertainty about the best way to create yearly, monthly and daily time series (including extreme events) for use in risk assessments.

Projections for extreme temperature, extreme rainfall, waves and cyclones

Temperature

Using four models and three emission scenarios temperature projections have been developed for 103 sites across Australia. Projections are for annual average number of days (and 3–5 day heatwaves) with Tmax over 30–45°C, Tmin over 20–30°C and Tmin under 0–10°C for present (1970–2000), 2030, 2050 and 2070, including changes in daily variability. There is clear evidence for an increase in hot days and a decrease in cold days. In areas that become drier, the increase in hot days is larger and the reduction in cold days is smaller.

Rainfall

Projections indicating the percentage change in intensity of 1-day and 3-day events with return periods of 10, 20 and 50 years for 2055 and 2090 for 11 models over 11 regions have been developed. Extreme rainfall tends to become more intense in most models and regions, even in regions that become drier on average.

Waves

Based on one CCAM simulation, with bias-adjusted surface winds driving the WW3 wave model, the mean significant wave height along the eastern Australian coast is projected to decrease slightly in future (approx 1 cm/decade), particularly during autumn and winter. Spring and summer wave heights are relatively unchanged.

Tropical cyclones

Tropical cyclone projections based on 12-15 CCAM simulations at 65 km resolution give only 60% of the observed cyclones. The reasons behind this discrepancy are being investigated. Finer resolution would improve the result. Fewer cyclones are likely in future near Australia, but there is likely to be an increased percentage of severe (Category 3-5) cyclones.

Development of easy-to-use projection products

ACCSP researchers have developed a web-based tool called 'Climate futures' that simplifies communication of projections and has proved popular in workshops. The interactive tool allows the user to group climate projections from up to 24 models into categories such as 'warmer, drier', 'hotter, wetter', 'more extreme rain, less extreme wind, 'more humid, less solar radiation' (see Figure 22). This can be done for a selection of future years, emission scenarios and regions. Model-specific results can be displayed for many climate variables, allowing the development of internally consistent projections. The tool and associated guidance material require further development before they can be made accessible to the public.

2055 A2

		Surface Temperature - Annual (° C)			
		Slightly Warmer < 0.50	Warmer 0.50 to 1.50	Hotter 1.50 to 3.00	Much Hotter > 3.00
Rainfall - Annual (% change)	Much Drier < -15.00				
	Drier -15.00 to -5.00			Likelihood: 8.3% 2 models	
	Little Change -5.00 to 5.00		Likelihood: 4.2% 1 model	Likelihood: 29.2% 7 models	
	Wetter 5.00 to 15.00			Likelihood: 45.8% 11 models	Likelihood: 4.2% 1 model
	Much Wetter > 15.00			Likelihood: 8.3% 2 models	

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Figure 152: Sample presentation of 'climate futures'

4.2 Extremes research supporting adaptation for infrastructure planning

Modelling spells

Limited work has been done to model runs of climate extremes, such as hot spells and heat waves, using historical data. Apart from increasing high temperatures and decreasing frost frequency, little can be said about how the duration and severity of extremes will change in the future.

ACCSP researchers are developing new statistical methods to realistically model spell-like behaviour of extremes for environmental time series using the observed data. This work will reveal the extent to which the apparent increased heat waves are natural variability-driven or climate change induced, informing policy options and adaptation actions in Australia.

In 2009–10, researchers completed a literature review that has allowed them to identify and describe candidate models in a framework document. Their approach will make use of developed methods from extreme value theory. It focuses on studying the asymptotic behaviour of times between two runs of extremes, the length of runs of extremes, and intensity of extreme events in each run at different locations and their linkage to the time-varying factors such as natural modes of variability (e.g. ENSO and Sothern Annular Mode) and long-term climate change in the atmospheric and oceanic circulation climate systems. The two leading modes of very hot days in summer with maximum temperature higher than 39°C capture more than 70% variance over south-west Western Australia. The modes appear to be associated with the large-scale wave-train pattern in sea level pressure circulations and the land-sea pressure gradient of south-west Western Australia.

Climate driver variable selection

Statistical methods for downscaling of climate variables require the user to provide 'explanatory' variables (i.e. input variables that the outputs depend upon). Usually, expert knowledge can provide these input variables, but where such knowledge is lacking, or where there is uncertainty about the drivers of climate variables, automatic variable selection may help. However, little work has been done on methodology for variable selection for extreme values.

ACCSP researchers have adapted a method known as RaVE (Rapid Variable Elimination) for selecting explanatory variables when the response has distribution from the generalised extreme value (GEV) family of distributions (e.g. maximum rainfall from a series of daily rainfall records within a season). RaVE can be used for generating parsimonious models when the number of observations is much less than the number of potential predictor variables.

In 2009–10, ACCSP researchers demonstrated proof-in-principle use of a new method for selecting a sparse subset of variables from a much larger ensemble of potential predictors. They found potential explanatory variables for maximum rainfall during the wet season at one station each in the Kimberley and Pilbara regions of Western Australia between 1958 and 2007. The ensemble of potential predictors consists of NCEP-NCAR reanalysis data obtained over a 2.5° × 2.5° grid for 99 grid points. The group of potential predictors consisted of 20 atmospheric variables at each grid point: air temperature, dew-point temperature depression, geopotential height, specific humidity, and east-west and north-south components of wind speed at 500, 700, and 850 hPa, as well as mean sea-level pressure and total-totals. There were a total of 1980 (20 predictors/grid point × 99 grid points) potential explanatory variables, roughly forty times more than the number of annual maxima.

After first assessing whether the behaviour of extreme rainfall had indeed changed over time at these stations, researchers constructed a parsimonious linear model for the location parameter of the GEV distribution at each station. For the station in the Kimberley, RaVE selected only one out of 1980 potential predictors—dew point temperature depression at 850 hPa at 10°S, 125°E (Figure 23), a result that is plausible, given the predominantly tropical rainfall mechanisms in the Kimberley. Even the addition of a single covariate explains some of the variability in the annual rainfall maxima.

Researchers will continue to refine the method and then extend it so that it selects groups of spatially contiguous variables, making the results easier to interpret and climatologically meaningful.

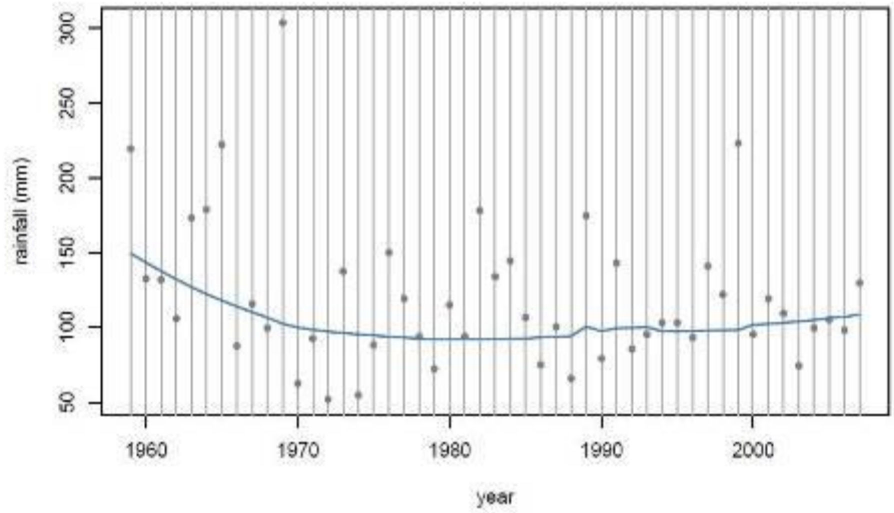

Figure 23: Annual rainfall maxima at Station 1 (Kimberley) during the wet season. The solid line indicates the smoothed location parameter, and it appears that a trend is evident, i.e. the pattern of rainfall maxima changes over time.

4.3 Enhancement of the Bureau of Meteorology statistical downscaling model

Information from GCMs is generally at too coarse a resolution to be suitable for the assessment of climate change impact at regional scales. To address this researchers have adapted the Bureau of Meteorology's statistical downscaling model (BoM-SDM) to provide downscaled climate projections onto a 0.05 degree grid over the entire Australian continent. As well as producing high resolution climate model projections, this new capability is an alternative directly comparable with the dynamical downscaling option based on RCM and a very cost-effective way to provide a 0.05 degree version of the ACCESS model.

After extending the BoM-SDM to the tropical half of the Australian continent during 2008–09, the emphasis of work in 2009–10 has been on adapting the BoM-SDM code to accommodate Australian Water Availability Project (AWAP) gridded climate observations (for rainfall, maximum (Tmax) and minimum temperature (Tmin)) while ensuring the gridded downscaled projections are consistent to those of the downscaled high quality observation network (HQ stations).

Consistency of grid point downscaling to HQ station networks

Climate regions defined in earlier work (Figure 24) were used to ensure that the performance of the SDM remains stable when downscaling to grid points. This was done to ensure that the set of predictors optimised for the downscaling to HQ stations remains valid when gridded outputs are generated and that the SDMs remain skilful.

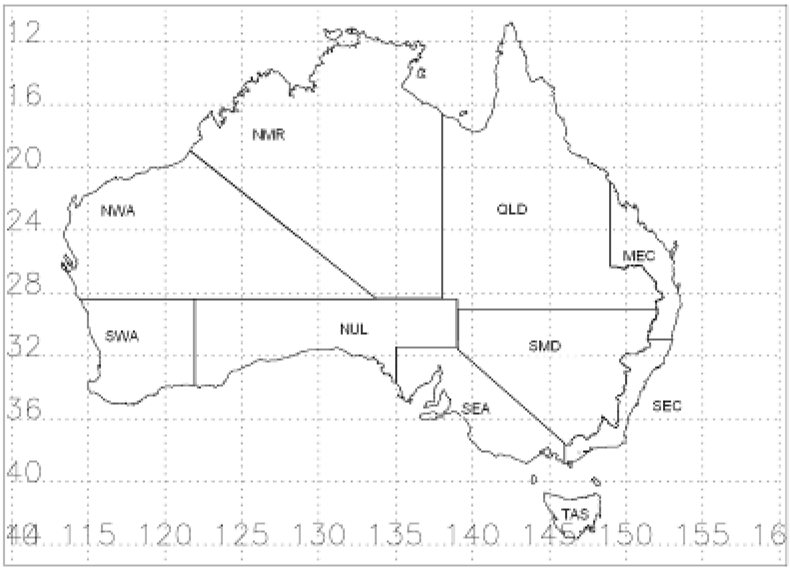

Figure 164: Boundaries of the ten regions used to separate the different climates existing around Australia: Tasmania (TAS), south-west Western Australia (SWA), Nullarbor Plain (NUL), south-west Eastern Australia (SEA), the southern part of the Murray-Darling Basin (SMD), the south-east coast (SEC), the mid-east coast (MEC), Queensland (QLD), the northern monsoon region (NMR) and north-west Western Australia (NWA)

The SDM's ability was tested by reproducing the period 1980–2006. Figure 25 displays an example: the year-to-year variability of Tmax (maximum daily temperature) for Bathurst NSW (33.43°S, 149.56°E) and the nearest grid point (33.45S, 149.55E) are shown; the dashed curves represent the downscaled, reconstructed counterparts. The correlation between the two downscaled time series is strong (r = 0.99), indicating that downscaling to grid points is consistent with downscaling to HQ stations.

Application of ACCESS–AMIP type simulations to HQ stations

The downscaling of ACCESS was performed first using the HQ dataset. Comparison of observed and reconstructed statistics of Tmax, Tmin and rainfall obtained from the downscaling of a 27-year AMIP-type simulation with the latest version of ACCESS to the HQ station networks showed temperature, the seasonal variance and seasonal mean at each station is well represented by the SDM. While the downscaled rainfall variance is relatively unbiased with respect to the observations, there is evidence of underestimation of the reconstructed totals, particularly for summer and autumn. The ability of the SDM to reproduce the variance and total rainfall accurately remains an issue under investigation.

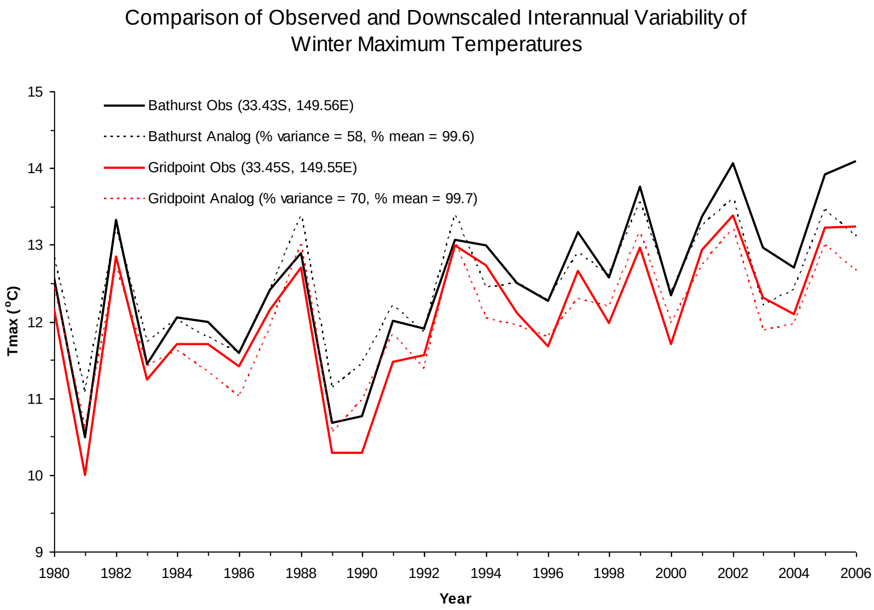

Figure 175: Comparison of the observed (solid curve) and downscaled (dashed curve) year-to-year variability of mean winter maximum temperatures. The red curves denote the observed and downscaled variability of the grid point data located close to the Bathurst observation stations (black curves).

Application of ACCESS–AMIP type simulations to AWAP grids

Despite the ACCESS model's ability to represent the large scale mean climate with sufficient accuracy, such as winter rainfall and maximum temperature compared with similar observations, the coarse resolution of the ACCESS model is inadequate for applications requiring finer spatial scales.

Having implemented the AWAP grids into the SDM code, ACCSP researchers downscaled ACCESS simulations to provide a simple and effective new product that can be used in the assessment of climate change impact at high resolution (0.05 degree or about 5 km horizontal resolution).

Overall, the ability of the SDM to downscale to high resolution grids is consistent with respect to both the ACCESS direct model output and the observed AWAP climate fields. However, in the case for rainfall there are differences between the boundaries for the SMD-QLD and NWA-NMR regions. This matter of consistency at the boundary between climate entities requires further investigation.

4.4 Uncertainty in future climate projections and water resources assessment

Estimates of future water availability are informed by projections from GCMs; however, the information the GCMs provide is too coarse to be used directly for water resource assessments. Different downscaling methods have been used to downscale GCM simulations to provide catchment-scale rainfall to drive hydrological models.

ACCSP researchers investigated the uncertainties in the different modelling components, in particular the downscaling methods, in an effort to improve modelling of future water availability. Specifically, they:

- assessed the rainfall downscaled from three GCMs using five downscaling models
- assessed the runoff modelled by the SIMHYD rainfall-runoff model using the downscaled daily rainfall
- compared the modelled changes in future rainfall and runoff characteristics.

This work was carried out using rainfall and stream flow data from eight unimpaired catchments near the headwaters of the Murray River in south-east Australia. The downscaling models used, in increasing order of complexity, were:

- a daily scaling model
- an analogue statistical downscaling model
- GLIMCLIM and NHMM parametric statistical downscaling models
- CCAM dynamic downscaling model.

All the downscaling models can generally reproduce the observed historical rainfall characteristics. The rainfall-runoff modelling using downscaled rainfall also generally reproduces the observed historical runoff characteristics. The future simulations are most similar between the daily scaling, analogue and NHMM models, all of them simulating a drier future. The GLIMCLIM and CCAM models simulate a smaller decrease in future rainfall.

The differences between the modelled future runoff using the different downscaled rainfall can be significant, and this needs to be further investigated in the context of projections from a large range of GCMs and different hydrological models and applications. The simpler to apply daily scaling and analogue models (they also directly provide gridded rainfall inputs) can be relatively easily used for impact assessments over very large regions. The parametric downscaling models offer potential improvements as they capture a fuller range of daily rainfall characteristics.

5. International research collaboration

5.1 Global Carbon Project: Regional and global carbon trends, budgets and drivers, and carbon-climate feedbacks

Annual update of the global carbon budgets (2008–09)

Human emissions of CO_2 are currently responsible for 80% of the growth of human-induced radiative 'forcing'. Thus, a global assessment of the magnitude and evolution of the various source/sink components provides a fundamental measure of long-term climate change and the mitigation requirements to stabilise global temperatures at any given level. This is essential information to design global climate policies and how the mitigation effort can be shared by countries.

The annual global carbon budget defines the magnitude of the human disturbance of the carbon cycle. It brings together all carbon sources, such as the combustion of fossil fuels and deforestation, and all carbon sinks including the fluxes of carbon going into the oceans, vegetation and remaining in the atmosphere. This annual effort is now a primary reference on the human effects on atmospheric CO_2 for governments and policy-makers around the world, and it is based on an international consortium established by the Global Carbon Project.

The researchers determined that human activities have released 500 Pg of carbon (a petagram is a billion tonnes) to the atmosphere in the form of CO_2 since the beginning of the Industrial Revolution. These emissions have led to an increase of 38% in atmospheric CO_2, from 280 ppm in 1750 to 387 ppm in 2009, and contributed 63% of all anthropogenic radiative forcing to date. Currently, CO_2 emissions are responsible for 80% of the growth of anthropogenic radiative forcing.

The total CO_2 emission flux from human activities was almost 10 Pg carbon per year (Pg C/year) in 2008, made up of 8.7 Pg C/year from fossil fuel combustion and industrial activities, and the rest from net land use change.

The dominant CO_2 emissions contribution from fossil fuels has accelerated in recent years, increasing at an average growth rate of 3.4%/year during the period 2000–2008, compared to 1.1%/year during the 1990s and an average of 2%/year since 1970. This growth rate was above the average of the most carbon intense IPCC scenarios published in 2000, emphasising the unprecedented and largely unexpected emissions growth of the last decade. An important aspect of this acceleration has been an increase in the global share of emissions from the combustion of coal for electricity generation in emerging economies, particularly China and India. Coal was the single largest source of fossil fuel emissions in 2007 and 2008, after more than 40 years of oil supremacy.

In 2008, developing countries emitted more fossil fuel CO_2 (55% of the total) than the developed world (45%); however, per capita emissions remained much higher in developed countries. The global financial crisis that began in 2008 is expected to have a discernable impact on global fossil-fuel

CO_2 emissions, but a scarcely detectable effect on the growth of the concentration of atmospheric CO_2 because of the large year-to-year variability in natural CO_2 sinks.

The findings indicate that natural carbon sinks, which play an important role in buffering the impact of rising emissions from human activity, have not been able to keep pace with rising CO_2 levels. On average 45% of each year's emissions remain in the atmosphere. The remaining 55% is absorbed by land and ocean sinks.

Vulnerability analyses of carbon pools and carbon-climate feedbacks

Researchers have developed a framework for assessing overall carbon-climate feedbacks and their effects on global average temperature as well as a first estimate of emissions from tropical peatlands.

Climate change resulting from fossil fuel emissions and deforestation might destabilise natural carbon pools, which in turn might result in enhanced emissions and amplification of climate change. Examples are the carbon pools in permafrost, peatlands and tropical biomass. Forested tropical peatlands in Southeast Asia store at least 42 Pg of soil carbon. Human activity and climate change threaten the stability of this large pool, which has been decreasing rapidly over the last few decades owing to deforestation, drainage and fire.

Researchers quantified and compared five sources of vulnerability in the carbon-climate-human system, associated with:

1. the partition of anthropogenic carbon between atmospheric, land and ocean reservoirs
2. effects of climate change on CO_2 fluxes, including release of carbon from previously undisturbed pools
3. uncertainty in climate sensitivity
4. changes in non-CO_2 radiative forcing
5. CO_2 emissions pathways.

The carbon-climate feedback can result in up to an additional 1.5°C of global temperature for total cumulative emissions of 2000 PgC.

Of the 27.1 million hectares (Mha) of peatland in Southeast Asia, 12.9 Mha had been deforested and mostly drained by 2006. This latter area is increasing rapidly because of increasing land development pressures. Carbon dioxide emission caused by decomposition of drained peatlands was between 0.355 and 0.855 Pg y^{-1} in 2006 of which 82% came from Indonesia, largely Sumatra and Kalimantan. At a global scale, CO_2 emission from peatland drainage in Southeast Asia is contributing the equivalent of 1.3% to 3.1% of current global CO_2 emissions from the combustion of fossil fuel. If current peatland development and management practices continue, these emissions are predicted to continue for decades. This warrants inclusion of tropical peatland CO_2 emissions in global greenhouse gas emission calculations and climate mitigation policies.

6. Management and communication

6.1 Project management and communication

ACCSP research is undertaken by more than 100 researchers at the Bureau of Meteorology and CSIRO. Project management and communication staff are responsible for ensuring effective communication between the researchers, and strong linkages with the Department of Climate Change and Energy Efficiency, and with relevant researchers in other Australian agencies, especially universities. The ACCSP employs a dedicated communicator with responsibility for ensuring strong internal and external information flow.

In 2009–10, as in earlier years, there has been strong research collaboration between the Bureau of Meteorology and CSIRO, with many projects involving scientists from both organisations.

The ACCSP has initiated and contributed to numerous meetings and workshops to support collaboration, development of research plans and to elicit science contributions from staff within and outside the Program.

CSIRO Marine and Atmospheric Research hosted a workshop on carbon cycle science to determine priority research areas.

The Bureau of Meteorology hosted a national workshop on climatic extremes led by the Department of Climate Change and Energy Efficiency in May. The meeting examined observed changes to climatic extremes and their causes, determined stakeholder requirements, presented the latest information on likely changes, and began development of a collaborative science plan to meet Australia's research needs.

In May, the ACCSP convened a workshop at for CSIRO and Bureau of Meteorology communicators, climate scientists and social scientists involved in the communication of climate change. The workshop objective was to improve working relationships between those involved in climate change communication across the two organisations, share information about recent activities and use insights from social science colleagues to improve the effectiveness of communication.

Planning for projects for 2010-11 began with a one-day meeting in November 2009, in which researchers presented on progress in their disciplines and identified future needs and collaboration opportunities.

The ACCSP annual meeting was held at CSIRO's Aspendale laboratories on 18–19 May 2010, with presentations and discussions reviewing progress in all components during 2009–10. Staff from the Department of Climate Change and Energy Efficiency participated on the second day.

Selected presentations from the GREENHOUSE 2009 conference, held in March 2009 and organised through the ACCSP, have been published as a book. ‘Managing Climate Change’, available through CSIRO Publishing, includes 23 papers (Figure 26). Editors are Imogen Jubb, Paul Holper and Wenju Cai.

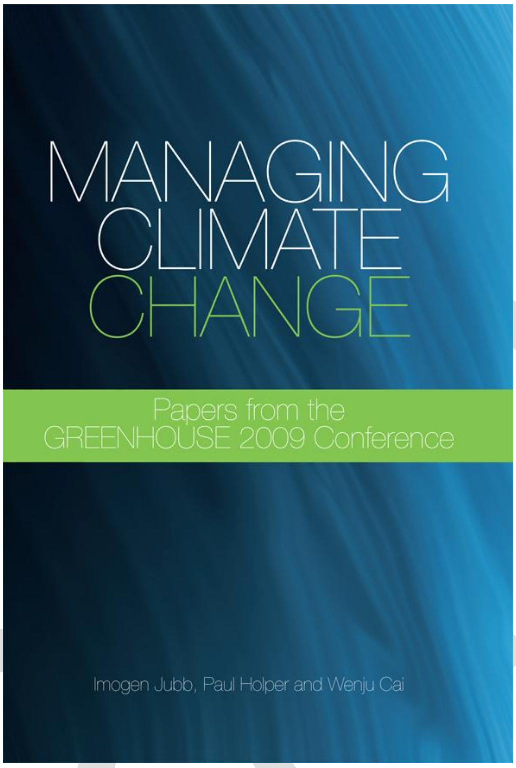

Figure 186: The cover of 'Managing Climate Change', selected presentations from the GREENHOUSE 2009 conference (published by CSIRO Publishing)

ACCSP communication products have included climate change science updates, vodcasts on greenhouse gas tracking and impacts of climate change on the Southern Ocean (Figure 27), improvements to web sites, and information papers.

Figure 197: Screenshot of a CSIRO vodcast on climate change, featuring ACCSP researchers

Preparations are well under way for GREENHOUSE 2011. This conference on climate change science will be held in Cairns in April 2011. See <www.greenhouse2011.com>

Appendix: Publications

The following is a list of 163 publications that ACCSP researchers have led or contributed to during 2009–10.

Understanding the key drivers of climate change in the Australian region

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