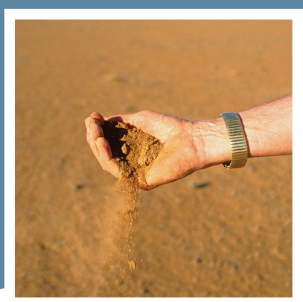
South Eastern Australian

Climate Initiative

Climate variability and change in south-eastern Australia

A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI)



Prepared for
South Eastern Australian Climate Initiative Steering Committee

Citation
CSIRO (2010) Climate variability and change in south-eastern Australia: A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI)

Contributors
The following people contributed to the production of this report:

Project Leaders – Bryson Bates, Paul Holper, Ian Smith.

Project Support Officer – Mandy Hopkins.

Project Coordinator – Gemma Ansell.

Theme Leaders – Bertrand Timbal, Francis Chiew, Harry Hendon.

Project Team – CSIRO: Deborah Abbs, Gael Alory, Wenju Cai, Edward Campbell, Tim Cowan, Steve Charles, Francis Chiew, Steven Crimp, Jeff Dunn, Guobin Fu, Paul Holper, Roger Jones, Dewi Kirono, Yun Li, John McGregor, Peter McIntosh, Gary Meyers, Kim Nguyen, Uday Nidumolu, Mark Palmer, Michael Pook, Tony Rafter, James Risbey, David Robertson, Ian Smith, QJ Wang, Ian Watterson, Penny Whetton, Susan Wijffels, Lu Zhang.

Bureau of Meteorology (BoM): Oscar Alves, Karl Braganza, Andrew Charles, Elodie Fernandez, Harry Hendon, Zhihong Li, Eun-Pa Lim, Guo Liu, Bradley Murphy, Clinton Rakich, Bertrand Timbal, Guomin Wang, Matt Wheeler.

Science Panel – Jason Alexandra (Murray–Darling Basin Authority), Tom Keenan (BoM), Mike Manton (Independent expert), Michael Martin (Department of Climate Change and Energy Efficiency), Rae Moran (Department of Sustainability and Environment Victoria), Graeme Pearman (Independent Chair), Glen Walker (CSIRO).

Steering Committee – Campbell Fitzpatrick (DSE VIC), Chris Johnston (DCCEE), Warwick McDonald (CSIRO), Neville Smith (BoM), Jody Swirepik (MDBA).

We acknowledge CSIRO communication staff for their assistance with the production of this report.

Address and contact details:

CSIRO Water for a Healthy Country Flagship
Ph (+61 2) 62465617 Fax (+61 2) 62465800
Email: seaci@csiro.au

SAMPLE
Lic: NMP–2008
geca.org.au

This publication has been designed by the Visual Resources Unit, CSIRO Plant Industry and printed by New Millennium Print to comply with a very high standard of environmental performance as stipulated in the Good Environment Choice environmental labelling standard GECA 20 – Printers and Printed Matter – www.geca.org.au/standardsregister.htm.

Climate variability and change in south-eastern Australia

A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI)

May 2010

Contents

South Eastern Australian Climate Initiative (SEACI)

Summary of major findings for policy makers and water managers

Observed hydroclimatic changes

- The current 13-year drought in the southern Murray-Darling Basin (MDB) and Victoria is unprecedented compared with other recorded droughts since 1900:
  - Being largely constrained to the southern-Australian region;
  - Having lower year-to-year rainfall variability; there being no 'wet' years through this period; and
  - The seasonal pattern of the rainfall decline being maximum in autumn but including losses in winter and spring as in previous droughts.
- There has been a 13 per cent reduction in rainfall in the southern MDB (the Goulburn-Broken, Campaspe, Loddon-Avoca and Wimmera basins) over the period 1997-2006 compared with long-term averages, which has led to an extreme decline in modelled annual streamflow of 44 per cent relative to the long-term average (1895 to 2006). The streamflow reduction during the current drought period is significantly higher than the reduction during the World War II drought (23 per cent) and Federation drought (27 per cent). This report considers only the impact of climate on streamflow (other drivers of streamflow such as interception and management activities are not considered explicitly).

Explaining the changes

- Factors that have contributed to this streamflow decline include the:
  - Disproportionate rainfall decline in autumn resulting in dry soil conditions at the start of the runoff season;
  - Rainfall decline in winter-spring when most of the runoff occurs;
  - Lack of high rainfall years in the past decade; and
  - Higher temperatures.
- The very low autumn rainfall and low winter/spring rainfall is linked to rising temperatures and associated changes in the large-scale circulation of the atmosphere. These effects are evidenced by the increasing intensity of the sub-tropical ridge (the high atmospheric pressure cells that tend to persist across southern Australia and are characteristic of the region's prevailing climatic conditions). A climate modelling study showed that the observed intensification of the sub-tropical ridge can only be achieved when anthropogenic greenhouse gases are included in climate models.
- This provides evidence that observed changes in the large-scale circulation affecting south-eastern Australia are associated with global warming which is therefore likely to be contributing to the drought. These changes do not account fully for the ongoing drought, and it remains likely that natural variability is also a contributing factor.

Anticipating the future

- The observed changes in the hydroclimatic data may indicate a shift in the climate for south-eastern Australia. A similar shift in climate evidenced via a reduction of rainfall and streamflow has also been experienced beginning in the 1970s in south-west Western Australia. That shift also has been linked to global warming and a range of other factors.
- Climate model projections for the coming decades indicate an increasing risk of below average rainfall for south-eastern Australia. SEACI research also shows that short-duration storms may become more intense across the region, especially over the inland plains.
- The current rainfall decline is at least in part attributed to climate change, raising the possibility that the current dry conditions may persist, and possibly intensify, as has been the case in south-west Western Australia.
- It is prudent to plan for conditions that are likely to be drier than the long-term historical average conditions because the current drought appears to be at least partly linked to climate change and climate model projections of a drier future across the south-east.
- There are questions remaining about how to apply climate change projections given that the recent observed changes in rainfall and streamflow are larger than the projected changes to mean climate for 2030. Further research is planned for Phase 2 of SEACI aimed at better understanding the relative roles of natural variability and climate change in the recent rainfall decline. This will assist in determining how to best combine the observed climate records with future projections.
- The SEACI research program has also produced improvements to both statistical and dynamical approaches to seasonal climate and streamflow forecasting. Such improved forecasting will assist resource managers and users to manage water resources in a changing climate.

Executive summary

Research in the South Eastern Australian Climate Initiative (SEACI) commenced in 2006 to investigate the causes, impacts and prediction of climate variability and change in south-eastern Australia. The research has been carried out by CSIRO and the Bureau of Meteorology with financial support from the Murray–Darling Basin Authority, the Victorian Department of Sustainability and Environment, the Commonwealth Department of Climate Change and Energy Efficiency, and the Managing Climate Variability Program.

Over the three years of Phase 1 of the program, there has been substantial progress in:

- analysing the historical climate record and explaining the main controls or drivers of the climate of the region, including the impact of global warming
- assessing potential changes in the hydroclimate of the region under climate change scenarios
- improving seasonal forecasts and demonstrating their potential value for agricultural decision making and water management.

The quality of the research is demonstrated by the appearance in the international scientific literature of a distinct group of papers that are focused on the region and that acknowledge links to SEACI. Such internationally-recognised strategic research provides the foundation for practical applications in land, water and catchment management.

Enhancing understanding of current climate

The current dry spell since 1996 in south-eastern Australia has been shown to be the driest 13-year period in the last 110 years of reliable climate records. It surpasses the previous record drought that extended from 1936 to 1945. The current drought is different from previous droughts in several ways:

- it is confined to southern Australia, rather than extending over most of the continent
- there have been no wet years over the whole dry spell
- the main decrease in rainfall has been in autumn, rather than winter-spring
- temperatures have been steadily rising.

The last three features have led to the decline in streamflow being much greater than expected based on previous droughts. For example, the 15 per cent reduction in rainfall during 1936-1945 led to a 23 per cent reduction in modelled annual streamflow in the southern Murray-Darling Basin (the Goulburn-Broken, Campaspe, Loddon-Avoca and Wimmera basins), while the 13 per cent reduction in rainfall during 1997-2006 led to a streamflow decrease of 44 per cent.

Large-scale factors that influence the climate of south-eastern Australia include the El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). The ENSO represents the effects of the Pacific Ocean, the IOD represents the Indian Ocean impacts, and the SAM represents the effects of the atmospheric circulation at high latitudes. While these factors have been shown to have varying influences on seasonal rainfall patterns, none of them appears to be able to explain the decline in autumn rainfall. On the other hand, it has been shown that changes in the Hadley Cell, which is the large-scale circulation transporting heat from the tropics to higher latitudes, are leading to increasing surface pressure across the region, represented by the sub-tropical ridge (STR). The increase in the intensity of the STR is found to be well correlated with decreasing rainfall in all seasons except summer, including the decrease in autumn rainfall. There is also evidence that the changes in the Hadley Cell and STR are linked to global warming, rather than simply being a natural fluctuation in the global circulation.

In summary, to the extent that the current changes in temperature and rainfall are linked (at least in part) to climate change, it is possible that the climate in south-eastern Australia is shifting. This raises the possibility that the current dry conditions in south-eastern Australia may persist, and even possibly intensify. However, given that natural variability is also likely to be playing a role in the rainfall decline, it is also possible that there may be a return to somewhat wetter conditions in the short-term. Overall, due to the influence of climate change, it would be expected that future conditions will be drier and warmer than the long-term historical climate in south-eastern Australia. Further work is being done to improve our understanding of the relative influences of natural variability and global warming on current changes in climate.

Assessing regional climate change

Various techniques have been used to estimate future climate in south-eastern Australia under global warming conditions based on the output of global climate models. Statistical methods relate the large-scale model output to local climate variables, while dynamical methods use the global model output to drive finer-scale models. All techniques indicate a warmer, drier climate in the future, especially in the southern part of the region. Initial results on the estimation of extreme events in the future suggest that short-duration events (2-hr storms) may steadily increase in intensity, while the intensity of longer-duration events (72-hr storms) may increase only up until about 2030.

A statistical method has been used to relate the output from 15 Intergovernmental Panel on Climate Change (IPCC) global climate models to the local rainfall and potential evaporation, and these local climate variables were then used to drive a hydrological model to estimate the changes in streamflow across the region in the future. There is strong consensus between the climate models indicating a reduction in future winter rainfall across the region. As most of the streamflow in the southern parts of the region occurs in winter, this translates to a significant reduction in winter and therefore annual streamflow. Nevertheless, there is considerable uncertainty in the future climate projections, and the modelled changes in long-term mean annual streamflow in the southern MDB and Victoria range from -30 per cent to +10 per cent for a 0.9 °C global warming (2030 relative to 1990).

The fact that the projected streamflow (and rainfall) reductions for 2030 across the region are smaller than the observed declines over the last decade raises important issues about how best to use the climate change projections – in particular, how to characterise the “baseline” climate (in light of natural decadal variability in climate) to which the future projections should be applied. Further work is being done to address these issues, including research aimed at better understanding the relative roles of global warming and natural variability in the recent observed changes.

Improving seasonal climate forecasts

A global climate model (called POAMA – Predictive Ocean Atmosphere Model for Australia) has been used to investigate the potential value of seasonal forecasts in south-eastern Australia based on dynamical methods rather than statistical methods. It is found that the model not only predicts ENSO events reliably, but it also identifies different types of ENSO events. Furthermore, POAMA is able to realistically translate these differences in the types of ENSO events into rainfall distributions in Australia. These differences help explain why the major ENSO event of 1997 had less impact on Australian rainfall than the smaller ENSO event of 2002, both of which were accurately forecast to a lead time of about one season with POAMA. This ability of the POAMA model to discern the different types of ENSO events translates into more accurate short lead time (1-2 months) forecasts of spring rainfall over Australia, especially in south-eastern Australia, than those from the current operational (statistically based) system of the Bureau of Meteorology. The loss of skill at longer lead times (one season and longer) was attributed primarily to systematic drift of the simulated mean climate in POAMA, rather than reflecting the upper limit of predictability. These research findings provide a clear pathway for improving POAMA in order to provide improved forecasting at longer lead times, which will be pursued in Phase 2 of SEACI.

A study has been carried out using the output of global climate models to assist farm-level decision making, specifically to assist decisions on the application of fertiliser for winter crops. The economic benefit of the forecasts varies from farm to farm, owing to regional differences in soil type and forecast accuracy. However, interviews with farmers after the project showed that the overall project assisted them in understanding the potential value of seasonal forecasts from global climate models.

A statistical model for seasonal forecasting of streamflow has been developed and tested on catchments in the Murray-Darling Basin. Much of the predictability arises from the use of antecedent streamflow as a predictor, but there is marginal benefit from the inclusion of indicators of large-scale climate factors (such as ENSO, IOD and SAM). Initial work has begun on using the outputs from the POAMA model as predictors.

In summary, there have been improvements in both statistical and dynamical approaches to seasonal climate forecasting; in particular, the POAMA model distinguishes differences in the impacts of ENSO events over Australia. Phase 1 of SEACI has provided a clear pathway for improving the POAMA forecasting at longer lead times, which will assist resource managers and users in adapting to a changing climate.

Future directions

It is clear that significant progress has been made on answering the key science questions specified at the commencement of the program. The research in Phase 1 of SEACI has identified a number of further issues, which will be investigated in Phase 2 of SEACI.

The South Eastern Australian Climate Initiative – Phase 1

The South Eastern Australian Climate Initiative (SEACI) was established in 2006 to improve understanding of the nature and causes of climate variability and change in south-eastern Australia in order to better manage climate impacts.

The SEACI study area covers all of Victoria, southern South Australia (including the agricultural areas of the Eyre Peninsula), and the Murray-Darling Basin. The Basin provides more than a third of Australia's food and generates 40 per cent of the nation's agricultural income. The Basin also includes 30,000 wetlands, which support many species of water-birds and native fish.

Phase 1 of SEACI was a three and a half year, $7.5 million research program that began in January 2006 and concluded in June 2009. CSIRO and the Bureau of Meteorology carried out research in three key areas – understanding our current climate, projecting our future hydroclimate, and improving seasonal forecasts. The program was managed by the Murray–Darling Basin Authority, which also provided funding, along with the Victorian Department of Sustainability and Environment, the Commonwealth Department of Climate Change and Energy Efficiency, and the Managing Climate Variability Program.

Research context

The variability of Australia's climate has always been a challenge for water management and agricultural industries. Global climate change is now recognised as a potential further threat to water resources, agriculture and natural ecosystems in many parts of the world. This threat has become apparent in south-eastern Australia where temperatures have been rising steadily and where rainfall has been low since the late 1990s. Similar rainfall declines started in the mid-1970s in south-west Western Australia. This was the motivation for the Indian Ocean Climate Initiative (IOCI), which was established in 1997 to provide a strategic research effort focused on understanding the climate of the region. IOCI research showed that global climate change is likely to be a significant factor in the observed changes in the region, and the success of the program is demonstrated by the continuing support of national and Western Australian stakeholders.

The clear benefits of IOCI were a motivation for the establishment of SEACI. As with IOCI, the first phase of the program for south-eastern Australia has involved essentially strategic research to clarify the nature and causes of the recent dry conditions in the region. To this end, three research themes were created to provide the framework for SEACI. Stakeholders identified a set of science questions that were relevant to the management of the natural resources of the region and associated social and economic impacts. Each of the three research themes is outlined below.

Research theme 1: Characterisation of current climate

Theme 1 focused on the documentation of recent climate variations and the main drivers of the climate of the region. Research in this theme included a review of past climate studies of the region, the analysis of the climate record, and modelling experiments to investigate the attribution of possible causes of the recent variations. A major aim was to place the current dry episode into context by comparing it with other similar episodes in the past, identifying how it differs from previous episodes and establishing how unusual it is in the light of observed and projected climate change. The key scientific questions posed were:

- How has climate changed in the region?
- What are the major drivers affecting historical and current climate?
- What are the relationships between the drivers operating at different time scales and have these changed over time?

- What are the causes of the dry conditions affecting parts of the study area over the last decade, and what is the prognosis?
- What is the current climate baseline?
- What criteria should be used to determine whether shifts in the climate baseline have occurred, or are likely to occur?

Research theme 2: High resolution climate projections and impacts

Theme 2 focused on estimation of the future climate of the region under the enhanced greenhouse effect. This research involved the use of global climate models and related techniques to improve projections of the climate and hydrological conditions in the region over the coming decades. The key scientific questions posed were:

- How is the climate (average, inter-annual variability and extreme events for rainfall, temperature and evaporation) likely to change over the next 25 to 65 years?
- What are the probabilities attached to these changes?
- How can methods for regional projections be improved so as to provide greater confidence for stakeholders?

Research theme 3: Seasonal forecasts

Theme 3 focused on whether reliable climate forecasts with a lead time of 3 to 12 months can be developed for the region, and whether these forecasts can be usefully applied in hydrology and agriculture. This research involved the application of global climate models and statistical techniques to predict climate and streamflow some months ahead. The output of the global models was used to drive agricultural models of crop yield. The key scientific questions posed were:

- Can reliable methods for forecasting climate 3 to 12 months ahead be developed for south-eastern Australia?
- Can these new forecast methods with greater skill and longer lead times be applied to forecast streamflow and crop yields?

Achievements of SEACI

SEACI research has generated wide interest in the international scientific community. The program has a strong communication program that aims to ensure that scientific results are disseminated to the broad Australian community. There is also a range of activities to ensure that the partner agencies of SEACI are able to benefit directly from the research.

Scientific community

The SEACI program has led to significant advances in our understanding of the climate of south-eastern Australia and to the nature of future changes to the hydroclimate of the region. These results have been communicated to the international scientific community through peer-reviewed articles in high-impact journals and through presentations at international conferences and workshops. Journal articles include descriptions and explanations of the observed changes in the climate of the region, as well as projections of future changes in climate and water availability under the impacts of climate change. There are also articles on both statistical and dynamical models for seasonal forecasting, including the use of a dynamical model to identify distinct modes of the El Niño phenomenon.

The scientific results from SEACI research have been presented at major conferences in Australia and overseas. There were specific sessions on SEACI research at the 9th International Conference on Southern Hemisphere Meteorology and Oceanography in Melbourne in February 2009, and at the Greenhouse 2009: Climate Change & Resources conference in Perth in March 2009.

Broader community

While the research from SEACI has been successfully highlighted and discussed in the international scientific community, it is also recognised that SEACI results are directly relevant to a wide range of stakeholders. The SEACI website <http://www.seaci.org/> provides access to detailed information on the operation and outputs of SEACI. The website also makes available results of relevance to the broad community through a series of accessible publications, including fact sheets and brochures providing answers to questions about the climate in south-eastern Australia.

About this report

This synthesis summarises the major findings from the research carried out over Phase 1 of SEACI, and assesses progress in answering the key scientific questions, as well as considering the future needs for related research.

Major findings

SEACI research has delivered many important findings that relate directly to policy and decision making in the region.

Major findings under each of the three SEACI research themes are detailed below.

Research theme 1: The climate of south-eastern Australia and its drivers

SEACI researchers have made significant progress on documenting the variations in the climate of south-eastern Australia and on identifying the likely causes of those changes.

The current drought

> *The current drought is the driest period since reliable climate records have been kept. It differs from previous droughts in its extent, year-to-year rainfall variability and seasonality of the rainfall decline.*

SEACI research* shows that the dry spell experienced from 1997 to 2009 represents the driest 13-year period in the last 110 years of reliable climate records (Timbal, 2009), with the change in average annual rainfall across the SEACI region (the area included in the red box in Figure 1) being -11.4 per cent. It surpasses the previous lowest 13-year period which extended from 1933 to 1945 during which the change in average annual rainfall across the region was -7.8 per cent.

It is well-known that the climate of eastern Australia is influenced by variability in the tropical Pacific Ocean as represented by the El Niño – Southern Oscillation (ENSO) phenomenon, which is associated with large-scale drought over much of the country, as well as Indian Ocean tropical variability as measured by the Indian Ocean Dipole (IOD). However, while there have been some El Niño years and IOD positive (dry) years embedded in the recent drought period, the recent dry spell over south-eastern Australia cannot be explained by ENSO or the IOD. Moreover, the major dryness has been largely across southern Australia (Figure 1) rather than in the north-east where the greatest ENSO impact tends to occur or across central Australia and the Murray-Darling Basin where the greatest IOD impact tends to occur.

* Note: The numbers for the rainfall deficits cited in this report are based on monthly data taken from the AWAP-v3 data set available at <http://www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseries.pl> for start coordinates 135.5E -33.5S and end coordinates 152.5E -39.5S.

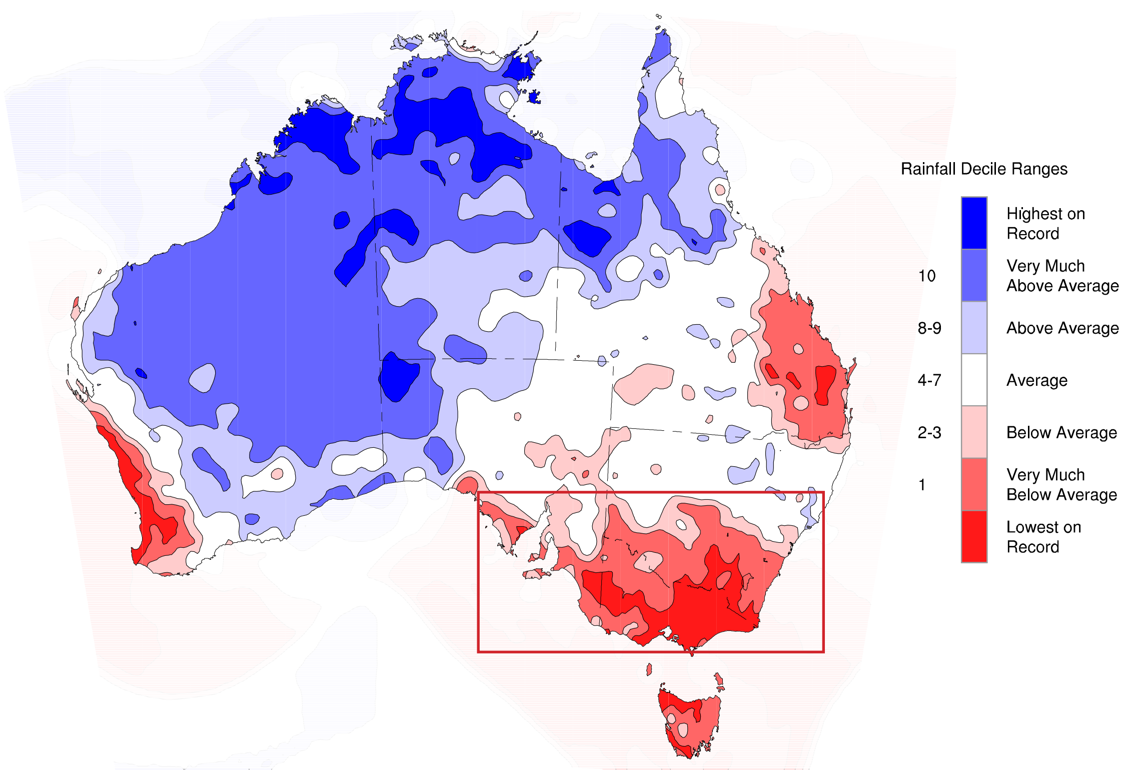


Figure 1. Rainfall deciles across Australia for 1 January 1997 to 31 December 2009; deciles based on climatology from 1900 to 2009 (Bureau of Meteorology).

The current drought is different from previous droughts in several ways:

- It has lasted longer than any previous period of rainfall deficiency: the previous record drought lasted 10 years from 1936 to 1945 during which the rainfall deficiency was -11.6 per cent. However, this period was both preceded and followed by above average rainfall years and the rainfall deficit was only -7.8 per cent for a comparable 13-year period (1933-1945).
- It tends to be confined to southern Australia, rather than extending over most of the continent. Indeed much of Australia has had above-average rainfall (with a major exception of south-west Western Australia) over the last 13 years.
- As well as the overall average rainfall being lower, there have been no individual 'wet' years. The most recent year with rainfall above the long-term average was 2000, when the annual rainfall was 619 mm, 28 mm (4.5 per cent) above the long-term (1900-2009) average of 581 mm.
- The main decrease in rainfall has occurred in autumn, while previous droughts tended to have a decrease in the winter-spring period. The autumn rainfall has declined by 25 per cent, accounting for about 52 per cent of the annual decline over the period 1997-2009. Smaller decreases have occurred during winter (9 per cent) and spring (5 per cent), but the decline in spring rainfall has intensified since 2006. Over the 13-year period there is now below-average monthly rainfall for the eight months from March through to October.

In addition, this drought has occurred in a period of rising temperatures, not only in south-eastern Australia but across most of the world. One likely result of the temperature rise (Nicholls, 2004) is an increasing impact of drought on natural and agricultural systems through increased heat stress.

While the current drought has seen annual rainfall decline by an average of 11.4 per cent across south-eastern Australia, the impact on streamflow[1] has been even more extreme. While some magnification of the response in streamflow relative to rainfall is expected (Chiew, 2006), the degree of this magnification in the recent drought is unusual. For example, it is evident that average inflows to the River Murray system over the period 1997-2009 are 50 per cent less than the long-term average, which is a greater reduction than in either the Federation (1896-1905) or World War II (1936-45) droughts (Figure 2). For the southern Murray-Darling Basin (the Goulburn-Broken, Campaspe, Loddon-Avoca and Wimmera basins), the ratio of the modelled streamflow reduction relative to the rainfall reduction is 2.51 for the Federation drought, 1.54 for the World War II drought and 3.24 for the current drought (Potter et al., 2010). This magnification of the streamflow response in the current drought is thought

[1] The terms 'runoff' and 'streamflow' are both used in this report. They refer to catchment runoff or streamflow from mid-sized catchments (50 to 2000 km^2). This is because the rainfall-runoff models used in the studies were calibrated against observed streamflow data from unregulated catchments with areas ranging from 50 to 2000 km^2. Other factors, in particular interception activities like farm dams and afforestation/deforestation, can also impact on streamflow, but these were not explicitly considered. Likewise, the impact of water management on streamflow in regulated systems was also not considered.

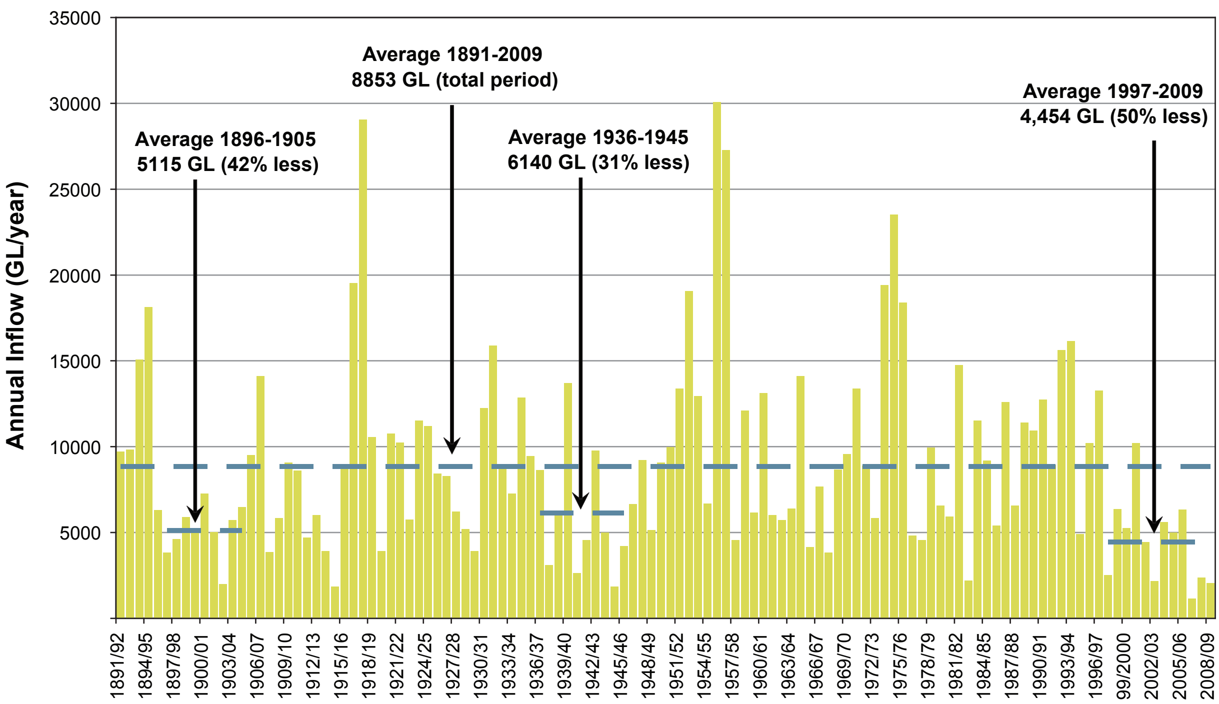


Figure 2. Inflows to the Murray River system (excluding Darling inflows and Snowy releases) for the period July 1891 to June 2009. The inflow over the current drought is seen to be lower than during earlier droughts (Murray–Darling Basin Authority).

likely to be related to various factors including the absence of wet years, increasing temperature and the change in seasonal rainfall patterns, which means that the land surface is not well moistened in autumn, resulting in a substantial reduction in runoff in subsequent seasons (Timbal et al., 2009). Further work is underway to better understand the reasons for the large reductions in streamflow.

Further details about the changes in climate throughout the region are given in the 'Progress on key science questions section' of this report.

Causes of climate variability and change

The rainfall decline in south-eastern Australia can be linked to changes in large-scale atmospheric circulation. There is evidence that these changes are at least partly due to global warming.

Australia is affected by many types of weather systems (Figure 3), the frequency and magnitude of which are often influenced by some large-scale features of the atmospheric circulation. These include:

- the ENSO, which leads to wide-spread drought when the sea-surface temperature rises in the equatorial eastern Pacific Ocean and falls in the west around Indonesia
- variations in the sea-surface temperature of the Indian Ocean (indicated by the IOD) which are linked to the frequency of north-west cloud bands that bring rain right across Australia
- weather systems such as east-coast lows that bring heavy rain to coastal areas and are affected by the sea-surface temperature patterns in the Tasman Sea
- high-latitude circulations associated with the Southern Annular Mode (SAM), which represents variations in the strength and position of the westerly winds south of Australia.

SEACI researchers analysed the observed climate record and found that while these large-scale climate phenomena had varying influences on seasonal rainfall and temperature they could not explain the decline in autumn rainfall in south-eastern Australia (Murphy & Timbal, 2008).

The Tasman Sea was found to have an effect on temperature in all seasons, but its effect on rainfall is less certain. The ENSO is known to have its maximum impact on rainfall and maximum temperature in spring. While the IOD can have an impact on rainfall and maximum temperature in winter and spring, there is no significant impact in summer and autumn. Similarly, earlier research by Hendon et al. (2007) suggests that the SAM has a significant effect on rainfall and minimum temperature in all seasons except autumn.

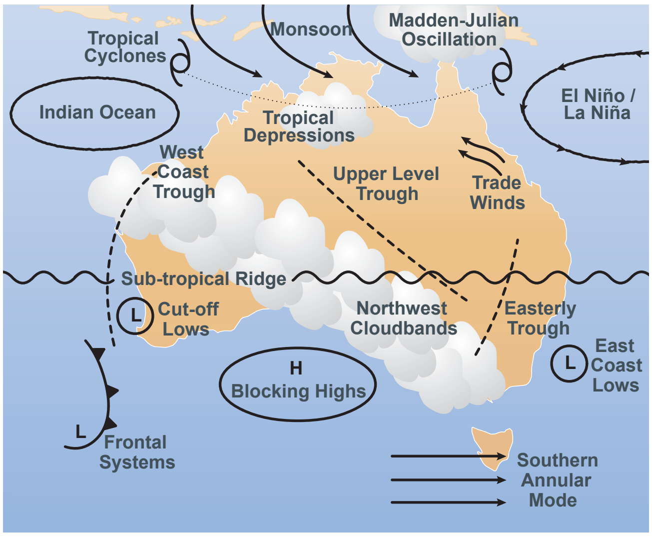


Figure 3. Large-scale features that affect the climate of south-eastern Australia (Bureau of Meteorology).

SEACI researchers also found a strong relationship between the rainfall in south-eastern Australia and the intensity of the sub-tropical ridge (STR) (Figure 4), with the decreasing rainfall associated with increasing surface pressure in the latitude band of the STR. This relationship was present in all seasons except summer (i.e. including autumn).

Research indicates that there are changes in the Hadley Cell (and hence changes in the STR) associated with global warming. In particular, the STR has intensified with increasing global surface temperature (Figure 5a). This result implies that the rainfall decline in south-eastern Australia may have some link to global warming. To test this, SEACI researchers conducted simulations of the global climate over recent decades using a global climate model. In these simulations the climate was forced by:

1. natural variations in the output of the sun and in aerosols from volcanoes over the last century
2. observed changes in anthropogenic sources of global warming (that is, anthropogenic greenhouse gases, aerosols and ozone)
3. a combination of natural and anthropogenic processes.

The observed increase in STR intensity was only reproduced in simulations that used anthropogenic forcing. The largest increase occurred when anthropogenic forcing was combined with natural processes, although the size of the changes in the simulations was smaller than the observed changes (Figure 5b).

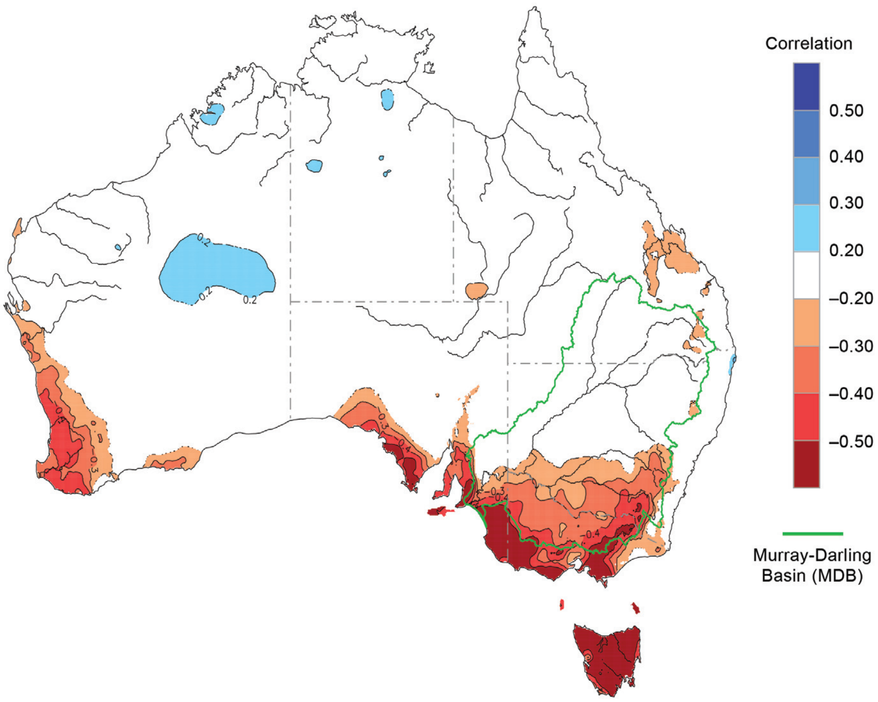


Figure 4. Correlation between Australian rainfall and the intensity of the sub-tropical ridge (STR) using annual means; there is a strong negative correlation in areas experiencing rainfall deficiency since 1996 – in particular across south-eastern Australia (Timbal, 2009).

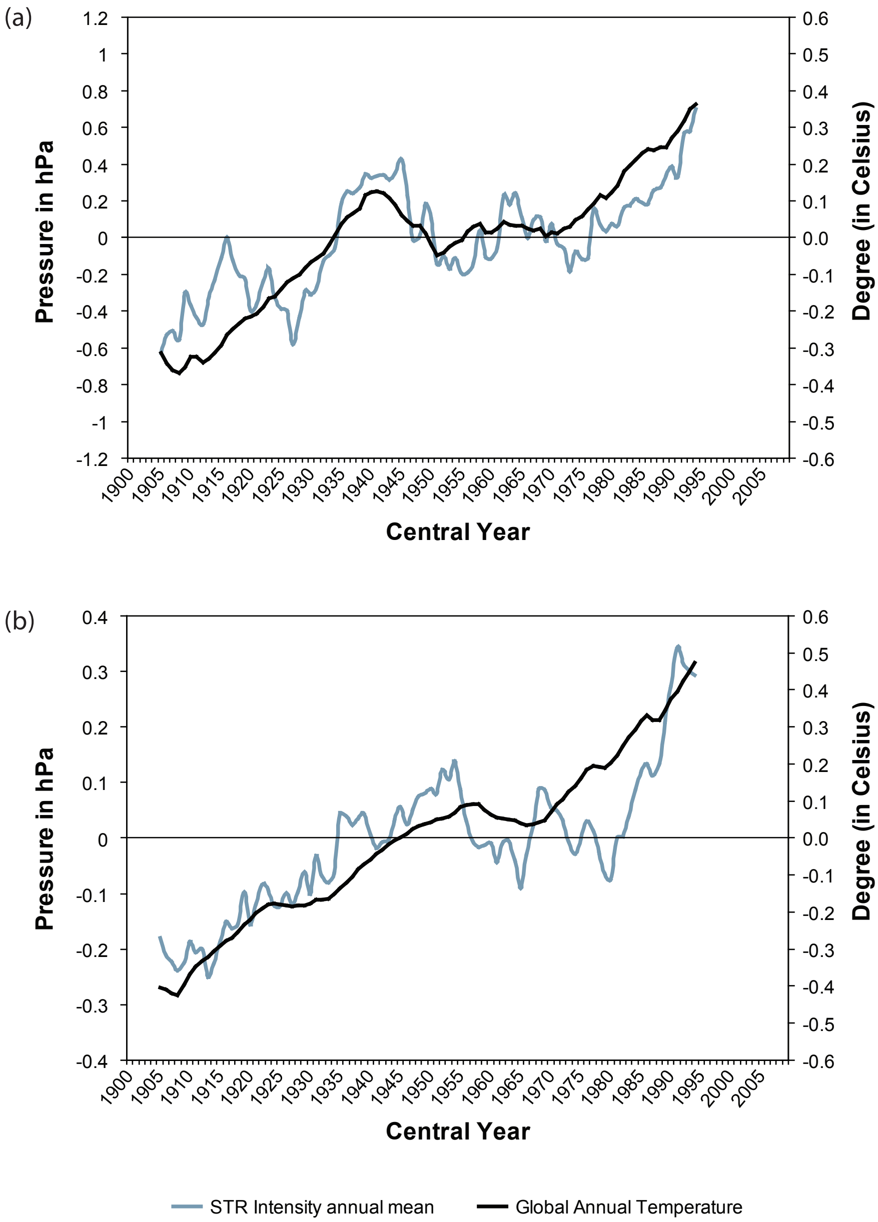


Figure 5. Time series of anomalies of annual STR intensity (in hPa on the left Y-axis) and global temperature (in °C on the right Y-axis) calculated from (a) observations, and (b) the average number of simulations with a state-of-the-art climate model forced with a combination of processes (Timbal et al., 2009).

Output from the climate models was also used to estimate the rainfall over south-eastern Australia. As with the STR, the best simulation of the observed rainfall decline occurred when both natural and anthropogenic forcing were included, but again the modelled reduction was less than observed.

Recent SEACI research has shown that around 80 per cent of the recent rainfall decline in south-eastern Australia is statistically associated with the strengthening of the STR. There has also been an apparent shift south in the position of the ridge, but this does not appear to be having an additional effect on the rainfall. The research has also shown that up to about a third of the rainfall decline in the World War II drought is statistically associated with a strengthening of the ridge at that time.

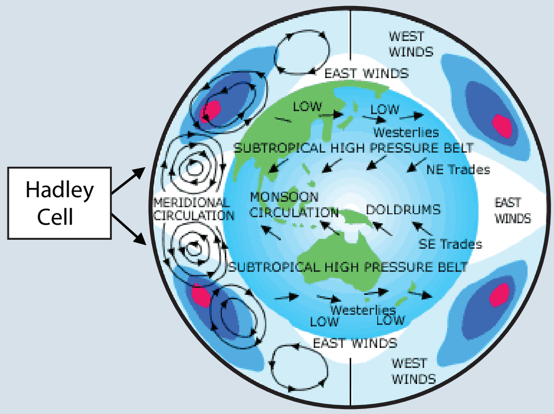
To the extent that the current changes in temperature and rainfall across south-eastern Australia may be linked to climate change (through the intensification of the STR), it is possible that the current dry conditions may persist, and even possibly intensify, as warming is expected to continue. It is of note that the rainfall in south-west Western Australia has continued to be below average for more than 30 years. There is some evidence (Hope et al., 2009) of links between the climate of that region and that of south-eastern Australia, with both regions being reliant on similar mid-latitude weather systems for their rainfall.

Given that natural variability is also likely to be playing a role in the rainfall decline, it is also possible that there may be a return to somewhat wetter conditions in the short-term. However, overall, due to the influence of global warming, it would be expected that future conditions will be drier and warmer than the long-term historical climate in south-eastern Australia.

Yet another possibility is that the current decline is a natural cycle in the climate of south-eastern Australia. There are only just over 100 years of quality rainfall records and similar episodes may have occurred in previous centuries. While other types of 'proxy' data are being used to look at past climate, it is more difficult to use the data to examine the likely drivers of any past dry episodes. In the absence of such understanding, it could be argued that a return to wetter conditions is likely in the near future, and that any association of the current dry period with global warming is simply fortuitous. This is considered to be unlikely by SEACI researchers.

The Hadley Cell and the sub-tropical ridge

The Hadley Cell is the most fundamental component of the global climate system. It is the process by which heat from the sun, which falls mainly in the tropics, is transported from equatorial zones to higher latitudes in the atmosphere. In the figure below it is shown as the central element of the 'meridional circulation'. There is a Hadley Cell in both hemispheres.



Global atmospheric circulation (Bureau of Meteorology).

The sun's heat leads to tropical thunderstorms that lift air from the surface and cause it to flow pole-ward at altitudes around 10 km. Owing to the rotation of the earth, the Hadley Cell does not extend to the poles. Rather, the downward return flow (subsidence) occurs along the sub-tropical ridge (STR) around 30° north and south. The STR is a region of high surface pressure in which rainfall is generally suppressed. The location and intensity of the STR vary from day to day and from season to season.

The Hadley Cell interacts with similar cells at higher latitudes, so the behaviour of the STR is expected to have some link with the variations in the SAM, which is associated with the westerly winds in the southern hemisphere.

Causes of changes in streamflow

Changes in rainfall patterns (lower mean annual rainfall, larger declines in autumn rainfall and lack of high rainfall years) are causing very significant declines in streamflow in south-eastern Australia.

It is well known that processes at the land surface tend to magnify any reduction in rainfall so that the associated percentage reduction in streamflow is typically two to three times as large (Chiew, 2006). During the World War II drought, the rainfall reduction of 15 per cent led to a 23 per cent reduction in modelled streamflow in the southern Murray-Darling Basin (the Goulburn-Broken, Campaspe, Loddon-Avoca and Wimmera basins). Over recent years, the streamflow reductions have been greater than expected relative to the observed decreases in annual rainfall. SEACI research shows that the 13 per cent reduction in rainfall in the southern Murray-Darling Basin over the period 1997-2006 has led to a streamflow decrease of 44 per cent (Potter et al., 2010), which is 3.4 times the percentage reduction in rainfall. In some parts of Victoria, the recent reductions in streamflow have been as much as four times the reduction in rainfall. Figures 6a and 6b show updated results for changes in rainfall and modelled streamflow over the period of 1997-2008 relative to the 1895-2008 long-term mean across south-eastern Australia.

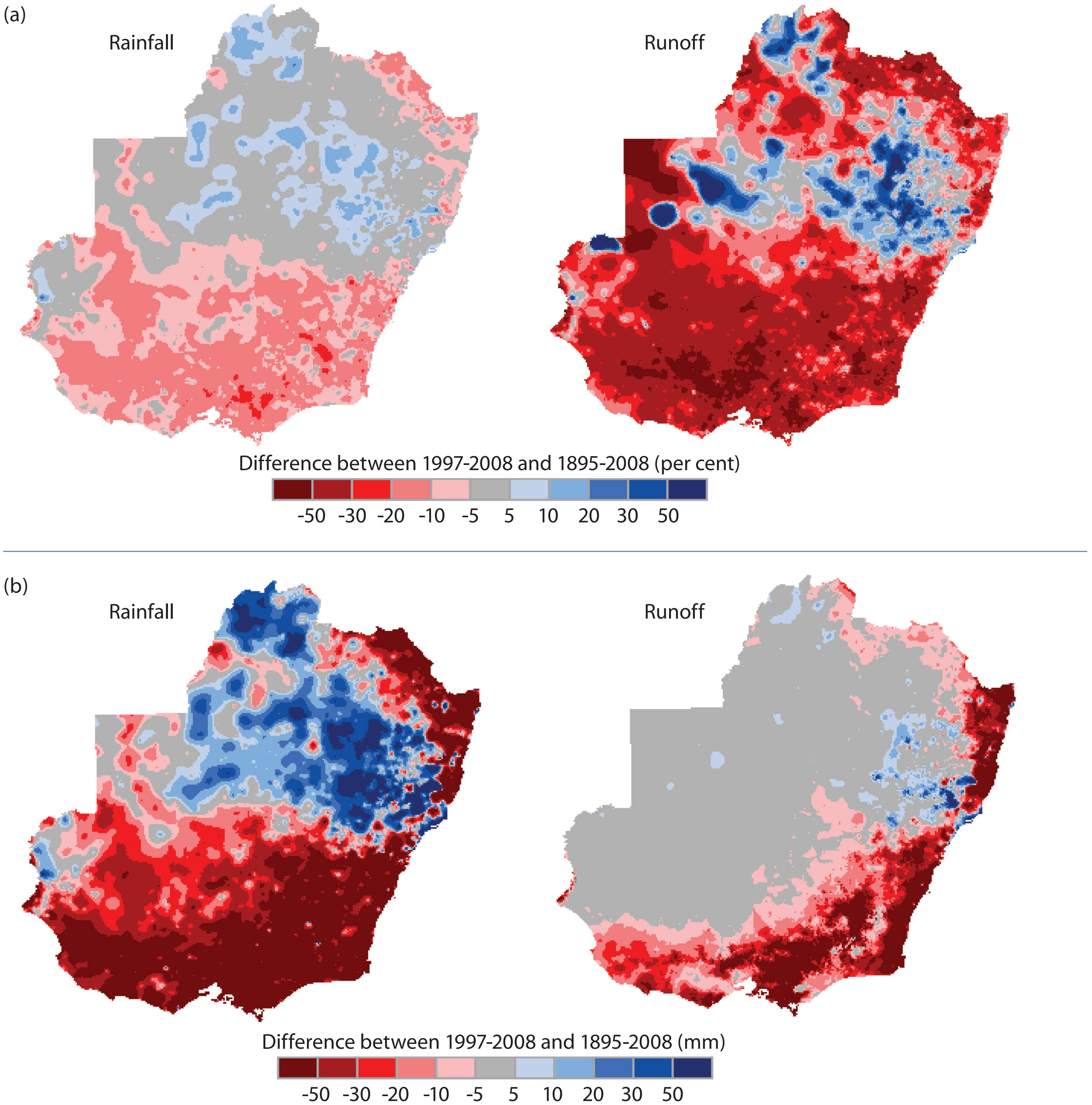


Figure 6. Recent (1997-2008) rainfall and runoff across south-eastern Australia (MDB, Victoria and NSW) relative to the 1895-2008 long-term mean; (a) per cent; (b) millimetres (Chiew et al., 2010).

The larger-than-expected response of streamflow to the rainfall decline is likely to reflect both the absence of wet years over the past decade, which has resulted in depleted soil moisture reserves, and the fact that the major rainfall decline has been in autumn. In the past, the rainfall decline during droughts has tended to be in winter and spring. In the recent drought, the reduction in autumn rain means that the ground has not been moistened before the onset of the winter rains; that is, the winter rain itself must now moisten the ground before any useful streamflow can begin. This, together with the decline in winter and spring rainfall, results in low streamflows in winter and spring when most of the streamflow in the south-eastern Australia occurs.

While the changes in rainfall are certainly the main reason for reduced streamflows across the region, SEACI researchers have shown that temperature as well as rainfall has a significant impact on the annual streamflow in south-eastern Australia (Fu et al., 2007; Cai & Cowan, 2008). The 1 °C rise in maximum temperature over south-eastern Australia in winter and spring over the last 50 years can be linked to a reduction in (modelled) streamflow of about 15 per cent of the total (Cai & Cowan, 2008). However, other research has shown that the increase in potential evaporation resulting from a 1 °C rise in temperature (with no change in other drivers of potential evaporation) reduces modelled streamflow by only about 3 per cent (Chiew, 2006; Jones et al., 2006; Potter & Chiew, 2009; Potter et al., 2010). Cai & Cowan's (2008) results may reflect a link between higher temperature and the changes in the rainfall patterns that drive (modelled) streamflow as discussed above. It is possible that the rainfall-runoff relationship is changing with the steady increase in temperatures across the world, and this is being investigated in SEACI Phase 2.

Research Theme 2: Projections of future climate for south-eastern Australia

While much research has been carried out to estimate future climate on a global and continental scale, most policy and management decisions need to be made at regional and local scales. It is important to note that climate variability increases with decreasing space and time scales (for example, the daily temperature in Melbourne varies much more than the annual mean temperature across Australia), so as the area of interest of climate projections decreases, uncertainties increase.

Projections of future climate under enhanced greenhouse gases are made on the basis of output from global climate models. These models, which are similar to the models used each day for routine weather forecasting, include the major physical processes that affect climate. Owing to the large computational requirements for projections many decades ahead, global climate models generally have a spatial resolution of a couple of hundred kilometres, which is too coarse to provide detailed information on local scales.

SEACI researchers have worked on techniques to bridge this gap and have developed a range of techniques to 'downscale' the output of global climate models to regional and local scales.

Types of downscaling

Statistical

Using the historical relationships between the large-scale outputs from the global climate model and local climate variables (such as temperature or rainfall at a specific site), statistical techniques can be developed to estimate the future state of the local variables in terms of the large-scale model projections. These techniques assume that the global climate models simulate the large-scale flow patterns reasonably well and that these patterns have a controlling influence on the local climate. Statistical downscaling techniques were originally developed to enhance the value of output from routine numerical weather forecasting models, and they have been successfully applied for many decades.

Dynamical

An alternative approach to downscaling is to use the output of a global climate model to drive another, but finer-resolution, numerical model that is focused on the region of interest. Such regional climate models can have a spatial resolution of a few tens of kilometres.

Statistical methods for estimating regional climate change

Statistical methods yield detailed projections of changes in local climate variables, such as temperature, rainfall, evaporation, and the frequency of frost days.

The non-homogeneous hidden Markov model (NHMM) is one statistical method that has been used to relate daily multi-site rainfall patterns to large-scale atmospheric circulation (Charles et al., 1999). It assumes that the rainfall patterns can be classified into a small number of discrete weather patterns or weather states. The model uses atmospheric circulation data to estimate the sequences of these weather states and hence can simulate realistic sequences of daily rainfall. For south-eastern Australia, the predominant weather states are a dry and a wet state, associated with high and low surface pressure over the region respectively. SEACI research has shown how atmospheric circulation changes have led to a decrease in the frequency of the wet state and an increase in the frequency of the dry state over the last few decades.

SEACI researchers applied the NHMM to the output of four global climate models to investigate the possible future climate conditions across south-eastern Australia under different climate change scenarios. Figure 7 shows that annual rainfall for 30 southern Murray-Darling Basin stations is projected to decline into the future under the A2 high emissions scenario. A measure of the reliability of the projections is given by comparing the observed data ('Observed' in Figure 7) to results downscaling both reanalysis and global models for 1961-2000 ('NCEP/NCAR' versus '20C3M' in Figure 7). The uncertainty in the results is due primarily to differences and errors in the large-scale atmospheric circulation of the global models. This result highlights the major limitation of all downscaling methods: significant errors in the large-scale atmospheric circulation from the global models cannot easily be corrected by the downscaling technique. For example, if a global climate model does not simulate the large-scale circulation associated with synoptic fronts, then the downscaled results cannot produce rain from those fronts.

An analogue statistical downscaling method (ASDM), based on the historical relationship between large-scale weather patterns and surface climate variables (such as temperature and rainfall), has also been developed (Timbal et al., 2009). The ASDM looks for historical weather patterns that closely match (are analogues for) the weather pattern simulated by a global climate model at a particular time. Then the historical relationship between those analogues and the surface variables is used to estimate the surface variables at that time. Using global model simulations for the past 100 years, it is found that the ASDM can well reproduce the mean of the observed daily time series across south-eastern Australia, but an empirical adjustment must be made to ensure that the variance is not under-estimated. The method (Timbal & Jones, 2008) captures the inter-annual and longer-term variability of surface climate across the region (including the observed downward trend in rainfall). The method has also been applied to global model projections of future climate change to provide estimates of a range of surface climate variables, including temperature, rainfall, evaporation and the occurrence of frost days.

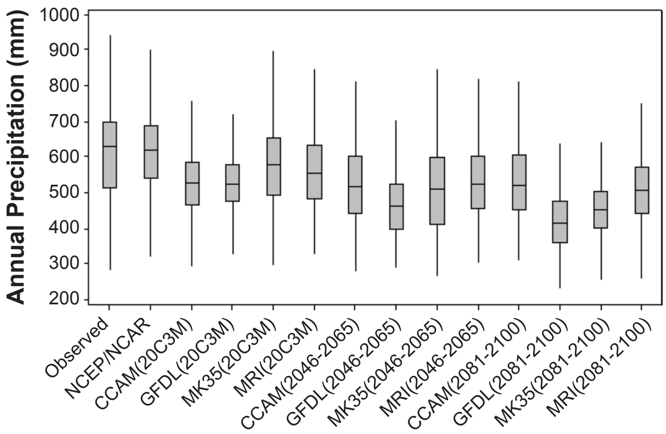


Figure 7. Box-plots comparing 1961-2000 observed ('Observed') annual precipitation totals for 30 southern Murray-Darling Basin stations to NHMM downscaled reanalysis ('NCEP/NCAR') and GCM ('20C3M') for 1961-2000 and A2 projections for 2046-2065 and 2081-2100. The box shows the median and 25th to 75th percentile range. (Charles and Fu, 2008).

Dynamical modelling of regional climate change

Longer-duration storms may increase in intensity up to 2030 but decrease by 2070. On the other hand, short-duration events are expected to steadily increase in intensity.

The Cubic Conformal Atmospheric Model (CCAM) has been used extensively to provide dynamical downscaling of output from global climate models for many regions of the world (Watterson et al., 2008). The method has been refined to ensure that the large-scale weather patterns are consistently transferred from the driving global model to CCAM. A version of CCAM is first run at a global resolution of 200 km, using bias-corrected sea-surface temperature fields from the driving global model. The CCAM is then run with a resolution of about 20 km over south-eastern Australia, using a digital filter to ensure that the broad-scale global fields in CCAM are consistent with those in the driving global model. The method is found to produce good simulations of the current climate across eastern Australia.

A further level of dynamical downscaling has been applied by using the global 200 km simulations of CCAM to drive another model, the Regional Atmospheric Modelling System (RAMS), at a resolution of first 65 km and then 4 km; that is, there are two levels of dynamical downscaling from the CCAM output. These 4 km simulations have been used to investigate possible changes in extreme rainfall events under climate change conditions. Such fine-resolution simulations are needed because extreme events occur on very small space and time scales that are not resolved by global climate models. Broad areas where an average decrease in the intensity of extreme rainfall events is simulated from a 200 km model can contain sub-regions (resolved in 4 km simulations) in which there are expected to be very large increases in intensity (Figure 8). Thus, small-scale variations in topography as well as mesoscale detail in broad-scale meteorological features can lead to local extreme events that cannot be captured at the normal resolution of global models. In addition, simple interpolation from a global model misrepresents the fine scale structure of temperature extremes (Watterson et al., 2008).

The two-stage dynamical downscaling using RAMS has been applied to about 300 events for current conditions and for conditions at 2030 and 2070 under the A2 (IPCC, 2000) climate change scenario, which has greenhouse-gas emission rates that are on the higher side of currently expected futures. Because it is inherently difficult to get reliable statistics for extreme events, the results of these investigations have considerable uncertainty. However, it appears that the intensity of longer-duration (72 hrs) storms may increase up to 2030 but by 2070 their intensities may decrease. On the other hand, short-duration events (2 hrs) are expected to steadily increase in intensity.

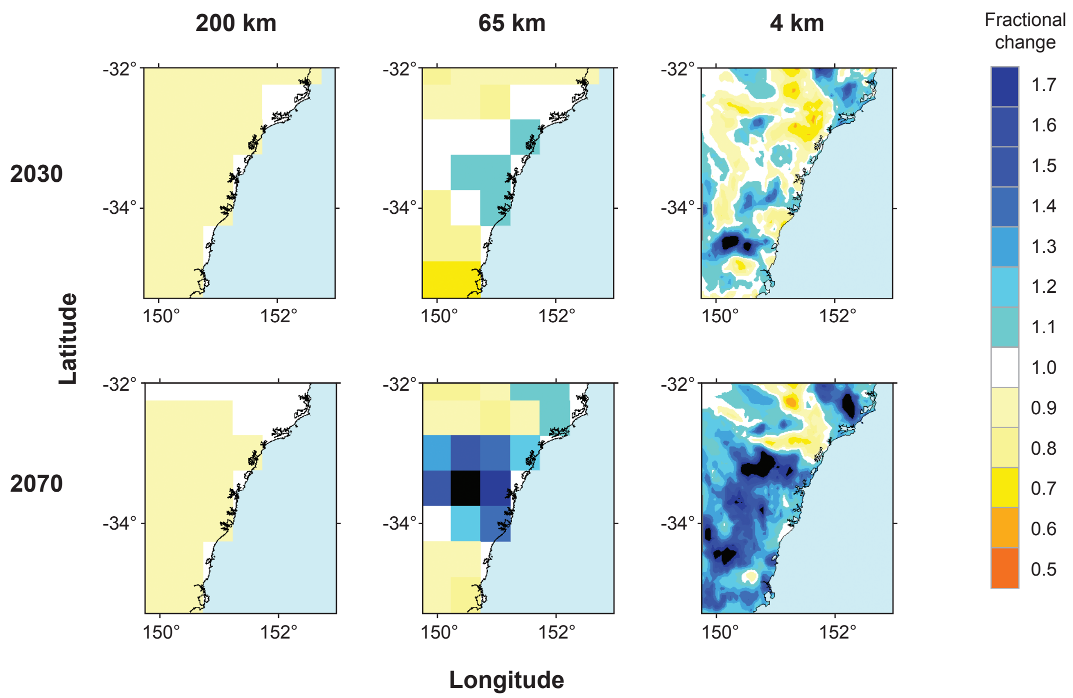


Figure 8. Fractional change in intensity of rainfall events with an average recurrence interval (ARI) of between 4 and 40 years at 2030 and 2070 under the A2 (high emissions) scenario compared with current conditions, as simulated by models with different spatial resolution around the Sydney region (D. Abbs).

Assessment of global climate models

Progress is being made in refining the methods to combine the best global climate models for regional climate projections.

Whether statistical or dynamical methods are used to downscale output from global climate models (GCMs) to estimate local climate, the accuracy of the local estimates is very dependent upon the quality of the output from the GCMs. The chaotic nature of climate means that projections of future climate must be represented in probabilistic terms, so a set of model runs is necessary to build up a picture of the possible future state of the climate. Model runs for decades ahead require many days of supercomputer time, and so it is usual to use the results of many different models to build up an appropriate set. The use of many models raises the question of the relative accuracy of each model and whether each model should receive the same weight when combined in an overall average across the set of models.

There has been a substantial research effort to determine how best to combine the results of different GCMs. Using results from 22 models, SEACI researchers found that, although some models are more accurate than others, the mean over all the models provides a reasonable representation of the climate of south-eastern Australia (Smith & Chandler, 2009). Chiew et al. (2009a) showed that, when all the global climate models used by the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report are considered, there is no clear difference in the future projections between the better and poorer GCMs based on their abilities to reproduce the observed historical rainfall. Smith & Chandler (2009) show, however, that a careful selection of the best five models indicate a drier climate in 2070 than if all of the 22 models are simply averaged (Figure 9) because the five models have better agreement in the future projections. Watterson (2008) used an alternative approach for combining GCM projections where probability density functions for climate variables (such as temperature and rainfall at the surface) are derived in terms of the model representations of global-scale warming and regional-scale changes in each variable. Using this approach the results were generally not very sensitive to the selected models.

More work is being done in Phase 2 of SEACI to ensure that the output of GCMs is combined in a manner that recognises the relative accuracy of each model and that provides optimal estimates of the uncertainties associated with the mean or expected values of climate variables. It is important that assessments of GCMs consider how well the models simulate the main drivers of regional climate, rather than just how well they simulate the current local climate (Chiew et al., 2009a).

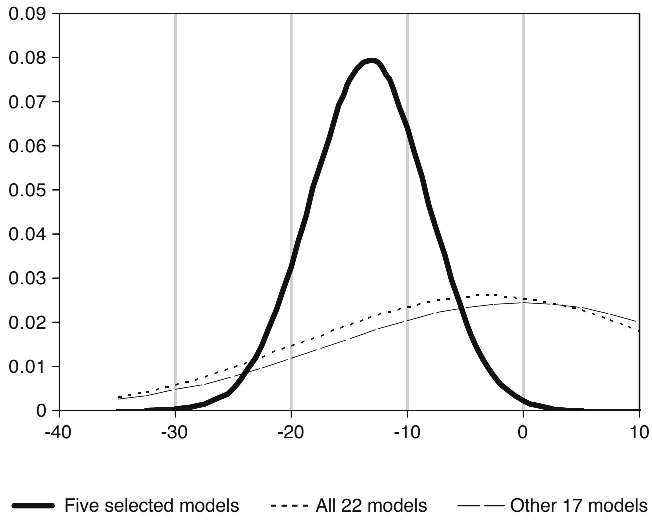


Figure 9. Cumulative probability distribution function of percentage change in rainfall in south-eastern Australia at 2070 under A1B (medium emissions) scenario (Smith & Chandler, 2009).

Future projections of regional changes in hydrology

Projections out to 2030 suggest rainfall and streamflow will fall across south-eastern Australia, particularly in the winter.

Methods used to obtain projections of future climate variables at local scales, such as temperature and rainfall, are based on the assumption that the global models represent the large-scale atmospheric flow reasonably well and that the local climate is directly related to the large-scale flow. However, local hydrological variables, such as streamflow, have a complex relationship with large-scale climate. The preparation of future projections of variables like streamflow therefore involves the use of hydrological models, driven by the output from the global climate models.

SEACI researchers have investigated alternative methods for scaling global climate model output to drive a hydrological model to estimate streamflow across Australia (Mpelasoka & Chiew, 2009). They found that most models project a wetter future for northern Australia and a drier future in southern Australia. Based on the model results, a 1 per cent change in mean annual rainfall is expected to result in a 2 to 3 per cent change in mean annual streamflow. However, it should be noted that the percentage changes in streamflow relative to rainfall have been greater than this over the recent dry period.

Chiew et al. (2009b) and Post et al. (2008) modelled future runoff for 50,000 0.05° grid cells (~5 km) across south-eastern Australia. The future climate series is informed by simulations from 15 global climate models used in the IPCC Fourth Assessment Report, taking into account changes in daily rainfall distributions and seasonal rainfall (and potential evapotranspiration) amounts, for an increase in global average surface air temperature of 0.9 °C (2030 relative to 1990). There is little agreement in the 15 modelling results in northern Murray-Darling Basin (Figure 10), and the future streamflow there is projected to be between +30 per cent and -30 per cent (Figure 11). The large majority of the global climate models agree on a reduction in future winter rainfall across south-eastern Australia (Figure 10c). As most of the streamflow in the southern parts occur in winter, this translates to a significant reduction in winter and therefore annual streamflow there. However, there is considerable uncertainty in the projections (arising mainly from the different sensitivities of different global climate models to greenhouse gases), and the modelled change in long-term mean annual streamflow in southern Murray-Darling Basin and Victoria range from -30 per cent to +10 per cent (for a 0.9 °C increase in global average surface air temperature) (Figure 11).

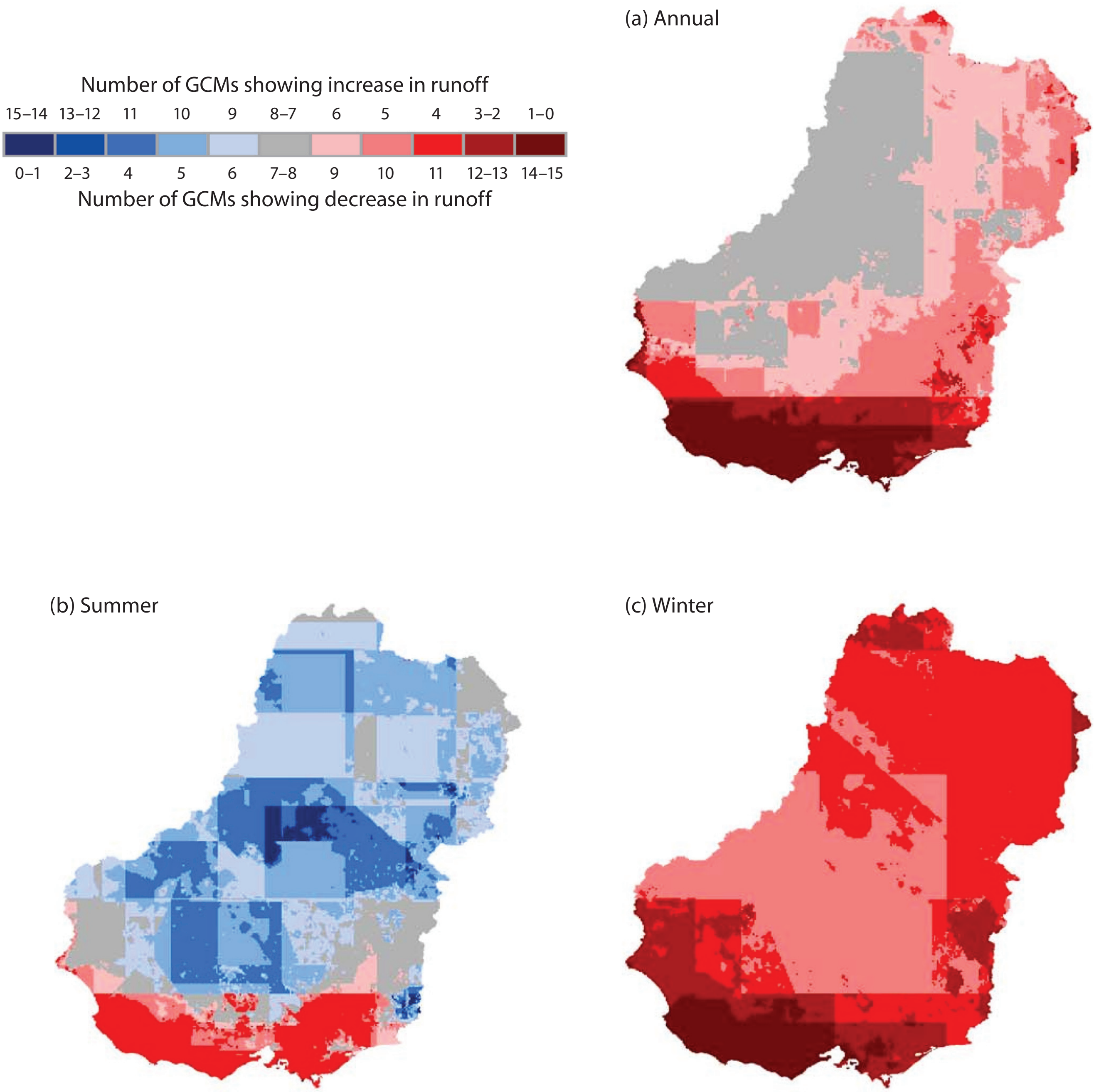


Figure 10. Number of modelling results (out of 15) showing an increase or decrease in runoff (for ~2030 relative to ~1990 global temperature) across south-eastern Australia (MDB and Victoria); (a) annual; (b) summer; (c) winter (Post et al., 2008).

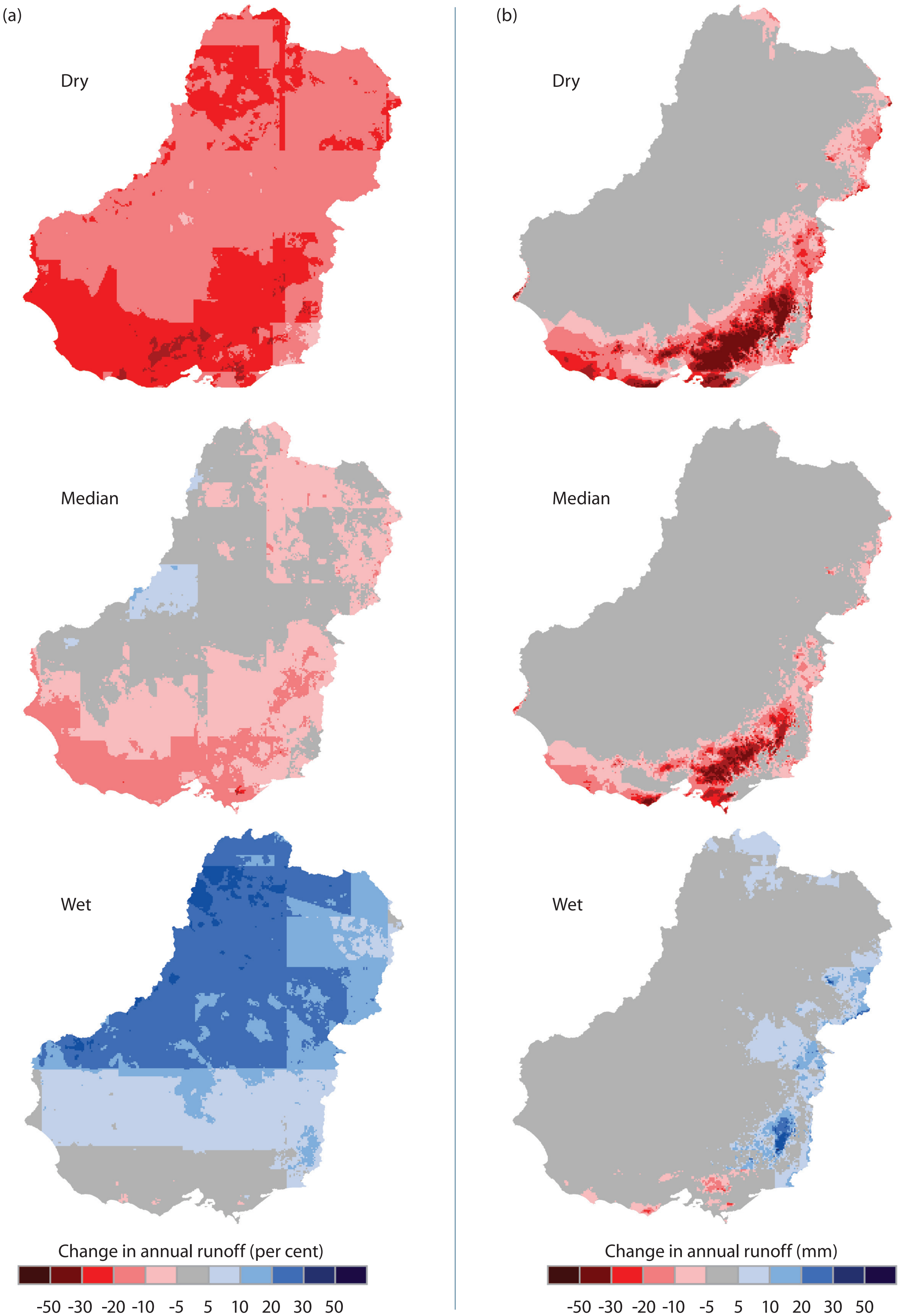


Figure 11. Changes in modelled mean annual runoff (for ~2030 relative to ~1990 global temperature) across south-eastern Australia (MDB and Victoria) showing the median result and the wet and dry ends of the possible range; (a) per cent; (b) millimetres (Post et al., 2008).

Research Theme 3: Improved seasonal climate forecasting for south-eastern Australia

There has been a sustained effort by SEACI researchers to improve both the foundations for seasonal forecasting and the methods for applying seasonal forecasting to practical problems in agriculture and hydrology.

Dynamical modelling for seasonal forecasting

The practical utility of the POAMA seasonal forecasting model has been increased through improvement in its ability to represent the large-scale processes that drive the climate of south-eastern Australia.

Dynamical climate models for seasonal forecasting were introduced over 20 years ago, and their continuing development is internationally recognised as the long-term strategy to improve seasonal to inter-annual forecasting. The coupled atmosphere-ocean-land climate model (POAMA) is run each day by the Bureau of Meteorology to predict global climate out to nine months ahead. The model, jointly developed by the Bureau and CSIRO, has been the basis of research on seasonal forecasting in SEACI.

An important aspect of seasonal forecasting is ensuring that the current state of the atmosphere, ocean and land surface is well represented in the model. For short-term weather forecasting, the focus is on capturing the detailed synoptic features such as cold fronts and mesoscale features such as regions of storm activity. For seasonal forecasting, this detail needs to be tempered by a greater focus on the large-scale features of the climate system that should provide some predictability on longer time scales. SEACI researchers have developed an initialisation system for POAMA (Hudson et al., 2010) that provides the required balance, and improves the model simulation of important features like the surface winds that drive the upper ocean (Figure 12). This improvement leads to more accurate simulations of ENSO events.

Much of the skill in seasonal forecasting arises from the observation that an ENSO event tends to evolve through a cycle over about a year once the event is established. Using the POAMA model, SEACI researchers have shown that the accuracy of a model forecasting depends not just on whether it can predict the occurrence of an ENSO event, but also whether it can identify the type of event (Hendon et al., 2009). There are two main types of ENSO event: the traditional cold tongue events with a maximum of surface warming in the eastern Pacific Ocean, and the warm pool events where the maximum warming is in the central Pacific (Figure 13). The existence of the different types of ENSO events helps explain why the largest ENSO event of the twentieth century (in 1997) did not have as large an impact on Australia as did the smaller event of 2002 (Wang & Hendon, 2007). Both types of ENSO event are captured by the POAMA model. POAMA's ability to distinguish the different types of event increases the utility of the global model for practical seasonal forecasting applications (Lim et al., 2009).

While the ENSO events of the Pacific Ocean are a very important basis for seasonal forecasting in south-eastern Australia, there is also some predictability arising from variations in the sea-surface temperature of the Indian Ocean. SEACI researchers have shown that the POAMA model captures some of the structure of the Indian Ocean Dipole, which is a dominant sea-surface temperature pattern in the Indian Ocean with some impact on Australian rainfall (Zhao & Hendon, 2009). However, there

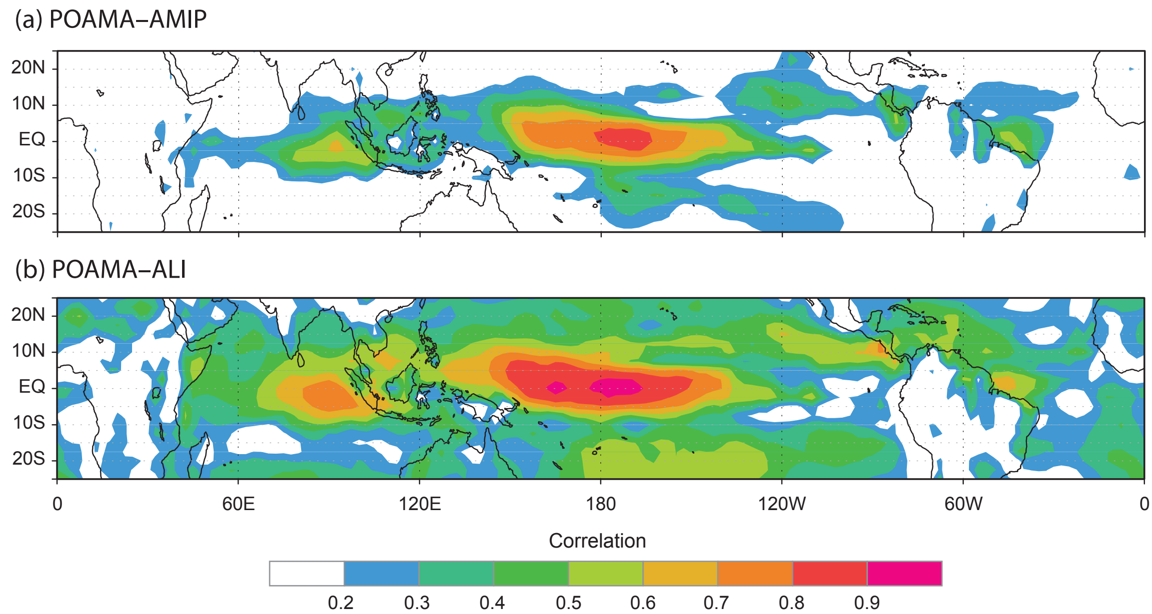


Figure 12. Monthly mean surface wind anomaly correlation with observed after one month of forecast in winter-spring from POAMA; (a) without initialisation, (b) with initialisation. Initialisation leads to higher correlations between POAMA and observations over a larger area (Hudson et al., 2010).

is scope for the model's representation of the IOD to be improved, so that greater skill in predicting Australian rainfall should be possible in the future.

While there has been progress in improving the capability of the POAMA model to represent the large-scale processes that drive south-eastern Australia's climate, it is also important to assess the accuracy of the model in predicting seasonal climate at the regional scale. SEACI researchers assessed the accuracy of POAMA over the period 1980 to 2006, and found that the main sea-surface temperature patterns associated with ENSO events are well simulated in the model (Lim et al., 2009). They also found that the model captured the relationship between the sea-surface temperature patterns and Australian rainfall, so the model can predict spring rainfall over eastern Australia and major droughts a season ahead. Predictions of above-median rainfall for spring are very accurate in south-eastern Australia, and they are more skilful than predictions from the current operational (statistical) system of the Bureau of Meteorology (Figure 14).

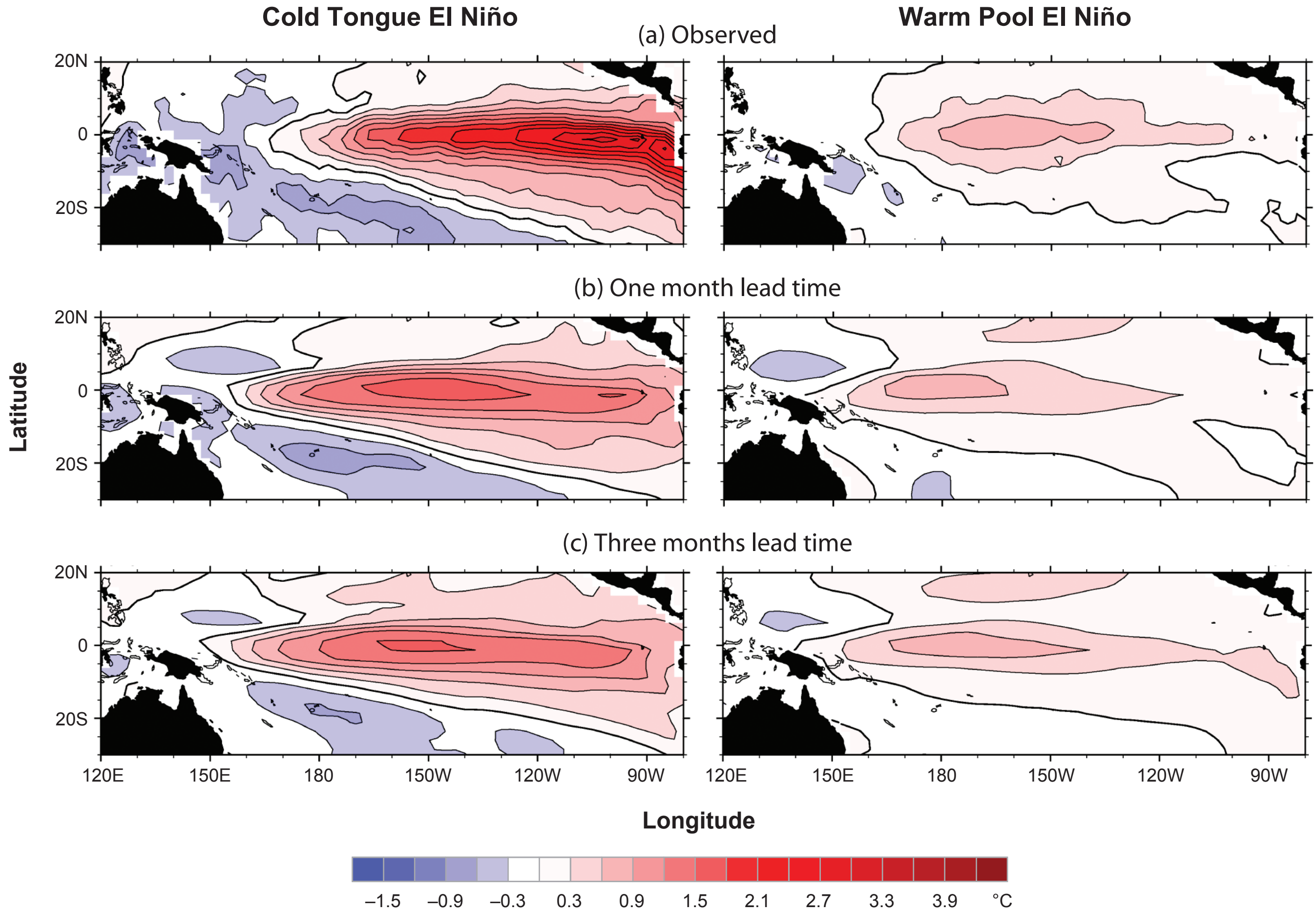


Figure 13. Sea-surface temperature anomalies for spring for (left) cold tongue and (right) warm pool ENSO events; (a) observations; (b) POAMA with one month lead time; (c) POAMA with three months lead time; contour interval is 0.3 °C where blue is negative (Hendon et al., 2009).

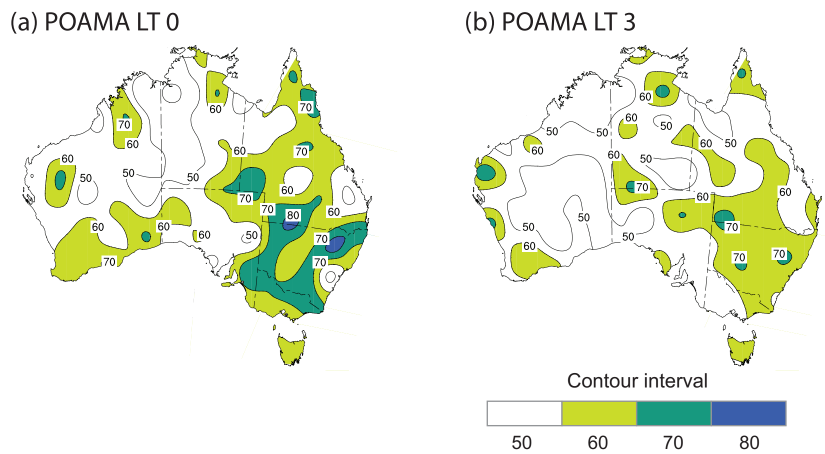


Figure 14. Proportion of correct predictions of above-median rainfall for spring; (a) POAMA at lead time 0; (b) POAMA at lead time three months; (c) current operational statistical system of Bureau of Meteorology based on forecasts for 1980-2006. (Lim et al., 2009).

Application of seasonal forecasting to agricultural decision making

A majority of stakeholders find that dynamical seasonal forecasts add value to on-farm decision making.

Owing to the chaotic nature of the climate system, credible seasonal forecasts must be made in probabilistic terms; that is, a forecast could be for the chance that the rainfall for the coming season is above its long-term median value (where the median value is exceeded 50 per cent of the time over the long term). The practical or economic value of a seasonal climate forecast depends upon the specific application and especially on how that application can use probabilistic information. As the community moves increasingly towards risk management strategies, the capability to use probabilistic information is expected to increase correspondingly.

During Phase 1 of SEACI the utility of seasonal forecasts from a number of global climate models, including the POAMA model, for on-farm decision making was evaluated. Seasonal forecasts can be used in many different forms. A simple approach is to make a decision based on whether the rainfall in the coming season is expected to be above or below the long-term median value for that season. SEACI researchers found that some models (including the POAMA model) have some skill predicting this "median hit rate". The best results were for the autumn-winter season of May-June-July. Similar evaluations have been carried out for other statistics, such as the hit rate for model predictions of rainfall terciles, in which rainfall is categorised as below normal, normal or above normal.

To test the economic utility of the model climate predictions, the rainfall tercile forecasts for May-June-July were used to make decisions about fertilizer application at the time of crop sowing. The amount of fertilizer is increased as the amount of expected rainfall increases, in order to take advantage of greater quantities of rain during the growing season. The test was applied to four farms in south-eastern Australia (two in Victoria and two in South Australia) for the period 1980 to 2001 using the APSIM (Agricultural Production System Simulator) crop model (Keating et al., 2003). The value of the forecasts was assessed in terms of the gross marginal difference in dollars per hectare between the return from the forecast-based application of fertilizer and the return from a constant (baseline) application equal to the long-term average optimum application. The results varied from farm to farm owing to regional differences in soil type and in the accuracy of the seasonal forecasts. Detailed examination of the results shows that the utility of many climate models is limited by their inability to accurately represent the regional impacts of ENSO events. The utility of the models could also be increased by using simple scaling or detailed downscaling of the model output to yield improved climate forecasts.

The results of this research were discussed widely with farming groups and scientists. A questionnaire was used to determine the perceived value of the forecasts and the analysis, and to seek comment on the need for further research. About 50 per cent of respondents indicated that that the presentation of materials about the evaluation framework, the performance and skill of the dynamic models, and the management decisions examined contributed significantly to their understanding (Figure 15). The remaining 50 per cent indicated a moderate contribution to their understanding.

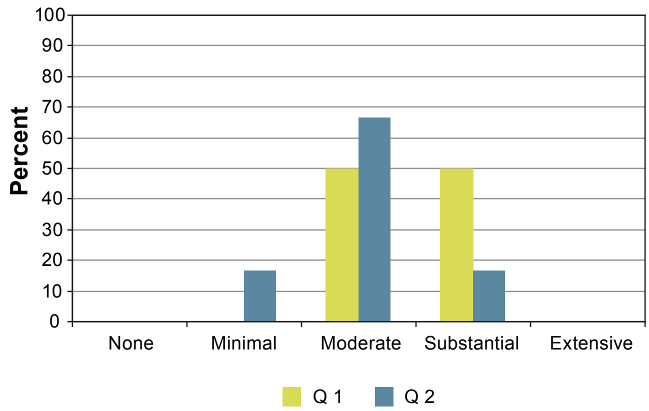


Figure 15. Response to Q1 'To what extent has this interaction contributed to your understanding of the performance of climate models in delivery of seasonal climate forecast information?' and Q2 'What value do you think dynamic forecasts currently have in assisting on-farm management?' (Crimp & Nidumolu, 2009).

Over 60 per cent of respondents indicated that the dynamical forecasts had moderate value to them in assisting on-farm management decision-making, while 17 per cent indicated the dynamical forecasts had significant value and a further 17 per cent indicated minimal value. Additional questions were raised to identify factors limiting the use of forecasts and what respondents had learned from the process. The responses suggested that farmers had not been aware of the availability of POAMA forecasts before the project, and that they would like to see continuing improvement in the accuracy and lead time of forecasts.

Seasonal forecasting for hydrological applications

A new statistical approach for the seasonal forecasting of streamflow in south-eastern Australia has been developed.

While global climate models provide the foundation for future improvement in seasonal forecasting, useful results can be obtained from forecasts based on the observed statistical relationships between large-scale climate features, such as ENSO, and variables of practical interest, such as streamflow. SEACI researchers developed a statistical model based on a Bayesian joint probability approach to the seasonal forecasting of streamflow in south-eastern Australia (Wang et al., 2009). The model uses indicators of ENSO as well as antecedent streamflow conditions as predictors, and it accounts for the correlations between multiple sites to obtain regionally consistent forecasts. The model quantifies uncertainties in the data and maximises the information extracted from the data so that records with non-concurrent and missing data can be used.

The statistical model has been applied to the forecasting of spring streamflow at three river gauges in the Murrumbidgee catchment. Cross validation used to assess the accuracy of the model shows that reasonably high skill is obtained (Figure 16).

The model has also been extended to use a stepwise process to select predictors that maximise the forecast skill. In addition to antecedent streamflow, twelve climate predictors have been considered including indicators of ENSO, the IOD and the SAM. The system has been applied to the production of seasonal forecasts of streamflow at three gauging stations in each of the Murrumbidgee and Goulburn catchments. For winter and spring forecasts of the coming season, inclusion of the climate predictors yielded only a marginal increase in skill to that from using only antecedent streamflow. The climate predictors are more important at longer lead times, but the contributions of these indicators are not particularly stable in time and space.

Some research has been carried out on the inclusion of output from the POAMA global climate model as a predictor in the statistical model. As with the use of external climate indicators, the inclusion of POAMA output yields marginal increases in forecast skill. Further work is planned to investigate the value of POAMA output for predictions of streamflow on longer time scales.

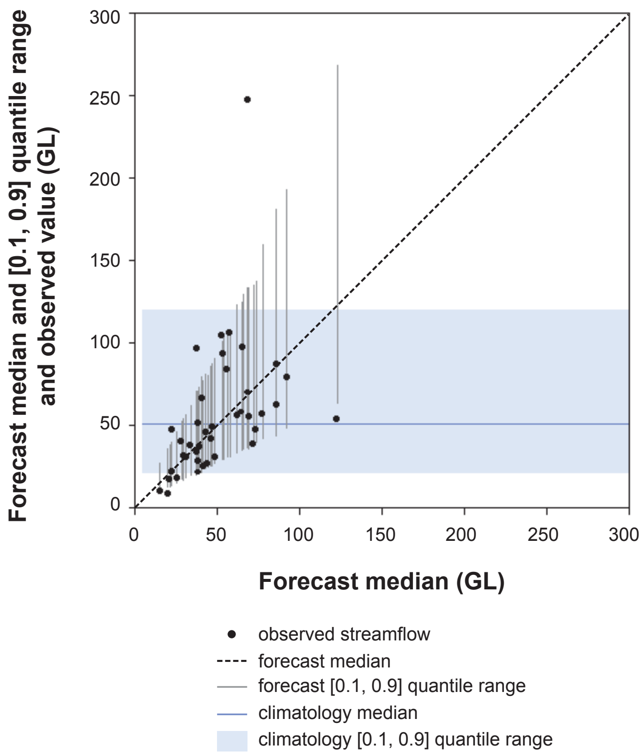


Figure 16. Cross-validation of streamflow forecasts in the upper Murrumbidgee comparing observed and forecast values (Wang et al., 2009).

Progress on key science questions

SEACI research is answering important questions about the current and future climate of south-eastern Australia, and applying this information to hydrological and agricultural problems in the region.

How has climate changed in the region?

The temperature of south-eastern Australia (as over most of Australia) has been rising in recent decades. The warmest year since 1910 was 2007 and every year since 1996 has been warmer than the 1961-1990 mean.

The rainfall in south-eastern Australia has been below the long-term mean every year since 1997, except in 1999 and 2000 (when the anomalies were only 13 mm and 28 mm respectively). The 13-year period from 1997 to 2009 has been the driest since 1900 with only 515 mm average annual rainfall across the SEACI region (see Figure 1) compared with a long-term historical mean of 581 mm. This represents a decrease of 11.4 per cent.

The autumn deficit is 25 per cent of the long-term mean, and it accounts for 52 per cent of the annual rainfall decline. Smaller deficits have occurred in winter and spring rainfall. Figure 17 shows the extent of the rainfall deficiencies. Thus, there has been a sustained period of reduced rainfall, especially in autumn, together with rising temperatures. While the autumn deficiencies remain significant, it is observed that the deficiency in spring rainfall is becoming more apparent, with seven of the last eight years (2002-2009) having spring rainfall below the long-term mean, and the spring rainfall deficiency being, on average, 26 per cent over the last four years.

The seasonal pattern of rainfall deficits for the period 1997-2006 (59 per cent in autumn, 28 per cent in winter and 13 per cent in spring) did not resemble the patterns of rainfall changes under global warming projected by climate models (which indicate little change in autumn rainfall, and larger declines in spring and winter). However, the seasonal pattern of rainfall deficits for the period 2006-2009 (31 per cent in autumn, 32 per cent in winter and 37 per cent in spring) more closely resembles the projected seasonal patterns of rainfall change. Further studies are required to better understand the relative contribution of climate change and climate variability to changes in seasonal rainfall.

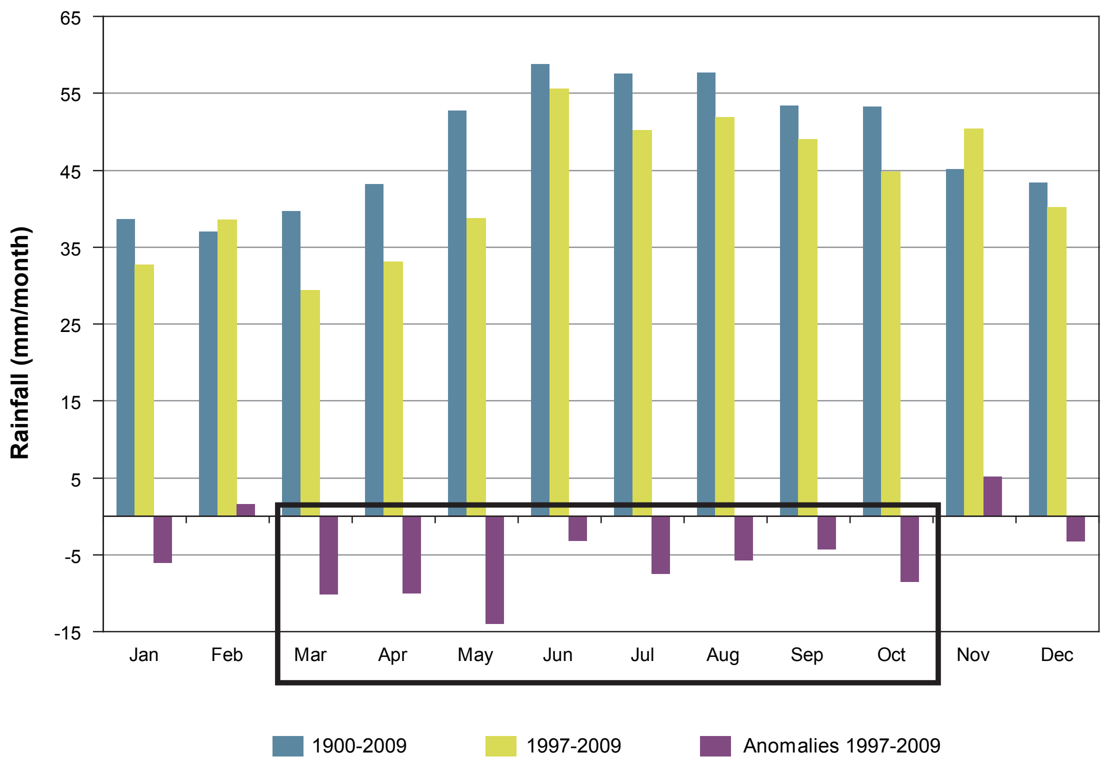


Figure 17. Monthly mean rainfall across south-eastern Australia; blue denotes long-term mean, lime denotes mean over 1997 to 2009, purple denotes anomaly of 1997-2009 from long-term mean; months with continuing negative anomalies are outlined in the black box (Timbal, 2009, updated to the end of 2009).

What are the major drivers affecting historical and current climate?

The climate of south-eastern Australia is affected by a number of large-scale factors, especially by the tropical factors of the El Niño – Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). These factors are the basis of seasonal predictability in the region. The independent and joint impacts of these factors on rainfall have been detailed by SEACI researchers (e.g. Myers et al., 2007). The Southern Annular Mode (SAM) influences the rainfall in southern parts of the region, except in autumn. In recent decades, there has been an increase in the mean sea level pressure across much of Australia, and SEACI research shows that this effect is reflected in an increase in the intensity of the sub-tropical ridge (STR), associated with the southern hemisphere Hadley Cell (Murphy & Timbal, 2008). The intensity of the STR is correlated with rainfall in all months except summer (i.e. including autumn) in south-eastern Australia, and around 80 per cent of the observed annual rainfall decline in the region has been shown to be statistically associated with the strengthening of the STR. Recent SEACI research suggests that these changes in the Hadley Cell are at least partly due to the enhanced greenhouse effect.

The work of Nicholls (2009) also suggests that trends in the SAM may be related to the rainfall decline in south-eastern Australia. Further research is needed to clarify the interactions between the large-scale circulation in the tropics (represented by ENSO and IOD) and in higher latitudes (represented by the SAM) and their respective interactions with the meridional circulation (Hadley Cell) and the regional driver of SEA rainfall (the STR).

What are the relationships between the drivers operating at different time scales and have these changed over time?

While the ENSO and IOD have some independent influence on the climate of south-eastern Australia, the effect of ENSO does extend from the Pacific to the Indian Ocean. Some research suggests that the Indian Ocean also has a significant impact (independent of ENSO) on the climate of the region, including an impact on the potential for major bushfires (Cai et al., 2009). However, the role of the Indian Ocean and its interactions with other drivers of the climate of the region are not clear at present. It is well established that the effect of large-scale factors on local climate varies on decadal time scales. In particular, the impact of ENSO on rainfall in south-eastern Australia and other areas is found to vary over time, and this observation has led to research on the Inter-decadal Pacific Oscillation (IPO) in attempts to explain these variations. Current evidence suggests that the IPO does not provide a source of predictability (Power et al., 2006), but research on decadal-scale predictability remains an international priority. Global warming appears to be linked to changes in the large-scale Hadley Cell, resulting in an intensification of the STR around south-eastern Australia. The relationships between changes in the Hadley Cell and ENSO (as well as IOD and SAM) have not been clarified at this time. There is also some evidence to suggest that global warming may be acting to increase the likelihood of the dry states associated with ENSO (Power & Smith, 2007) and IOD (Cai et al., 2010).

What are the causes of the dry conditions affecting parts of the study area over the last decade, and what is the prognosis?

The low-rainfall conditions of the last decade in south-eastern Australia have led to a very significant and unprecedented decline in streamflow in southern MDB and Victoria. While changes to rainfall are typically amplified as a two to three times larger percentage change in streamflow, the streamflow decline in southern MDB and Victoria is greater than expected. This extreme reduction in streamflow reflects not only the very low mean annual rainfall but also:

- the disproportionate rainfall decline in autumn (resulting in dry soil conditions at the start of the runoff season);
- the rainfall decline in winter and spring when most of the runoff occurs;
- the lack of high rainfall years in the past decade;
- higher temperatures; and
- potentially, other factors not yet accounted for.

To the extent that the changes in both temperature and rainfall across south-eastern Australia are linked to climate change, it is possible that the impacts could continue and even possibly intensify, as warming is expected to continue. It is worth noting that the rainfall in south-west Western Australia has continued to be below its long-term mean for more than 30 years, and that there is some evidence of links between the climates of that region and of south-eastern Australia with both regions being reliant on similar mid-latitude weather systems for their rainfall (Hope et al., 2009) which have been affected by surface pressure increases (Timbal and Hope, 2009).

What is the current climate baseline?

Broadly speaking, a baseline climate is a characterisation of the 'typical' climate of a region or particular locality over a particular period. How a 'baseline' climate is defined depends on the application for which it will be used.

The World Meteorological Organization (WMO) updates its 30-year baseline every decade, with a view to providing a measure of the local climate at a given time. This approach may allow for gradual changes in local climate and may support planning on time scales of a decade or two. However, it is not robust under conditions of rapid changes in climate or of sustained trends. On the other hand, because the Kyoto Protocol has 1990 as a baseline year for climate change calculations, the 1961-1990 period continues to be used for many climate studies, so that differences from the baseline for a specific year do not keep changing as studies continue over a long period. For these studies, the 1961-1990 period is an essentially arbitrary (but stable) baseline from which past and future anomalies can be measured. This 1961-1990 period was used as the baseline for climate change projections provided by IPCC3, while projections by IPCC4 assumed that 1990 conditions were characterised by the 1981-1999 period.

For SEACI stakeholders, water planning processes historically have involved assumptions of a stationary (i.e. a non-changing average) climate which was assumed to continue into the future. Because of the large decadal variability of Australian rainfall, stakeholders generally took the full climate record (about 100 years) as the baseline climate for future planning purposes.

Over recent years, this assumption of stationarity has been challenged by the persistently dry conditions, which raises the issue as to whether the baseline climate (as previously defined by the historical record) is changing. In addition, the need to allow for the influence of climate change in future planning processes has been recognised. As a consequence, a primary interest has been in characterising an appropriate baseline climate to which climate change projections (which are expressed as percentage changes relative to the baseline) can be applied. While the climate community focuses on characterising 1990 conditions as a baseline for climate change projections, both the IPCC3 (in particular) and IPCC4 periods are somewhat wetter than the long-term historical average across much of south-eastern Australia, and are certainly not representative of the conditions of the last 13 years.

As discussed above, there is increasing evidence that the large-scale circulation affecting the climate of south-eastern Australia is changing due to global warming. In particular, the observed increase in the intensity of the sub-tropical ridge appears to be linked to changes in the Hadley Cell, which in turn are being driven by global warming. Under conditions of climate change, it follows that the early decades of the last century may not be appropriate measures of the current climate. Moreover, the climate may continue to change in future decades. Indeed projections of rainfall in south-eastern Australia from global climate models suggest that rainfall may continue to decrease. Any long-term trend associated with global warming will be modulated by decadal-scale variability due to internal factors, such as ENSO, and external factors, such as volcanoes and solar radiation.

What criteria should be used to determine whether shifts in the baseline have occurred, or are likely to occur?

There is strong evidence of an increasing trend in temperature in south-eastern Australia, which could be projected ahead for the next few years. Rainfall in the region shows substantial decadal variability and it is difficult to discern a long-term trend in the observed rainfall record, although the last decade has certainly been unusual in the observed Australian rainfall record. There is also increasing evidence that at least part of the current reduction in rainfall is associated with climate change. Global climate models suggest reduced rainfall across the region in future decades due to climate change. Based on analysis of the climate record and on model projections of future climate, it is therefore likely that the climate baseline is shifting due to the global warming. Further attribution studies are being carried out to clarify the nature and causes of the changes in the large-scale circulation that influence the climate of south-eastern Australia. These studies will provide an improved understanding of the relative roles of climate change and natural variability in the recent observed changes. This, in turn, will help researchers decide how best to combine climate change projections with observed climate records.

In other countries, there are substantial research programs aimed at estimating the climate of the next few years (for example, Keenlyside et al., 2008). In these programs the model predictions are extensions of seasonal climate forecasting research, like that being carried out with POAMA in SEACI. Such techniques can be used to estimate whether recent climate variations will persist over the next few years, and so they provide a bridge between seasonal forecasting and long-term climate change projections.

How is hydroclimate (average, inter-annual variability and extreme events for rainfall, temperature, evaporation and runoff) likely to change over the next 25-65 years?

Based on projections from global climate models and associated downscaling, south-eastern Australia is likely to be warmer and drier in future decades, especially in the winter.

Hydrological modelling, driven by climate model projections for a global warming of 0.9 °C (2030 relative to 1990), indicates that the future mean annual runoff is likely to change by between -30 per cent and 30 per cent in the northern MDB and by between -30 per cent and 10 per cent in the southern MDB and Victoria (Post et al., 2008; Chiew et al., 2009b).

In terms of extreme events, SEACI research suggests that short-duration storms may become more intense across the region in the future, especially over the inland plains.

The fact that the projected runoff (and rainfall) reductions for 2030 across the region are considerably smaller than the observed declines over the last decade raises important issues about how best to use these climate change projections – in particular, how to characterise the baseline climate to which the future projections should be compared. This is not a trivial matter given the high natural variability in climate on a range of time scales, the relative short records of high quality climate data (at best around 100 years), and the recent prolonged dry conditions. As described above, further work is required to determine how to link the long-term projections to current conditions.

What are the probabilities attached to these changes?

Probabilistic climate projections have been developed for Australia by CSIRO and the Bureau of Meteorology. They are available at <http://www.climatechangeinaustralia.gov.au>. SEACI research suggests that the range of the uncertainties in probabilistic projections could be reduced by careful selection of the global climate models (e.g. by giving more weight to simulations from 'better' models or by ignoring simulations from 'poor' models) on which the assessment is based (Smith & Chandler, 2009).

For south-eastern Australia, in the light of the unusually dry conditions over the past 13 years, an important additional source of uncertainty is associated with characterising an appropriate baseline climate to which the climate projections should be compared. This means that it is difficult to quantify the probabilities associated with various future climate states.

Qualitatively it can be said that:

- The current rainfall decline is apparently linked (at least in part) to climate change, raising the possibility that the current dry conditions may persist, and even possibly intensify (as has been the case in south-west Western Australia).
- Given that natural variability is also likely to be playing a role in the rainfall decline, it is also possible that there may be a return to somewhat wetter conditions in short-term. However, overall, due to the influence of global warming, it would be expected that future conditions will be drier and warmer than the long-term historical climate in south-eastern Australia.
- Yet another possibility is that the current decline is a natural cycle in the climate of south-eastern Australia. However, we have only just over 100 years of quality rainfall records and similar episodes may have occurred in previous centuries. While other types of 'proxy' data can be used to look at past climate, it is more difficult to examine the likely drivers of any past dry episodes. In the absence of such understanding, it could be argued that a return to wetter conditions is likely in the near future, and that any association of the current dry period with global warming is simply fortuitous. However, this is considered to be unlikely by SEACI researchers.

The attribution studies for Phase 2 of SEACI are aimed at better understanding the relative roles of natural variability and global warming in the recent rainfall decline and will be important in underpinning improved projections of future climate and streamflow.

How can methods for regional projections be improved so as to provide greater confidence for stakeholders?

SEACI researchers have used a range of downscaling methods to provide greater regional detail on future climate projections. Probabilistic scaling of the climate model output has been used to develop multi-site and gridded daily climate time series to drive hydrological models. Different statistical downscaling methods, based on a range of model variables, have been developed to support climate change attribution and impact studies (for example, Timbal & Jones, 2008). Dynamical downscaling has also been used to provide detailed estimates of future regional climate change, including the nature of extreme events.

Some research (Smith & Chandler, 2009) suggests that uncertainties in climate projections can be reduced by careful selection of the global climate models, with less weight being given to models that do not simulate current climate adequately. Other work suggests that explicit model selection may not be necessary (Watterson, 2008; Chiew et al., 2009c). Further research is being done to determine how to combine the output of global climate models to develop more accurate region-scale projections of climate change.

As outlined above, further research is also being done to determine how best to relate future projections to the current climate regime.

Can reliable methods of forecasting climate 3-12 months ahead be developed for south-eastern Australia?

The coupled atmosphere-ocean-land climate model (POAMA) has been refined during the SEACI program to improve its accuracy for seasonal forecasting. The model now provides greater accuracy over most of Australia (but especially in the south-east) than the current operational seasonal outlook system of the Bureau of Meteorology from autumn through to spring. The improved accuracy is mainly due to its ability to capture the occurrence and nature of ENSO events.

Planned improvements in the model are expected to increase the accuracy of the seasonal forecasts, especially at longer lead times where the skilful prediction of ENSO events is not currently translated into skilful prediction of regional climate due to some systematic errors in the model.

Some predictability of climate for south-eastern Australia is also based on variations in the sea-surface temperature patterns of the Indian Ocean. While the POAMA model does capture some of this variability, further refinement of the model is expected to improve its capability in the Indian Ocean. The application of statistical adjustments to the output of POAMA is found to improve both the accuracy and reliability of its forecasts.

Can these new forecast methods with greater skill and longer lead times be applied to forecast streamflow and crop yields?

SEACI research has included an assessment of the economic utility of seasonal climate forecasts from a number of global climate models (including POAMA) for on-farm decision making. The results are found to vary from farm to farm owing to regional differences in soil type affecting the impact of decision making. The results of the economic analysis are also dependent upon the capability of each model to predict ENSO events. Interviews with farmers confirm that most of them believe the output of dynamical prediction models can assist their decision making. The impact of the models is expected to be increased if the model output is adjusted by some downscaling before being applied to the agricultural decision system; for example, both the accuracy and reliability of POAMA has been increased through the application of statistical adjustments to its output.

While global climate models provide the basis of future improvements in seasonal climate forecasting, useful information can be obtained from statistical methods based on the relationship between rainfall in south-eastern Australia and large-scale climate drivers such as ENSO. During the SEACI program, a statistical seasonal climate forecasting system (Wang et al., 2009) has been developed to forecast streamflow in catchments across the region. The system is useful for hydrological purposes, and it has been modified to include the output of POAMA as a predictor. Much of the forecast skill of the system is derived from the persistence of antecedent streamflow conditions, and so the inclusion of climate information gives only marginal increases in skill.

Next steps

Phase 2 of SEACI will continue to progress our understanding the climate of south-eastern Australia and apply that understanding to practical ends.

Phase 1 of SEACI has achieved the significant outcome of promoting a substantial amount of strategic research on understanding and predicting the climate of the region. A distinct group of papers is now appearing in the international scientific literature with a focus on the region and with acknowledgement to the support of SEACI. Such internationally-recognised strategic research provides the foundation for practical outcomes.

The research results from SEACI have demonstrated that the initial strategy was appropriate, as it has helped clarify the unusual nature of the current dry spell in south-eastern Australia. This clarification has in turn provided the context for the research on improving both seasonal forecasts and long-term projections of the climate of the region.

While there has been progress in each of the three themes of the program, a number of issues require continuing research. These are:

- A number of large-scale climate features have been shown to play a role in driving the climate of the region, but the interactions between these features (especially between the Hadley Cell through the sub-tropical ridge and the circulation at higher latitudes through the Southern Annular Mode) need to be clarified.
- The changing nature of the relationship between the climate and the hydrology of the region has been well documented, but the detailed changes in the various components of the water balance at the land surface need to be identified to better understand the nature and causes of the changes in hydroclimate.
- Some work has been done to show links between the current climate of south-eastern Australia and that of south-west Western Australia, but these regional changes need to be put into a global context.
- There is some evidence linking the rainfall change in the region to global warming, but more work is needed to clarify or attribute the causes of the regional change.
- Building on progress with seasonal climate prediction models, research on inter-annual to decadal prediction should provide a means to consider the possible duration of the current dry spell in south-eastern Australia.
- The sea-surface temperature patterns of the Indian Ocean affect the climate of south-eastern Australia, and more research is needed to improve the representation of that ocean in global climate models.
- While some progress has been made in using the output of global climate models for seasonal forecasting applications, more integrated approaches are needed to optimise the model output for practical purposes.
- The practical application of long-term climate projections depends upon the use of output from sets of global climate models of varying quality, and more research is needed to optimise the blending of these outputs.
- Current projections of climate change over south-eastern Australia give climate changes comparable with the difference between the climate of the past century and that of the last decade, and so more work is needed to relate projections for decades ahead to the current unusual climate regime.

Phase 2 of SEACI has commenced with the aim of essentially addressing these issues. The foundation laid by the first phase should ensure that there will be continuing progress on understanding the climate of south-eastern Australia and on applying that understanding to practical ends.

References

Cai, W. & Cowan, T. (2008) Evidence of impacts from rising temperature on inflows to the Murray-Darling Basin. Geophys. Res. Lett., 35, L07701, doi:10.1029/2008GL033390.

Cai, W., Cowan, T. & Raupach, M. (2009) Positive Indian Ocean Dipole events precondition southeast Australia bushfires. Geophys. Res. Lett., 26, L19710, doi:10.1029/2009GL039902.

Cai, W., van Rensch, P., Cowan T. & Sullivan A. (2010) Asymmetry in ENSO teleconnection, its collapse and impact. J. Climate. In Press

Charles, S.P. & Fu, G. (2008) Stochastic downscaling for regional precipitation projections. Proceedings HydroPredict'2008, 15-18 September 2008, Prague, Czech Republic, pp 269-272.

Charles, S.P., Bates, B.C. & Hughes, J.P. (1999) A spatio-temporal model for downscaling precipitation occurrence and amounts. J. Geophys. Res.-Atmospheres, 104, 31657-31669.

Chiew, F.H.S. (2006) Estimation of rainfall elasticity of streamflow in Australia. Hydrol. Sci. J., 51, 613-625.

Chiew, F.H.S., Teng, J., Vaze, J. & Kirono, D.G.C. (2009a) Influence of global climate model selection on run-off impact assessment. J. Hydrology, 379, 172-180.

Chiew, F.H.S., Teng, J., Vaze, J., Post, D.A., Perraud, J.M., Kirono, D.G.C. & Viney, N.R. (2009b) Estimating climate change impact on run-off across southeast Australia: method, results, and implications of the modeling method. Water Resources Res., 45, W10414, doi:10.1029/2008WR007338.

Chiew, F.H.S., Cai, W., & Smith, I.N. (2009c) Advice on defining climate scenarios for use in Murray–Darling Basin Authority Basin Plan modelling, CSIRO report for the Murray–Darling Basin Authority.

Chiew, F.H.S., Young, W.J., Cai, W. & Teng, J. (2010) Current drought and future hydroclimate projections in southeast Australia and implications for water resources management. Stochastic Environmental Research and Risk Management, In Press.

Crimp, S. & Nidumolu, U. (2009) Agricultural analysis for decision-support tools. Final report for SEACI Phase 1 Project 3.1.6

Fu, G., Charles, S.P. & Chiew, F.H.S. (2007) A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow. Water Resource Res., 43, W11419, doi:10.1029/2007WR005890.

Hendon, H.H., Lim, E., Wang, G., Alves, O. & Hudson, D. (2009) Prospects for predicting two flavors of El Nino. Geophys. Res. Lett., 36, L19713, doi:10.1029/2009GL040100.

Hendon, H.H., Thompson, D.W.J. & Wheeler, M.C. (2007) Australian rainfall and surface temperature variations associated with the Southern Hemisphere Annular Mode. J. Climate, 20, 2452-2467. doi: 10.1175/JCLI4134.1

Hope, P., Timbal, B. & Fawcett, R. (2009) Associations between rainfall variability in the southwest and southeast of Australia and their evolution through time. Int. J. of Climatol., DOI: 10.1002/joc.1964

Hudson, D., Alves, O., Hendon, H. & Wang, G. (2010) The impact of atmospheric initialisation on seasonal prediction of tropical Pacific SST. Submitted to Clim. Dyn.

IPCC (2000) IPCC Special Report on Emission Scenarios, Summary for Policymakers. Intergovernmental Panel of Climate Change, pp27.

Jones, R.J., Chiew, F.H.S., Boughton, W.C. & Zhang, L. (2006). Estimating Hydrological Model Sensitivity to Climate Change. Advances in Water Resources, 29: 1419-1429.

Keating, B.A. et al. (2003) An overview of APSIM, a model designed for farming systems simulation. European J. Agronomy, 18, 267-288.

Keenlyside, N.S., Latif, M., Jungclaus, J., Kornblueh, L. & Roecknew, E. (2008) Advancing decadal-scale climate prediction in the North Atlantic sector. Nature, 453, 84-88.

Lim, E.P., Hendon, H.H., Hudson, D., Wang, G. & Alves, O. (2009) Dynamical forecast of inter-El Nino variations of tropical SSR and Australian spring rainfall. Mon. Weath. Rev., 137, 3796-3810.

Mpelasoka, F.S. & Chiew, F.H.S. (2009) Influence of rainfall scenario construction methods on run-off projections. J. Hydrometeor., 10, 1168-1183.

Murphy, B. & Timbal, B. (2008) A review of recent climate variability and climate change in southeastern Australia. Int. J. Climatol., 28, 859-879.

Myers, G., McIntosh, P., Pigot, L. & Pook M. (2007) The years of El Nino, La Nina, and interactions with the tropical Indian Ocean. J. Climate, 20, 2872-2880.

Nicholls, N. (2004) The changing nature of Australian droughts. Climatic Change, 63, 323-336.

Nicholls, N. (2009) Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958-2007. Clim. Dyn., DOI 10.1007/s00382-009-0527-6.

Post, D.A., Chiew, F.H.S., Vaze, J., Teng, J., Perraud, J.M., & Viney, N.R. (2008) Future Runoff Projections (~2030) for Southeast Australia. SEACI Technical Report 2.2.2.

Potter, N.J. & Chiew, F.H.S. (2009) Statistical characterisation and attribution of recent rainfall and run-off in the Murray-Darling Basin. 18th World IMACS/ MODSIM Congress, Cairns, Australia, 13-17 July 2009.

Potter, N.J., Chiew, F.H.S. & Frost, A.J. (2010) An assessment of the severity of recent reductions in rainfall and runoff in the Murray-Darling Basin. J. Hydrol., Volume: 381, Issue: 1-2, February 5, 2010, 52-64,

Power, S., Haylock, M., Colman, R. & Wang, X. (2006) The predictability of interdecadal changes in ENSO activity and ENSO teleconnections. J. Climate, 19, 4755-4771.

Power, S.B. & Smith, I.N. (2007) Weakening of the Walker Circulation and apparent dominance of El Nino both reach record levels, but has ENSO really changed? Geophys. Res. Lett., 34, doi: 10.129/2007/GL30854

Smith, I.N. & Chandler, E. (2009) Refining rainfall projections for the Murray-Darling Basin of south-east Australia – the effect of sampling model results based on performance. Climatic Change DOI 10.1007/s10584-009-9757-1.

Timbal, B. (2009) The continuing decline in south-east Australian rainfall: update to May 2009. CAWCR Res. Lett., 2, 4-10, July 2009.

Timbal, B., Fernandez, E. & Li, Z. (2009) Generalization of a statistical downscaling model to provide local climate change projections for Australia. Environ. Modelling & Software, 24, 341-358.

Timbal, B. & Hope, P. (2009) Observed early winter mean sea level pressure changes over southern Australia: a comparison of existing datasets. CAWCR Res. Lett., 1, 1-7, December 2008.

Timbal, B. & Jones, D.A. (2008) Future projections of winter rainfall in southeast Australia using a statistical downscaling technique. Climatic Change, 86, 165-187.

Wang, G. & Hendon, H.H. (2007) Sensitivity of Australian rainfall to inter-El Nino variations. J. Climate, 20, 4211-4226.

Wang, Q.J., Robertson, D.E. & Chiew, F.H.S. (2009) A Bayesian joint probability modeling approach for seasonal forecasting of streamflows at multiple sites. Water Resources Res., 45, W05407, doi:10.1029/2008WR007355.

Watterson, I.G. (2008) Calculation of probability density functions for temperature and precipitation change under global warming. J. Geophys. Res. 113: D12106, doi:10.1029/2007JD009254.

Watterson, I.G., McGregor, J.L. & Nguyen, K.C. (2008) Changes in extreme temperatures of Australasian summer simulated by CCAM under global warming, and the roles of winds and land-sea contrasts. Aust. Meteor. Mag., 57, 195-212.

Zhao, M. & Hendon, H.H. (2009) Representation and prediction of the Indian Ocean dipole in the POAMA seasonal forecast model. Quart. J. Roy. Meteor. Soc., 135, 337-352.

For more information:

Email **seaci@csiro.au**
Visit **www.seaci.org**

Australian Government
Bureau of Meteorology

Australian Government

MURRAY–DARLING
BASIN AUTHORITY

Australian Government
Department of Climate Change

State Government Victoria
Department of Sustainability and Environment

MANAGING CLIMATE VARIABILITY
R & D PROGRAM

CSIRO