
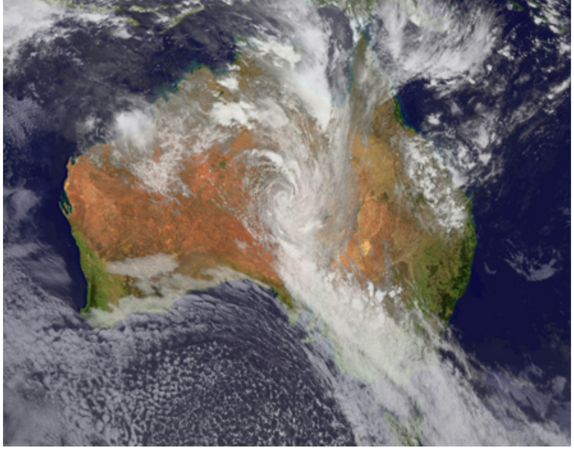


South Eastern Australian

Climate Initiative

Climate and water availability in south-eastern Australia

A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI)



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Climate and water availability in south-eastern Australia

A synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI)

September 2012

Key messages for policy makers 2

Summary of major scientific findings 4

The recent climate of south-eastern Australia: the 1997–2009 Millennium drought and 2010–11 floods 8

What influences the climate of south-eastern Australia? 13

- Inter-annual variability produces a land 'of droughts and flooding rains' 13
- The meridional circulation and south-eastern Australian rainfall 17

How does climate variability and change affect water availability? 22

- Assessing and weighting global climate models 23
- Downscaling for hydrological modelling 24
- Hydrology in a changing climate 27
- Projections of future water availability for south-eastern Australia 30

How well can we predict rainfall and streamflow for the next few months and seasons? 32

- Progress in seasonal climate prediction systems 32
- Progress in seasonal streamflow forecasting 35

Future directions 37

Glossary 38

References 39

Key messages for policy makers

South-eastern Australia has experienced a range of climate extremes in recent times (both drought and floods). These conditions reflect both the inherent natural variability of the climate system, as well as an underlying drying trend which appears to be partly attributable to climate change.

Future conditions across the region are expected to be warmer and drier, although there is considerable uncertainty about the magnitude and timing of projected changes. Water resource managers need to ensure their planning and management processes are robust and adaptive across a wide range of future climate and streamflow scenarios.

The recent climate of south-eastern Australia

South-eastern Australia has experienced a range of climate extremes in recent times, including the worst drought of the instrumental record; the Millennium drought (1997–2009), which was broken by Australia's wettest two-year period on record (2010–11).

The Millennium drought was unusual in terms of its duration, severity and extent. The average annual rainfall over this period was 512 mm; 12 percent below the long-term (1900-2010) average of 582 mm. In addition, it was unprecedented in terms of being largely restricted to southern Australia, containing an absence of wet years and very wet months, and including a large decline in autumn rainfall. Moreover, the decline in rainfall was found to produce a larger than anticipated decline in runoff. These conditions proved challenging for water management and planning processes.

The rainfall decline during the Millennium drought was in sharp contrast to the frequent heavy rain events in the spring and summer of 2010/11, and again in 2011/12, leading to Australia's wettest two-year period on record. The exceptional rainfall experienced across much of Australia during the spring and summer of 2010/11 and 2011/12 was caused by consecutive La Niña events, coupled with very warm sea surface temperatures to the north of Australia and in the eastern Indian Ocean. However, across south-eastern Australia, there was a continuation of below average rainfall during the cool season (April to October). This is consistent with the observed underlying drying trend across the region.

Projected changes in climate

There appear to be long-term reductions occurring in cool season rainfall and streamflow across the region. Evidence indicates that these are associated with changes in the global atmospheric circulation via an expansion of the tropics, with the Hadley circulation expanding at the rate of 0.5° of latitude (approximately 50 km) per decade, pushing mid-latitude storm tracks further south and leading to reduced rainfall across southern Australia. These changes are at least partly attributable to global warming, indicating a possible future climate characterised by continued below average late autumn and winter rainfall across south-eastern Australia. These trends are evident in a range of observational data and can be reproduced by global climate models only when human influences (in the form of greenhouse gases, aerosols and stratospheric ozone depletion) are included. The models also indicate that these trends are expected to continue.

The state of the three oceans surrounding the Australian continent (as expressed by the status of the El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM)), will continue to have an important role in influencing the seasonal and inter-annual variability of rainfall. It is expected that the SAM will trend towards more positive values in a warmer world, leading to drier conditions across south-eastern Australia in winter. There may also be an increase in the number of positive IOD events, bringing drier conditions to south-eastern Australia from winter to spring. It is currently not known how ENSO might change in the future or how this may affect the other two variables.

The best estimate of the impact of these changes is for reductions in rainfall and runoff across the southern part of south-eastern Australia (south of 33° S latitude) in particular. For example, with 1 °C of global warming, average annual rainfall is expected to decline by 0 to 9 percent (median of 4 percent), and average annual runoff is expected to decline by 2 to 22 percent (median of 12 percent). For 2 °C of global warming, the reductions in both rainfall and runoff are approximately double these. The situation is less clear in the northern part of the region.

Yarrawonga Weir on the River Murray, Victoria, 2000 © CSIRO

Implications of these changes

From a water planning and management viewpoint, one implication of these findings is that the traditional 'filling season' for water supply systems across most of south-eastern Australia, which historically was considered to run from about May through to November, may not be as reliable in the future. Rather, replenishment of storages (and soil moisture reserves) may in future be more dependent on spring/summer rainfall events, depending on the status of ENSO, the IOD and the SAM. While it appears that changes in the IOD and SAM may lead to reduced cool season rainfall across south-eastern Australia, changes in the ENSO are much less certain. It is unclear as to the extent to which likely reduced cool season rainfall and streamflows might be offset by higher spring/summer flows. The expansion of tropical influences on climate will be important in influencing streamflow, particularly in the northern part of the Murray–Darling Basin.

Given that the Millennium drought was found to be partly attributed to human-induced impacts on the climate system, a return to drought conditions in the short-term remains a possibility, although the likelihood cannot be quantified. Climate change projections show a wide range of possible and plausible impacts, and there is therefore a high degree of uncertainty about future rainfall and streamflow scenarios. This means water resource managers need to ensure that their planning and management processes are robust and adaptive across a wide range of future climate and streamflow scenarios and are subject to regular review.

In terms of the sensitivity of the runoff response to rainfall and other environmental factors, research has shown that changes in rainfall are the dominant influence, with changes in temperature and carbon dioxide (CO_2) concentrations having only a secondary impact. The importance of understanding the linkages between surface and groundwater systems and how these change during drought has also been highlighted. In turn, this has implications for the structure of rainfall-runoff models and their calibration. It was shown that rainfall-runoff models can generally cope so long as changes in rainfall are not greater than about 15 to 20 percent. Ideally it would be desirable for rainfall-runoff models to perform well across the full range of historical conditions, including the Millennium drought.

The River Murray east of Morgan in SA during the 2007 drought, October 2007 © MDBA Photographer Arthur Mostead

Summary of major scientific findings

The South Eastern Australian Climate Initiative is aimed at improving the understanding of the causes of climate variability and change and their impacts on water availability in south-eastern Australia.

SEACI Phase 1 – 2006 to 2009

Phase 1 of SEACI made substantial progress in documenting recent changes in climate in south-eastern Australia and identifying the large-scale circulations that significantly influence the natural variability (seasonal and inter-annual) of the climate of south-eastern Australia, namely:

- El Niño – Southern Oscillation (ENSO), where *El Niño* events typically result in *reduced rainfall*, and *La Niña* events typically result in *increased rainfall* for south-eastern Australia from *winter to summer.*
- Indian Ocean Dipole (IOD), where *positive IOD* events typically result in *reduced rainfall,* and *negative IOD* events typically result in *increased rainfall*, for south-eastern Australia from *winter to spring.*
- Southern Annular Mode (SAM), where *positive SAM* phases typically result in *reduced rainfall* for the western part of south-eastern Australia during *winter* and *increased rainfall* on the eastern side during *summer.*

A key finding from SEACI Phase 1 was that the decline in rainfall in south-eastern Australia during the Millennium drought (from 1997 to 2009) was unusual in terms of its geographical extent, its severity and duration, the absence of any intervening wet years, and the fact that the rainfall decline occurred predominantly in autumn and early winter. Much of the rainfall decline was shown to be accounted for by an increased intensity of the sub-tropical ridge, although the southward shift of the sub-tropical ridge in autumn also contributed to the seasonal pattern of rainfall decline. Research during Phase 1 of SEACI also established that the observed increase in the intensity of the sub-tropical ridge was associated with global warming, and therefore the decline in rainfall across south-eastern Australia was at least partly attributable to climate change.

The decline in rainfall during the Millennium drought resulted in a larger than expected decline in streamflow. This, in turn, was shown to largely be a result of:

- a change in the seasonality of rainfall with disproportionate rainfall declines in autumn (resulting in dry soil conditions at the start of the runoff season) and winter-spring (when most of the runoff occurs),
- the absence of intervening wet years,
- a reduction in the number of very large rainfall events, and
- to a lesser extent, an increase in temperatures.

Climate change projections made in SEACI Phase 1 indicated an increasing risk of below average rainfall for south-eastern Australia, particularly in southern parts of the region. SEACI Phase 1 also produced improvements to both statistical and dynamical approaches to seasonal climate and streamflow forecasting.

The findings of SEACI Phase 1 suggested that it would be prudent for water resource managers to plan for conditions that are likely to be drier than the long-term historical average conditions because:

- the Millennium drought was found to be at least partly linked to climate change and therefore there was a possibility that it might persist (as has been the case in south-west Western Australia since the mid-1970s), and
- climate model projections indicate a drier future across the south-east.

However, it was also acknowledged that it was not possible to quantify the relative roles of natural variability and climate change in the drought, and that natural variability, in particular as influenced by the state of the three oceans surrounding the continent, would continue to play a key role. The importance of natural variability was in fact borne out by the subsequent back-to-back La Niña events that occurred in 2010/11 and 2011/12, which brought record rainfall and flooding to much of south-eastern Australia. A more detailed synthesis of progress made in the first phase of SEACI can be found in CSIRO (2010a).

SEACI Phase 2 – 2009 to 2012

Phase 2 of SEACI has built on the understanding developed in SEACI Phase 1. It has addressed the key research questions arising from Phase 1 related to the attribution of causes for variations in recent climate, and improving projections of future climate and water availability on both a short-term (seasonal predictions) and a longer-term (climate change projections) basis. The research has been conducted in three themes and has led to further advances in our understanding of the climate of south-eastern Australia, as well as how water availability may be expected to change over coming seasons and decades. It was conducted as a research partnership between CSIRO Water for a Healthy Country Flagship, the Bureau of Meteorology, the Murray–Darling Basin Authority, the Victorian Department of Sustainability and Environment, and the Australian Government Department of Climate Change and Energy Efficiency. This report summarises that work, while a more detailed description of the research can be found in CSIRO (2010b, 2011, 2012).

Theme 1: Understanding past hydroclimate variability and change in south-eastern Australia

> *Research in Theme 1 has contributed to a better understanding of the Millennium drought and of the factors that influence variability and trends in the climate of south-eastern Australia.*

The Millennium drought in historical context

SEACI research evaluated the Millennium drought (1997 to 2009) in a longer historical context by extending instrumental rainfall records across the region back to 1865. It showed that the Millennium drought was more severe than either the World War II (1936 to 1945) or Federation (1896 to 1905) droughts. Rainfall across south-eastern Australia during the Millennium drought was the lowest 13 year period on record. The average annual rainfall for south-eastern Australia during the drought period was 512 mm; 12 percent below the long-term (1900 to 2010) average of 582 mm. In addition, the Millennium drought was unprecedented compared with previously recorded droughts in that it was:

- largely constrained to southern Australia,
- characterised by lower year to year variability and an absence of wet years and wet months, and
- characterised by a different seasonal pattern of rainfall decline, in particular a larger autumn, and to a lesser extent winter, rainfall deficit.

These additional analyses confirm that the characteristics of the Millennium drought were 'outside' what would be expected based on natural variability as characterised by the instrumental record, and raises the possibility that there may have been a shift in the climate 'baseline'.

Changes in global atmospheric circulation and impacts on south-eastern Australia

An analysis of a combination of atmospheric observations and reanalysis datasets has shown that the Hadley circulation is expanding towards the poles at a rate of approximately 0.5° (50 km) per decade. In simple terms this means that the tropics are expanding. Experiments using a global climate model have shown that this expansion can only be reproduced when human influences (in the form of greenhouse gases, aerosols and stratospheric ozone depletion) are included in the model runs. This provides evidence that the expansion of the Hadley circulation is at least partly attributable to human activities. This expansion is associated with an increase in the intensity of the sub-tropical ridge and is responsible for pushing mid-latitude storm tracks further south. These mechanisms are resulting in the observed decline in rainfall in autumn and early winter across south-eastern Australia.

Consistent with these findings, SEACI research has also shown a downward trend in the percentage of rainfall originating from low pressure weather systems centred within the south-eastern Australian region relative to weather systems that have their origins further north, particularly in April and May. Further, SEACI research has also shown the importance of both the intensity and position of the sub-tropical ridge in influencing autumn rainfall. If pressures in the ridge are high, then below average rainfall can be expected across the region. However, if the position of the ridge is further south, even with relatively high pressures in the ridge, autumn rainfall can be above average (e.g. autumn 2007 and March 2010 and 2011). This can be thought of as a summer-like, tropically-influenced autumn season when rainfall originates mainly from more northerly weather systems. Winter-like wet autumns are characterised by low pressures and a more northerly position of the ridge, with rainfall originating primarily from systems embedded in the westerly wind belt south of the ridge. Such winter-like wet autumns, once common, have not occurred in the region since 1995.

The 2010/11 and 2011/12 floods

The record rainfalls and flooding experienced across much of the region, and throughout Australia, in the 2010/11 and 2011/12 summers highlighted the importance of the status of the three oceans – Pacific, Indian and Southern – in influencing seasonal and inter-annual rainfall variability. The spring/summer of 2010/11 saw one of the strongest La Niña events on record combined with a negative IOD event and a positive SAM – i.e. all three key influences were in their wet phases in terms of expected rainfall impacts on south-eastern Australia.

These conditions, coupled with the warmest sea-surface temperatures on record to the north of the Australian continent, contributed to making 2010-11 Australia's wettest two-year period on record. While the extensive flooding of 2010/11 was, by and large, consistent with natural variability, it is possible that ongoing global warming contributed to the magnitude of the event through its impact on ocean temperatures. The spring and summer of 2011/12 saw the re-emergence of another (weaker) La Niña event, combined with a positive SAM during early summer, but this time the Indian Ocean played a lesser role.

Despite the La Niña events of 2010/11 and 2011/12, which resulted in above average annual rainfall totals across the region, late autumn and winter rainfalls in 2011 continued to be below average, which is consistent with the trends associated with an expansion of the Hadley circulation.

Snow melting into the Eucumbene River at Kiandra, NSW, August 2008 © MDBA Photographer Arthur Mostead

Theme 2: Long-term hydroclimate projections for south-eastern Australia

> *Research in Theme 2 has provided updated projections of climate and streamflow for south-eastern Australia for 1 °C and 2 °C of global warming.*

Climate change projections

Climate change projections were updated using improved methods for determining the impacts of a changing climate on future water availability. This included assessing the source of the large uncertainties in future projections of runoff. Much of this uncertainty was due to the large range in the rainfall projections coming from the outputs from global climate models, with lesser amounts attributable to the choice of downscaling technique and hydrological model used. An assessment of global climate models was carried out based on their ability to reproduce the key climate influences on south-eastern Australian rainfall based on the outputs of Theme 1 (such as ENSO and the sub-tropical ridge); however, this was not able to reduce the uncertainty inherent in the range of projections from current global climate models.

Additionally, a range of downscaling techniques were assessed, comparing the results from a simple empirical daily scaling approach with statistical and dynamical downscaling. These downscaling techniques improve the spatial and temporal resolution of projections such that the outputs are better suited for input to rainfall-runoff models and river system models. The results suggest that more complex downscaling techniques may have a role to play in reducing uncertainty, although further research is needed to determine whether this conclusion holds when multiple downscaling techniques are used with multiple global climate models. Such techniques would allow decision makers to test a range of more spatially and temporally explicit climate scenarios in order to consider policy and management responses to changes in climatic patterns.

Overall, climate change projections continue to indicate the likelihood of a warmer and drier future in the southern Murray–Darling Basin and Victoria, although there is a large range of uncertainty in the magnitude of the projected reductions in rainfall.

Averaged over the southern part of the SEACI region (south of 33° S) mean annual rainfall is projected to reduce by 0 to 9 percent (median of 4 percent) and mean annual runoff by 2 to 22 percent (median of 12 percent) for a 1 °C warming (by approximately 2030 relative to 1990). The projections indicate a rainfall decline in the cool season (April to October) consistent with expected changes in the large-scale atmospheric and oceanic influences on rainfall in a warmer world as described in the outputs of Theme 1. In particular, the models typically show a further intensification of pressures in the sub-tropical ridge and the southward movement of this ridge, resulting in a further southward movement of the westerly wind belt and associated mid-latitude storm tracks. There is less agreement among climate models in the northern part of the region. Averaged over the region north of 33° S, for a 1 °C warming, the mean annual rainfall is projected to change by –11 to +4 percent (median of –3 percent) and the mean annual runoff is projected to change by –29 to +12 percent (median of –10 percent). Projected changes for 2 °C of global warming are approximately double those for 1 °C of global warming.

Given that it is not currently possible to quantify the relative roles of natural variability and climate change in the recent observed changes in climate, the climate change projections have been applied to a baseline characterised by the full instrumental climatic record. The issue of how best to characterise this baseline and apply the projections, given the fact that there appears to be some climate change signal in recent observations, requires further consideration.

Changes in key hydrological processes

Research in Theme 2 also examined how key hydrological processes changed during the Millennium drought and how they may similarly change under a future drier climate. The results suggested that during an extended drought, rainfall in low-relief medium-rainfall catchments replenishes the near-surface water and groundwater stores rather than being converted to runoff. Activities like farm dams also intercept proportionally more water during dry periods. As a result, some catchments show a disconnection between surface and groundwater, leading to much lower runoff coefficients than would typically be expected. Combined with the observed changes in rainfall variability and seasonality during the Millennium drought, this helps explain why runoff was much lower than expected based on the observed reduction in mean annual rainfall. The same processes may accentuate the decline in future water availability under a drier climate.

The research also examined the sensitivity of runoff to changes in a range of factors including temperature and atmospheric CO_2 concentrations. An analysis using spatially aggregated climate and modelled runoff data over the 20 percent of grid cells contributing 60 percent of Murray–Darling inflows indicates that a 1 °C increase in average daily maximum temperature led to around a 4 percent decrease in streamflow. Rising CO_2 levels may also affect runoff due to changes in plant physiology. Initial results indicate an increase in runoff of about 9 percent per 100 parts per million increase in CO_2, due to decreased stomatal conductance and hence decreased transpiration. However, additional feedbacks associated with plant growth and structure are likely to modify this result and further research is necessary to determine the likely net overall consequences of increases in both CO_2 and temperature.

Theme 3: Seasonal hydroclimate predictions in south-eastern Australia

Research in Theme 3 has improved seasonal forecasts of both rainfall and streamflow across south-eastern Australia.

Key to improving forecasts of water availability at the seasonal scale is improving forecasts of rainfall over the same timeframe. To address this issue, the Predictive Ocean Atmosphere Model for Australia (POAMA) was improved. This was done by assessing the capability of the model to reproduce the large-scale factors that have been shown to be important for driving the climate of the region (as identified in Theme 1). Specifically, the patterns of Pacific Ocean sea-surface temperatures which affect the climate of south-eastern Australia can be represented reasonably accurately in the model, although the simulation of the Indian Ocean remains problematic. A further significant advance in forecasting was the identification of some useful predictability of the SAM in summer, through its links with ENSO.

The improved rainfall forecasts were used in conjunction with updated representations of initial catchment conditions to further develop seasonal forecasts of water availability across south-eastern Australia. Predictive skill was found to vary between catchments and with seasons, with more skilful results being obtained for catchments with deep soil profiles and therefore large groundwater storages which release water to streams relatively slowly. Because of the importance of initial conditions, forecasts also tend to be most skilful for seasons when streamflow is declining (spring and summer in south-eastern Australia). This improved model is currently being implemented for use in operational streamflow forecasting by the Bureau of Meteorology (www.bom.gov.au/water/ssf/index.shtml).

Chicory trial crop near Grogan, NSW, 2006 © CSIRO

The recent climate of south-eastern Australia: the 1997–2009 Millennium drought and 2010–11 floods

South-eastern Australia has historically experienced large variability in climate from year to year and decade to decade, but the climate over the past 15 years has been outside the historical record. Between 1997 and 2009, the region had its lowest 13-year rainfall total of the entire instrumental record (1865 onwards). The term 'Millennium drought' has been used extensively to describe this period of extremely low rainfall occurring at the beginning of the new Millennium (e.g. Leblanc et al., 2011). Using rainfall reconstructions based on climate proxy data, Gallant and Gergis (2011) have shown that there is a very high likelihood that the drought resulted in the lowest volume of streamflows in the Murray–Darling Basin since 1783. The drought was broken by frequent and widespread heavy rainfall events from spring 2010 to autumn 2011, and again in late 2011, which resulted in Australia's wettest two-year period on record.

The 1997–2009 Millennium drought

The mean annual rainfall of 512 mm for south-eastern Australia (here defined by the black box in Figure 1) over the period 1997 to 2009 was 12 percent below the 1900–2010 mean annual rainfall of 582 mm. This deficit of 70 mm is much larger than that for the next driest 13-year period which occurred from 1937–1949 (46 mm). Interestingly, the Millennium drought in south-eastern Australia happened at a time when the Australian continent as a whole was experiencing above average rainfall, which was primarily due to high summer rainfall over the north-west regions of the continent. In contrast, previous droughts across south-eastern Australia tended to occur when the entire continent was also in drought.

In addition to the large reductions in annual and, particularly, cool season rainfall, the Millennium drought was also remarkable for its lack of very wet months. The number of very wet months in each year from 1900 to 2011 is shown in Figure 2. It illustrates the extreme nature of the Millennium drought, with 180 consecutive months without a very wet month.

The historical rainfall record for south-eastern Australia was extended back to 1865 (Timbal and Fawcett, in press) to allow a comparison of the characteristics of the Millennium drought with the prolonged droughts during World War II and at the time of the Federation of Australia. Three 21-year periods encompassing these historical droughts (1895–1915, 1925–1945 and 1991–2011) were compared using drought depth duration curves.

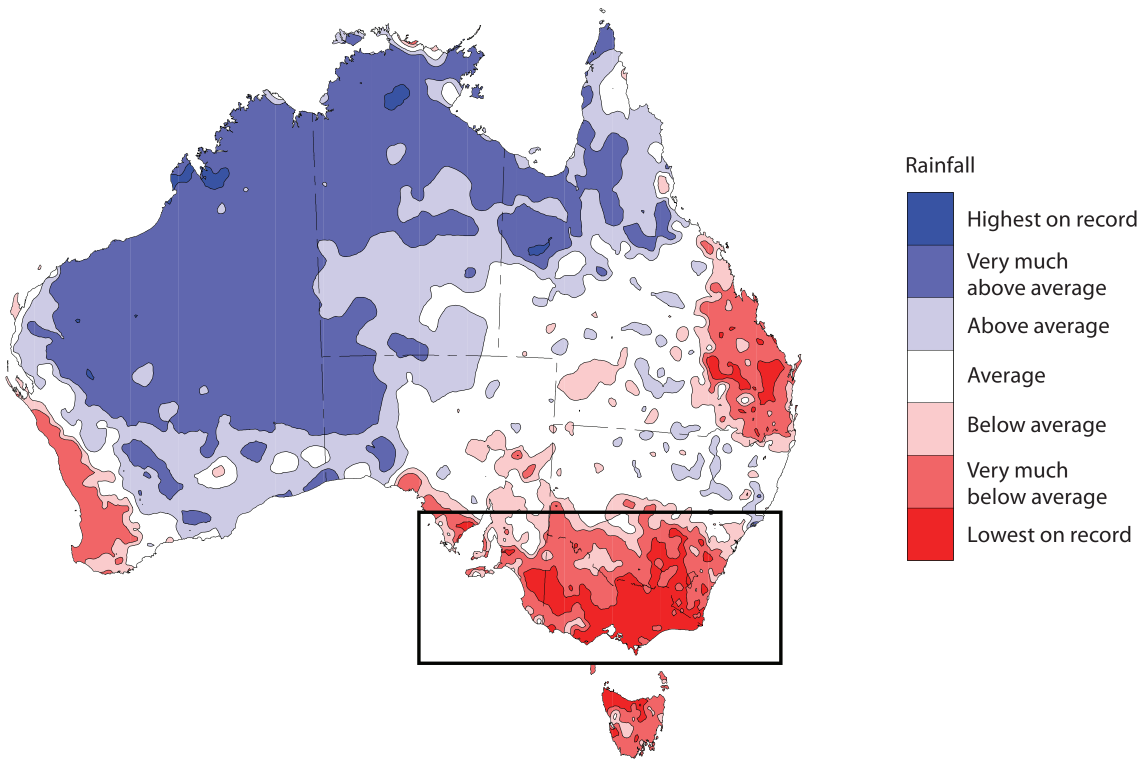


Figure 1. Australia-wide rainfall distribution maps for the Millennium drought (1997–2009). The black box shows the area over which the averages for south-eastern Australia in the text were calculated.

(Source: National Climate Centre, Bureau of Meteorology, 2012).

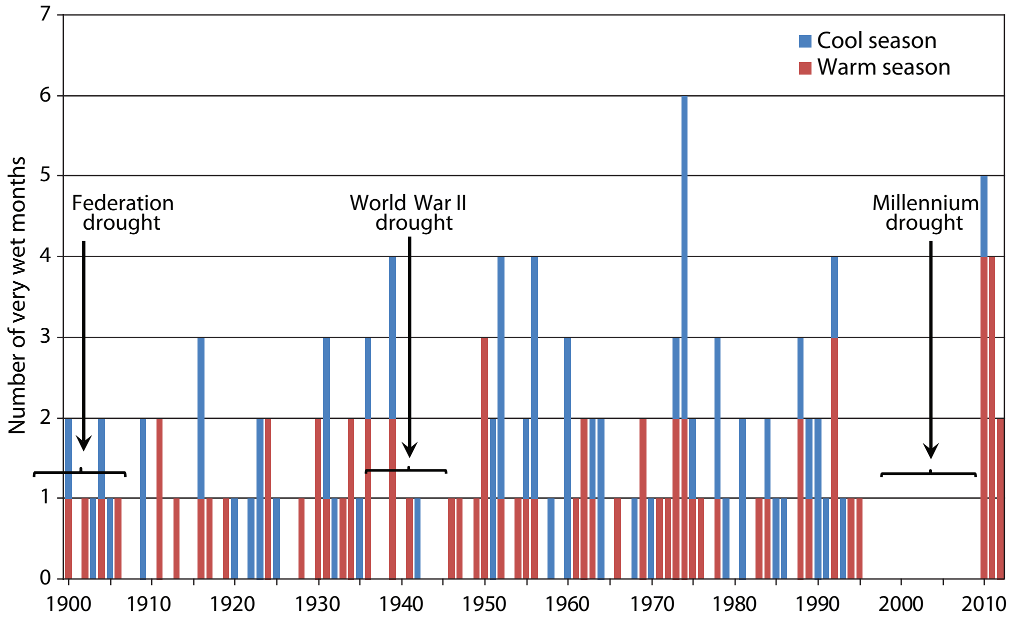


Figure 2. Number of very wet months in each year from 1900 to July 2012. Here 'very wet' is defined as being above the 90th percentile of rainfall. By chance, one would expect one or two of these in every year. The Millennium drought stands out as having no very wet months for 180 consecutive months. Additionally, during the breaking of the drought in 2010–12, only one very wet month was recorded during the cool season – the other 10 being recorded during the warm season.

These curves are created by calculating the lowest 1, 2, 3 … 21 year annual rainfall totals during each of the three drought periods, then plotting the percent reductions in rainfall versus duration. This is shown in Figure 3 where it can be seen that the Millennium drought was unprecedented in the instrumental record and was worse than the two previous historical droughts for all durations from 3 to 19 years. The difference is particularly large for durations between 13 and 17 years; for example, for 16 years, the rainfall deficit during the Millennium drought (13 percent) was about twice as large as was observed during either of the previous two historical droughts (6 to 7 percent).

Seasonally, the Millennium drought was far more pronounced in autumn, whereas the previous droughts showed a larger reduction in rainfall in summer, and to a lesser extent, spring. All three droughts showed a reduction in winter rainfall. This loss of autumn and winter rainfall during the Millennium drought was important as it resulted in reduced streamflows during the traditional filling season for water supply systems in the southern Murray–Darling Basin and Victoria.

Drought depth duration curves were also used to evaluate the chances of getting dry periods of varying durations based on the instrumental record (assuming there is no memory in the system from year to year). This was done by calculating the likely driest 21-year period for the entire record by re-sampling the observations 20,000 times and extracting the driest 1, 2 … 21 year period. For durations from 4 to 18 years, the deficit during the Millennium drought was larger than what would be expected by chance (Timbal and Fawcett, in press).

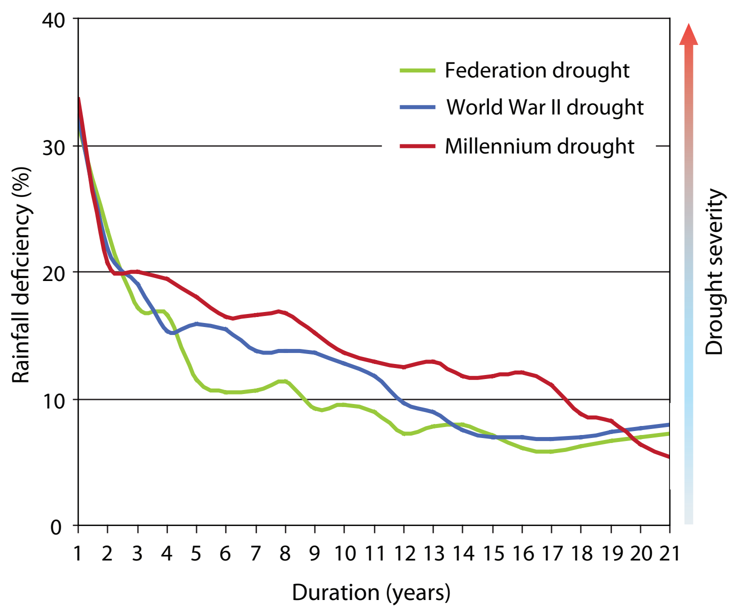


Figure 3. Drought depth duration curves computed using annual rainfall for periods from 1 to 21 years for three historical droughts: Federation drought in green, World War II drought in blue and Millennium drought in red. The severity of the drought increases up the graph with units on the y-axis showing the rainfall deficiency as a percent reduction compared to 1872–2009. The Millennium drought was the worst drought in the instrumental record for all durations between 3 and 19 years. (Source: Timbal and Fawcett, in press).

This result suggests the possibility that the latest part of the rainfall record may be statistically different from the entire instrumental record, and implies that the climate baseline for south-eastern Australia may have shifted. This is an important observation as water planning processes are traditionally based on the assumption of a stationary baseline, assumed to be characterised by the historical climatic or streamflow record. More recently, water planning processes have allowed for the impacts of climate change. However, most climate change projections (including those in this report) are applied to a reference baseline, which is typically assumed to be characterised by the full historical record. Given that it is possible that part of the future climate change projected by climate models has already been observed (see Box 1 on p12), this means that an improved methodology needs to found for accounting for a changing baseline in climate change projections. This is the subject of current research (e.g. Chiew and Post, 2012).

The 2010–11 floods

The Millennium drought was unprecedented in duration and intensity, and SEACI research indicates that human-induced global warming probably contributed to the severity of this drought. However, even under the effects of climate change, natural variability in the climate system, especially as related to swings between El Niño and La Niña, continues to operate. This means that years of abundant rainfall can still be expected, even if overall the average climate has become drier. This is exactly what occurred in 2010/11, which saw one of the strongest La Niña events on record. This was followed by another La Niña event in 2011/12 and these back-to-back La Niña events resulted in a two-year Australia-wide rainfall total for the calendar years of 2010–11 of 1409 mm (Figure 4), just surpassing the old record of 1407 mm set during 1973–74 (Bureau of Meteorology, 2012a,b).

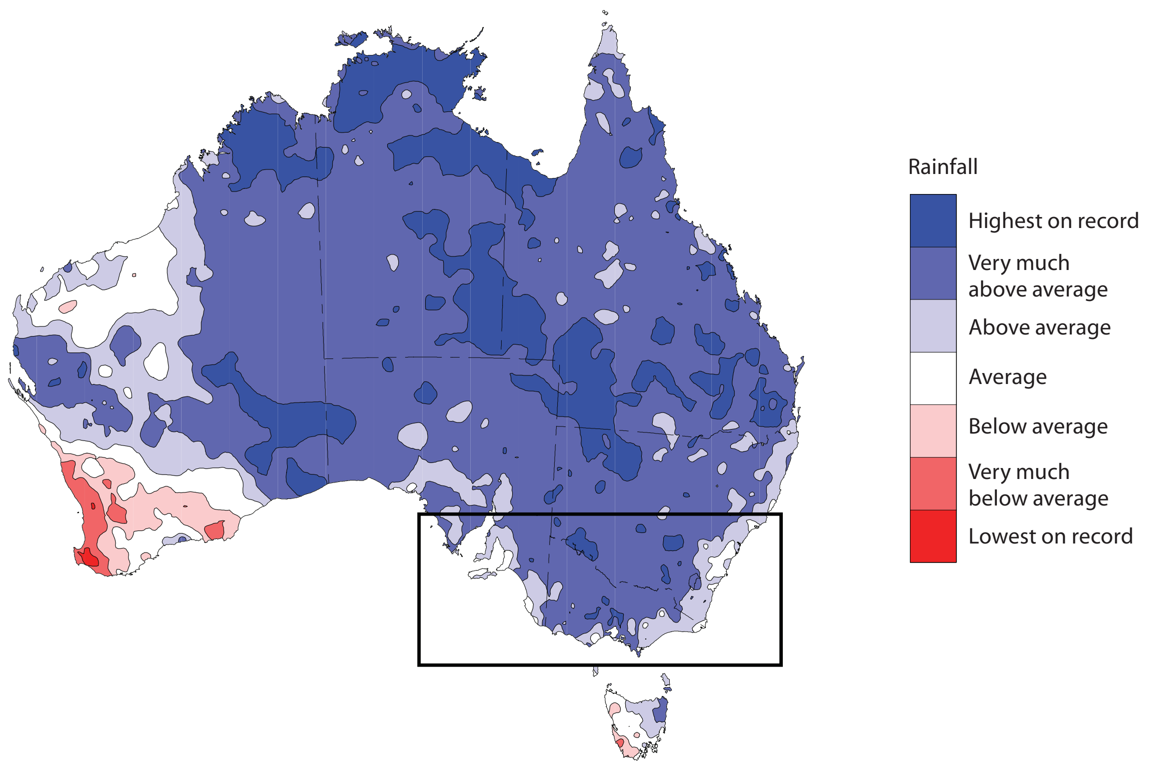


Figure 4. Australia-wide rainfall distribution maps for the back-to-back La Niña years of 2010–11. The black box shows the area over which the averages for south-eastern Australia in the text were calculated.

(Source: National Climate Centre, Bureau of Meteorology, 2012).

Across south-eastern Australia, rainfall was somewhat less extreme than elsewhere across the country, with 2010 being the fourth wettest year on record (811 mm) compared to 879 mm in 1956, 877 mm in 1974, and 820 mm in 1973. Similarly, the two-year total for south-eastern Australia for 2010–11 ranked fourth (1529 mm) behind 1973–74 (1697 mm), 1956–57 (1590 mm) and 1974–75 (1552 mm). This somewhat lower rainfall across south-eastern Australia was due to a continuation of below average rainfall during the cooler months of the year. The April to September rainfall deficit during the Millennium drought (1997–2009) was 49 mm (15 percent below the long-term average). Incorporating 2010 and 2011 into the records reduces this deficit by just 3 mm, still 14 percent below the long-term average (as illustrated by the very small differences between the orange and red bars between April and October in Figure 5). SEACI research has linked the below average rainfall in the cool months of the year to the strengthening of the belt of high pressure known as the sub-tropical ridge which has occurred in conjunction with global warming (Timbal and Drosdowsky, 2012). These changes are also related to ongoing changes in the meridional circulation consistent with a warmer world.

In sharp contrast to the cool months of the year where the sub-tropical ridge intensification was associated with long-term rainfall deficits, rainfall anomalies (differences from the average) during the warm months of the year during 2010–11 were record breaking across south-eastern Australia. Most remarkable was the summer of 2010/11, when 304 mm of rainfall was recorded across south-eastern Australia, which is more than two and a half times the long-term average of 120 mm, and greatly exceeded the previous record of 225 mm set in 1910/11. South-eastern Australian rainfall for the spring and summer of 2010/11 was also the highest on record (see Box 2 on p14 for details). Figure 2 shows that of the eleven very wet months recorded in 2010–12, only one occurred during the cool season of the year, with the other ten occurring during the warm season, highlighting the importance of warm season rainfall in the breaking of the drought.

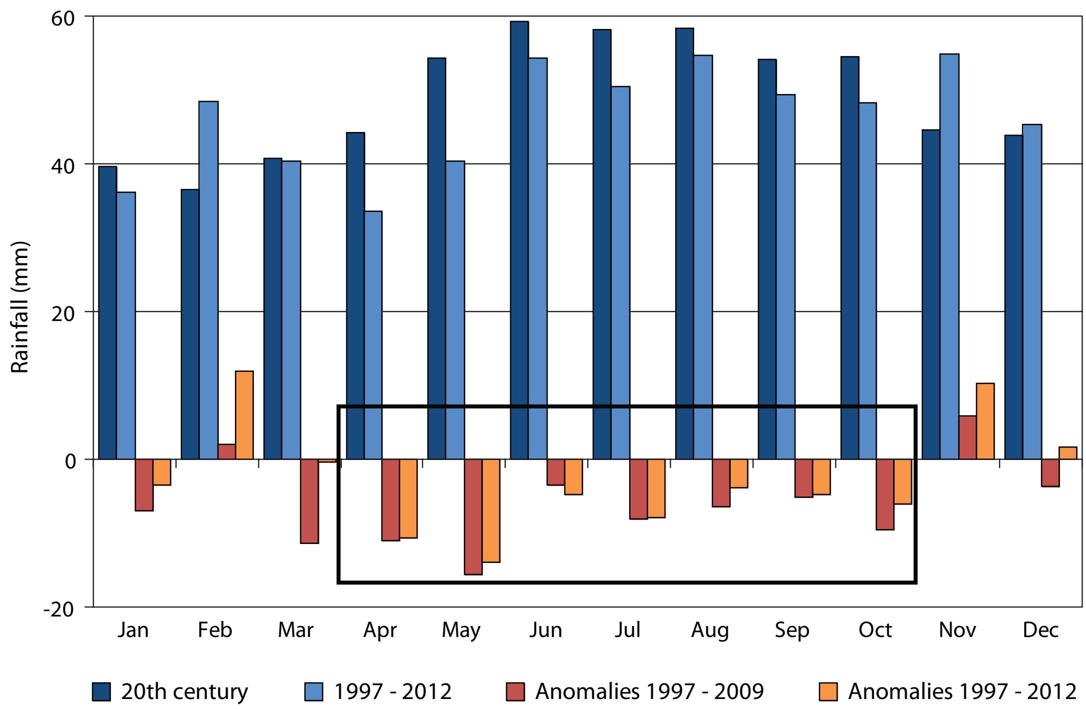


Figure 5. Monthly mean rainfall across south-eastern Australian for the 20th century (dark blue bars) and for the period January 1997 to July 2012 (light blue bars). Anomalies from the 20th century climatology during this latter period (1997–2012) are shown as orange bars and anomalies for the period of the Millennium drought (1997–2009) are shown as red bars. Cool season months with negative rainfall anomalies since 1997 (outlined with a black box) remained similar despite the addition of the very wet 2010–12 years, in contrast to the warm season months where the differences between the orange and red bars are much larger.

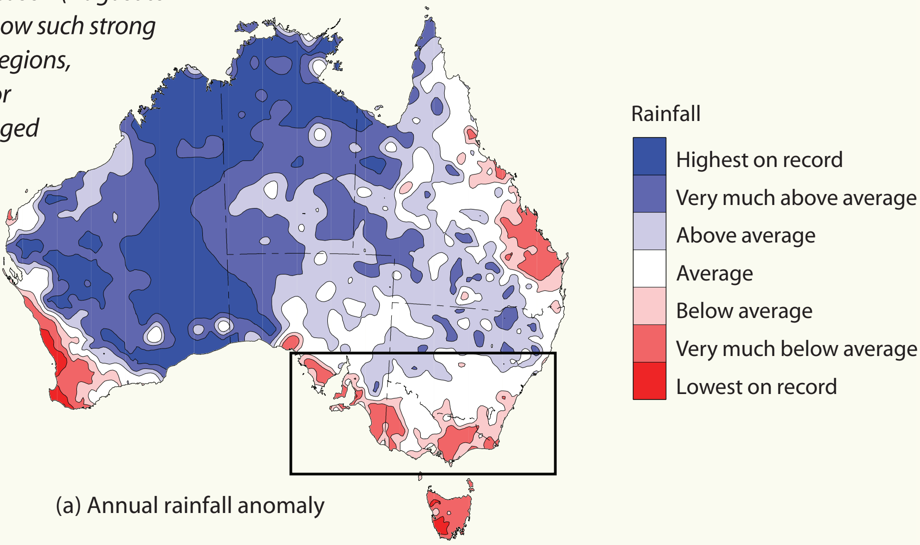
(Data source: Bureau of Meteorology, http://www.bom.gov.au/cgi-bin/silo/cli_var/area_timeseries.pl).

Box 1: Recent climate trends

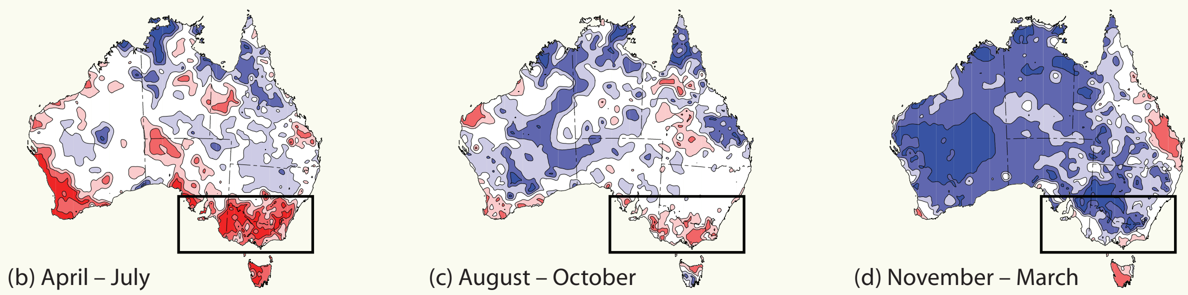
A critical question for determining long-term changes in water availability is what defines the climate (and the hydrologic) baseline for use in water planning. In the absence of clear trends, it is considered best practice to make use of the longest possible period of record in order to capture as much of the natural variability of the climate system as possible. However, it has become clear that for some variables (e.g. temperature and sea level), at least at a global scale, the assumption of stationarity (that the statistics of the relevant variables have remained constant through time) no longer holds true. However, for relatively small regions such as south-eastern Australia, the risk that observed trends are due to natural inter-annual variability rather than a systematic response to ongoing external factors needs to be considered and balanced against the possible gain in using a shorter baseline. The World Meteorological Organization recommends using 30 years as a minimum to describe a climate baseline.

Across Australia, rainfall for the last 30 years depicts a continent which is getting wetter in terms of mean annual rainfall (Figure 6 (a)) with the exception of south-eastern Australia (including Tasmania), and south-western Australia as well as south-eastern Queensland. Rainfall in southern Australia is primarily linked to frontal storm tracks and is dominated by cool season rainfall. The observed recent reductions in rainfall across these regions are predominantly a late autumn-early winter phenomenon (Figure 6 (b)). The rest of the cool season (August to October in Figure 6 (c)) does not show such strong reductions in rainfall across these regions, although there is still a tendency for rainfall to be below average. Averaged across the Australian continent, there has been a slight increase in rainfall for the August to October period. This is the time of the year when the influence of tropical modes of variability (ENSO, IOD) are at a peak, suggesting a weak but positive contribution to continental rainfall over the last 30 years. Finally, rainfall over the warm season (November to March in Figure 6 (d)) shows a continent which has become overwhelmingly wetter, although that signal is much diminished along the southern edge of the continent and south-eastern Queensland. However, the south-east Queensland rainfall deficiency is primarily a warm season phenomenon, and is therefore different from the rainfall reduction seen across south-eastern Australia.

In summary, the emerging picture for rainfall over Australia during the last 30 years is of a tropical north dominated by warm season rainfall which has been wetter than the long-term average, contrasted with an extra-tropical southern edge of the continent dominated by cool season rainfall which has been drier than the long-term average. The reductions in rainfall across southern Australia have predominantly occurred during the early part of the cool season, as rainfall in the latter part of the cool season has been mitigated by a positive contribution from tropical modes of variability. There is a reasonable degree of similarity between this emerging continental picture and the projections from climate models. This is discussed further on p18.



(a) Annual rainfall anomaly



(b) April – July

(c) August – October

(d) November – March

Figure 6. 30 year (1982–2011) rainfall anomaly maps (compared to the period 1900–2011) for (a) the annual mean and three distinct parts of the annual cycle: (b) April to July; (c) August to October; and (d) November to March.

(Source: National Climate Centre, Bureau of Meteorology, 2012).

What influences the climate of south-eastern Australia?

The three major large-scale indicators of the dominant modes of variability that influence the climate of south-eastern Australia are the El Niño – Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Southern Annular Mode (SAM). In addition, the meridional circulation has a large impact on rainfall across south-eastern Australia through its impacts on the location and intensity of the sub-tropical ridge. This section of the report provides an overview of current understanding of these factors, as well as how they may change into the future in order to place SEACI research in this area into context. A more detailed description can be found in Gallant et al. (2012).

Inter-annual variability produces a land 'of droughts and flooding rains'

The El Niño – Southern Oscillation and the Indian Ocean Dipole

The El Niño – Southern Oscillation (ENSO) is a Pacific Ocean phenomenon, where the El Niño phase refers to a state in which the eastern equatorial Pacific is warmer than normal, pressures are higher across much of Australia, and rainfall is reduced across much of south-eastern Australia. La Niña represents the opposite conditions. ENSO tends to have its greatest impact on rainfall in south-eastern Australia from winter through spring and into summer. It is typically quantified using the Southern Oscillation Index (SOI), a measure of the normalised atmospheric pressure difference between Tahiti and Darwin.

Corduroy Swamp, May 2009 © MDBA Photographer David Kleinert

The Indian Ocean Dipole (IOD) refers to an out of phase variation in sea-surface temperatures between the western and eastern tropical Indian Ocean. It is quantified using the Dipole Mode Index (DMI) that is based on the measured difference between sea-surface temperature in the western (50° E to 70° E and 10° S to 10° N) and eastern (90° E to 110° E and 10° S to 0° S) equatorial Indian Ocean. The IOD typically develops in early winter, peaks in October–November and disappears by January. A negative IOD is associated with wetter conditions across south-eastern Australia, while a positive IOD is associated with drier conditions. The IOD is the most dominant large-scale influence on climate in south-eastern Australia in winter and spring, when it explains up to 40 percent of the rainfall variance in parts of south-eastern Australia.

ENSO and the IOD are strongly correlated in spring but not in the other seasons. Since 1980, high El Niño indices have been accompanied by positive IOD indices all five times they have occurred, while high La Niña indices have been accompanied by negative IOD indices on three of the four times they have occurred (Hendon et al., submitted). Despite this relationship, predicting rainfall variations in south-eastern Australia requires good predictions of the IOD even during ENSO events. This is because the pathway for tropical ocean conditions in the Pacific Ocean (indicated by ENSO) to affect rainfall in south-eastern Australia, is primarily via the Indian Ocean (Cai et al., 2011a). Poor representation of the temperature of the Indian Ocean (especially in the representation of the IOD) is common in many CMIP3 climate models (used in the IPCC Fourth Assessment Report). These poor representations contribute significantly to the uncertainty of climate change impact projections in south-eastern Australia, particularly in spring (Cai et al., 2011b).

Although the status of ENSO and the IOD have a major impact on south-eastern Australian rainfall in winter and spring, they exert little influence on autumn rainfall, thus indicating that the most prominent modes of natural variability in the tropics (ENSO and the IOD) are not the primary cause of the Millennium drought in south-eastern Australia. Linear reconstruction of rainfall in south-eastern Australia using a tripole index (capturing both ENSO and IOD indices; Timbal and Hendon, 2011) suggests that tropical sea-surface temperatures also played no role in influencing the Millennium drought. In contrast, the tropical modes of variability, as measured by ENSO, the IOD and the tripole indices, strongly influenced the extended wet period in 2010–11 which broke the Millennium drought (see Box 2 on p14 for details).

Box 2: The record breaking rainfall of 2010–11

Rainfall across Australia for the two-year period 2010–11 was the wettest on record at 1409 mm. Across south-eastern Australia, the vast majority of this rainfall was received in spring and summer, with the spring and summer rainfall of 2010/11 of 551 mm being about twice the long-term average, surpassing the previous record of 486 mm set in 1992/93.

Several factors contributed to the record rainfall across south-eastern Australia in the spring and summer of 2010/11 (Hendon et al., submitted), and these are summarised in Figure 7. Foremost, the 2010/2011 La Niña was the strongest La Niña event of the past 50 years, as judged by the Southern Oscillation Index (SOI) and the unusually high sea-surface temperatures in the western equatorial Pacific Ocean. Additionally, the cold La Niña conditions in the central Pacific were shifted westward compared to the location of their typical El Niño counterparts. This feature is known to increase the impact of both phases of the Southern Oscillation (El Niño and La Niña) on Australian rainfall. The Indian Ocean Dipole (IOD) was also very strongly negative with sea-surface temperatures to the north of Australia being near a record high. This is perhaps not surprising since both these things typically occur during La Niña conditions, but, taken together, they all contributed to producing wet conditions across much of eastern Australia. Hence, the pattern of tropical ocean temperatures in late 2010 and early 2011 provided a 'perfect' set of conditions conducive to promoting the extremely wet conditions observed in the spring and summer of 2010/11.

In addition to the development of La Niña conditions in the tropics, the Southern Annular Mode (SAM) was also remarkably high in late 2010, with spring 2010 recording the largest amplitude of the positive phase of the SAM index since 1960. This record high value of the index was estimated to have contributed up to 40 percent of the high springtime rainfall anomaly along the eastern coastal strip and further inland in the Murray–Darling Basin. The SAM is generally understood to result primarily from internal variations of the atmosphere and so is not thought to be predictable on seasonal time scales. However, during late spring, the high phase of the SAM is modestly affected by the occurrence of a La Niña. The exceptional strength of the 2010 La Niña therefore appears to have contributed to the high SAM and therefore high rainfall along the eastern seaboard of Australia.

A notable feature of the 2010–11 conditions was the warmest sea-surface temperatures on record to the north-east and north-west of the Australian continent. The persistence of the highest sea-surface temperatures on record during the summer months was at least partly due to the ongoing warming of the Indian and western Pacific oceans. Thus, although the extensive flooding of 2010–11 was, by and large, consistent with the natural occurrence of a very strong La Niña event, it is possible that ongoing global warming may also have contributed to the magnitude of the flooding. This is particularly true in the northern part of the Murray–Darling Basin where it is estimated that elevated sea-surface temperatures may have contributed 10 to 25 percent of the total rainfall.

Scrivener Dam on Lake Burley Griffin has three flood gates open for the first time since the floods in 1977, Canberra, December 2010 © MDBA Photographer Arthur Mostead

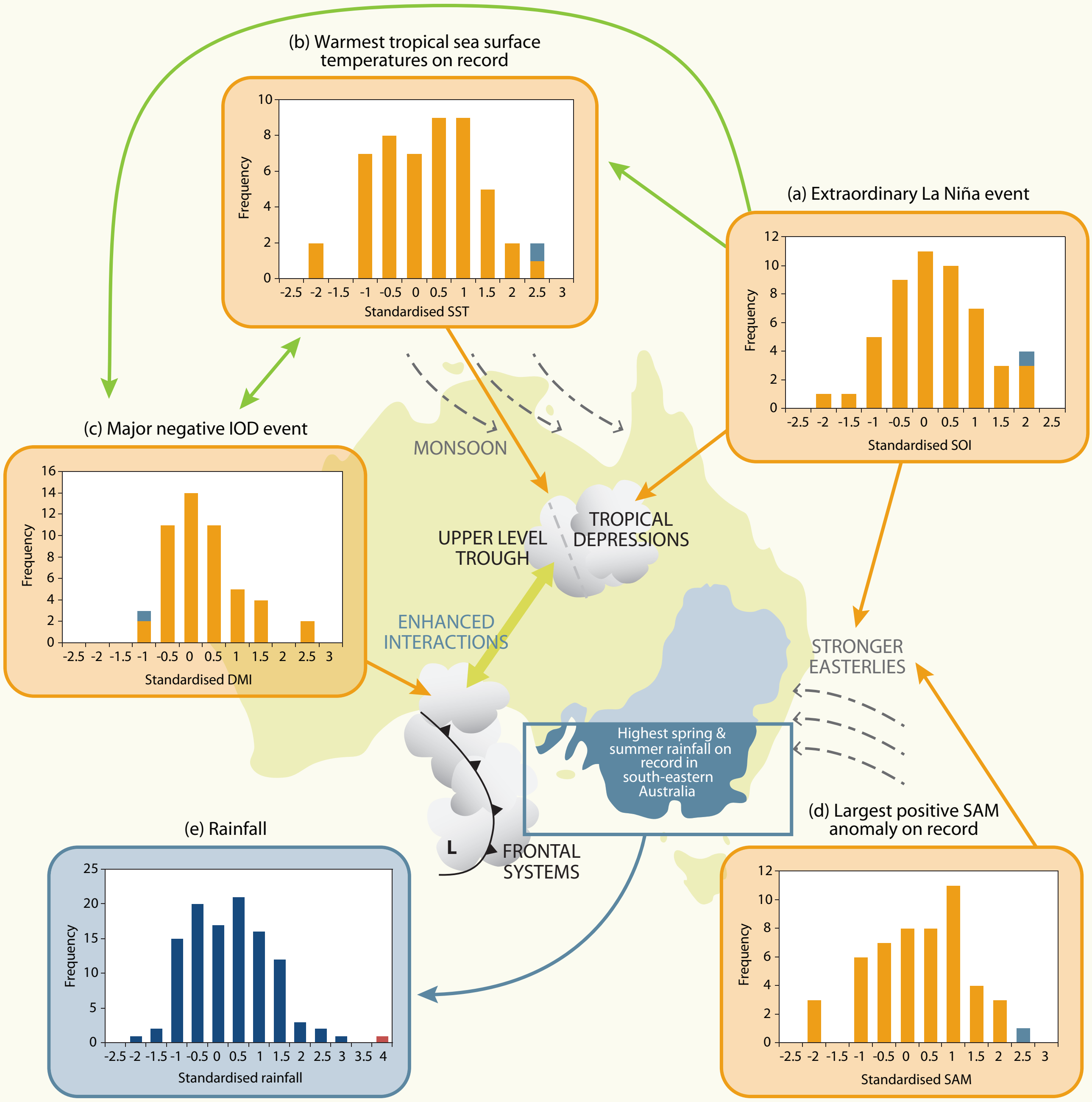


Figure 7. Indices of the internal modes of climate variability relevant to the 2010-11 floods in south-eastern Australia. Histograms for spring season (a) Southern Oscillation Index (SOI); (b) Sea-surface temperatures (SST) north of Australia; (c) Indian Ocean Dipole (as measured by the Dipole Mode Index, DMI) and (d) Southern Annular Mode (SAM) show that the 2010 anomalies (indicated by light blue bars) were at the most extreme end of their distributions for the past 51 years. As a result, spring-summer rainfall in 2010/11 (e) was the highest on record (shown in red). The elements shown on the map of Australia are the meteorological elements through which the identified modes of climate variability influence the rainfall of south-eastern Australia (as shown by the orange arrows). Green arrows indicate interactions between the climatic elements.
(Adapted from Hendon et al. (submitted) and Risbey et al. (2009)).

The Southern Annular Mode

While ENSO and the IOD are the dominant modes of low-latitude variability of the climate system, the Southern Annular Mode (SAM) is the dominant mode of mid- and high-latitude variability. The SAM is characterised by north-south shifts in atmospheric mass between the polar regions and the mid-latitudes resulting in north-south shifts of the westerly jet stream and associated rain-bearing weather systems (the mid-latitude storm tracks). It is quantified by an index derived from the difference in the normalised monthly zonal-mean sea-level pressure between 40° S and 70° S.

The SAM influences rainfall differently in different seasons. A high value of the SAM in winter tends to reduce rainfall across the western part of south-eastern Australia (due to a poleward shift of the mid-latitude storm tracks). However, a high value during spring and summer tends to lead to increased rainfall in the eastern coastal region due to increased onshore transport of moist air from the Coral Sea. Importantly, although the climatic state indicated by the SAM is largely independent of the state of ENSO, it can either amplify or reduce the effects of ENSO in terms of impacts on rainfall for the region. For example, in 2010, strong La Niña conditions and a very high positive value of the SAM both contributed to the very wet conditions in spring/summer in south-eastern Australia (Hendon et al., submitted; see Box 2 on p14 for details).

The seasonal variability of the SAM is, however, modestly associated with ENSO during late spring and early summer, especially during extreme events such as the La Niña of 2010. During La Niña, the Hadley circulation weakens and expands towards the pole, resulting in a shift to more positive values of the SAM and hence increased onshore moist flow in eastern Australia during spring and summer. The opposite happens during El Niño. Improved seasonal prediction of climate in south-eastern Australia during the warm season may be achieved by exploiting this interaction between the SAM and El Niño/La Niña.

Future changes in ENSO, the Indian Ocean Dipole and the Southern Annular Mode

Although studies involving a relatively large number of international models have been conducted, the effect of global warming on ENSO is not clear, leading the IPCC (2007, 2012) to conclude that model projections of changes in ENSO are not consistent and that there is therefore low confidence in projected changes.

Conversely, climate models do show that climate change is projected to increase the number of positive IOD events in the future (Cai et al., 2009) predominantly through a weakened Walker circulation (the atmospheric circulation across the tropical Pacific Ocean) and an enhanced temperature contrast between the land and Indian Ocean. This is despite the models exhibiting a great diversity in their ability to simulate the intensity of the IOD (Saji et al., 2006), which arises from how they simulate dynamical and thermodynamical air-sea feedbacks in the tropical Indian Ocean (Liu et al., 2011). This finding has relevance to south-eastern Australia as positive IOD events are associated with drier conditions across the region, particularly in winter and spring. For this reason, most models tend to show long-term rainfall decline in spring in response to global warming.

All climate models exhibit a trend in the SAM towards its positive phase when determining the impact of increasing greenhouse gas concentrations (Miller et al., 2006). One concern however is that climate models tend to display too strong a SAM under historical climate and also produce too strong a rainfall response to the SAM especially during spring/summer. This consistency of projections towards a more positive index of the SAM may thus be influenced by this systematic bias. Recent observed trends of an increasing SAM, especially in late spring/summer (Arblaster and Meehl, 2006), are also likely to be due to declining stratospheric ozone as well as natural variability. However, while the ozone hole is projected to recover within the next 50 years, further rises in greenhouse gas concentrations are likely to contribute to an upward trend in the value of the SAM throughout the 21st century. These projected trends in the SAM are related to the observed and projected trends in the meridional circulation as described in the next section. The impacts of these changes are a likely reduction in rainfall in the cool season across south-eastern Australia, although this may be offset to some extent by increased rainfall in the warm season.

The meridional circulation and south-eastern Australian rainfall

The climate of south-eastern Australia is greatly influenced by the mean meridional circulation. Much of south-eastern Australia is located under the descending (dry) branch of the Hadley circulation. Variations in the location of the descending branch and the associated variations in the location and intensity of the sub-tropical ridge have a profound impact on rainfall across south-eastern Australia (see Box 3 on p20 for details).

Observed changes

Based on all climate reanalysis datasets, an expansion in the Southern Hemisphere Hadley circulation has occurred over the last 30 years (Figure 8 (a); Nguyen et al., submitted). The trend is largest in summer and autumn and smallest in winter. The range of results across the available reanalyses is large (Figure 8 (a)), but all agree that an expansion of the Hadley circulation has been underway over the last 30 years, with the exception of winter where contractions are seen in some of the reanalyses.

This expansion of the Hadley circulation (and therefore of the tropics) has also been observed using radiosonde data. This work relies on the facts that:

- the height of the tropopause (the top of the layer of the atmosphere where the water vapour and 'weather' are contained) varies markedly between the tropics (height of 15–16 km) and the extra-tropics (height less than 12 km), and
- the drop in tropopause height between the tropics and extra-tropics is abrupt and distinctive.

Although tropopause height variations can be analysed with reanalysis datasets, direct analysis of the radiosonde data provides a more accurate identification of the variations. Across the Southern Hemisphere, the average rate of expansion of the tropics, as indicated by a poleward shift of the high tropopause heights in the tropics and lower tropopause heights in the extra-tropics, has been approximately 0.5° (of latitude) per decade since 1979. The rate is slightly greater over the Australia – New Zealand region as shown in Figure 8 (a). This equates to an expansion southwards of approximately 180 km since 1979. Furthermore, there is some suggestion of decadal variability in the record, with greater expansion being observed in the first part of the period (Lucas et al., in press).

Results from the radiosonde data are broadly similar to those obtained from the reanalysis datasets. The major difference is that the reanalysis datasets suggest only a small expansion in winter while the radiosonde results suggest an expansion all year round. One possible explanation is that the reanalysis datasets are derived across the entire Southern Hemisphere, while the radiosonde data are focused on the Australia – New Zealand region.

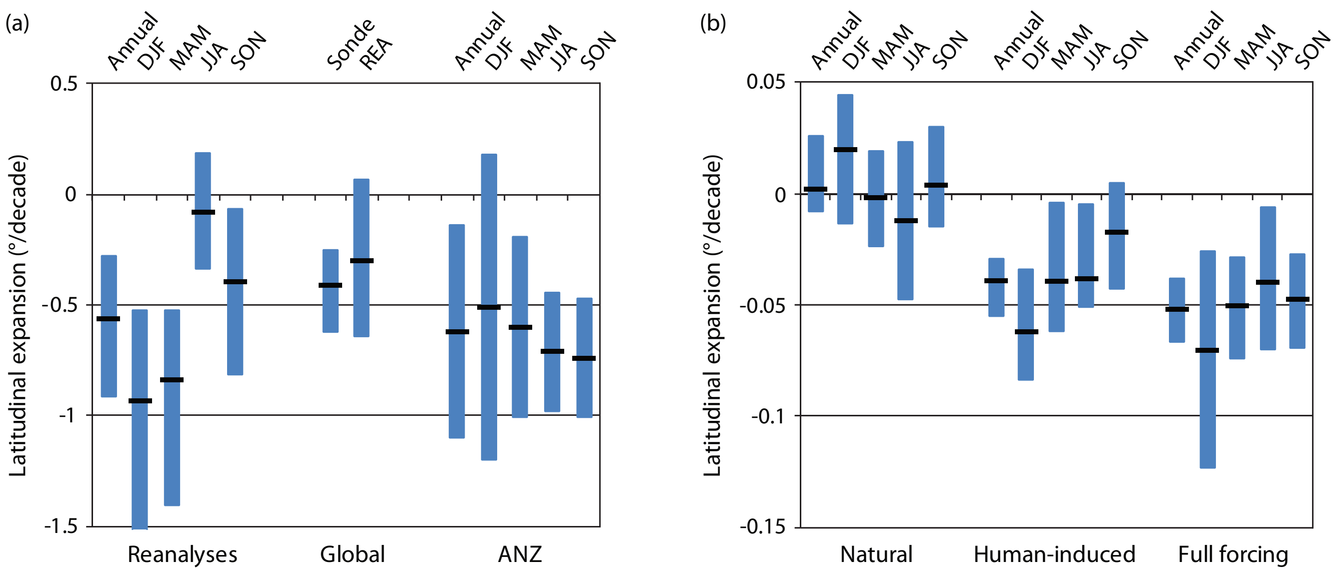


Figure 8. Trends in degrees latitude per decade for a range of indicators of the Hadley circulation expansion. (a) Average of Hadley circulation width from eight reanalysis datasets, edge of the tropics for the globe as derived from radiosonde data alone (Sonde) and from radiosonde and reanalyses data (REA) for the annual mean alone, and for just Australia and New Zealand (ANZ) for the annual mean and the four calendar seasons as derived from radiosonde data alone. (b) Expansion of the tropics as modelled by a global climate model (CCSM3), for natural forcing alone, human-induced forcing alone, and full forcing. Note the different scales on y-axes of the two figures. The black line represents the median and the blue bar the range of results.

(Source: Nguyen et al., submitted; Lucas et al., in press).

Attribution of observed changes

Climate model simulations of the 20th century were analysed in order to determine possible causes of the expansion of the tropics. When the NCAR CCSM3 global climate model was driven with natural inputs only (solar input changes and volcanoes, Figure 8 (b)), the Hadley circulation showed a slight shrinkage. Only when human-induced inputs (greenhouse gases, aerosols and stratospheric ozone depletion) were added did the Hadley circulation show an expansion. However, the rate of expansion is much reduced compared to that observed in the reanalyses (about one-tenth the size). Results from a second global climate model (CSIRO Mk3.6) were also analysed. It gave an expansion even less than that of the CCSM3 model. As the CSIRO Mk3.6 model also underestimates the magnitude of global warming compared to the CCSM3 model, this may indicate that the tropical expansion and broadening of the Hadley circulation are related to global average temperature. The results of the global climate models indicate that the expansion of the Hadley circulation is partly related to human-induced changes in atmospheric composition. This is shown in Figure 9 (a) where in the natural forcing runs, the cloud of points remains close to zero. Only when human-induced factors are included in the models and global temperature rises does the Hadley circulation show an expansion over the 20th century comparable in magnitude to that indicated by the reanalyses, although the models need a much larger warming to produce the same signal as seen in the reanalyses.

The extent of the Hadley cell is associated with both the intensity and the position of the sub-tropical ridge. It is perhaps surprising that the intensity of the sub-tropical ridge has only a weak association with the intensity of the Hadley circulation, but a stronger relationship with the Hadley cell expansion (Figure 9 (b)). Autumn is the critical season when both Hadley circulation broadening and the relationship between the sub-tropical ridge intensity and rainfall is observed. Earlier in summer, the sub-tropical ridge does not have a major influence on rainfall, while later in winter the Hadley circulation expansion is far less pronounced. These observed changes involve complex interactions between the strengthening and displacement of the sub-tropical ridge in the transition season of autumn, when the sub-tropical ridge shifts from south of the region in summer to north of the region in winter. In autumn, if pressures in the ridge are high, then below average rainfall can be expected across the region. However, if the position of the ridge is further south, even with relatively high pressures in the ridge, autumn rainfall can be above average (e.g. autumn 2007 and March 2010 and 2011). This is a summer-like, tropically-influenced autumn season where rainfall originates mainly from more northerly systems. Winter-like wet autumns are characterised by low pressures and a more northerly position of the ridge, with rainfall originating primarily from systems embedded in the westerly wind belt south of the ridge. Such winter-like wet autumns, once common, have not been observed in the region since 1995 (Whan et al., submitted).

Irrigation spray boom in lucerne crop near Albury, NSW, 2001 © CSIRO

Projection of future changes

Climate model simulations generally suggest a Hadley circulation poleward expansion of a further 1 to 2° of latitude (approximately 100 to 200 km) by the end of the 21st century, and an expansion of the sub-tropical dry zone coincident with this change. However, climate models predict a slower rate of expansion than has been observed thus far (0.5° per decade since 1979 as stated above), and thus this projection may be an underestimate. Some studies (e.g. Davis and Rosenlof, 2012) have reported a greater projected expansion of the winter cell in the Southern Hemisphere and also a north-south asymmetry, with greater expansion in the Southern Hemisphere. This could be explained by the direct radiative effects of greenhouse gases and stratospheric ozone depletion or by the differences in orography between the Northern and Southern Hemispheres.

Climate models project that the sub-tropical ridge intensity in the vicinity of Australia will increase over the 21st century while its mean position will move further south (Kent et al., 2011). These observed (and predicted) changes in the mean meridional circulation are likely to lead to decreases in cool season rainfall and little change or slight increases in warm season rainfall. These predicted changes are seen in the projections given in this report. However it is important to note that global climate models do not represent all of the climatic features well. For example, most climate models fail to reproduce the correlation between the sub-tropical ridge intensity and south-eastern Australian rainfall.

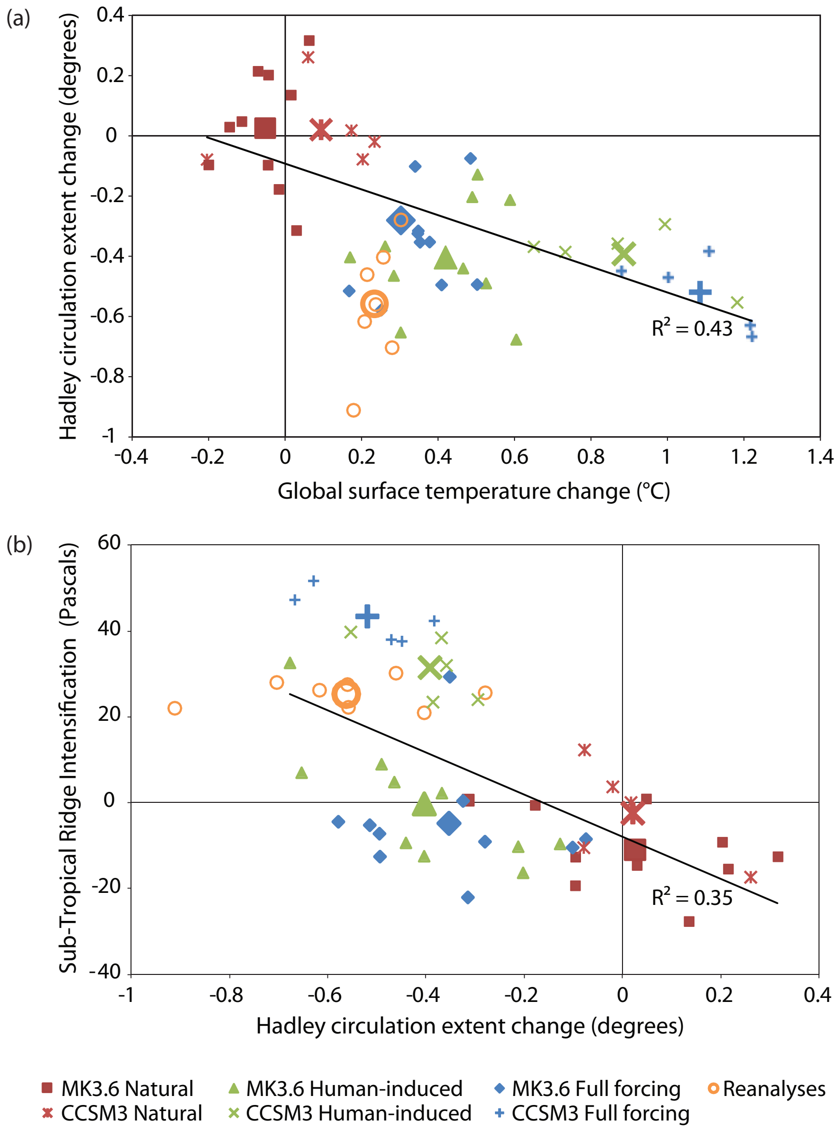


Figure 9. (a) Relationship between global warming and Hadley circulation expansion and (b) between Hadley circulation expansion and sub-tropical ridge intensification across a range of global datasets: eight reanalyses (orange circle), two climate model simulations (NCAR CCSM3 and CSIRO Mk 3.6) of the 20th century using different external inputs (natural only: red symbols, human-induced: green symbols and full forcing: blue symbols). In all instances, individual model simulations are shown as well as model averages (bold).

Box 3: The mean meridional circulation

The mean meridional circulation acts to transport the solar energy received in the equatorial regions to higher latitudes. In this process, water vapour and its phase transitions are crucial, as are radiative effects. The feedbacks between these processes and the resulting dynamics cumulatively result in the mean meridional circulation as represented in Figure 10.

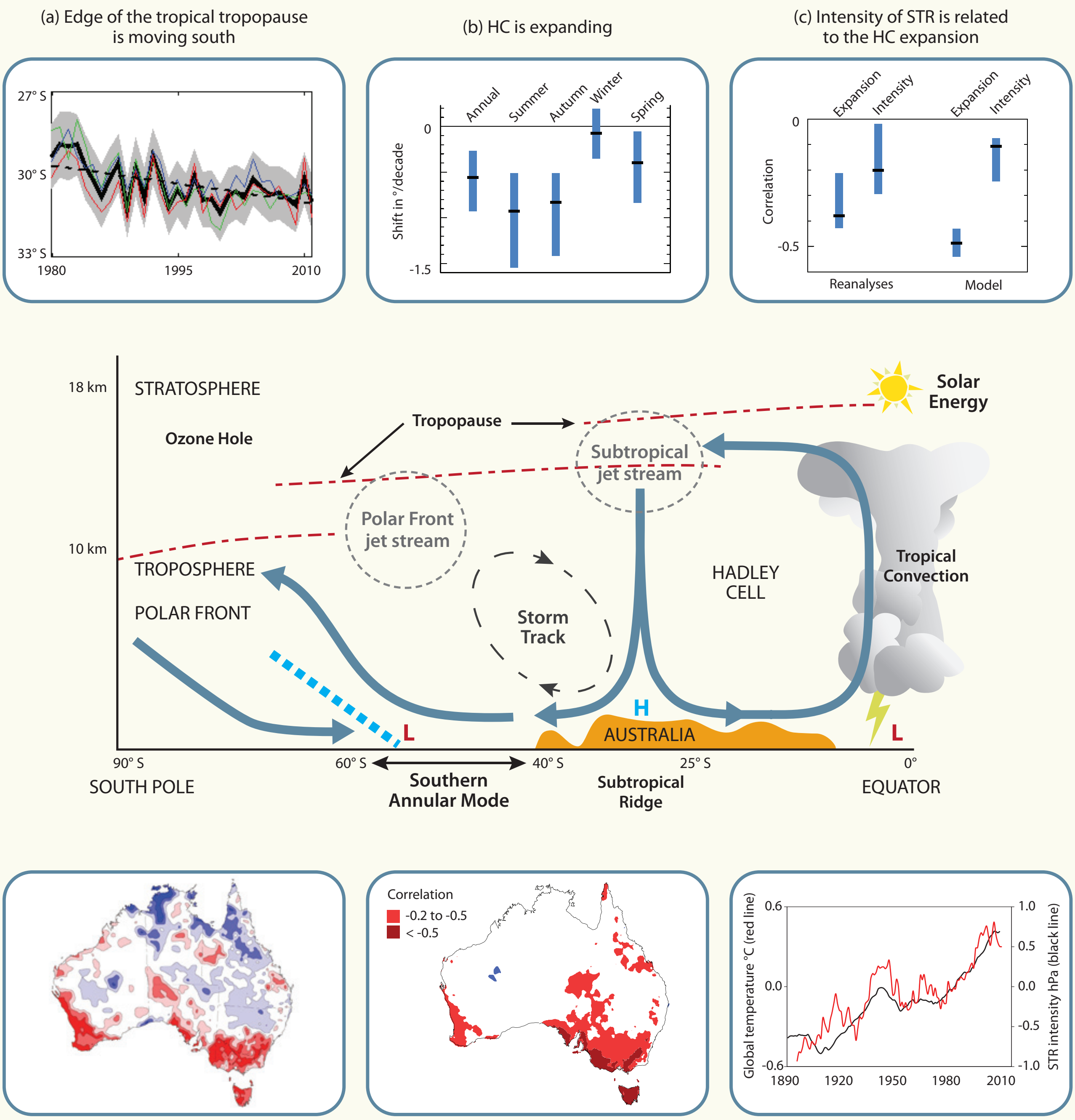
In the ***tropics*** *the overturning Hadley circulation is dominant. The upward branch of the Hadley circulation is associated with tropical thunderstorms. Radiative cooling drives the descent. The sub-tropical jet stream marks the end of the upper arm of the circulation. Low-level trade winds close the loop.*

The ***sub-tropics*** *are that part of the hemispheric mean meridional circulation which is relevant to south-eastern Australia. We define this region as extending from the descending branch of the Hadley circulation poleward to the polar front. The region is dominated by subsidence of air forming the sub-tropical ridge, resulting in relatively dry air and little rainfall. That rainfall which does occur tends to be delivered by mid-latitude storm tracks. Both the descending branch of the Hadley circulation and tropical/extra-tropical interactions are important here. These influences vary both seasonally (e.g. the sub-tropical ridge migrates southward in summer, when extra-tropical influences become less important over south-eastern Australia) and inter-annually (e.g. variability of the equatorial ocean as indicated by the Southern Oscillation Index influences the extent of the Hadley circulation).*

In the ***extra-tropics*** *the 'polar front' is dominant and marks the region of the 'mid-latitude storm tracks'. The position and variability of the polar front is related to the annular modes (the SAM in the Southern Hemisphere). Moist air ascends in the polar front, precipitates and subsequently returns towards the equator.*

These circulations extend through the troposphere, whose upper boundary is marked by the tropopause. The tropopause height changes markedly between the tropics (15–16 km) and the extra-tropics (12 km or less). The sub-tropics have tropopause heights characteristic of both the tropics and the extra-tropics.

Figure 10. The mean meridional circulation between the Equator and the South Pole is made of several key components as shown in the central figure. In addition (a) the tropical tropopause is moving south; (b) the Hadley circulation (HC) is expanding; the intensity of the sub-tropical ridge (STR) is related to (c) the Hadley circulation (HC) expansion and (d) the global average temperature; while (e) the annual rainfall deficiency is inversely related to the intensity of the sub-tropical ridge (STR), particularly in that part of the continent (f) where rainfall has declined for the months of April to July over the last 30 years.



(f) April-July rainfall deficiencies (red) (1982-2011) coincide with areas where STR intensity influences rainfall

(e) Annual rainfall is related to intensity of STR across southern Australia

(d) Intensity of STR is related to global temperature

How does climate variability and change affect water availability?

Estimating future water availability under a changed climate involves three main components: global climate modelling; downscaling global and regional climate simulations to the catchment and region of interest; and hydrological modelling (Chiew and Prosser, 2011; Chiew et al., 2011). These three components are illustrated in Figure 11. There is uncertainty associated with each of these modelling components. The following sections describe the methods used in SEACI to estimate climate change impacts on water availability including an assessment of the uncertainty in each step, followed by the projections of future rainfall and water availability.

In climate modelling, there is uncertainty around the future level of greenhouse gas emissions, how the global climate (including the concentration of greenhouse gases in the atmosphere) will respond to the emissions, and how the regional climate will change in a warmer world. To quantify and reduce the uncertainty, SEACI research assessed a range of results from global climate models with a view to placing more weight on projections from better models.

Global climate models operate on a very coarse spatial resolution. For example, Victoria is typically represented by less than five cells in most global climate models. For regional and catchment hydrological modelling, SEACI research uses statistical and dynamical downscaling models to downscale coarse resolution global climate model outputs to daily rainfall and other climate variables at the catchment scale.

Future water availability is driven by changes in climate input characteristics as well as potential changes in the climate-runoff relationship and dominant hydrological processes in a warmer and higher CO_2 environment. SEACI research has assessed and used hydrological models to predict climate change impacts on future streamflow. It has also investigated how reduced connection between surface and groundwater, and interception activities like farm dams, in long dry spells can accentuate the impact of climate change on future water availability.

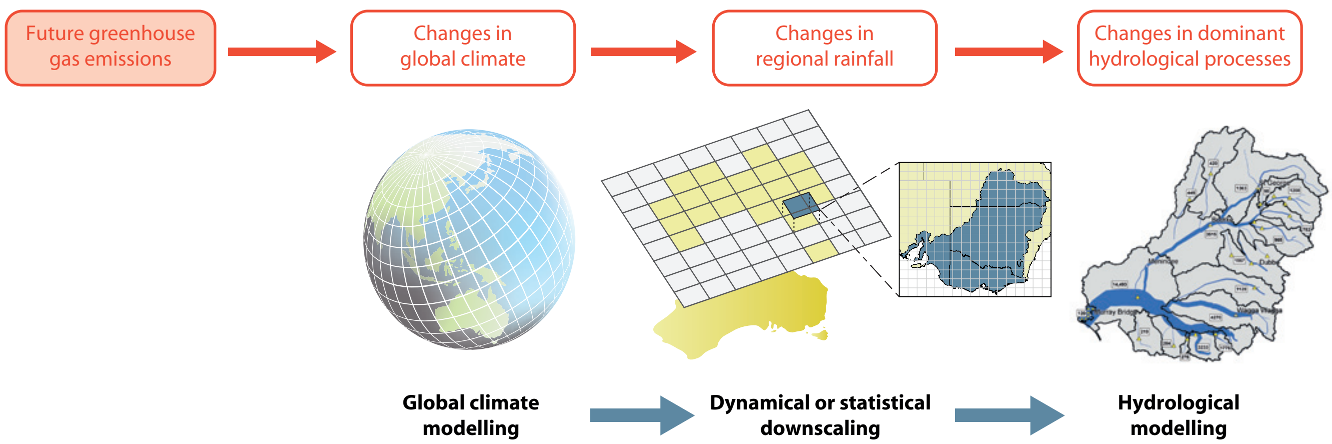


Figure 11. Modelling components for estimating climate change impact on future streamflow with the main sources of uncertainty shown in red.

Assessing and weighting global climate models

There is a large body of literature on assessing the performance of global climate models and how best to combine results from different models (e.g. Chiew et al., 2009; Smith and Chandler, 2009). The rationale behind these assessments is to give more weight to models that can simulate observed historical climate characteristics, as they may be more likely to provide reliable future projections. However, there are many different ways to assess and weight models, resulting in a lack of consistency and comparability between studies.

SEACI research has developed a framework for consistently assessing how well a global climate model can simulate the (i) historical climate characteristics, (ii) large-scale climate-ocean indices that correlate with regional climate, and (iii) relationships between climate-ocean indices and regional climate (Kirono et al., 2011). The framework considers several widely used skill scores including the M-Statistic (a skill score, as defined in Watterson (1996)) used for the CSIRO and Bureau of Meteorology climate change projections for Australia (CSIRO and Bureau of Meteorology, 2007). This framework was used to assess the CMIP3 models (Kirono and Kent, 2011).

Figure 12 shows the M-Statistic summarising the ability of 23 CMIP3 models to reproduce the observed historical (1961 to 2000) climate across south-eastern Australia, the climate-ocean indices that correlate with rainfall in south-eastern Australia (ENSO, the IOD, the SAM and the sub-tropical ridge) and the correlation between these indices and south-eastern Australian rainfall. Overall, the climate models capture the long term average climatology, but not the inter-annual variability as reflected by their poor performance in representing the large-scale indices and their links with rainfall.

Figure 13 shows the range (as defined by the 10th and 90th percentiles) of projected change in mean annual rainfall averaged across the Murray–Darling Basin for a 1 °C global warming based on all models and on the 'best' five models assessed against different measures. Most of the models project a decline in rainfall across the Murray–Darling Basin. The projected decline in rainfall is different when we select models based on different measures, but the range of results (uncertainty) when using only the best models or placing more weight on the better models is similar to when equal weight is given to projections from all 23 models.

The assessment also indicates that none of the models are consistently better than all the other models for all the measures.

It is recommended that, given:

- the results are very dependent on the measures that the models are assessed against, and
- weighting the better models does not necessarily reduce the range of projections,

for now, climate change projections for hydrological application are probably best developed using all available models, apart from perhaps excluding those models that perform poorly against most of the measures. This will ensure that a fuller range of plausible impacts are represented and is consistent with risk assessment, where there is good reason to retain many climate models to represent a fuller range of potential impact.

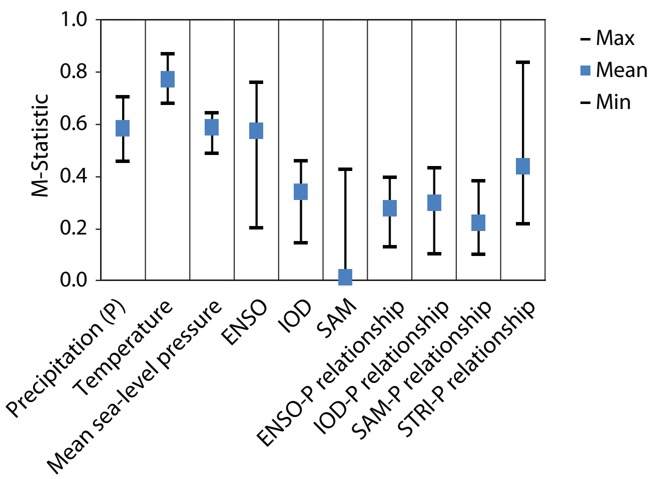


Figure 12. Range of M-Statistic summarising the ability of the 23 CMIP3 models to simulate the observed historical (1961–2000) characteristics over south-eastern Australia. An M-Statistic of 1 indicates a perfect match between the modelled and observed values and an M-Statistic of 0 indicates a very poor match.

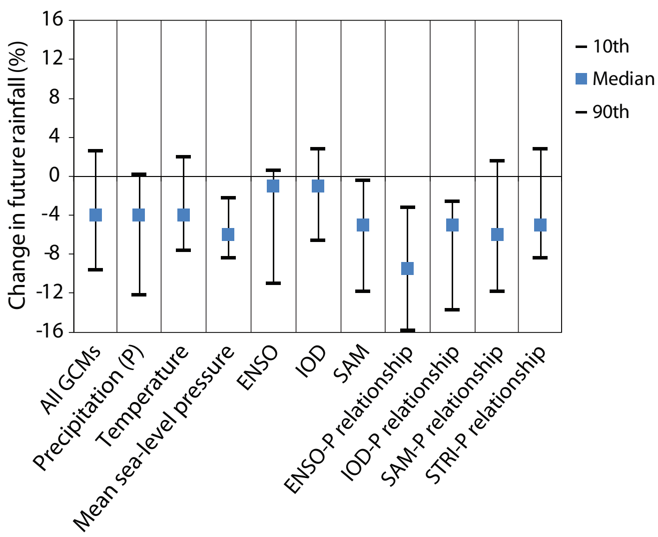


Figure 13. Range of projected change in mean annual rainfall averaged across the Murray–Darling Basin for a 1 °C global warming based on all 23 global climate models (first column) and based on the best five models selected on their performance against the identified measures (Columns 2 to 10).

Downscaling for hydrological modelling

In general, assessments of the potential impacts of climate change on water availability and streamflow characteristics require future climate information at a much finer spatial resolution than global climate models can directly provide. The large majority of these hydrological studies use the 'delta-change' or empirical scaling methods to obtain future climate series to drive calibrated hydrological models to make future water predictions. For example, the future climate series used to model the future water availability projections given in this report was obtained by scaling the historical daily climate series based on the outputs of global climate models (Chiew et al., 2009; Post et al., 2011). This empirical scaling method is simple and robust, and can easily be used with many models and global warming scenarios to represent the large range of uncertainty in future climate and water projections over very large regions. The main limitations of the scaling method are:

- it uses coarse-scale rainfall from global climate models (rather than a more realistic finer scale rainfall), and
- it does not consider potential changes to rainfall characteristics other than the seasonal means and daily distribution (that is, it uses the same sequence of historical rainfall to represent the future).

Statistical and dynamical downscaling models can overcome these limitations of the empirical scaling method. Statistical downscaling establishes relationships between large-scale weather characteristics and observed local scale weather, while dynamical downscaling nests a regional climate model into a global climate model to better represent the atmospheric physics within a limited area of interest. Some of the advantages of downscaling models are that (Teng et al., in press):

- downscaling estimates local rainfall from large-scale climate features that are generally well represented in global climate models,
- climate change projections are provided at finer spatial resolutions,
- downscaling has the potential to reduce the range of uncertainty in future projections because a single precipitation parameterisation can be used in the downscaling technique compared to different parameterisations in different climate models, and
- downscaling considers potential changes to a larger range of rainfall characteristics, such as lengths of dry spells, etc.

Recognising the limitations of empirical scaling, three downscaling methods were investigated within SEACI: analogue scaling (Timbal et al., 2009), Non-Homogeneous Markov Model (NHMM) statistical downscaling (Fu et al., submitted), and dynamical downscaling with the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008).

The analogue downscaling model first defines weather states based on large-scale predictors (the main predictors used here are mean sea level pressure, large-scale rainfall, 850 hPa horizontal wind components and 850 hPa specific humidity). For each day simulated by the global climate model, the analogue model then uses the climate from the day in the historical dataset with the most similar weather state to that simulated by the model. The NHMM statistical downscaling model develops relationships between point or catchment scale rainfall and large-scale atmospheric and ocean predictors, and then uses the relationships to downscale the predictors simulated by the global climate models to point or catchment scale rainfall. Once calibrated, the analogue and NHMM models can be relatively easily used with many global climate models to provide a range of plausible variants of future daily climate series.

WRF is a mesoscale numerical prediction system developed primarily by the National Center for Atmospheric Research (USA) for operational forecasting and atmospheric research. In collaboration with the Climate Change Research Centre (CCRC) of the University of New South Wales, SEACI researchers tested WRF for downscaling purposes across south-eastern Australia (Evans et al., 2012). Whilst dynamical downscaling offers spatially complete and sub-daily estimates of local variables, the computer run time is significant. For this reason, no large-scale hydrological experiments have yet been undertaken with the WRF configurations optimised for rainfall events in the SEACI region.

The spatial distribution of 2046–2065 mean annual rainfall relative to 1961–2000 mean annual rainfall simulated by 10 global climate models is shown in Figure 14 (a), while that downscaled from the same 10 global climate models using the analogue downscaling method is shown in Figure 14 (b). It demonstrates that the analogue method produces rainfall changes at a much finer resolution. The relative difference between the 2046–2065 and 1961–2000 rainfall averaged across south-eastern Australia for both methods is shown in Figure 14 (c). The change in rainfall as determined using the analogue method has a smaller range than that derived directly from the global climate models.

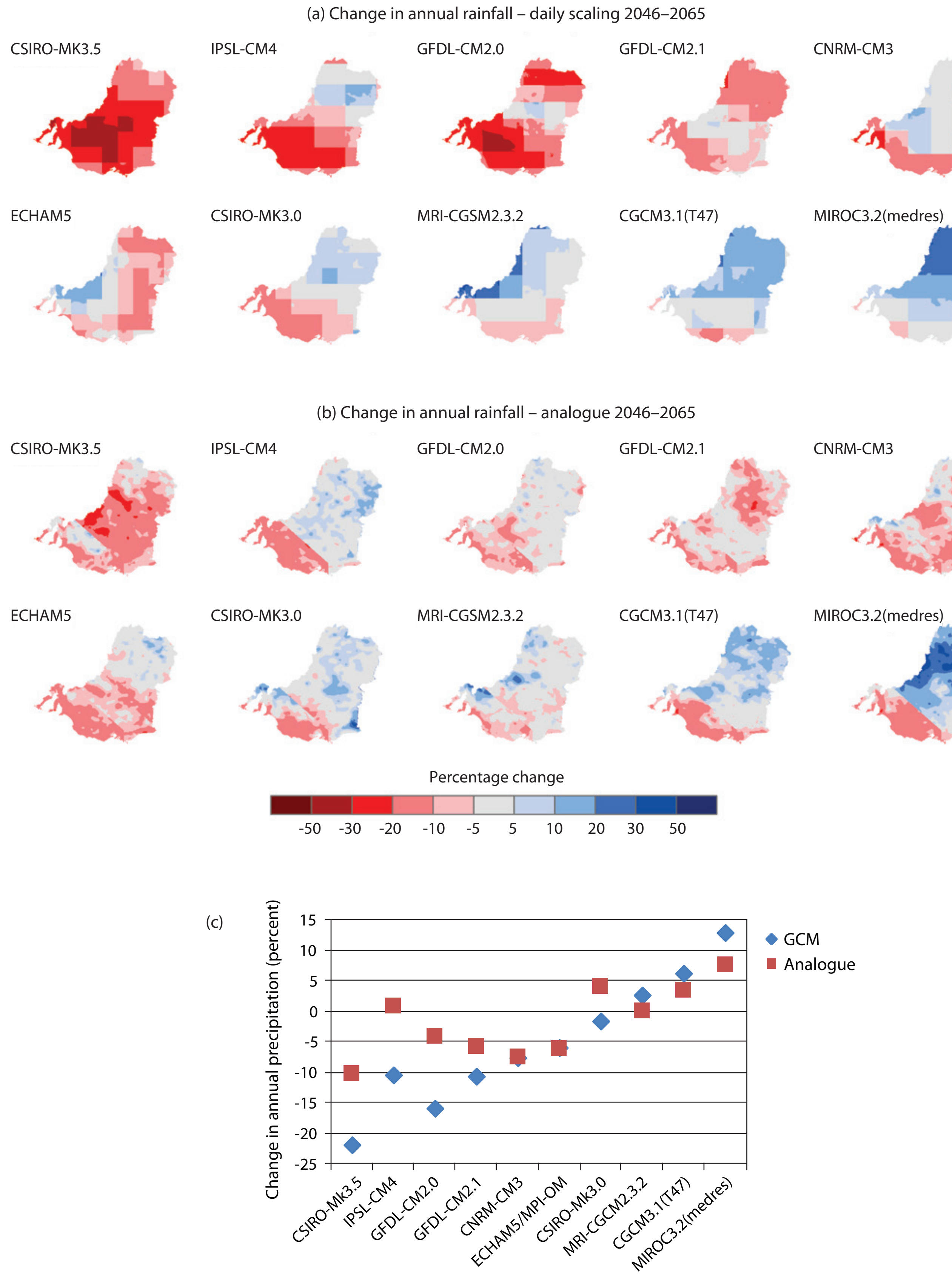


Figure 14. (a) Percentage change in future mean annual rainfall (2046–2065 relative to 1961–2000) across south-eastern Australia from (a) 10 global climate models; (b) analogue downscaling of the same models, and (c) percentage change averaged over the south-eastern Australian region.

Observed and modelled historical (1985–2000) daily rainfall and runoff distributions are shown for one example catchment (the Yea River at Devlins Bridge) in Figure 15. It illustrates that, although promising, the analogue, NHMM and WRF downscaling models do not currently produce daily rainfall sequences that are sufficiently similar to historical rainfall sequences for direct input into hydrological models.

To overcome this problem, various bias correction methods can be applied to 'adjust' the downscaled rainfall for hydrological modelling (e.g. Timbal et al., 2006; Bennett et al., 2012). Figure 15 (a) shows that the analogue downscaled rainfall (which has already been bias-corrected to match mean seasonal and annual rainfall) matches the observed daily rainfall distribution reasonably well (slightly overestimating the peak rainfalls), while the WRF output rainfall (which is not bias-corrected) does not. The best (uncorrected) simulation comes from using daily rainfall downscaled using the NHMM statistical downscaling model (even though the peak rainfalls are still slightly underestimated). SEACI research has shown that the NHMM approach (and most statistical downscaling models) can give realistic daily rainfall because they can potentially be calibrated to directly relate hydrologically-important multi-site or multi-catchment daily rainfall characteristics to large-scale atmospheric predictors. However, the use of the NHMM statistical downscaling model is limited to applications over smaller regions because of the difficulty in calibrating the model for rainfall from large numbers of points (the analogue and WRF models directly produce gridded rainfall over large regions). Figure 15 (b) shows that the inability of downscaling approaches to reproduce the high rainfall amounts will be amplified as errors in modelled high flows and potentially also mean annual runoff.

Many downscaling studies suggest that there is no single best downscaling model and the optimum model will depend on the application and region (Chiew et al., 2010; Frost et al., 2011). SEACI research has shown that downscaling approaches can potentially provide more informative estimates of changes to seasonal and annual local rainfall compared to those obtained by empirical scaling from global climate models. As downscaling cannot currently reproduce all of the relevant characteristics of observed rainfall, downscaled outputs cannot be used directly in hydrological models. However, at the very least, empirical scaling from the finer resolution downscaled outputs is likely to give better spatial projections than scaling directly from the coarse-scale global climate models. Future research efforts should focus on integrated consideration of global climate modelling, downscaling and hydrological modelling, for example, by weighting results from different combinations of models based on their ability to reproduce historical streamflow characteristics.

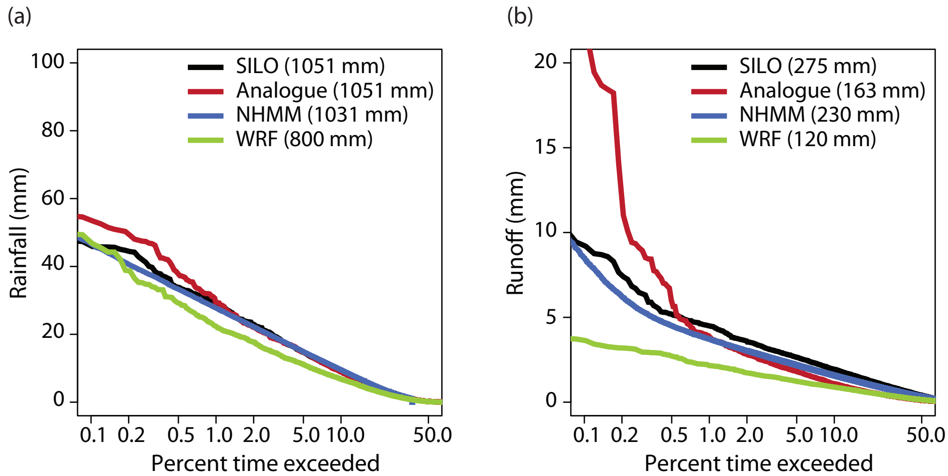


Figure 15. Modelled versus observed (SILO) daily (a) rainfall and (b) runoff distribution (1985–2000) for the Yea River at Devlins Bridge. Daily rainfall is derived from analogue downscaling (bias corrected) NHMM statistical downscaling (fitted to observed rainfall), and WRF dynamical downscaling (non bias corrected) models. Mean annual rainfall and runoff are shown in brackets after the name of the downscaling approach.

Hydrology in a changing climate

The high inter-annual and inter-decadal variability in Australian rainfall and streamflow presents particular challenges for water resources management. See, for example, Figure 16 which shows annual inflows into the River Murray. These challenges are compounded by the potential impacts of climate change; both in terms of impacts on average flows and on the frequency and severity of droughts and floods.

Water managers use long historical records of climate and water data (to characterise hydroclimate variability) and projections of future water availability (to account for climate change impacts) to guide water resources planning. In this section, we describe the challenges in estimating the potential impact of climate change on water resources and streamflow characteristics.

In south-eastern Australia, a 10 percent change in mean annual rainfall is generally amplified as a 20 to 30 percent change in mean annual runoff, while a 10 percent increase in potential evaporation generally results in about 10 percent reduction in runoff (Chiew, 2006; Jones et al., 2006; Teng et al., 2012b). However, these general relationships are different in different catchments and they can also change over time.

For example, the runoff decline during the Millennium drought was unprecedented and higher than would have been expected based on these simple 'rules of thumb'. It resulted in declining storage levels in reservoirs, several years of low water allocations to irrigators in the southern Murray–Darling Basin, severe water restrictions in Melbourne and regional towns, and major environmental impacts (Chiew and Prosser, 2011).

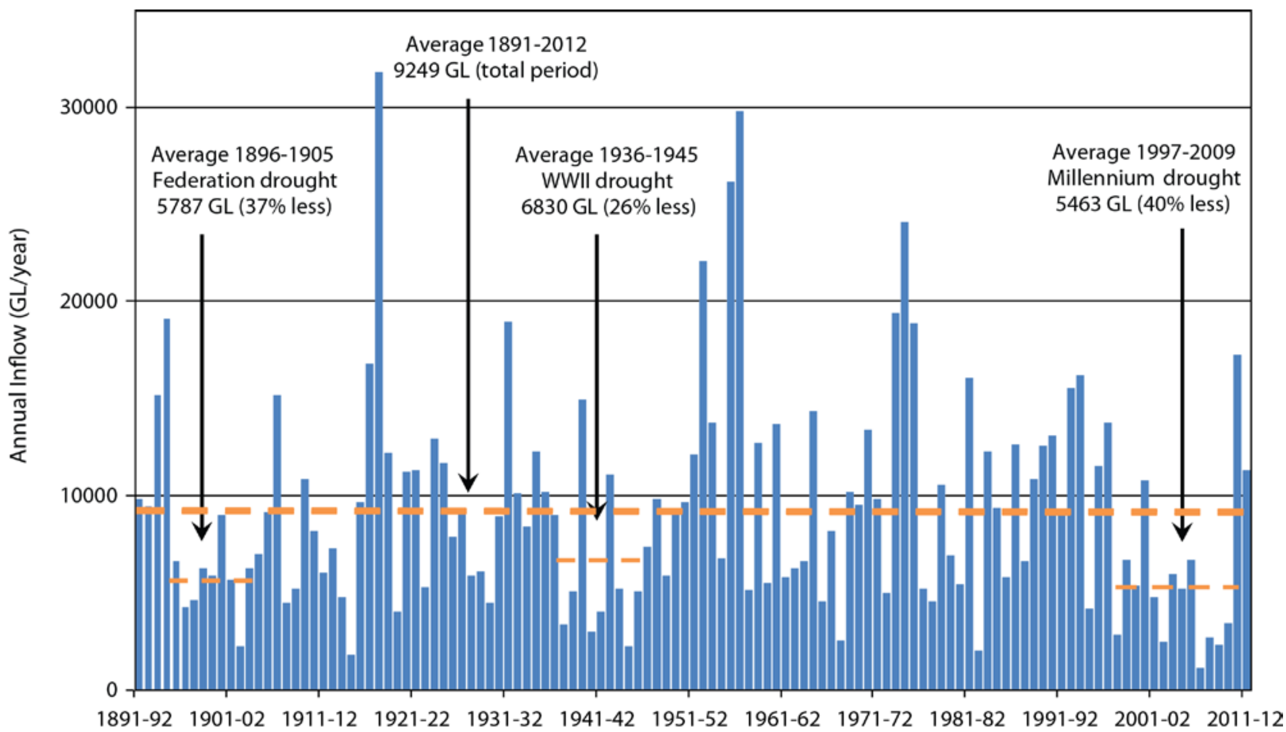


Figure 16. Annual total inflows into the River Murray showing the long-term average, and average inflows during the Millennium (1997-2009), World War II (1936-1945) and Federation (1896-1905) droughts.

SEACI modelling using long-term historical data from the Campaspe River catchment in north-central Victoria indicates that a little over half of the decline in mean annual runoff during the Millennium drought was explained by the decline in mean annual rainfall (Potter and Chiew, 2011). Figure 17 illustrates this and the other climate factors contributing to the unprecedented decline in runoff during the Millennium drought. In decreasing order of influence they were: a reduction in inter-annual rainfall variability (lack of high rainfall years); changed rainfall seasonality (proportionally greater reduction in autumn and winter rainfall, resulting in low antecedent soil moisture at the start of the runoff season and then low winter rainfall during the runoff season); and increased potential evaporation. The relative roles of these climate factors were also found to vary from catchment to catchment across the Murray–Darling Basin (Potter et al., 2010).

SEACI research also shows the importance of using the appropriate spatial scale to estimate the influence of climate on streamflow. This is particularly so for large regions like the Murray–Darling Basin, where the climate (and the projected change in climate) in the runoff generating areas in the upland regions can be very different from the climate in the very large dry areas of the Basin. Empirical regression analysis using observed historical climate and streamflow data from 34 catchments in south-eastern Australia shows that a 10 percent change in annual rainfall results in a 20 to 30 percent change in annual runoff, while a 1 °C increase in temperature alone (after removing the rainfall signal) results in a 0 to 20 percent decrease in annual runoff with an average decrease of 7 percent. Modelling studies using conceptual rainfall-runoff models (Chiew, 2006) and the BIOS2 land surface model (CSIRO, 2012) also show similar results. Previous studies (Cai and Cowan, 2008; Fu et al., submitted) using data aggregated across the entire Murray–Darling Basin showed a runoff response to temperature of about twice the average decrease of 7 percent found here. This was because the use of data aggregated across the entire Murray–Darling Basin, rather than data from catchments and regions where most of the runoff is generated, gives incorrect estimates of the climate (in particular temperature) elasticity of runoff because of the changing nature of the rainfall-runoff relationship with increasing area and dryness. It should also be noted that historical estimates of the temperature influence on runoff are much more uncertain than similar estimates of rainfall influence on runoff, mainly because of the much smaller variability in observed historical annual temperature than in rainfall.

In the near- to medium-term, streamflow is much more sensitive to changes in rainfall than to changes in temperature or potential evaporation (Potter et al., 2011).

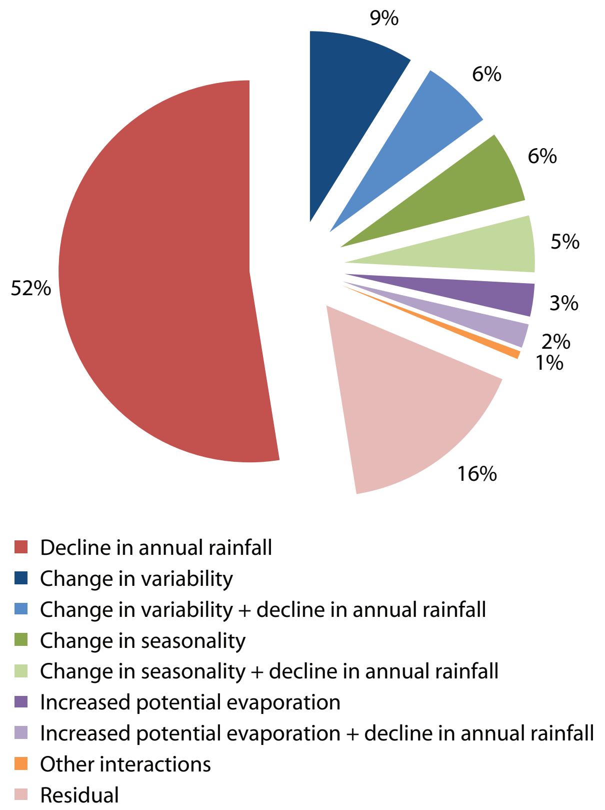


Figure 17. Relative climate influences on the observed decline in streamflow from the Campaspe River catchment in north-central Victoria during the Millennium drought. Change in variability refers to the lack of high rainfall events and change in seasonality refers to the larger decline in rainfall in the autumn and winter months.

In the longer-term, the larger increases in temperature may affect streamflow in different ways. Higher temperatures may drive changes in the amounts, seasonal patterns and characteristics of rainfall. Higher temperatures are also likely to increase the potential for evaporation, as seen in the increase in potential evaporation during the Millennium drought (Roderick and Farquhar, 2011). However, Roderick et al. (2009) noted that potential evaporation does not necessarily increase with increasing temperature, mainly because of the observed reduction in wind speed globally (McVicar et al., 2008).

Reduced connection between surface and groundwater, and interception activities such as farm dams can accentuate the decline in water availability during long dry spells. For example, Figure 18 shows the annual time series of rainfall, runoff, runoff coefficient, number of cease to flow days, and groundwater levels from the Axe Creek catchment in north-central Victoria. The plots show a very rapid decline in runoff as the Millennium drought progressed. The rapid increase in the number of days with no flows, and declines in groundwater levels provide strong evidence of a reduction in subsurface flow to the river. Hydrological modelling with a semi-distributed physically-based process model for several catchments in this region was able to reproduce this feature, showing a non-linear response to surface saturation during extremely dry periods with rainfall replenishing the near-surface and groundwater stores rather than becoming runoff. The modelling also indicates that, starting from an extremely dry catchment, the runoff response to rainfall will only return to 'normal' or 'pre-drought' conditions after 10 to 20 years of average rainfall. In comparison, very large rainfall events (such as those experienced in 2010-12) may return a catchment to pre-drought conditions much more quickly.

SEACI research also shows that changes in groundwater connectivity are most likely to affect runoff from moderate-rainfall low-relief catchments which have hydrologic and topographic conditions that are more likely to lead to a reduced connection between surface water and groundwater in long dry spells (Petheram et al., 2011). However, these catchments are also those with a high density of farm dams. As farm dams intercept proportionally more water during dry periods (Nathan and Lowe, 2011), it is difficult to separate the relative influence of farm dams and surface-groundwater connection in reducing runoff. This is an area of ongoing research which has important implications for future water availability in a warmer and drier climate.

Future water availability may also be affected by the biosphere influence as expressed through catchment vegetation (CO_2 fertilisation), fire dynamics, and ecosystem succession in a warmer and higher CO_2 environment. These processes and feedbacks are complex and they may mediate or exaggerate the rainfall and climate influence on water availability (Betts et al., 2007; Donohue et al., 2009; McVicar et al., 2010). This is a large area of ongoing research worldwide. Preliminary findings from SEACI using the BIOS2 biosphere land surface model suggests that that runoff across the region could increase by around 9 percent per 100 ppm increase in CO_2, other factors remaining constant (CSIRO, 2012).

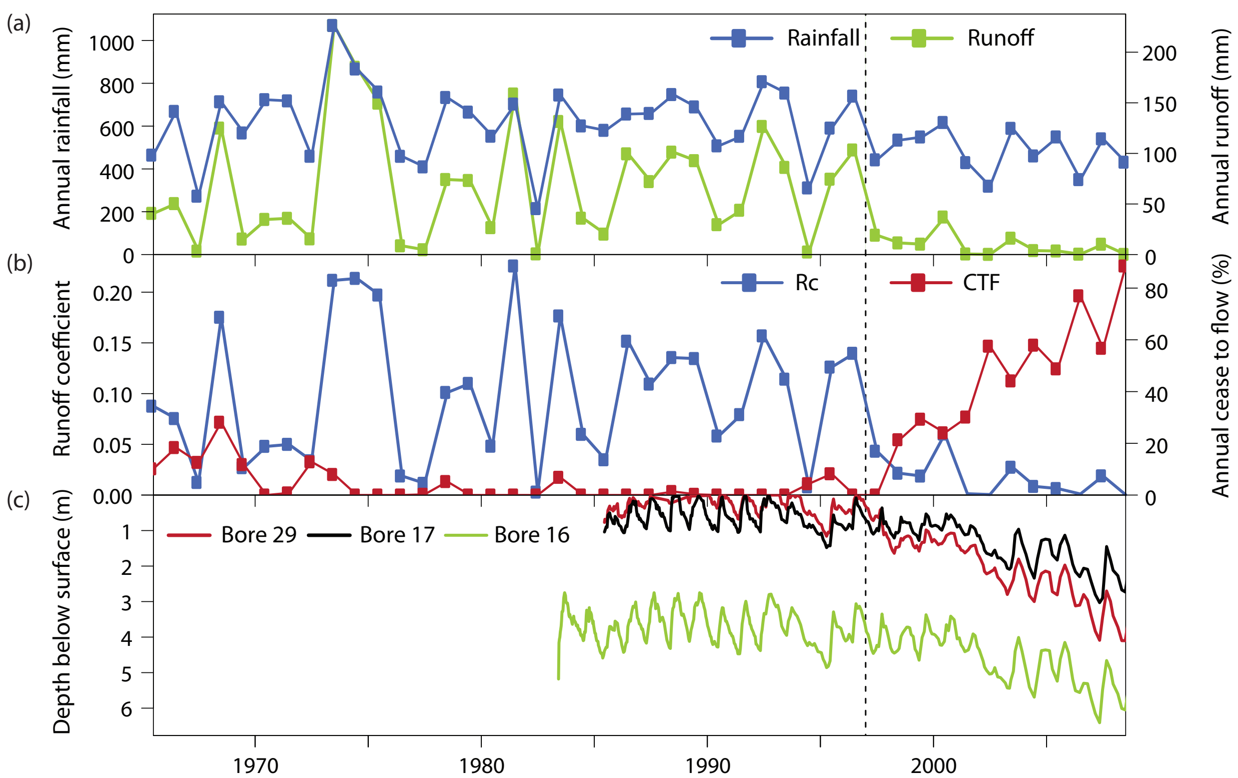


Figure 18. Annual time series of hydrologic metrics for the Axe Creek catchment in north-central Victoria. (a) shows rainfall (blue line) and runoff (green line); (b) shows the runoff coefficient, Rc (blue line) and cease to flow, CTF (red line); (c) shows groundwater levels for three different bores in the catchment.

Projections of future water availability for south-eastern Australia

The projected change in future mean annual rainfall and runoff across south-eastern Australia for a 1 °C global warming is shown in Figure 19. The best estimate of annual average warming for Australia is 1 °C by 2030 relative to 1990 and between 0.8 to 1.8 °C (low emission scenario) and 1.5 to 2.8 °C by 2050 (high emission scenario). The future climate (rainfall and potential evaporation) scenarios were obtained using simple empirical scaling, where changes in seasonal means were estimated from global climate model simulations for 2001 to 2100 and the historical climate data were scaled to reflect the changes in seasonal means and daily rainfall distribution (Chiew et al., 2009).

The scenarios were informed by simulations from 15 global climate models. The future daily rainfall and potential evaporation series were used to run a daily rainfall-runoff model (SIMHYD), using parameter values calibrated against historical data. The hydrological modelling therefore only considered runoff response to changes in future climate. Vaze et al. (2010) showed that this model calibration and simulation approach is reasonable for near- and medium-term projections, but that model parameterisation and calibration for more distant projections must also consider potential changes in the climate-runoff relationship and dominant hydrological processes. Modelling results using several other rainfall-runoff models gave very similar results.

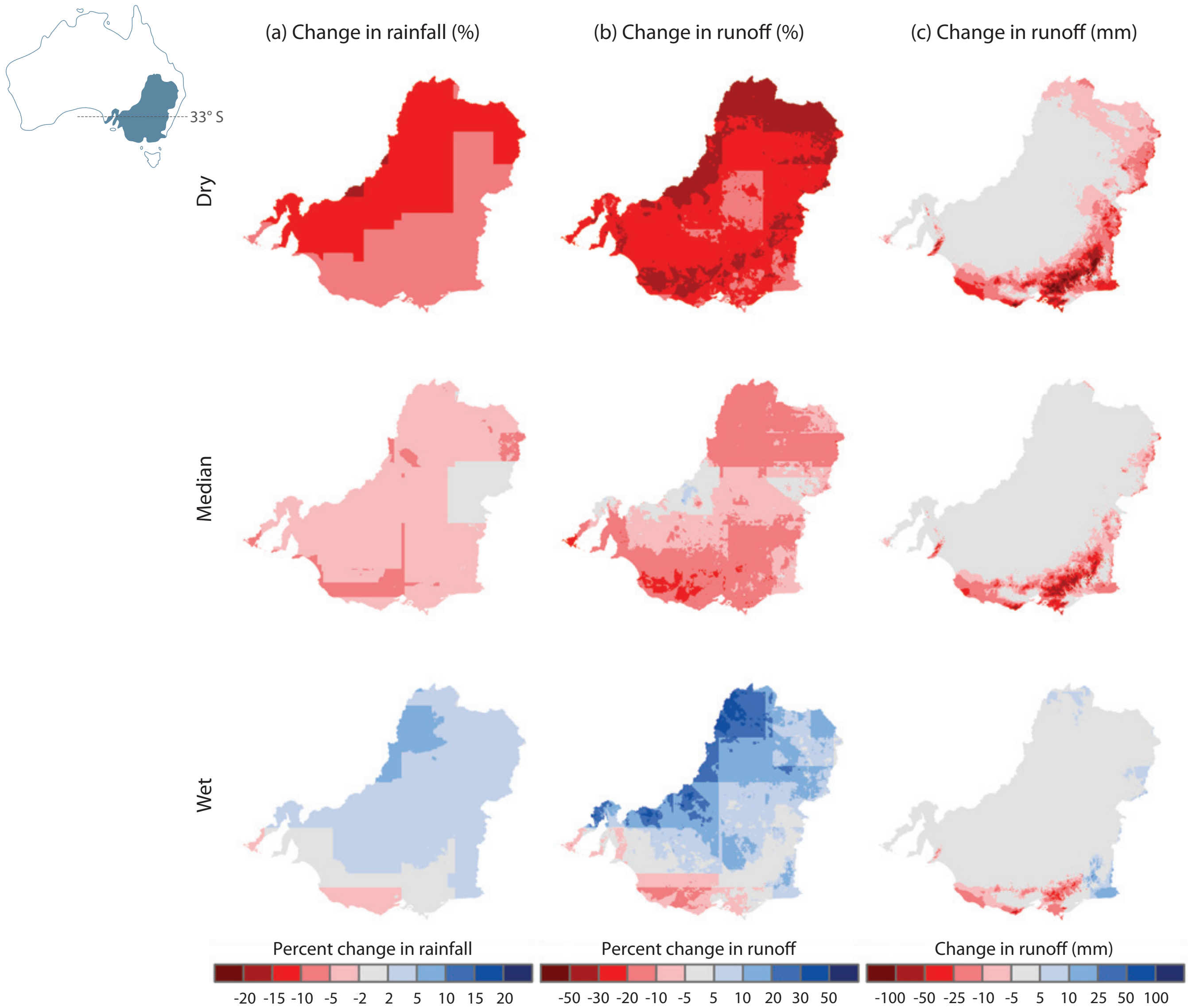


Figure 19. Projected change in (a) mean annual rainfall (percent change); (b) mean annual runoff (percent change); and (c) mean annual runoff (mm change) for a 1 °C global warming. The dry and wet estimates represent the 10th and 90th percentile of projected changes based on the outputs of 15 global climate models.

The large range in future runoff projections mainly reflects uncertainty in future projections of annual and seasonal rainfall (Teng et al., 2012a). Nevertheless, the large majority of climate models indicate that the southern Murray–Darling Basin and Victoria will, on average, be drier in the future. All the climate models project a rainfall decline in winter, when most of the runoff in this region occurs, translating to a considerable reduction in winter and annual runoff. The projections of rainfall decline in winter are consistent with the expected changes in the large-scale atmospheric and oceanic drivers of rainfall in this region in a warmer world as discussed on p17.

Averaged over the southern half of the region (south of 33° S), mean annual rainfall is projected to reduce by 0 to 9 percent (median of 4 percent) and mean annual runoff is projected to reduce by 2 to 22 percent (median of 12 percent) for a 1 °C global warming. There is less agreement in the north. Averaged over the northern half of the region (north of 33° S), mean annual rainfall is projected to change by –11 percent to +4 percent (median of –3 percent) and mean annual runoff is projected to change by –29 percent to +12 percent (median of –10 percent) (Post and Moran, 2011).
The projected decline, as well as the range of uncertainty, is larger for higher levels of warming, and although not scaling exactly linearly (Post et al., 2011) is roughly twice as large for a 2 °C global warming. The projected changes in seasonal and annual rainfall and runoff informed by each of the 15 global climate models for 1 °C and 2 °C global warming can be downloaded from http://www.seaci.org.
The hydrological modelling in SEACI also estimates changes to other streamflow characteristics such as low flows and peak flows that are important for water resources planning and climate change impact assessment and adaptation in water and related sectors. These new projections are described in Post et al. (2012).

Barmah Lake, Victoria, November 2010 © MDBA Photographer Keith Ward

Aerial view of the Cotter Dam showing low water level, near Canberra, ACT, July 2008 © CSIRO

The changes in long-term averages identified here are relatively small compared to the large variability seen in Australian streamflow. The future climate will still produce long wet and dry periods, but the projected decline in the long-term average in south-eastern Australia means that water resources systems will need to be able to cope with more frequent and potentially more severe and longer droughts. The projections in Figure 19 should be interpreted as changes relative to the long-term baseline climate (1895–2009), which as stated on in Box 1 on p12 does not account for the fact that some of the impacts of climate change may have already been observed in the latter part of the climate record and that a shift in the baseline may have occurred. However, until a new climate baseline is definitively established, it is most appropriate to consider these projected changes relative to the long-term baseline (Chiew and Post, 2012). It is also noted that the changes in runoff shown in Figure 19 are less than those seen during the Millennium drought. This is because the projections shown are for departures from the long-term baseline, and should not be interpreted as reflecting inter-annual climate variability. The implications of this are that the streamflow reductions observed during the Millennium drought could be even larger if the conditions that led to it were to recur in a warmer world.

How well can we predict rainfall and streamflow for the next few months and seasons?

Progress in seasonal climate prediction systems

Coupled atmosphere-ocean climate models are routinely used at national meteorological centres worldwide to make seasonal forecasts of regional climate. The basis for making these forecasts is the strong relationship between regional climate and large-scale, slowly varying climate influences such as variations in sea-surface temperature. The success of the seasonal climate forecasts depends both on the strength of such relationships, as well as the ability of numerical models to predict the characteristics of large-scale atmospheric and oceanic circulations and their connection to the regional climate. For south-eastern Australia, the forecast model needs to predict tropical ocean temperatures in the equatorial Pacific and Indian oceans associated with El Niño and the Indian Ocean Dipole, and to simulate the remote impact of these conditions on south-eastern Australian climate via the atmosphere. In order to make forecasts that are reliable as well as accurate (see Box 4 on p33 for definition of these terms), the model needs to produce forecasts that represent the full range of possible outcomes, acknowledging that only a fraction of climate variation each year is predictable. Research in SEACI has improved both the reliability and accuracy of seasonal forecasts.

The model used for seasonal climate prediction in SEACI is the Predictive Ocean Atmosphere Model for Australia (POAMA). SEACI research has led to an improved method to generate the set of forecasts, thereby increasing forecast reliability, and an improved method to define the initial state of the ocean, thereby increasing forecast accuracy (Lim et al., 2010; Wang et al., 2011a). Improved ocean initial conditions are generated by the POAMA Ensemble Ocean Data Assimilation System that incorporates ocean temperature and salinity observations, as well as deriving a range of ocean states to initialise the forecasts. A range of forecasts using slightly different initial conditions is used to account for the facts that the model outcomes have been shown to be highly sensitive to initial conditions, and the accurate observation of these initial conditions is limited by uncertainty in the observations. Forecasts produced in SEACI Phase 1 were overly confident (and hence not reliable). To overcome this, the POAMA2 forecasts use three slightly different versions of the model so as to better sample forecast uncertainty due to differences in model physics and dynamics. Additionally, POAMA2 generates three times more forecasts than POAMA1.5b, which better describe the range of possible evolution of the observed climate.

Forecasts from POAMA2 show a significant improvement in accuracy compared to the previous version of the model, POAMA1.5b, for prediction of the occurrence of El Niño (Wang et al., 2011a). This is attributed to the improved depiction of the initial ocean state provided by the POAMA Ensemble Ocean Data Assimilation System. The improvement in predicting El Niño is found regardless of the starting month for the forecast, although skill is greatest for start months from June–December when El Niño/La Niña is typically well established.

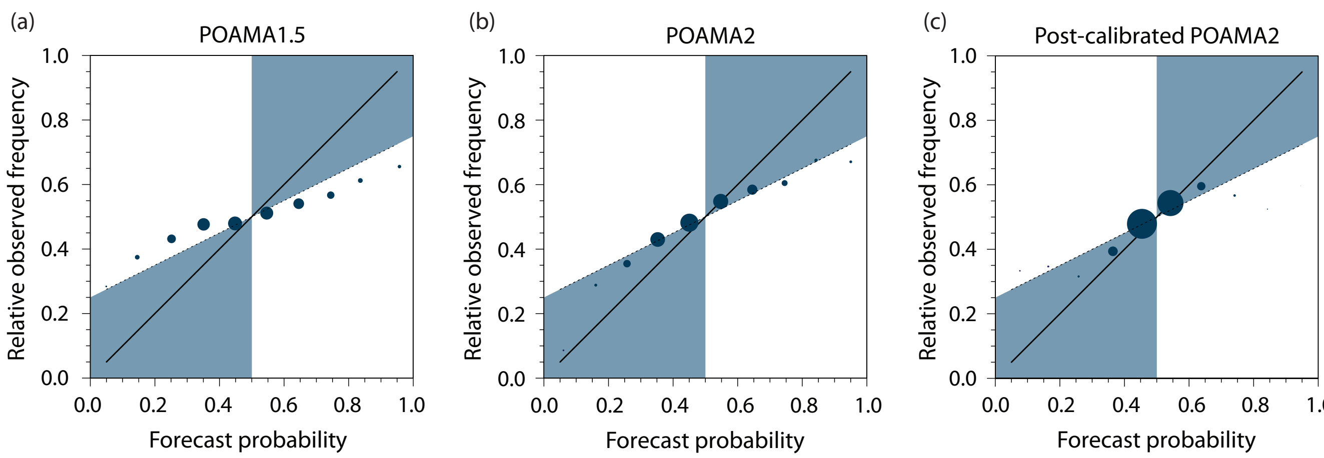


Figure 20. Accuracy and reliability of (a) POAMA1.5, (b) POAMA2 and (c) post-calibrated POAMA2 forecasts of above median rainfall for south-eastern Australia. Forecasts for all points across south-eastern Australia are used for all 12 seasons during 1980–2006 at lead time one month. The size of dots represents forecast frequency in each forecast category. Forecasts in the blue areas are considered to be skilful as they are correct in predicting the occurrence/non-occurrence of above median rainfall, and their errors are smaller than a climatological forecast.

Box 4: Quantifying forecast quality

Forecast quality depends on reliability, resolution and sharpness as well as accuracy. These can be illustrated using an attributes diagram. In the attributes diagram, forecasts of a certain outcome (here, the chance of exceeding median rainfall) are gathered into categories covering a specified range (eg 0-10%, 10-20% etc) and compared to what actually occurred. The total number of forecasts in each category is represented by the size of the dot. The blue area indicates the range where the probabilistic forecasts predict the occurrence and non-occurrence of the event with smaller uncertainties than a climatological forecast and so are considered to have some useful skill.

Figure 21 (a) shows how resolution and sharpness combine to produce a forecast with a certain reliability. Some example attributes diagrams, illustrating their use, are also shown in Figure 21. Figure 21 (b) is an example of a forecast system with high reliability (i.e. all of the dots fall nearly on the diagonal) but low sharpness (most forecasts are near the climatological probability of 50 percent) and the occurrence/non-occurrence of events is not well resolved. These results are typical of a forecast system that has been calibrated by post-processing such as Figure 20 (c).

Figure 21 (c) represents a perfect forecast system, whereby every time the observed rainfall was above median, the forecast was for 100 percent chance of exceeding median rainfall, and every time the observed rainfall was below median, the forecast was for 0 percent chance of exceeding median rainfall. These forecasts are said to have perfect reliability as indicated by the two dots of equal size (each containing half of the forecasts) falling on the diagonal line. These forecasts are also said to have extreme sharpness (in this case either 100 percent or 0 percent). Sharpness is thus the capacity to forecast probabilities away from climatology (i.e. the spread of the forecast probabilities along the x-axis). For this perfect system, the forecasts also perfectly resolve the occurrence and non-occurrence of events (i.e. the range of forecast outcomes along the y-axis).

Figure 21 (d) is an example of a typical seasonal forecast system with poor reliability (the dots do not fall on the diagonal) and low resolution (no matter what the forecast probabilities are, the overall occurrence rate of an event is close to the climatological occurrence rate). The forecasts do however have some sharpness (forecasts are issued with a range of probabilities from 0 to 1). The low reliability is indicative of an overconfident system whereby high forecast probabilities tend not to occur as often as observed and low forecast probabilities tend to occur more often than observed.

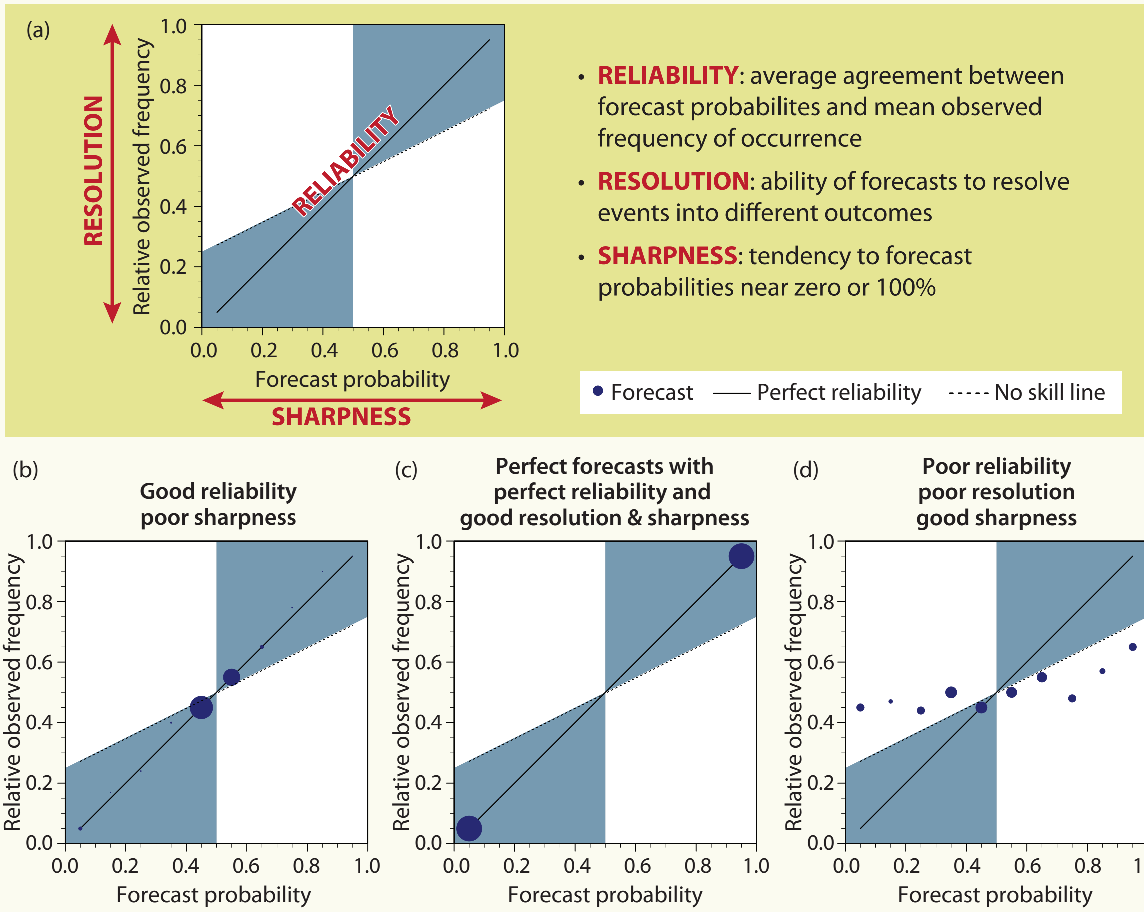


Figure 21. Example attributes diagrams demonstrating representation of reliability, resolution, and sharpness of forecasts (in this case, the probability of exceeding median rainfall).

In contrast to the improved predictions of El Niño, little progress has been made in improving prediction of the IOD. This is probably because although improvements in ocean initial conditions have been made, large model errors related to Indian Ocean variability prevent these improvements from producing improved forecasts. Much of the error appears to originate in depicting the mean climate in the Indian Ocean, and so improvement of the mean climate is currently a high priority research focus.

Another important large-scale climate mode that affects south-eastern Australia climate is the Southern Annular Mode (SAM) (Hendon et al., 2007). As the SAM is driven primarily by internal atmospheric dynamics that have a lifespan of approximately two weeks, it has received limited attention for predictability of seasonal climate despite its significant influence. SEACI research has focused on the feasibility of predicting monthly variations of the SAM. These monthly variations are now able to be skilfully predicted by POAMA2 in the first month of the forecasts, indicating that POAMA is able to represent some aspects of the future evolution of the SAM that depend on the initial conditions. During late spring, modest predictive skill of the SAM is also found with lead times up to six months. This is attributable to the association with El Niño in this season (e.g., L'Heureux and Thompson, 2006; Hendon et al., 2007). The influence of ENSO conditions on the SAM during spring/summer is well captured in the POAMA system.

Seasonal rainfall for south-eastern Australia is well predicted by both POAMA1.5b and POAMA2 for all seasons except late autumn and summer, as indicated by the ability of the models to predict above median rainfall more than 55 percent of the time over the majority of the region for a lead time of one month. Although the performances of POAMA1.5b and POAMA2 are similar (Figure 20 (a) and (b)), POAMA2 rainfall forecasts are more reliable without losing resolution and sharpness, which is attributed to the larger number of forecasts in, and use of three model versions of, POAMA2 (Langford and Hendon, 2011).

The strong 2010 La Niña and associated record wet conditions over Australia (Hendon et al., submitted) provided a challenging but excellent opportunity to test the performance of POAMA2. Credible forecasts for wet conditions in south-eastern Australia for spring 2010 were provided by the POAMA2 system for a lead time of about six months. Predictions for a one month lead time are shown in Figure 22. These extremely high rainfall forecasts were a result of POAMA2 correctly predicting the strong La Niña conditions in the Pacific Ocean together with a negative IOD and a very strong positive SAM, all of which made major contributions to the record wet spring (see Box 2 on p14 for details).

Research in Phase 2 of SEACI indicates that there are good prospects for improving the prediction of seasonal rainfall at longer lead times. The model issues that prevent the good predictions of tropical boundary forcing associated with El Niño and the IOD from being properly translated into good regional rainfall predictions at lead times greater than three months are being addressed for the next version of POAMA. Also, producing multi-model averages in collaboration with other international climate centres appears to be another viable avenue to improve the skill of south-eastern Australia climate forecasts (Langford and Hendon, 2011).

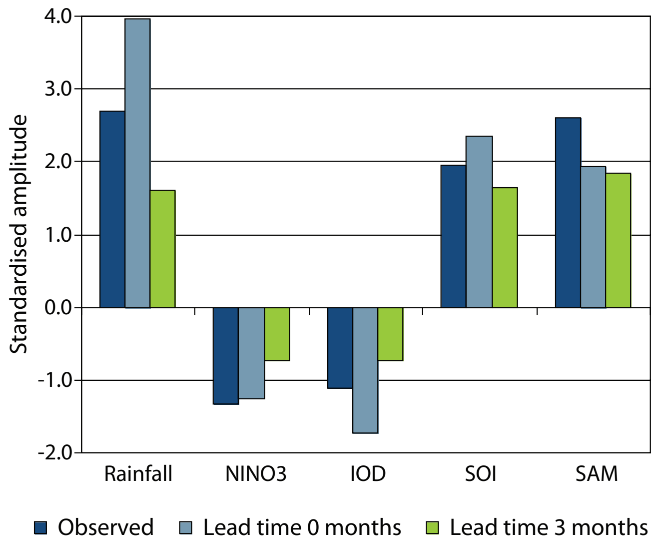


Figure 22. Observed and predicted (lead time 0 months in light blue, 3 months in green) anomalies of various climate indices for spring 2010. From left to right they are: rainfall averaged over south-eastern Australia (here defined as 25°–40° S, east of 135° E), and the NINO3, IOD, SOI and SAM indices. Magnitudes of the indices are in respective standard deviations.

Progress in seasonal streamflow forecasting

Seasonal streamflow forecasts can be useful for the management and allocation of water resources. One of the highlights of SEACI research has been the adoption by the Australian Bureau of Meteorology of the Bayesian joint probability (BJP) modelling approach, which was developed through SEACI in association with the Water Information Research and Development Alliance (WIRADA), as the basis for a new national service for seasonal streamflow forecasting. The operational BJP model uses predictors related to catchment wetness and climate condition to forecast streamflows over the coming three months.

Operational adoption

The Bureau of Meteorology officially commenced the streamflow forecasting service in December 2010. The current service covers more than 50 sites in eastern Australia, and there are plans to roll it out nationally. Probabilistic forecasts of next season streamflows are available from the Bureau's website (www.bom.gov.au/water/ssf). Hindcasts of historical events are also provided, together with skill and reliability assessment information. An example of a seasonal streamflow forecast across a number of sites in Victoria is shown in Figure 23. It shows that, at the height of the Millennium drought, very low streamflows were forecast for most sites for the period September to November 2009.

The operational BJP forecasting model consists of three main components: a modelling engine, a predictor selection module, and a suite of forecast verification techniques.

a) Modelling engine

The BJP forecast model assumes a transformed multivariate normal distribution for the predictor and prediction variables. Bayesian methods are used to infer model parameters including their uncertainties. Forecasts are probabilistic to indicate the likelihood of streamflow in the next season exceeding various volumes. The modelling engine has the flexibility to handle a wide range of variables, including using data that contains missing and non-concurrent records and zero flows for intermittent streams, as well as the ability to handle multiple sites jointly.

b) Selection of predictors

The two principal influences on streamflows for the next season are the catchment condition at the start of the forecast period, and climate during the forecast period. The catchment condition at the time of prediction can be characterised by antecedent streamflows, rainfall or soil moisture. The future seasonal climate can be predicted using indices of large-scale climate anomalies, such as the Southern Oscillation Index. Predictors are selected based on the statistical evidence supporting their inclusion into the forecasting model. Initial catchment condition predictors were selected for their ability to forecast future streamflows, while the predictors of future climate were selected for their ability to forecast future rainfall.

c) Forecast verification

Several measures and diagnostics are used to assess how well probabilistic forecasts correspond to observed streamflows. Skill scores provide an overall measure of forecast performance by assessing the reduction in forecast error relative to a reference forecast (commonly a

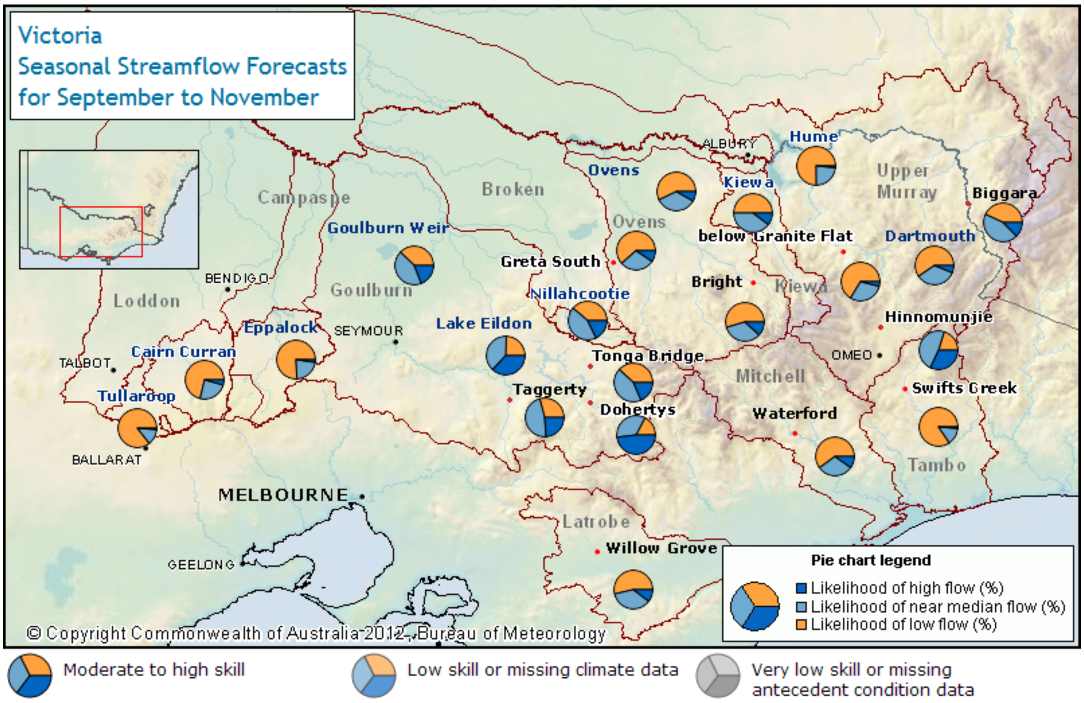


Figure 23. Map of seasonal streamflow forecasts for sites in Victoria, issued by the Bureau of Meteorology for the period September to November 2009. The probabilistic forecasts were produced using the Bayesian joint probability (BJP) operational forecast model.

climatology forecast). More detailed methods are used to assess forecast distribution reliability.

Further Developments

To further improve the BJP forecast model, SEACI research investigated the use of outputs from dynamical hydrological and climate models as predictors to represent catchment wetness and climate condition, as well as the use of multiple models to produce merged forecasts.

The Water Partition and Balance (WAPABA) monthly hydrological model (Wang et al., 2011b) was used to make a prediction of streamflow in the upcoming season under mean seasonal climate conditions. This prediction reflected the influence of initial catchment conditions only and was used as a predictor in the BJP forecast model. This version of the forecast model incorporating WAPABA outputs produced more skilful forecasts than the operational model for most of the catchments tested in eastern Australia. The greatest increases in forecast skill tend to occur:

- when the catchment is wetting up but antecedent streamflows have not yet responded to antecedent rainfall,
- when the catchment is drying and the dominant source of antecedent streamflow is in transition between surface runoff and base flow, and
- when the initial catchment condition is intermittently near saturation.

Two further improvements to the forecasting system were also investigated. These involved the use of multiple models, and the incorporation of rainfall from POAMA in the BJP forecasting model. Because the choice of the best climate index for use in the operational BJP model can be subject to sample error, an alternative is to use multiple models, each with a different climate index. A Bayesian model averaging technique was developed to merge forecasts from multiple models. The merged forecasts are more skilful in many situations. Importantly, the merged forecasts also appear to moderate the errors of the worst forecasts from using only the best climate index. Forecast rainfalls from POAMA were also used as predictors to establish additional BJP models. Forecasts from these models were then merged with forecasts from other available models. The use of the POAMA rainfall forecasts led to some improvement in streamflow forecasts, but only for a few catchments and in some seasons.

Figure 24 shows the skill score from the forecast system incorporating all the model developments outlined above, showing significant improvements in most catchments and seasons over the operational model. The Bureau of Meteorology is currently upgrading its operational model through incorporating the version of the forecast model incorporating WAPABA outputs.

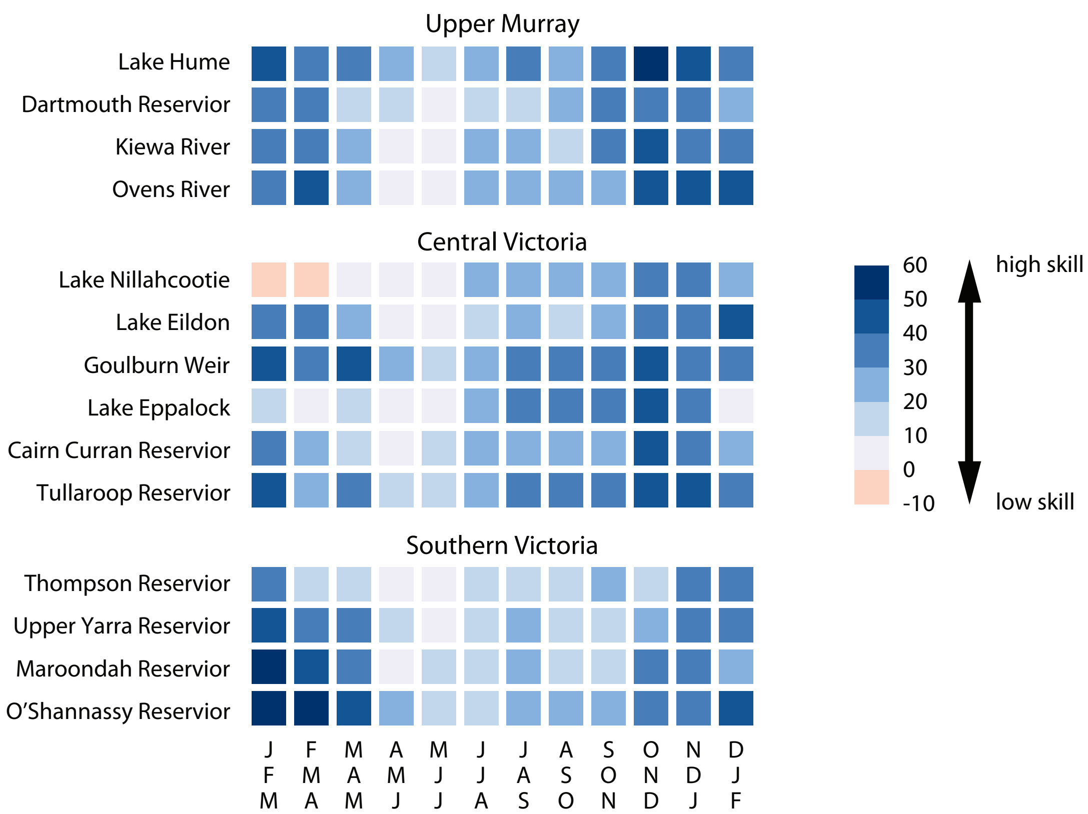


Figure 24. Skill score, in percentage and based on root mean squared error in probability, of merged seasonal streamflow forecasts for 12 overlapping seasons at 14 catchments.

Future directions

Future research should aim to further improve understanding of key climatic and hydrologic processes in order to improve hydroclimate outlooks on time scales from weeks to decades.

Scientific challenges

Phase 2 of SEACI has provided improved understanding of the key drivers of the climate of south-eastern Australia. This has led to improved predictions of climate and water availability on a seasonal timescale, as well as improved projections of water availability for 1 °C and 2 °C of global warming.

Future research directions should further progress our understanding of the key climatological and hydrological drivers of water availability in south-eastern Australia, and determine how these are likely to change in the future. This will lead to improved projections of climate and water availability across a range of timescales from seasonal, to decadal and longer time frames. This can be achieved by reducing uncertainties through:

- determining the key influences on observed changes in the mean meridional circulation and how these changes are likely to progress in a warmer world,
- determining how changes in the mean meridional circulation and other key indices of climate (e.g. ENSO, IOD and SAM) will impact upon future rainfall,
- representing changes in these key climate influences in global and regional climate models,
- determining whether the climate baseline of south-eastern Australia has shifted (as has happened in south-west Western Australia) and how to account for this shift in climate projections,
- developing improved climate and streamflow projections informed by the new CMIP5 global climate models (used in the Fifth Assessment Report of the IPCC), weighted towards the better-performing models where necessary,
- assessing the use of global climate models for climate forecasting several years ahead in order to improve predictions of multi-year water availability,
- deriving improved projections of rainfall using downscaling which account for changes in rainfall extremes and sequencing,
- determining how the rainfall-runoff relationship changes under conditions of extended drought, and the implications of this for projections of water availability,
- adapting hydrological models to represent changes in the rainfall-runoff relationship under drought conditions, and
- determining how the rainfall-temperature-runoff relationship may change under enhanced CO_2 conditions through changes in biological water demand and vegetation function.

Science delivery

In addition to carrying out research to improve projections of future climate and water availability, it is important to ensure these projections are delivered to end-users in a format which can be used to improve the application of projections for water resource management and planning.

While SEACI will not continue in its current format, some of the key learnings from SEACI can be used to guide the development of future regional climate-hydrology research programs. One of these is the value of having an active Science Panel, composed of a mix of researchers, independent experts and key stakeholders. Such a structure allows for regular communication both within the research team, and importantly, between the research team and the end-users. It keeps the research on track to deliver to end-users, and the independent experts ensure that the research is world-class. The value of a properly-functioning, representative Science Panel cannot be overemphasised.

It is also vital for regional climate science programs to be in regular communication with related programs. The key influences on the climate of south-eastern Australia are also those that influence the climate of south-western Australia, southern Australia, and much of the remainder of the continent. There is a large body of researchers working in these areas, and regular communication is essential. Formal and informal means of maintaining cross program relationships should be considered in the early stages of program development with appropriate institutional structures and resourcing allocated to promote cross-program collaboration.

Finally, having the hydrology and climate research community working together provides benefits to both parties. Climate is clearly the main driver of hydrology, and in turn, the needs of the hydrological community can influence the research focus of the climate community, recognising for example the importance of capturing hydrologically-relevant aspects of rainfall (extreme rainfall events, changes in the length of dry or wet spells, three-day rainfall totals, etc) in their climate models. The nexus between climatology and hydrology provides opportunities for meaningful interfaces between research disciplines that should be increasingly forged in order to understand the complex interrelationships associated with climate variability and climate change.

Glossary

Cool season

The seven months from April to October inclusive.

CMIP3

Refers to the third Coupled Model Intercomparison Project, or more typically, the global climate models involved in this project. They are also the models used in the IPCC Fourth Assessment Report.

CMIP5

Refers to the fifth Coupled Model Intercomparison Project, or more typically, the global climate models involved in this project. They are also the models used in the IPCC Fifth Assessment Report. Note that to make the numbers line up with the IPCC Assessment Reports, there was no CMIP4.

Downscaling

Commonly, so called downscaling methods are used to derive estimates of local scale climate variables from large-scale global climate model outputs. These methods are typically classed as either statistical or dynamical, where the former includes regression or weather pattern based relationships between large and local scale variables and the latter refers to the use of a fine-scale regional climate model.

ENSO

The El Niño – Southern Oscillation. It can be in an El Niño, La Niña or neutral state. El Niño conditions tend to bring drier conditions to south-eastern Australia, while La Niña conditions tend to bring wetter conditions. It is quantified using the southern oscillation index (SOI) which is a measure of the normalised atmospheric pressure difference between Tahiti and Darwin.

Hadley cell

The name given to each of the two cells of the Hadley circulation, typically the Southern Hemisphere cell as used in this report.

Hadley circulation

The large-scale atmospheric circulation that transports heat from the tropics to the sub-tropics.

IOD

The Indian Ocean Dipole. When the western Indian Ocean is warmer than the eastern part of the ocean, it is termed a positive IOD and it tends to bring drier conditions to south-eastern Australia. The opposite phase is termed a negative IOD and tends to bring wetter conditions to south-eastern Australia. It is quantified using the dipole mode index (DMI) based on the measured difference between sea-surface temperature in the western (50° E to 70° E and 10° S to 10° N) and eastern (90° E to 110° E and 10° S to 0° S) equatorial Indian Ocean.

Mean meridional circulation

The mean meridional circulation refers to the overall atmospheric circulation of the Earth, transporting heat and moisture from the tropics towards the poles. It includes the Hadley circulation.

NINO3

One measure of the state of the ENSO based on the sea-surface temperature in the central Pacific Ocean and used to indicate whether it is in an El Niño, La Niña, or neutral state.

Radiosonde

A scientific term for a weather balloon and its instrument package.

Reanalysis dataset

Synthesised assimilation of historical datasets that aim to describe the state of the climate system in a consistent manner.

SAM

The Southern Annular Mode, a measure of the strength of westerly winds across southern Australia based on the difference between the surface pressure at 40 and 65° S. Positive SAM phases typically result in weaker westerly winds and therefore drier conditions across the western part of south-eastern Australia in winter. In summer, the main impact is an increase in easterly winds, leading to wetter conditions across the eastern part of south-eastern Australia.

SIMHYD

A rainfall-runoff model which uses observed rainfall and potential evaporation data and produces estimates of streamflow. Here, it is run on a 5 km grid cell basis at a daily timestep.

SOI

The Southern Oscillation Index is based on the surface pressure difference between Tahiti and Darwin and used to indicate if ENSO is in an El Niño, La Niña, or neutral state.

Sub-tropical ridge

The region of high pressure that exists across the mid-latitudes resulting from the descending branch of the Hadley circulation.

Warm season

The five months from November to March inclusive.

Walker circulation

The atmospheric circulation that occurs across the tropical Pacific Ocean with air rising above warmer ocean regions (normally in the west), and descending over the cooler ocean areas (normally in the east). Its strength fluctuates with that of the Southern Oscillation.

Water availability

For the purposes of this report, water availability is synonymous with surface water runoff or streamflow from mid-sized catchments (50 km^2 to 2000 km^2).

For more detailed information on Australian climate, refer to www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml

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