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ORIGINAL PAPER

Current drought and future hydroclimate projections in southeast Australia and implications for water resources management

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Abstract Southeast Australia is currently in a prolonged drought. The ongoing drought has placed immense pressure on the limited water resources and a perception that this may be the start of a persistent change from historical conditions. Several studies have suggested that part of the current drought could be associated with global warming, and many global climate model projections for southeast Australia are for a drier future on average. However, it is difficult, if not impossible, to separate a global warming signal from the high natural variability observed over the last two centuries and revealed in palaeo-climate records.

Historically, water resources planning have considered past climate variability over different timescales together with impacts of other drivers of water availability. Currently, projections of future climate are highly uncertain and they are best treated as multiple plausible futures. In the future, improved hydroclimate projections, with reliable probabilistic quantification of uncertainties, would help make more informed risk-based water sharing and management decisions. Given the current prolonged drought and predictions of a generally drier future in southeast Australia, it is prudent to plan for conditions that will be drier than those experienced in the long-term historical climate. For short-term and medium-term planning, the recent climate should be considered as one possible scenario because there is a need to manage the drought and there is every possibility that the drought will continue for some time yet (either under climate change or as part of long-term natural variability).

Keywords Southeast Australia · Rainfall · Runoff · Drought · Climate change · Water resources · Planning and management

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1 Introduction

The southeast Australian region discussed in this article is about 1.4 million km^2 (20% of mainland Australia) (Fig. 1). The region generates more than half of Australia's agricultural income, and more than half of Australia's population lives in the southeastern parts of the region (Australian Bureau of Statistics, http://www.abs.gov.au). The two biggest cities, Sydney and Melbourne, and the national capital, Canberra, are located in this region. The region includes the Murray-Darling Basin and the Southeast Coast drainage divisions, with the Great Dividing Range separating the two drainage divisions.

The development of large-scale water infrastructure through much of the region in a time of relative plenty has raised expectations of reliable and plentiful water availability. Increasing demands are being put on water resources by expanding irrigation, urban populations and industrial water use, and the formal inclusion of environmental flow allocations. The persistent and unprecedented drought in the last decade has placed immense pressure on the water resources. Projections from climate modeling also suggest a drier future in this region. The increasing demand for water and the likely reduction in future water availability due to climate change and development drivers present significant challenges to the management of water resources in the region. The management challenges are compounded

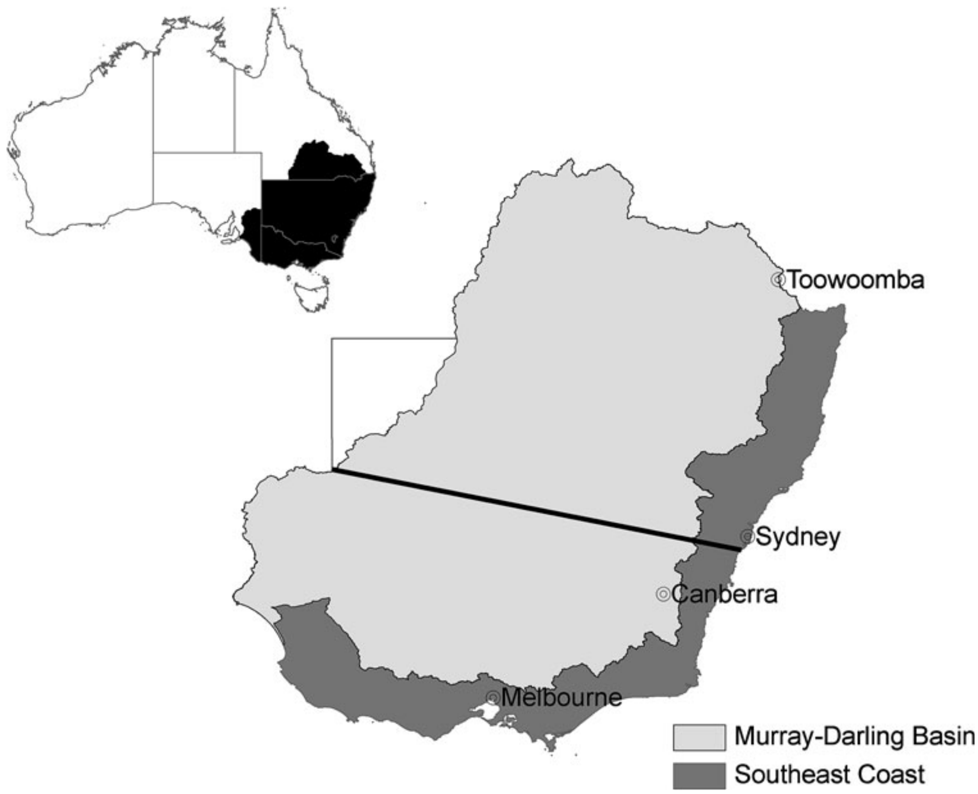


Fig. 1 Study area in southeast Australia

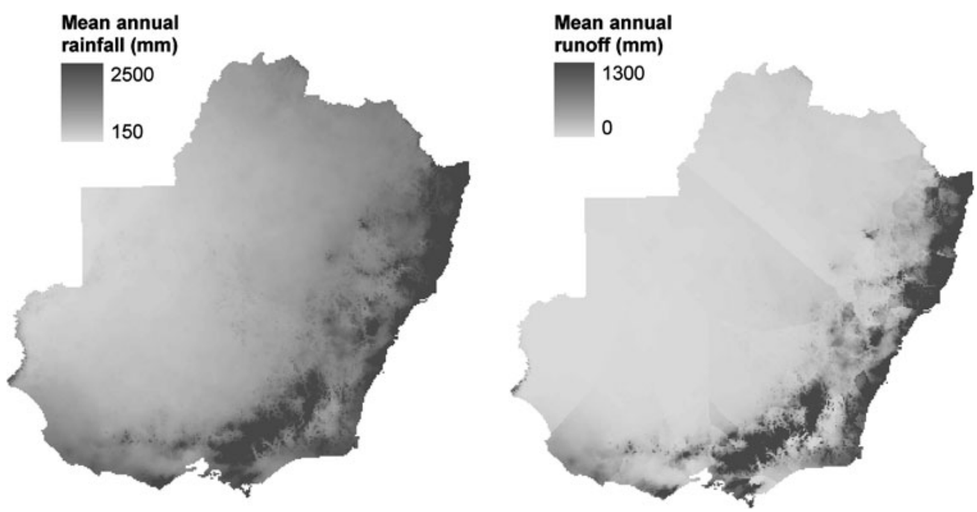


Fig. 2 Mean annual rainfall and runoff (averaged over 1895–2008)

because runoff coefficients are lower and streamflow variability is higher here (and Australia in general) compared to elsewhere in the world (Peel et al. 2004).

The above issues have led to numerous research studies that attempt to put the current prolonged drought in the context of long-term hydroclimate variability and climate change, and to predict future water availability in the region. Results from these studies are being used to guide future resource planning, management, and investment (e.g., development of the Murray-Darling Basin Plan, http://www.mdba.gov.au/basin_plan). This article provides an overview of the hydroclimate, the current prolonged drought and future hydroclimate projections across southeast Australia, based on several research studies, in particular the South Eastern Australian Climate Initiative (http://www.seaci.org) and the Murray-Darling Basin Sustainable Yields Project (http://www.csiro.au/partnerships/MDBSY.html). The implications of a changing hydroclimate on water resources planning and management are also discussed.

2 Rainfall and runoff in southeast Australia

Figure 2 shows the mean annual rainfall and runoff across southeast Australia, averaged over 1895–2008. The rainfall come from the SILO Data Drill (http://www.longpaddock.qld.gov.au/silo), which provides surfaces of daily rainfall and other climate data for 0.05° grids across Australia, interpolated from point measurements made by the Australian Bureau of Meteorology. The runoff is modeled using the lumped conceptual daily rainfall-runoff model SIMHYD (Chiew et al. 2002). The modeled runoff generally compares well with the observed data, particularly in the high runoff areas where there are many gaged streamflow data to calibrate the model. The rainfall-runoff modeling is described in detail in Chiew et al. (2008).

The climate varies considerably across the region, from temperate near the coast to semi-arid and arid further inland towards the northwest and west. There is a strong east to west gradient in rainfall, where rainfall is highest in the southeast and along the east coast (mean annual rainfall of more than 1200 mm) and lowest in the west (less than 300 mm). The gradient in runoff (and runoff coefficient) is much more pronounced than the gradient in rainfall, with runoff in the upland areas in the southeast and along the east coast (mean annual runoff of more than 200 mm) being much higher than elsewhere in the region (less than 10 mm in the western half). Averaged across the region, the mean annual rainfall is 525 mm, of which about 10% (53 mm) becomes runoff. In the north, rainfall and runoff are summer-dominated, and in the south, rainfall is relatively uniform through the year and most of the runoff occurs in the winter-half (Fig. 3) (the line in Fig. 1 approximately separates the summer-dominated runoff area in the north and the winter-dominated runoff area in the south). Rainfall and runoff vary considerably between years and decades (as discussed below; Fig. 6), with the variations largest in the drier areas of the west and least in the wetter areas of the southeast and east coast.

The major atmospheric-oceanic drivers of rainfall variability in southeast Australia are El Niño-Southern Oscillation (ENSO), sea surface temperature anomalies in the Indian Ocean northwest of Australia, and the Southern Hemisphere extratropical circulation (Fig. 4). The influence of ENSO on Australian rainfall has been known for many decades, and major droughts are often linked to El Niño events, when the sea surface temperature rises in the eastern Pacific Ocean and cools in the west around Indonesia (Drosdowsky 2002; Chiew and McMahon 2002; Verdon-Kidd and Kiem 2009).

Recent studies on the Indian Ocean teleconnection have focused on the Indian Ocean Dipole (IOD), which has been linked to the frequency of northwest cloud bands that bring rain to southeast Australia in winter and spring. Low winter and spring rainfall in the southern parts of the region have been associated with a positive phase of the IOD (colder in the east and warmer in the west) or lack of negative IODs (Smith 1994; Ummenhofer et al. 2009; Cai et al. 2009). There is some debate over the influence of the western pole of the IOD, and some studies have shown that the sea surface temperatures around Indonesia and northern Australia alone are strongly related to rainfall variability in southeast Australia, questioning the role of the anomaly in the west Indian Ocean (Verdon and Franks 2005; Nicholls 2009).

The Southern Annular Mode (SAM), which is the dominant mode of the Southern Hemisphere extratropical circulation, operates beyond the weather scale and has been

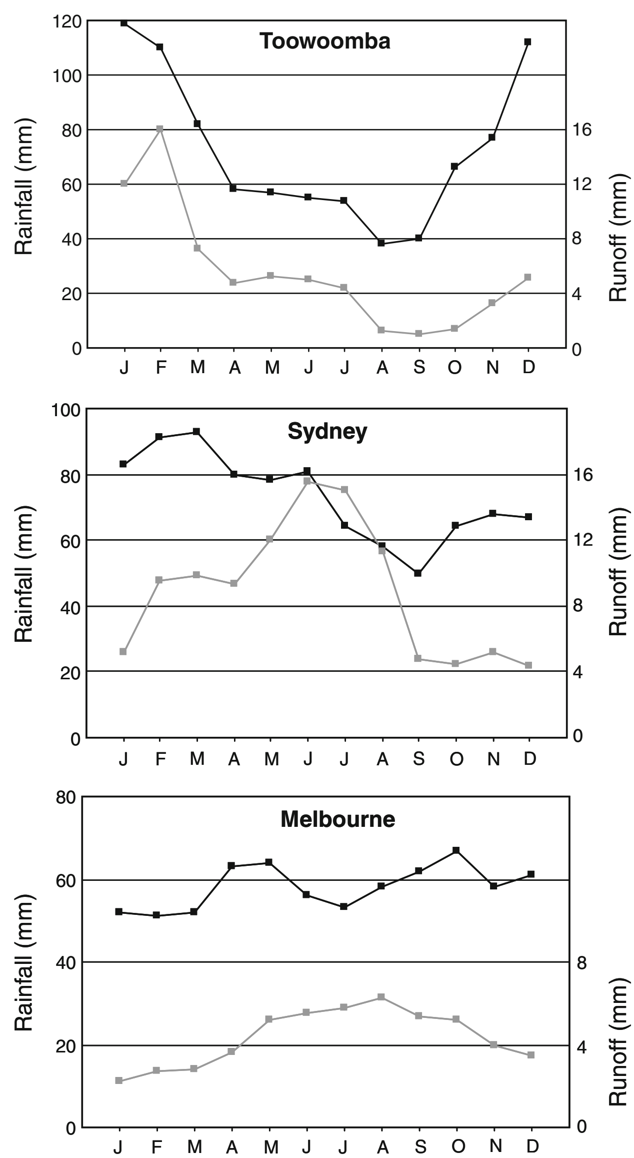


Fig. 3 Mean monthly rainfall and runoff at three locations (averaged over 1895–2008)

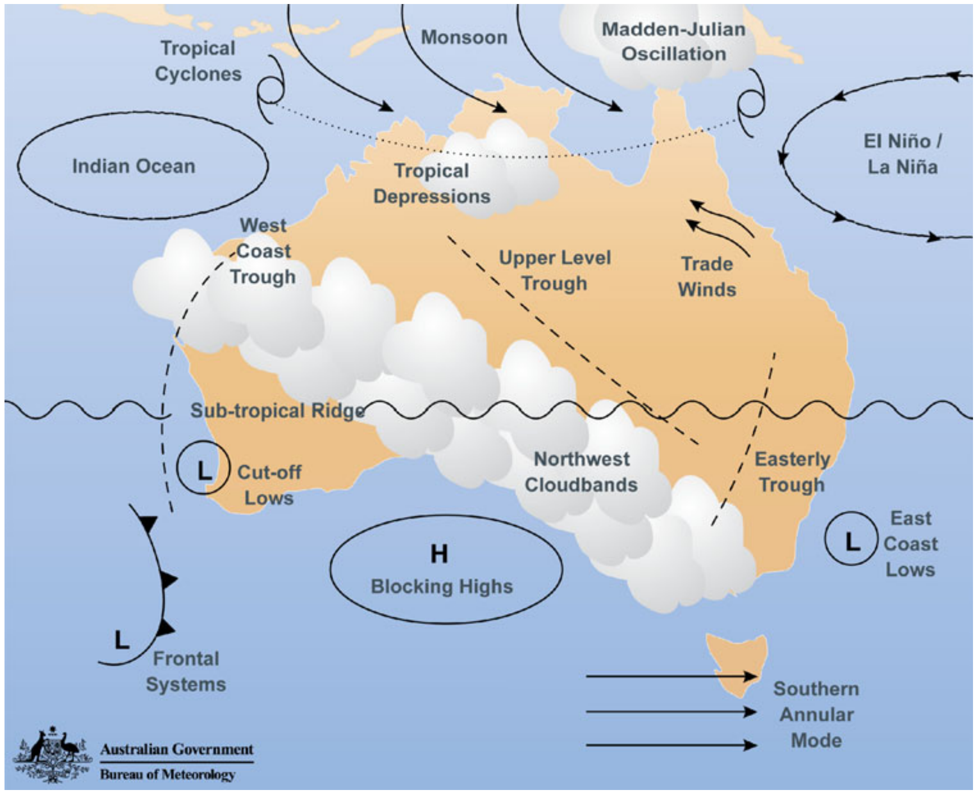


Fig. 4 Atmospheric-oceanic drivers of Australian rainfall (from Australian Bureau of Meteorology)

linked to interannual and interdecadal winter rainfall variations over southern Australia. When the SAM is in a positive phase (low sea level pressure over Antarctica and high sea level pressure over the Southern Hemisphere mid-latitudes), low winter rainfall is more likely across southern Australia (McBride and Nicholls 1983; Nicholls 1989; Hendon et al. 2007). Studies have also shown that the relative phasing of ENSO and SAM can influence autumn rainfall in the southern parts of the region, in that dry conditions are more likely if an El Niño event occurs in combination with a positive phase of SAM (Verdon-Kidd and Kiem 2009).

3 Current drought and global warming

The southern part of the region is currently in a prolonged drought. Fig. 5 shows the difference between the mean annual rainfall and mean annual runoff across the region in the past 12 years (1997–2008) relative to the long-term (1895–2008) means. Figure 6 shows the annual rainfall and runoff time series, averaged over the southern half of the region (south of the line in Fig. 1). Figure 7 compares the mean monthly distributions of rainfall and runoff averaged over 1895–2008 and averaged over 1997–2008.

Rainfall in the past 12 years (1997–2008) averaged across the southern half of the region is 11% lower than the long-term mean (more than 15% lower in the southernmost parts). Nevertheless, rainfall is very variable from decade to decade and there were similar dry periods around 1900 (the 'Federation' drought) and around 1940 (the 'World War Two' drought) (Fig. 6), with evidence pointing towards longer dry periods in the paleo-climate records (Cook et al. 1991; Verdon and Franks 2006). The autumn rainfall decline is the most significant component of this rainfall decline (25% less than the long-term mean and accounting for more than half of the decline in mean annual rainfall). The rainfalls in every month except February and November over this period are also lower than the long-term mean (Fig. 7).

Runoff in the past 12 years (1997–2008) averaged over the southern half of the region is 35% lower than the long-term mean (more than 50% lower in the southernmost parts). This persistent low runoff is unprecedented, with average recurrence interval of more than 300 years in the southernmost parts of the region (Potter et al. 2010). The extreme decline in mean annual runoff cannot be explained by the decline in mean annual rainfall alone. Other factors that have contributed to this extreme decline in runoff include: the disproportionate rainfall decline in autumn (resulting in dry antecedent soil conditions and, therefore, lower winter and spring runoff when most of the runoff in the southern parts of the region occurs); the rainfall decline in the winter-half when most of the runoff is generated

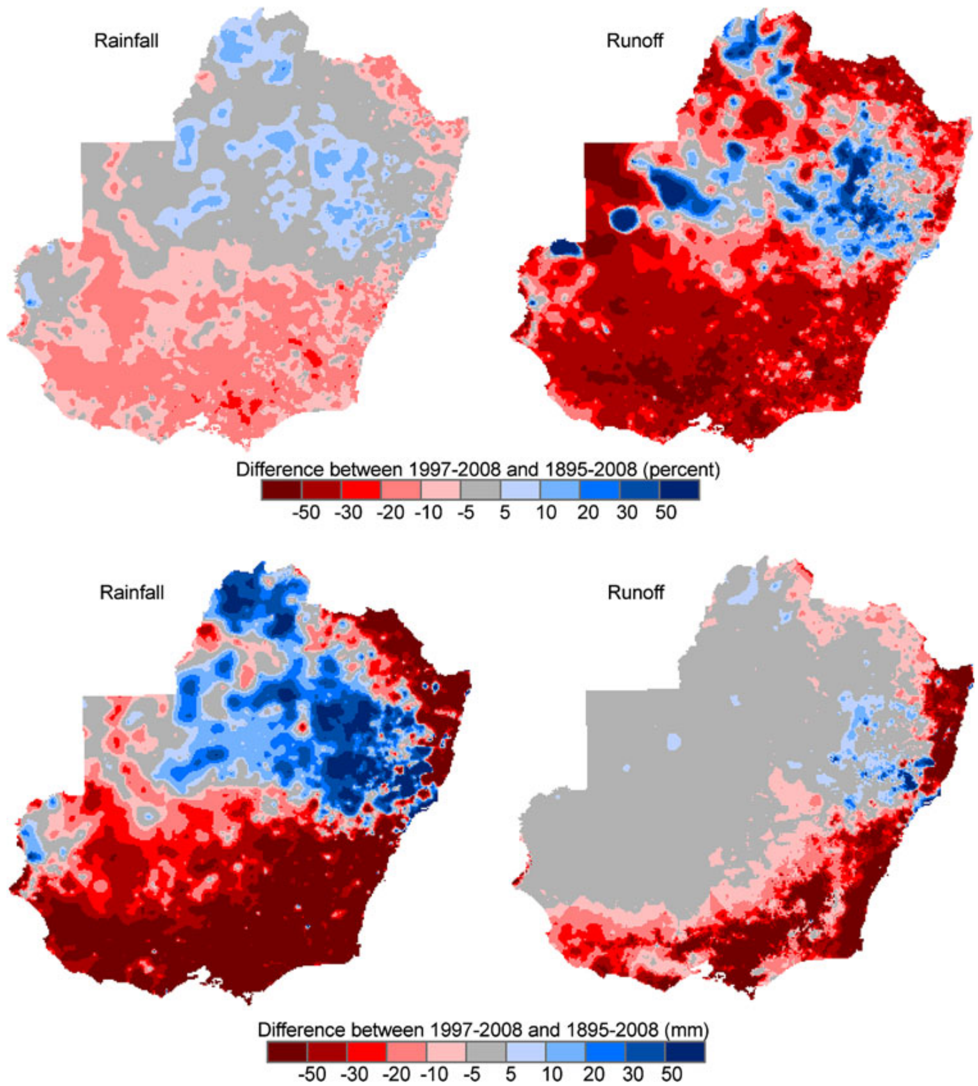


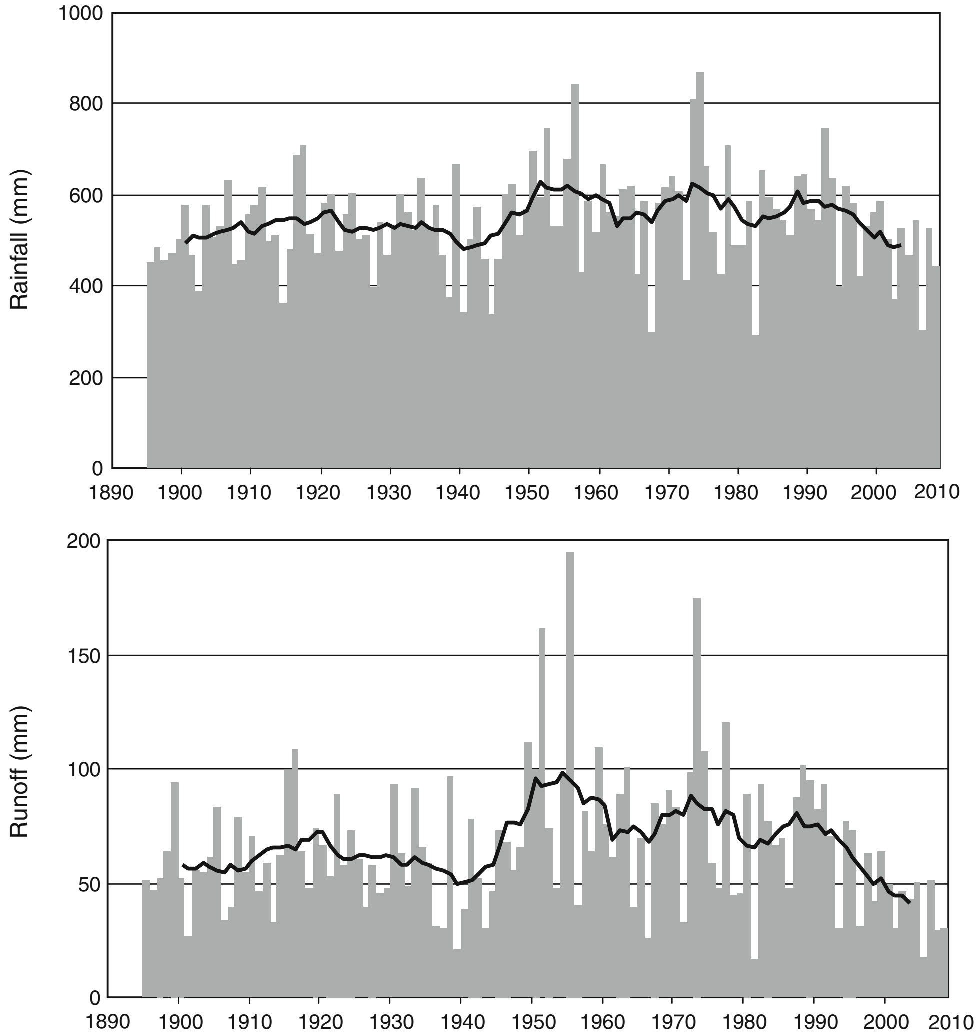
Fig. 5 Difference (percent and mm) between mean annual rainfall and runoff in the past 12 years (1997–2008) and the long-term means (1895–2008)

(Fig. 7); the lack of high rainfall years in the past decade (Fig. 6); higher temperatures; and possible changes in the dominant hydrologic processes (Murphy and Timbal 2007; Cai and Cowan 2008b; Potter and Chiew 2009; Timbal 2009). Because of the very dry antecedent conditions and possible loss of connectivity to subsurface systems, significant amounts of rainfall are now required before significant runoff will occur.

Several studies have suggested that part of the current prolonged drought is associated with global warming. Studies in the South Eastern Australian Climate Initiative (SEACI 2009) have shown that the large decline in autumn rainfall is likely to be associated with the mean sea level pressure across southern Australia, and in particular the intensification of the sub-tropical ridge (a belt of high pressure located in the mid-latitudes around 30°S) (Fig. 4). The sub-tropical ridge is associated with the southern hemisphere Hadley cell, which is the dominant global circulation pattern responsible for transporting excess heat from the equator towards temperate latitudes (Drosdowsky 2005). Pressures along the sub-tropical ridge have increased during the twentieth century, and this intensification of the ridge appears to be related to global warming (Timbal et al. 2007). Recent studies have noted global scale changes in the extent and intensity of both the Hadley circulation and the tropics (Lu et al. 2007; Seidel and Randel 2007), suggesting that the sub-tropical ridge may be part of a larger scale change in the global circulation, particularly as it provides a physical link between the large rainfall decline in southwest Western Australia since the 1970s and that now seen in southeast Australia (Hope et al. 2009).

Part of the late autumn rainfall decline has also been linked to the decreased frequency in La Niña events and changing north–south gradients in the southern Indian Ocean (Cai and Cowan 2008a), both of which are

Fig. 6 Annual rainfall and runoff averaged over the southern half of the region (the lines show the two-sided 11-year moving averages)



consistent with future projections from global climate models. Research studies have also attributed the decline in spring rainfall to the high frequency of positive IOD phase (Meyer et al. 2007; Cai et al. 2009; Ummenhofer et al. 2009) and weakening of the Walker circulation (Power and Smith 2007) in recent years, the decline in winter rainfall to a shift of the SAM towards a positive phase (Cai and Cowan 2006; Nicholls 2009) and the decline in winter and spring rainfall to the more frequent occurrence of El Niño events in combination with a positive phase of SAM (Verdon-Kidd and Kiem 2009).

The above studies suggest that part of the current prolonged drought over southern Australia could be associated with global warming. Climate projections from many global climate models are for a drier future on average, suggesting that dry conditions similar to those being experienced now are likely to become more common. However, it is difficult to definitively or quantitatively attribute the current drought to global warming because the same types of changes to global circulation that are predicted to occur under climate change also occur naturally as part of decadal-scale variability in the climate (Power et al. 1999; Verdon et al. 2004).

4 Future hydroclimate projections

Figure 8 shows the percent change in future mean annual runoff, modeled using future climate series informed by 15 global climate models (GCMs) for a 0.9°C increase in global average surface air temperature. The modeling of climate impact on runoff is described in detail in Chiew et al. (2009). Rainfall is the main driver of runoff, and the percent changes in mean annual runoff in Fig. 8 are generally about two to three times the percent changes in mean annual rainfall (Chiew 2006; Chiew et al. 2009). The 0.9°C corresponds to the IPCC (2007) midrange increase in global average surface air temperature by 2030 relative to

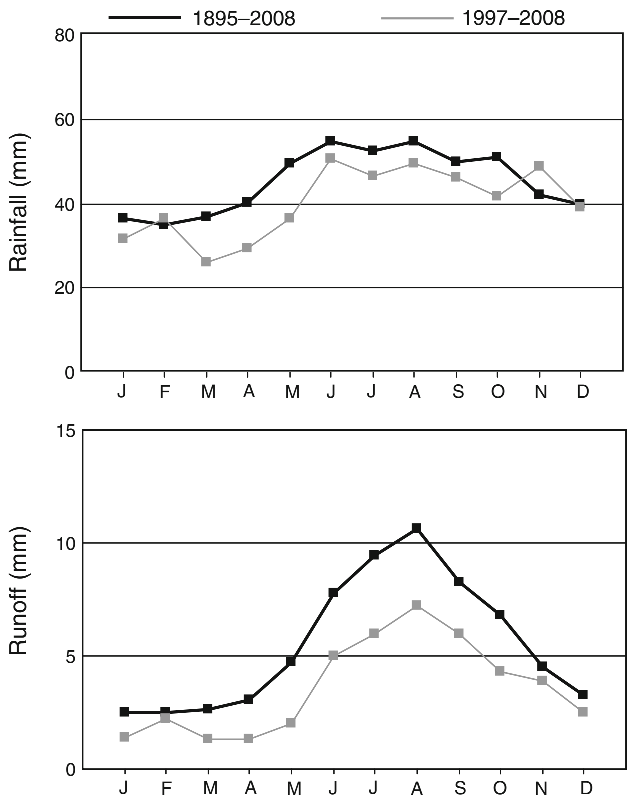


Fig. 7 Mean monthly rainfall and runoff averaged over the southern half of the region for the past 12 years (1997–2008) and for the long-term (1895–2008)

1990 (this timeframe being relevant to water resources planning).

The biggest uncertainty in the future runoff predictions come from the uncertainty in GCM modeling of local and regional rainfall, where the GCMs often disagree on even the direction of rainfall change (Fig. 8). The different warming scenarios mainly affect the magnitude of the change and not the direction of change in rainfall or runoff (although very large increases in temperature and potential evaporation may influence runoff as much as the rainfall impact on runoff).

Figure 9 shows the number of results that indicate a decrease (or increase) in mean annual, summer (December–January–February) and winter (June–July–August) runoff. In the northern half of the region, there is little agreement in the direction of change in mean annual rainfall and runoff, but in the southern half more than three quarters of the results show a decrease in mean annual runoff. A large majority of the results also agree on a decrease in winter runoff throughout the entire region. As most of the runoff in the south occurs in winter, the decrease in winter runoff there translates to a significant decrease in mean annual runoff.

Figure 10 shows the change in the future mean annual runoff for a 'dry' (second driest of the 15 modeled results), median (median of the 15 results) and 'wet' (second wettest of the 15 results) estimate, calculated at each of the $\sim$50,000 0.05° grid cells across the region. The dry and wet estimates represent notional 5th to 10th percentile and 90th to 95th percentile results, respectively. The median estimate indicates that the future mean annual runoff in the region will be lower, by up to 10% in the northeast and southern half and by 10 to 20% in the southernmost parts (for a 0.9°C increase in global average surface air temperature). However, there is considerable uncertainty in the estimates, with the dry and wet estimates ranging from −30 to +30% in the northern half, −30 to +10% in the southern half, and −40 to 0% in the southernmost parts. Most of the runoff comes from the upland areas in the southeast and along the east and south coasts, and the highest reductions in runoff depths occur there. Averaged across the region, the median estimate is a 6% decrease in mean annual runoff, with the dry and wet estimates ranging from a 17% decrease to a 7% increase in mean annual runoff.

5 Discussion and implication for water resources management

The assumption of stationarity in traditional hydrologic considerations may no longer be valid under climate change (Milly et al. 2008) or indeed under natural variability (Franks and Kuczera 2002). This is particularly so in southeast Australia where rainfall in the past decade is significantly lower than the long-term mean and the low runoff in the past decade is unprecedented in the instrumental record. The characteristics of the historical water resources in the region are, therefore, very dependent on the (baseline) climate period chosen for a modeling exercise. The choice of a suitable climate baseline is less of a problem elsewhere because, unlike southeast Australia, the rainfall and runoff in the past one or two decades in most other parts of the world are not at the dry extreme end of the historical distribution.

As climate is changing on a variety of timescales, scenario planning should be broader than just comparing a baseline to an alternative future. However, most water resources planning studies consider long climate baseline sequences to account for inter-annual and longer-term variability, storage responses, return periods, and long-term performance and resilience of hydrologic and environmental systems. The 1895–2008 period offers a suitable long sequence for this region as (i) it encapsulates a large range of likely hydroclimate conditions, (ii) it covers three prolonged drought periods (around 1900, around 1940, and

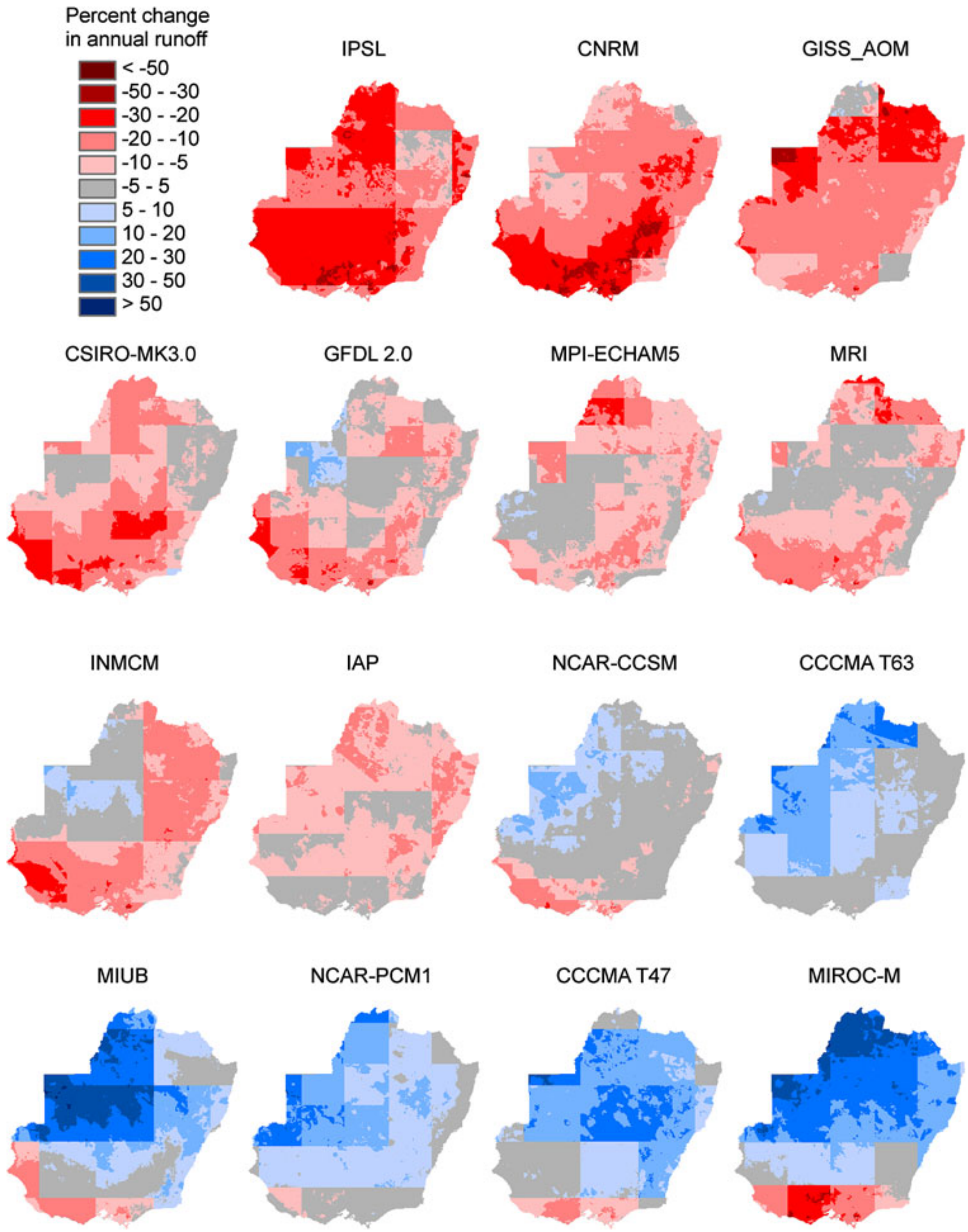


Fig. 8 Percent change in future mean annual runoff modeled using future climate series informed by 15 global climate models for a 0.9°C increase in global average surface air temperature (see CSIRO and BoM (2007) for details of the GCMs shown at the top of the maps)

the current drought) and (iii) it has a similar mean annual rainfall and mean annual runoff as the past 30 years (1979–2008).

The ongoing drought has placed immense pressure on the water resources of southeast Australia and has led to the perception that this may be the start of a persistent change from historical conditions. Perhaps more importantly, however, the drought has clearly shown that current water management approaches are inadequate to deal with the high variability in water availability, whatever the root cause. In the Murray-Darling Basin, a history of over-allocation of water (NWC 2007) has exacerbated the effects of the prolonged drought with severe environmental degradation, including, for example, significant and potentially irreversible die-back of long-lived River Red Gums along nearly 1000 km of the Murray River (Murray-Darling Basin Commission 2003), and the drying of Lakes Alexandra and Albert in the Ramsar-listed terminus of the Murray-Darling Basin (Kingsford et al. 2010).

Water resources managers are currently faced with trying to overcome the problems of decades of over-allocation of water at the same time as managing industries, cities, and the environment through the worse drought in over a century. In this context, climate change is a major and complex challenge for water planning, but not the only challenge. Predictions of future water availability and demand are clearly critical for making informed policy and management decisions on sharing the limited water

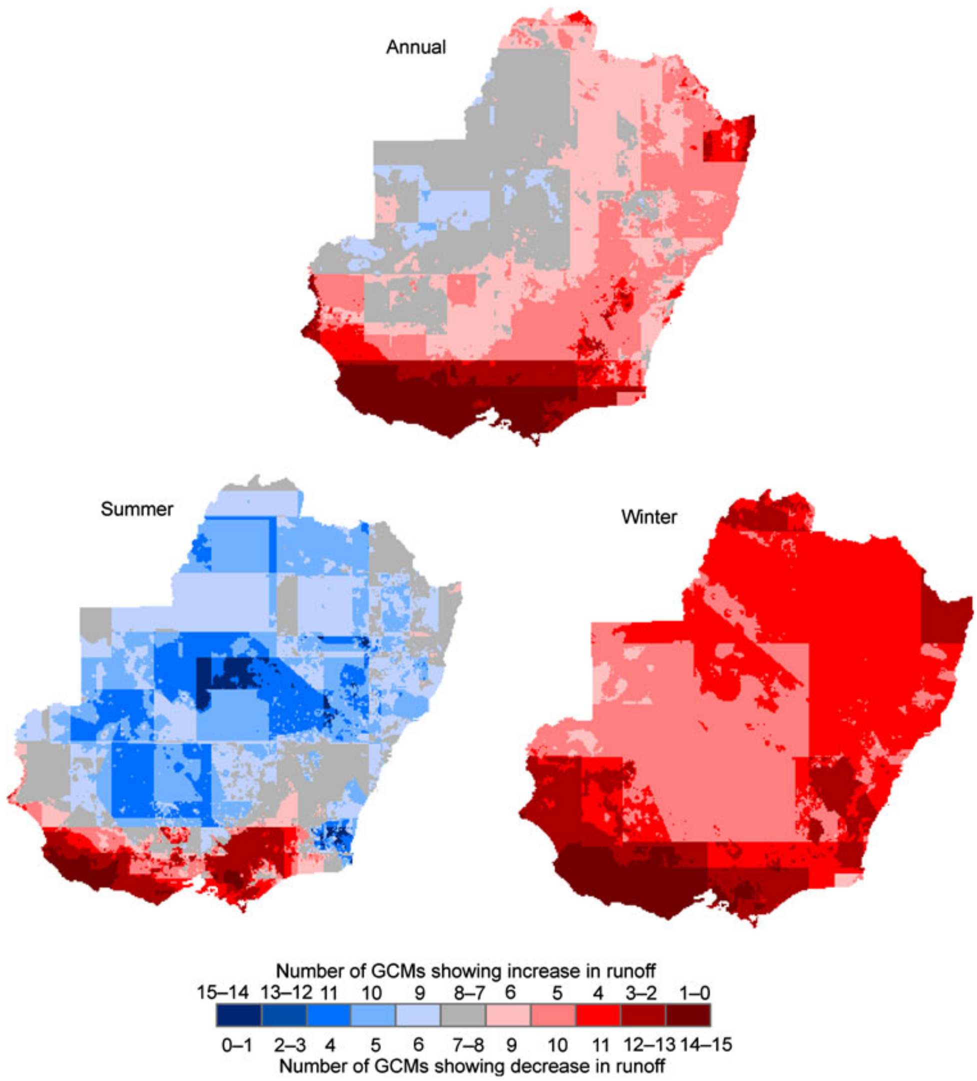


Fig. 9 Number of modeling results (out of 15) showing a decrease (or increase) in future mean annual, summer (December–January–February), and winter (June–July–August) runoff

resources, as is detailed information on the river flow and flood regimes required to sustain key river and floodplain environments.

Although several studies have suggested that at least part of the current drought is associated with global warming, it is difficult, if not impossible, to separate a global warming signal from the high natural low frequency climate variability observed over the last two centuries and apparent in paleo-climate records. Climate projections from many GCMs are for a drier future on average, suggesting that dry conditions similar to those being experienced now are likely to become more common. Given the current prolonged drought and predictions of a drier future across southeast Australia, it is prudent to plan for conditions that will be drier than the long-term historical climate. It is also wise to bring forward the implementation of no-regret or win–win options (options that will provide a net benefit regardless of the future hydroclimate, e.g., implementing water recovery for the environment, improving water use efficiency, facilitating shifts in water use especially via water markets).

Planning decisions will need to consider the planning horizon and the balance between risk and rewards and whether the system can adapt to climate change and other development drivers on water. For example, planning decisions need not be

based on the worse-case scenario, but a management plan is needed to deal with it if it does eventuate. These challenges are not new to water resources managers, and whilst climate change may be a key driver, it is one of many drivers and considerations in water resources planning and management. Currently, it is not possible to assign robust probability estimates to alternative climate projections, and projections are best considered as plausible alternative futures to guide planning. In the future, improved hydroclimate projections, with reliable probabilistic quantification of uncertainties,

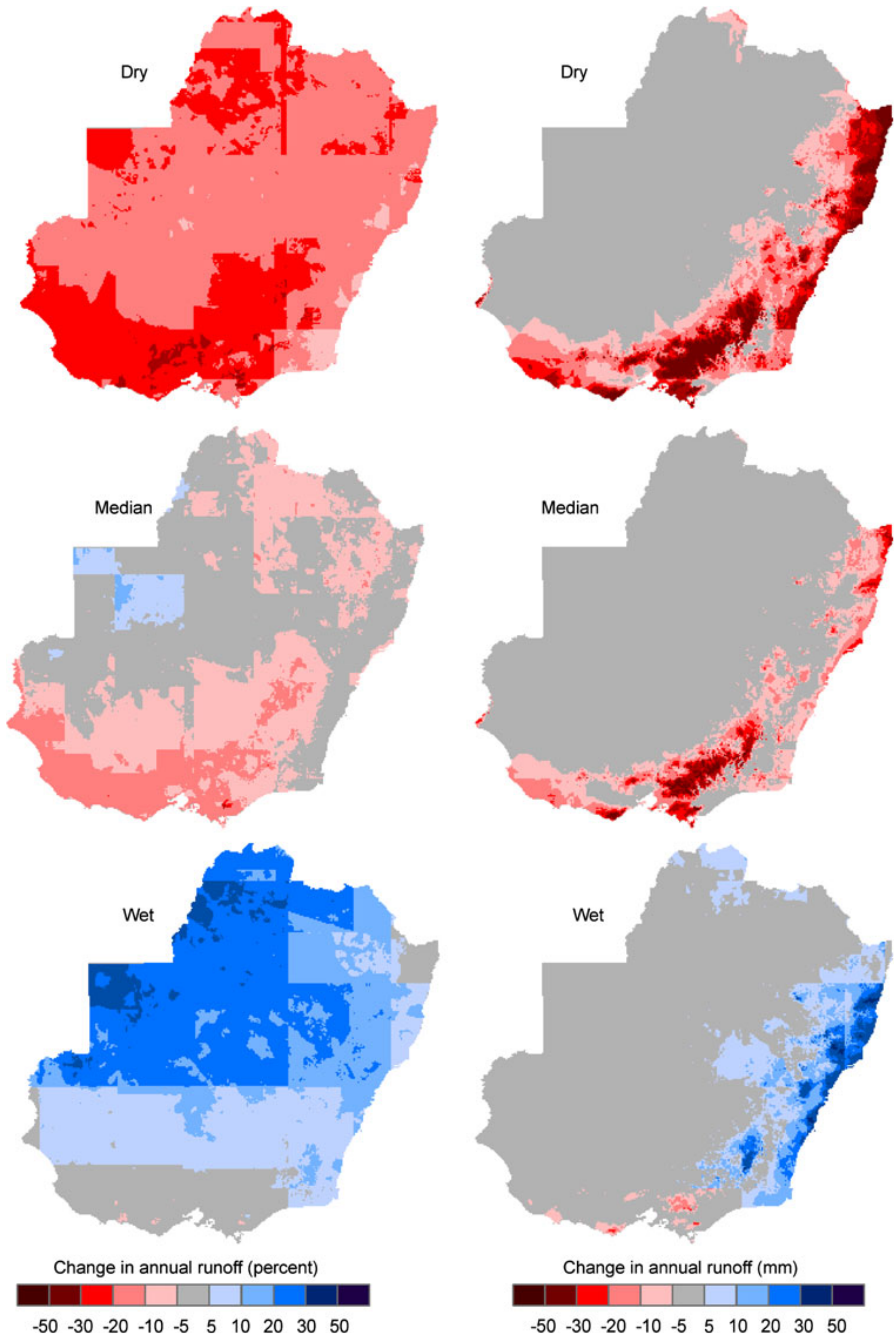


Fig. 10 Change in future mean annual runoff (percent and mm) for a 0.9°C increase in global average surface air temperature for the dry, median, and wet estimates

will help make more informed risk-based water sharing and management decisions.

For short- to medium-term planning (next 10–15 years), the recent climate (past 10–20 years) should also be considered as a possible scenario. This is because (i) much longer dry periods have been shown to be possible in the paleo-climate, (ii) the dry conditions may continue for some time yet because of initial conditions in the atmosphere–ocean system, and (iii) there is some evidence partly attributing the current drought to global warming. This is particularly so for hydrologic systems, where, because of low storage levels and very dry antecedent catchment conditions, significant amounts of rainfall are now required before there is an increase in streamflow and storage levels.

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