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Review

A review of recent climate variability and climate change in southeastern Australia

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ABSTRACT: Southeastern Australia (SEA) has suffered from 10 years of low rainfall from 1997 to 2006. A protracted dry spell of this severity has been recorded once before during the 20th century, but current drought conditions are exacerbated by increasing temperatures. Impacts of this dry decade are wide-ranging, so a major research effort is being directed to better understand the region's recent climate, its variability and climate change. This review summarizes the conditions of these 10 years and the main mechanisms that affect the climate.

Most of the rainfall decline (61%) has occurred in autumn (March–May). Daily maximum temperatures are rising, as are minimum temperatures, except for cooler nights in autumn in the southwest of SEA closely related to lower rainfall. A similar rainfall decline occurred in the southwest of western Australia around 1970 that has many common features with the SEA decline. SEA rainfall is produced by mid-latitude storms and fronts, interactions with the tropics through continental-scale cloudbands and cut-off lows.

El Niño-Southern Oscillation impacts on SEA rainfall, as does the Indian Ocean, but neither has a direct influence in autumn. Trends have been found in both hemispheric (the southern annular mode) and local (sub-tropical ridge) circulation features that may have played a role in reducing the number and impact of mid-latitude systems around SEA, and thus reducing rainfall. The role of many of these mechanisms needs to be clarified, but there is likely to be an influence of enhanced greenhouse gas concentrations on SEA climate, at least on temperature. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Australia's population and agricultural production are highly concentrated in the southeast of the country. Rainfall variability over these parts, and indeed over most of the continent, is very high. The southeast is now suffering from an extended dry spell similar to the one that began around 1970 in the southwest of western Australia (SWWA) (IOCI, 2002; Power *et al*., 2005). Mean rainfall over the decade, from spring 1996 to the end of 2006 in the southeast, has been below average. 1996 was the last year when mean annual rainfall over the south-east was in the upper tercile. Drought is a recurring problem in this part of the country and many systems have been designed to cope with this variability. However, Australians rely on wet years to compensate for drought to replenish water and, in the agricultural sector, economic resources. The current extended dry period has led to a number of extreme impacts in the region.

The relationship between the amount of water that reaches water catchments and rainfall is not linear since it depends on soil moisture levels. During a long dry spell such as this, very high rainfall over a short period is required to first saturate the soil before producing significant runoff. The implication for water management is that a given fall in rainfall leads to a greater reduction in the water flowing into catchments. Inflows into the River Murray system from July 2001 to July 2005 were the lowest on record, only 40% of the long-term mean (Murray-Darling Basin Commission, 2006). This study pointed out that not only have water allocations from the system for irrigation been much below average, but there have also been unprecedented environmental impacts. In the Lower Murray region, three-quarters of river red gum and black box heath trees were already unhealthy in August 2004, and large floodplains and wetlands are under serious threat as they have not been flooded for 10 years.

As a result of the record low inflows, water storage in catchments that supply many of southeastern Australia's (SEA) major urban centres are at very low levels (National Water Commission, 2006). This has led to the

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implementation of significant water restrictions in many centres. The Wimmera-Mallee regions of western Victoria have not had significant inflows for 7 years, and water storage levels as of late 2006 were at only 7% capacity. Inflows to metropolitan water storages have also been very low, particularly those of Melbourne (Figure 1). The high inter-annual variability is evident across the period from 1937 to 2003, as is the very low mean for the 1996–2003 period and the lack of an above average year since 1996.

The agricultural impacts of the dry conditions up to the end of October 2006 were assessed by the Australian Bureau of Agricultural and Resource Economics (ABARE, 2006). They forecast that the 2006 production for the three main winter grain crops would be 60% lower than in 2005, and about 9% lower than production during the 2002–2003 drought. Total crop and livestock production are expected to be 35% below 2005 levels (16% less than 2002–2003), resulting in a 0.7% reduction in Australian economic growth. In many parts of the wheat belt in eastern Australia there has been reduced rainfall, very much above-average temperatures, strong winds and frosts.

Another indicator of climate change in SEA is the decrease in snow depths observed in the Australian Alps (Nicholls, 2005). Winter snow depth has only fallen slightly at Spencer's Creek, but in spring a much stronger decrease has been observed. Spring snow cover is determined largely by the precipitation during winter and spring temperatures. During 2006, the alpine regions had one of the worst snow seasons in several decades due to the low winter snowfall and high spring temperatures. The falling spring snow cover at Spencer's Creek is an indication of the warming that has occurred in late winter and spring as well as a drop in observed precipitation. Inter-annual pressure changes in the region are closely related to the snow depth, but they have shown only weak trends and hence, the warming that has occurred is due to background warming rather than changes to synoptic weather patterns. Nicholls' (2005) results suggest that the fall in spring snow depth is due to higher temperatures rather than changes in the amount of snow that falls during the snow season.

The continuing dry and warm weather has also impacted on bushfires in the southeast. In their Seasonal Bushfire Assessment 2006–2007, the Australian Bushfire Cooperative Research Centre announced above-normal fire potential as well as an expected early start to the fire season (Lucas *et al*., 2006). The extended drought led to high fuel loads in the southeast of the country and the impact of the 2006–2007 El Niño exacerbated the fire risk as water shortages worsened and fuel loads increased (Jones and Trewin, 2006). Significant fires broke out on 1 December 2006 and affected large areas of Victoria, particularly in the east, burning with little control until rain fell in the middle of January 2007. Hennessy *et al*. (2005) studied the likely changes to weather-related fire danger in the future and suggest that the drier and hotter climate predicted for 2020 would increase fire risk by 4–25% for different sites in SEA.

Some of these impacts of the 10-year drought in the southeast of Australia are unprecedented in historical records. With these extreme conditions there is an urgent need to better understand climate variability and the uncertainty in climate change over the southeast in order to provide greater certainty in planning and decision making. The aims of this review are firstly to summarize the main characteristics of this recent warm and dry

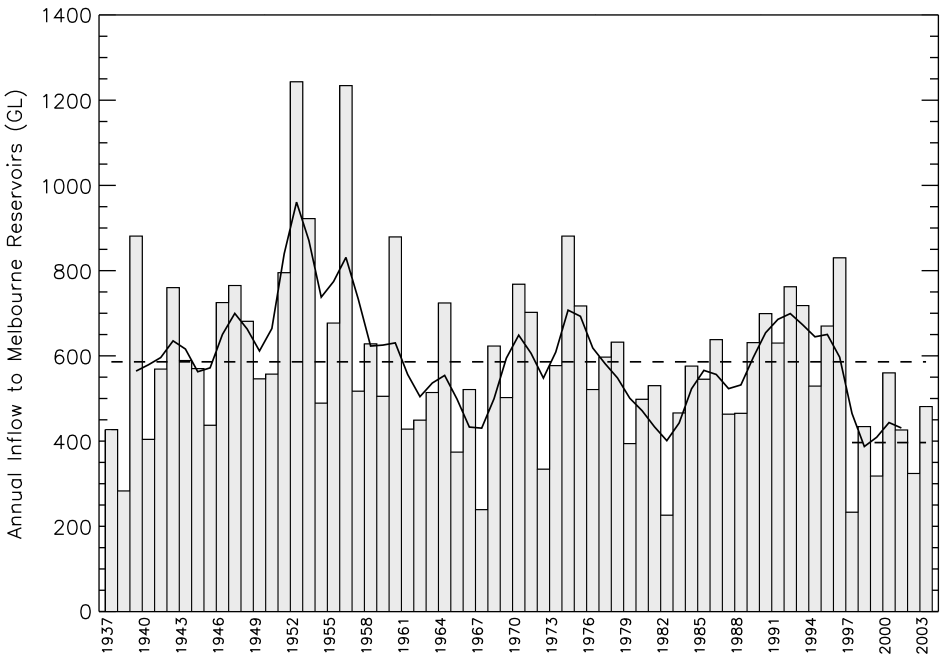

Figure 1. Annual inflows into main Melbourne reservoirs from 1937 to 2003. Also shown are means over the whole period, that from 1997–2003 (dashed lines) and the 5-year running mean (solid line).

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period in SEA and then to synthesize the most likely mechanisms responsible for these observed changes. The first aim includes determining the context of the last decade within the climate record and to find any unprecedented features that may explain the extreme impacts discussed above. This is intended as a review of the current state of knowledge of climate variability and climate change in southeast Australia, and to highlight the areas of research that are being focused upon in order to better understand this climatic variability.

The next section covers the main features of the climate anomalies of the 1997–2006 period and places them in the context of the historical records. A comparison is then made with similar climate changes that occurred in the southwest of Australia. The most important mechanisms that influence the climate of southeastern Australia are then discussed with a summary of those most likely to have a role in the climate over this decade.

2. Observed recent climate variability in SEA

SEA is considered here to consist of mainland Australia south of 33 °S and east of 135 °E (Figure 2). This region includes parts of the states of South Australia (SA) and New South Wales (NSW) and all of Victoria, covering the southern half of the Murray-Darling River basin (MDB). It represents a large geographical area covering temperate and grassland climates (Stern *et al.*, 2000) that receives a significant part of its rainfall in the winter half of the year.

The picture on global climate change, and that in Australia, has become clearer in the past few years. There is now little doubt that the country as a whole, and the southeast region in particular, is undergoing observable, significant shifts to higher temperatures. Rainfall, too, has been lower than average in the southeast in recent years, with only 2 years from 1997 to 2006 having more rainfall than the 1961–1990 mean. Along with these it is expected that humidity, and possibly evaporation, have also changed.

2005 broke many of the previous records for temperature and rainfall (see Watkins, 2005; Bettio, 2006). It was the hottest year on record for Australia as a whole and for the Murray-Darling basin. For southeast Australia, the autumn of 2005 was the driest, and it had the highest mean maximum temperatures (Tmax) on record. April 2005 saw the largest mean Tmax anomalies on record for any month for SEA and Australia as a whole. SEA has had five of the hottest 10 years on record since 2000, and only one autumn since 1996 has had above average rainfall. Some more details of conditions elsewhere in Australia and at specific locations can be found for the decade October 1996–September 2006 in Trewin (2006).

2.1. Rainfall

Previous studies have considered Australian rainfall trends for periods prior to the recent dry spell. Nicholls and Kariko (1993) found that at east Australian stations annual rainfall variations were mostly driven by the intensity of rainfall events, and that rainfall increased from 1910 to 1988 due to more rain days, while the intensity

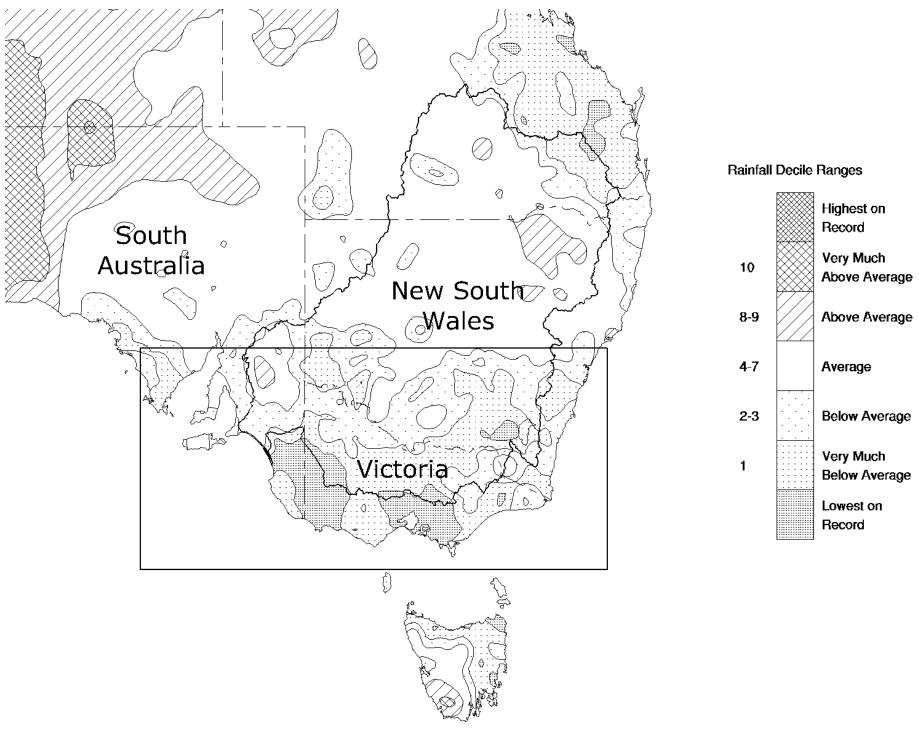

Figure 2. Rainfall deciles for Australia from January 1997 to December 2006. Data cover the period from 1900 to the present. “Lowest on record” regions had the lowest 10-year mean rainfall on record. The rectangle bounds the “southeastern Australia” region. The Murray-Darling basin outline is also shown.

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of events had declined. Hennessy *et al*. (1999) showed that from 1910 to 1995, rainfall had increased by a statistically significant 14% in Victoria (and by similar, non-significant amounts in NSW and SA). They found that high rainfall events had become more extreme in Victoria in autumn and that inter-annual variations were generally driven by changes in heavy rainfall events. This evidence showed that rainfall had been increasing in SEA during the period before the recent decline. The historical record shows that Australia-wide rainfall has increased since 1950, with a linear trend of 8.1 mm/decade, driven principally by much wetter summer conditions in the north, centre and west of Australia (Smith, 2004).

More recently, the question of a downward trend in rainfall has been addressed. Stern *et al*. (2005) suggested that there was no long-term trend in annual mean rainfall in Melbourne. However, Fawcett (2004) showed that there is evidence of an abrupt fall in Melbourne rainfall around 1997, rather than there being a gradual decline. He suggests, therefore, that a new rainfall regime began around this time. He also found another jump around 1946 to a higher rainfall regime. These changes appeared in gridded rainfall data over the region surrounding Melbourne and not just at the one-point location.

High quality rainfall records for Australia are available from the National Climate Centre as monthly means beginning in 1900. We will use both station records and Australia-wide gridded data (Jones and Weymouth, 1997) in our analysis below. Little trend exists in Australian rainfall over the whole record (1900–2006) but strong trends have been identified since about 1950 (Smith, 2004). In addition, the climate 'base-line' is generally taken as the World Meteorological Organization (WMO) standard period for reference climatologies, years 1961–1990. Thus, only the second half of the 20th century is considered in many planning decisions. It is useful to put the 1997–2006 period in this context, and so we will consider trends in rainfall and temperature in SEA since 1950, and anomalies from 1961 to 1990 means.

The map of rainfall deciles for the 10-year period from January 1997 to December 2006 (we hereafter refer to this 10-year period as 'the decade to 2006') in Figure 2 shows that over this period virtually the entire SEA region has had below average to lowest rainfall on record (1900–2006). Thus, while the low rainfall is not unprecedented everywhere the spatial extent of the deficiencies is extraordinary, certainly since 1950, with 76% of Victoria recording a 10-year mean in the lowest 10% on record.

Across SEA as a whole, (mainland Australia south of 33 °S and east of 135 °E) the period from 1950 to 1996 (Figure 3) was generally wetter than the period from 1900 to 1950 (Nicholls *et al*., 1997). The drop in rainfall since late 1996 may therefore be a return to conditions of the first half of the 20th century (Nicholls, 2006). Figure 3 illustrates the high inter-annual variability of rainfall over the region and the presence of variability on inter-decadal time scales. Nevertheless, SEA decadal rainfall variability is relatively low when compared to other regions of Australia (Power *et al*., 1999).

The trend in SEA rainfall has been to drier conditions, in contrast to mean Australian rainfall: since 1950 the linear trend in SEA annual rainfall is −20.6 mm per decade. Each season has a negative linear trend, with a decline of −11.2 mm/decade in autumn, −3.3 in winter,

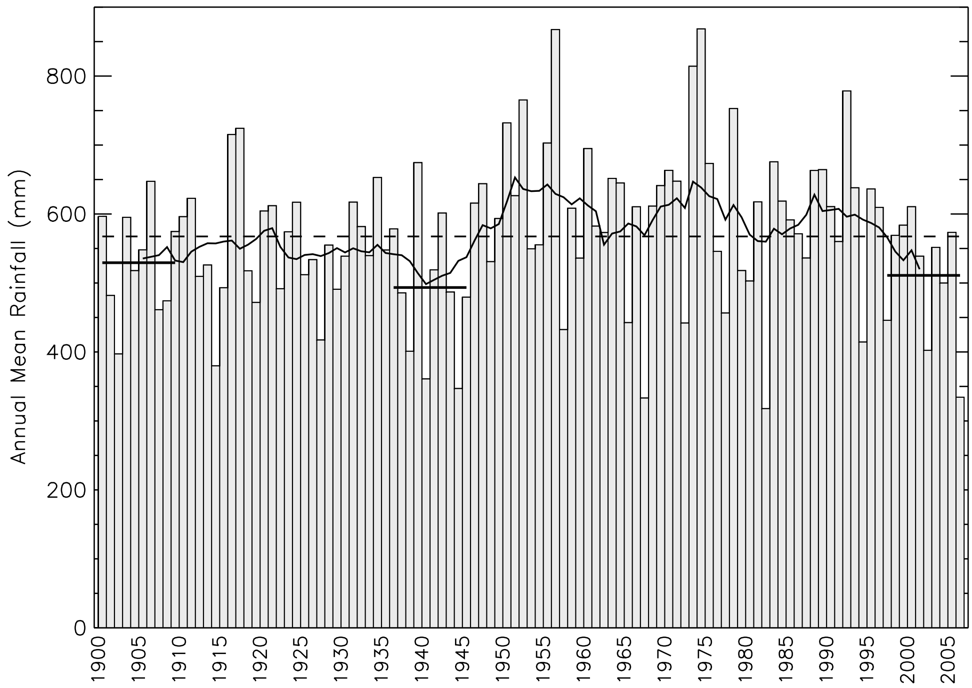

Figure 3. Mean annual rainfall over the southeastern Australia region (mainland south of 33 °S, east of 135 °E) for each year from 1900 to 2006. Also shown are the 1900–2006 mean (dashed line), the 10-year means for 1997–2006, 1900–1909 and 1936–1945 (thick, short horizontal lines) and the 11-year running mean (solid black). Units are in mm.

−3.5 in spring and −2.7 mm/decade in summer. The 1997–2006 autumn mean rainfall for SEA was 98.4 mm compared to the 1961–1990 mean of 149.4 mm. The annual and autumn trends in SEA rainfall, as well as the difference in the 1997–2006 annual and autumn means from the 1961–1990 means are all significantly different from zero at the 5% level according to Student's t-test. No trends or differences in the other seasons are significant.

Hence, the majority (61%) of the rainfall decline in SEA is due to much drier autumns. However, it must be noted that inter-annual rainfall variability is very high: the standard deviation of autumn rainfall in SEA is 51.2 mm. Nevertheless, the 1997–2006 mean is 50.9 mm below the 1961–1990 mean, which is a greater change than one would expect by chance (assuming a normal distribution, with this standard deviation the 10-year mean would lie within 31.7 mm of the long-term mean 95% of the time, and the change is statistically significantly). Rainfall during the recent decade of autumns is 65.9% of the climatological mean, and by the above reasoning it is unlikely that this decline is due to chance or is within the levels of natural variability. The decline in annual mean rainfall over SEA began in 1997, but autumn-mean rainfall has been below average since 1991. From 1991 to 2006 only one autumn (in 2000) has had above average rainfall.

The recent dry period has meant that no very wet years have been recorded in the decade to 2006. There has been a failure of the usual 'autumn break' (rains that signal the beginning of the winter wet season, Pook *et al*., 2006a) to bring significant rain to SEA for the seven consecutive years 2000–2006, a situation that has never before been recorded in the MDB (National Water Commission, 2006). The year-to-year variability has been lower from 1997 to 2006. Details of the mean rainfall and its variability for the pre- and post-1997 periods are given in Table I. It is clear that 1997–2006 was very dry, particular in autumn, and that inter-annual variability has been below average for this decade.

Figure 3 also shows the mean annual rainfall over SEA for the decade to 2006 (511 mm) as well as two earlier 10-year periods when rainfall was extremely low [1900–1909 (529 mm) and 1936–1945 (494 mm)]. The mean rainfall over the second of these earlier periods was lower than for 1997–2006. Rainfall over the recent decade is, therefore, not unprecedented, but it differs from the earlier dry spells in that the recent dry spell is mostly due to dry autumns. While both earlier periods also had drier than average autumns, the seasons that were especially dry were spring and particularly summer for 1900–1909 and all seasons for 1936–1945. Further comparison of the three dry periods is given in Table II: clearly the last decade has been extremely dry in autumn relative to the other extended dry spells. Year-to-year variations in annual and autumn mean rainfall have been particularly low during the last decade compared to the mean and earlier dry periods. Maximum and minimum annual mean temperatures were above the climatological mean during 1997–2006, while both were below the mean during 1936–1945. There are obvious consequences with increased evaporation during the recent dry spell relative to the earlier dry decade.

The 10-year mean autumn rainfall in the last decade over SEA is the lowest on record. The change in monthly mean rainfall for SEA for the 10 years since 1997 relative

Table I. Summary of southeastern Australia rainfall, maximum and minimum temperature annual and autumn means: mean anomalies 1997–2006 from the 1961–1990 mean, 1961–1990 standard deviations (σ) and linear trends since 1950. Rainfall in mm, temperatures in °C, trends per decade. Anomalies and trends in bold are statistically different from zero at 5% level.

	Annual anomaly	Annual 61–90 σ	Annual trend	Autumn anomaly	Autumn 61–90 σ	Autumn trend
Rainfall (mm)	**−83.8**	120.3	**−20.6**	**−50.9**	51.2	**−11.2**
Maximum temp. (°C)	**0.71**	0.50	**0.17**	**0.50**	0.58	**0.16**
Minimum temp. (°C)	**0.10**	0.43	**0.07**	**−0.54**	0.92	−0.02

Table II. Means and standard deviations (σ) of annual and autumn rainfall over SEA, and of annual maximum and minimum temperature over Victoria from 1997 to 2006, as well as for the 1961–1990 mean, and two previous 10-year dry spells: 1900–1909 and 1936–1945. Values in bold are statistically significantly different from those for 1961–1990 at the 5% level according to Student's t-test.

	1997–2006		1900–1909		1936–1945		1961–1990	
	Mean	σ	Mean	σ	Mean	σ	Mean	σ
Annual Rainfall (mm)	**511.0**	89.6	529.4	76.6	**493.8**	105.5	594.8	120.3
Autumn Rainfall (mm)	**98.4**	32.4	135.2	52.3	**115.5**	35.8	149.4	51.2
Maximum Temp. (°C)	**20.4**	0.27	–	–	19.7	0.47	19.9	0.48
Minimum Temp. (°C)	8.4	0.31	–	–	**7.7**	0.42	8.3	0.42

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to the 1961–1990 mean is shown in Figure 4, and indicates that the drop in rainfall has come mainly in autumn months, but some other months have also been drier. However, the changes in the three autumn months (March, April and May) are all significantly different from zero at the 5% level, but none of the changes in the other months are significant. The significant changes in SEA rainfall are, therefore, confined to the three autumn months. It should be noted that the climatological period 1961–1990 (the WMO reference period) lies in the relatively wet half of the 20th century.

This pattern of rainfall decline in autumn is present across SEA. We have examined changes in the mean monthly rainfall for the 1997–2005 period relative to the 1961–1990 mean at the 51 high-quality rainfall stations available in SEA (Lavery *et al.*, 1997) (we use the 1997–2005 period with the high-quality rainfall station data as they are not yet available for 2006). At least 48 of the stations have lower than average rainfall in the latest decade in each of the autumn months. The most consistent declines occurred in May, although none of the changes reach a full standard deviation from the earlier mean value, reflecting the high rainfall inter-annual variability across SEA.

Looking at the seasonal changes for autumn (Figure 5) at these stations it is clear that there is a consistent fall since 1997: all stations in SEA had lower autumn rainfall. The changes in rainfall amount have been standardized by dividing by the standard deviation of monthly rainfall over the 1961–1990 period and multiplying by 100. Several stations have had autumn rain declines greater than one standard deviation of autumn mean rain, and the decline is statistically significant at 30 of the 51 stations. The most consistent difference between the periods is that the number of days of rain during autumn (i.e. days with at least 1 mm of rain) is lower at all stations (statistically significant at 33 stations). The daily rain intensity (rain amount per rain day) is generally lower as well, but less spatially homogeneous, and the decline is significant at only 11 stations. It appears that the autumn rainfall decline is linked to fewer rain days across the SEA region and, to a lesser extent, less rain falling when a rain event occurs. Similar results have been found by Hope *et al.* (2006) for SWWA.

While the mean rainfall in a month or season is obviously important for water users, it does not always give an indication of their requirements. One measure that has been developed to help agriculture determine the likely rainfall they will receive throughout a season is the 'rainfall reliability' (Laughlin *et al.*, 2003). The reliability can be defined as the percentage of years in which each month in a season (climatological or growing) receives at least a set amount or a set percentage of the usual rainfall. It therefore demonstrates the likelihood of getting a useful distribution of rainfall throughout a season, and it does not necessarily follow that reliability will fall if mean seasonal rainfall decreases.

We have calculated the reliability for the early winter season for each high-quality rainfall station in SEA for the long-term climatology and also for 1997–2005. We define reliability as the percentage of years during which at least 75% of the climatological mean rainfall is received for each month from April to June, the pre- to early-winter season during which good rainfall is vital for establishing crops. The results are shown in Figure 6. It is evident that consistent rainfall throughout the season normally occurs in about one in four or five years over most of SEA (less often in the marginal interior regions). However, 1997–2005 saw a considerable reduction in this frequency. Only a handful of stations have had two of these years in the last ten. In Victoria and SA most stations have recorded either one or, in most instances, no

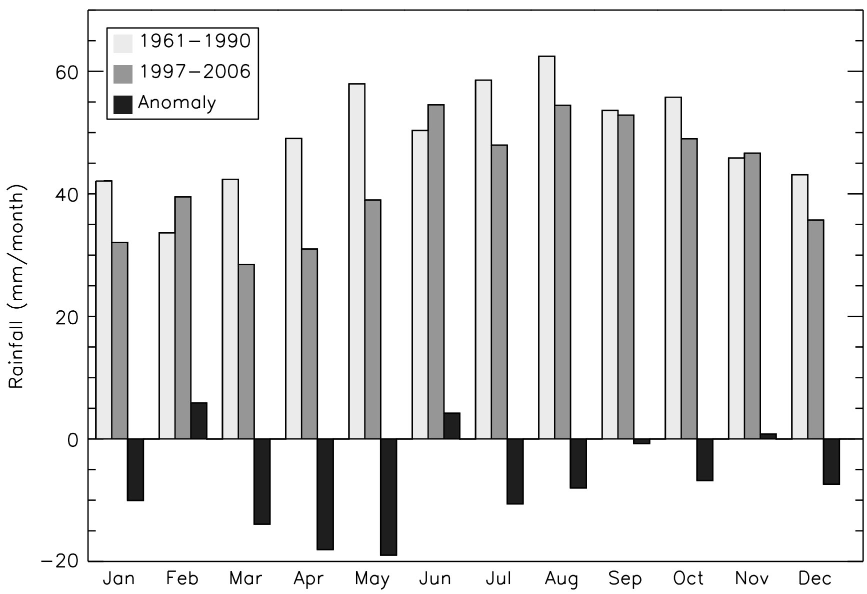

Figure 4. Monthly mean southeastern Australia rainfall for period from 1961 to 1990 (light grey), 1997 to 2006 (dark grey) and the change from the earlier period to the later (black) in mm per month.

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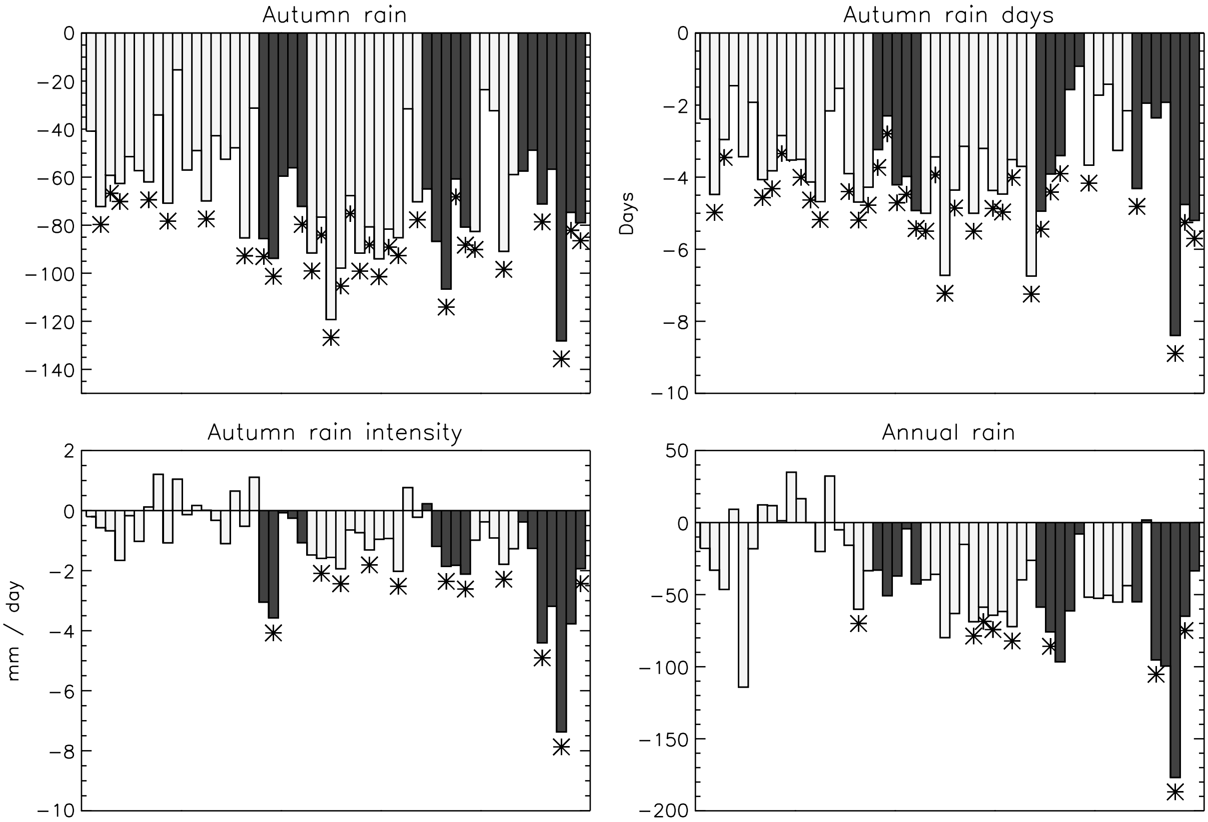

Figure 5. Change between 1997–2005 and 1961–1990 of mean autumn (March–May) rainfall, number of rain days (at least 1 mm per day), mean rainfall intensity (rain per rain day in mm per day) as well as annual mean rainfall. Shaded bands from left to right are for high-quality rainfall stations in South Australia, southwestern Victoria, northern Victoria, western NSW, eastern Victoria and eastern NSW. Mean autumn and annual rainfall changes are given in percentage of one standard deviation. Asterisks mark changes significantly different from zero at 5% level.

years of these reliable rains. For example, most of western Victoria has not had this rainfall throughout the season for over 10 years. The current extreme water deficiencies in this region are, therefore, linked to the lack of good reliable autumn and early winter rainfall.

2.2. Temperatures

The mean temperature for Australia as a whole has been increasing, and the warming has accelerated in recent decades. This warming affects the severity of drought as it means higher temperatures and, therefore, greater evaporation. The linear trend in Australian mean temperatures from 1910 to 2006 is 0.09 °C per decade while that for 1970–2006 is more than double that rate (0.19 °C/decade). Similar trends and accelerating warming have occurred in both daily Tmax and, although less extreme, daily minimum temperatures (Tmin).

Strong relationships between rainfall and temperatures have been shown by several studies. Nicholls (2003) demonstrated a negative correlation between mean annual Australian rainfall and Tmax, so that low rainfall years correspond to those with above average temperatures. However, he showed that the positive trend in mean annual Tmax would have been expected to be associated with a rainfall decline, but in fact Australian mean rainfall has increased. He stated that the observed warming cannot be accounted for through the strong correlations with rainfall and, hence, it is highly unlikely that the additional warming is due to natural variability and, therefore, anthropogenic greenhouse warming is a probable cause.

Power *et al.* (1998a) looked at the inter-relationship between all-Australia rainfall, minimum and maximum temperature together with the Southern Oscillation Index (SOI) and their response to increased CO_2 levels in a coupled climate model. They found that the response mimicked the observations in that precipitation, minimum and maximum temperatures increased while the SOI and the diurnal temperature range (DTR) decreased. They noted that these changes were different to the inter-relationships on inter-decadal and decadal time scales in the absence of enhanced greenhouse gas forcing. Karoly and Braganza (2005) found significant observed increases in Australian mean, maximum and minimum temperatures that were reproduced by climate model simulations that included natural and anthropogenic forcings, but not by simulations including natural forcings alone. They, therefore, concluded that the chance that the observed temperature trends could be explained by natural variability or natural external forcing alone was very small.

Trends in Tmax since 1950 have been positive across all of SEA in all seasons. Annual mean Tmin trends have been positive over all of SEA, but in autumn and winter the trends have been weaker, and in some parts have actually been negative. Table I lists the annual and

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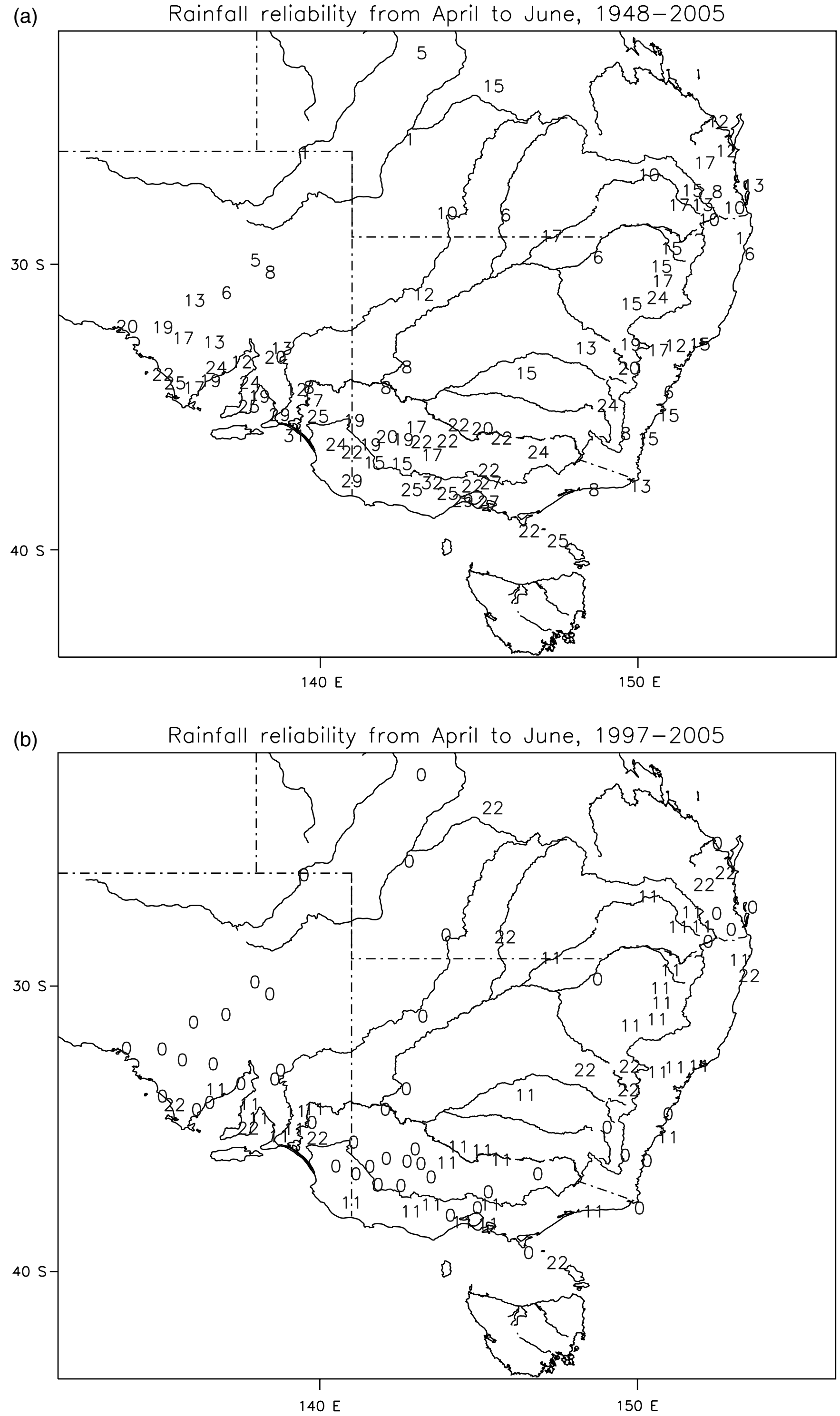

Figure 6. Rainfall reliability for April–June (a) for 1948–2005 and (b) for 1997–2005. Numbers give the percentage of years when all months from April to June receive at least 75% of the climatological mean rainfall for the month.

autumn anomalies in Tmax and Tmin for 1997–2006 as well as the trends since 1950 in the SEA-mean values. All except the Tmin trends in autumn are significantly different from zero at the 5% level. The Tmin anomaly in autumn is negative but of similar magnitude to the positive Tmax anomaly. While the annual and autumn anomalies for 1997–2006 in Tmax are consistent with the trends since 1950, those in Tmin are much colder than expected from the trends. Since 1970, the temperature trends (Figure 7) show spatial patterns very similar to the 1997–2006 anomalies. These are positive for Tmax across SEA but for Tmin they are very weak or negative over most of SEA, mainly due to cold Tmin anomalies in autumn during the decade to 2006. These large negative Tmin anomalies cover all of SEA except along the NSW coast.

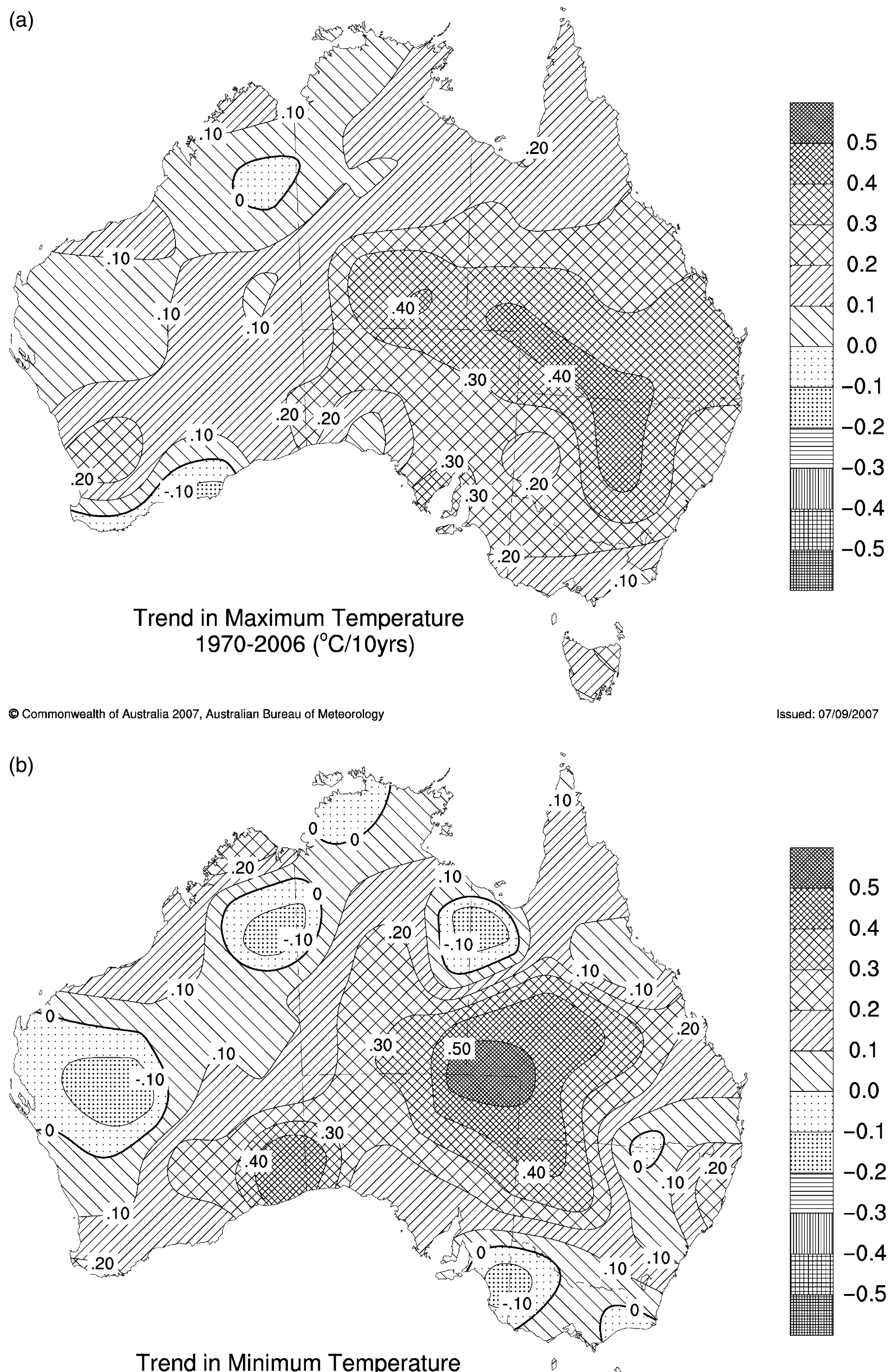

Figure 7. Trends in annual mean (a) maximum and (b) minimum temperatures from 1970 to 2006. Units are °C/decade.

The cooler autumn nights in SEA appear to be at least partly attributable to the low rainfall over the past decade. Nicholls (2004) found the partial correlation between mean May–October Tmin and rainfall over the MDB is 0.60, so that on this spatial scale rainfall accounts for 36% of variability in Tmin. We find that in autumn the correlation for SEA is 0.72 (52% of rainfall variability). The reason for the rainfall decline will, therefore, help to explain this night-time cooling over much of SEA in autumn. The low rainfall over SEA in autumn during the last decade has, therefore, contributed to the lower Tmin as expected (see Power *et al.*, 1998a; Jones and Trewin, 2000).

The combination of higher Tmax and lower rainfall is expected to lead to more severe droughts (Nicholls, 2004) as enhanced evapotranspiration that accompanies higher temperatures will amplify the aridity caused by declining rainfall. There have been periods of low rainfall in the past, but with the temperature increases water resources are being put under more stress than in these previous dry spells. Table II compares the mean Tmax and Tmin over Victoria during the decade to 2006 to climatological means and those during the 1936–1945 drought (only annual mean temperatures extending back to 1910 are available, and only as certain regional averages). We see in Table II that 1997–2006 was warmer than the previous dry period (also noted by Nicholls, 2004) and the climatological mean and, as with rainfall, temperature inter-annual variability was also lower. Despite the low rainfall, the last decade has had warmer nights (except in autumn) than the earlier periods, reflecting the background warming.

The trends towards higher Tmax and lower Tmin in autumn since 1950 have combined to increase the DTR over much of SEA, and the trend has been accelerating more recently. Other seasons are showing similar, if weaker trends, except winter in which the DTR is decreasing over a significant fraction of SEA. The cooler nights may also be resulting in more frosts, particularly in northern and western Victoria. Indeed, in Mildura in the northwest of the state the average number of frosts in a year over the decade to 2006 was 40% higher than over any other 10-year period since high-quality records began in 1947.

Even without lower rainfall over the southeast, the higher air temperatures would be expected to increase evaporation and therefore reduce water availability. The so-called pan evaporation paradox of Roderick and Farquhar (2004) has caused considerable debate. The reduced pan evaporation across Australia that they reported seems to be at odds with the rising temperatures that have been observed. However, further analysis of the pan evaporation data suggest that many of the changes can be linked to local wind effects caused by changes in the local environments around observation stations (Rayner, 2006) or other changes in observational sites (Jovanovic *et al.*, 2006). The paradox is therefore unlikely to be an independent counter-argument to climate change over Australia but rather an artefact of changes in observing sites that are particular to pan evaporation measurements. Pan evaporation is an observed estimate of potential evaporation, which is the amount of evaporation that would occur if unlimited water were available. It is not clear as to how potential evaporation is linked to actual evapotranspiration. The real evapotranspiration that occurs is strongly constrained by the amount of water available, and so the relevance of potential evaporation in a changing climate regime is likely to be minimal.

3. Climate variability studies from SWWA

The SWWA experienced rainfall declines around 1970 similar to those seen in SEA since 1997. Considerable effort has been put in to understanding the decline in SWWA rainfall, and recent work has clarified the issue (IOCI, 2002). Since the late 1960s, the drop in rainfall in SWWA has been principally during the months of May–July. The fall was sudden, of the order of 15–20%, and it appears that SWWA has entered a new winter rainfall regime, the lower winter rainfall now considered the norm. Temperatures have increased steadily, but more gradually, most markedly in winter and autumn.

Some of the advances that have been made to understand the SWWA rainfall decline around 1970 may be applicable to the low rainfall in SEA since 1997. Many of the changes in the large-scale atmospheric circulation of the southern hemisphere that have been implicated in the SWWA rainfall decline would also be expected to affect SEA, since many of the weather systems that bring rain to these two regions are the same. As with SEA, SWWA rainfall is greatest in the winter half of the year and is brought about mainly by mid-latitude storms and fronts (Wright, 1974), with some additional influence of cloudbands from the northwest early in autumn and early winter (Wright, 1997; Telcik, 2001). As these weather systems move from west to east and because SWWA is at similar latitudes (33°–35 °S) to SEA, many low-pressure systems that pass over SWWA move on to SEA over the following 48 h. Indeed, there is a robust relationship between surface pressure observations in SWWA and those in SEA 48 and 72 h later (Timbal and Hope, 2006). Year-to-year variations in May–July pressure and rainfall are strongly correlated locally in both regions (linear correlation coefficients of 0.76 for SWWA, 0.73 for SEA). Furthermore, a strong relationship exists between mean May–July mean sea level pressure of the two regions, the two having a linear correlation coefficient of 0.81.

Hope *et al.* (2006) showed that the number of fronts affecting SWWA has fallen and that the amount of rainfall that these types of systems bring has also fallen. Smith *et al.* (2000) showed that the rainfall decline is related to fewer low-pressure systems in the region. Sea surface temperatures (SST) in the south Indian Ocean may also be important although these have risen over the last few decades while SWWA rainfall has fallen, thus creating a simple association that may not have a cause-and-effect relationship (IOCI, 2002). Frederiksen and Frederiksen (2005) suggest that the atmospheric stability since 1975 is different from that in earlier periods. Stability has become higher around 30 °S and lower to the south, meaning that low-pressure systems are more likely to form further south and that they are more often deflected to the south. Timbal *et al.* (2006) related the large-scale atmospheric circulation in climate model simulations to observed local-scale rainfall. They found that the simulations including only natural external forcings (solar variability, volcanic aerosols) could not reproduce the rainfall decline. However, three of the four fully forced simulations (adding anthropogenic sulphate aerosols and greenhouse gas emissions) did reproduce the observed reduction in rainfall. They concluded that the rainfall changes in SWWA were at least partly attributable to anthropogenic factors and that large-scale changes in atmospheric pressure and stratiform rainfall are the main

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drivers of the changes. In addition, Timbal and Arblaster (2006) found that changes in land clearance over the 20th century may also be an important contributor to the rainfall decline through the impact on the large-scale rainfall, confirming previous results of Pitman *et al.* (2004).

It is not yet clear as to which processes have caused the circulation changes and why the rainfall decline occurred so much later in SEA when compared to SWWA. However, there are some rain producing processes in SEA that do not affect SWWA such as cut-off and east-coast lows, and in northern SEA cloudbands from the northeast (Coral Sea) may also bring rain (Pook *et al.*, 2006b; Frederiksen and Frederiksen, 1996). These differences may play a role in the different times of the onset of the rainfall declines in the two regions. Two circulation features that have been investigated in SEA that are undoubtedly related to both the mid-latitude storm track and to each other are the Southern Annular Mode (SAM) (Thompson and Wallace, 2000) and the latitude of the sub-tropical ridge – STR (Drosdowsky, 2005). Their effects on SEA climate variability and the role they may have played in the recent long dry spell in SEA are reviewed, along with many other mechanisms, in the following section.

4. Mechanisms that affect SEA climate variability

In order to synthesize the main mechanisms that affect climate variability in SEA it is important to consider the processes that bring precipitation to the region and affect the atmospheric temperature. A number of studies have produced climatologies of the systems that bring rain to different parts of the southeast, including Whetton (1988), Wright (1997) and Pook *et al.* (2006b). Others have considered the influence of climate factors on precipitation and temperature, among them the El Niño-Southern Oscillation (ENSO) phenomenon (e.g. McBride and Nicholls, 1983; Jones and Trewin, 2000), tropical and extratropical Pacific and Indian Ocean SST variability (Nicholls, 1989; Drosdowsky and Chambers, 2001), the STR (Pittock, 1975; Drosdowsky, 2005), the SAM (Hendon *et al.*, 2007; Meneghini *et al.*, 2007) and the Madden-Julian Oscillation – MJO (Donald *et al.*, 2006; Wheeler and Hendon, 2006).

Generally, the southern part of southeast Australia (south of 33 °S) receives most of its precipitation in the winter half of the year (see Wright, 1997). The south coastal regions are influenced principally by the passage of fronts and mid-latitude storms that bring rain. Further inland, the influence of other features such as cut-off lows and tropical-extratropical interactions become important. Several studies have quantified their relative contributions to rainfall, but the mechanisms that bring rain vary widely with location and season.

Whetton (1988) calculated the main patterns of rainfall variability in Victoria and related them to the sea level pressure anomalies that accompanied them. This study showed that different pressure patterns brought rain to each of the five rainfall regions following mechanisms that were easily identified as circulation anomalies. Wright (1989) carried out a detailed examination of the synoptic weather patterns that brought rain to Victoria in winter (June–September) and found five principal types of rain-bearing systems. Their contribution to the amount of rainfall varied with location. Fronts that interacted with tropical air masses (mostly northwest cloudbands (NWCB)) brought most rain to the north of the state (closest to the tropical moisture source), while fronts that were non-interacting produced precipitation mainly in the south of the state. Post-frontal rain only had a major role in regions where orographic uplifting occurred (southwestern Victoria ranges). He found that cut-off lows (see also below) brought roughly a quarter of winter rain to all Victorian regions except the east where they produced more than half the winter rainfall. The main month-to-month variability occurred in July, which tended to have more tropical interacting fronts than the other winter months. Wright (1997) showed that the interaction of cloudbands with fronts brings significant rainfall, the contribution increasing to the north and west.

More recently, Pook *et al.* (2006b) decomposed the wet season rainfall in northwestern Victoria. They classified three classes of synoptic events and found that over half of all April–October (i.e. the cropping season) rain in the region came from cut-off lows. Frontal rain accounted for about a third (decreasing further north), while other types brought around 15% of all winter rain. The cut-off low was therefore identified as the principal rain-bearing system in the northwest of Victoria, producing a higher proportion of rain early and late in the season than in the middle.

These studies have found the principal synoptic situations bringing rain in northern SEA. They generally used subjective classification methods to decompose the synoptic events. A more objective method of classifying weather types may be able to provide a clearer picture, such as self-organizing maps (Hewitson and Crane, 2002) that have been applied to the SWWA rainfall decline by Hope *et al.* (2006). However, these studies do agree on the importance of tropical influences for the northern regions of SEA, while the extratropical circulation seems to drive rainfall variability in southern districts. Pook *et al.* (2006a) suggest that the timing of the autumn break (i.e. start of the local wet season) in northern Victoria is largely determined by cut-off low occurrence, and that over the past decade the autumn break is occurring later than previously or not at all.

Pook *et al.* (2006b) make the point that cut-off rain has higher inter-annual variability and is, hence, less reliable than frontal rain in the region. They found no trend in cut-off low numbers, but low winter rainfall is generally associated with low cut-off rain (noticeably in El Niño years). Wright (1988) similarly showed that the ENSO-rainfall relationship in northern Victoria can be attributed to the attenuation of tropical-extratropical interactions by ENSO.

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The temperature trends that were discussed in Section 2 are almost certainly due in part to background warming of the atmosphere and oceans. The detection and attribution work of Nicholls (2003), Power *et al*. (1998a) and Karoly and Braganza (2005) leave little chance that the warming trends are due solely to natural variability. Additional changes in temperature variability could also be occurring in response to shifts in the frequencies of weather patterns in the Australian region. Therefore, any climate mechanisms that alter rainfall patterns have the potential to similarly affect temperature.

These main rain-bringing processes for SEA (mid-latitude storms and fronts, tropical moisture entrainment and low pressure systems out of the westerlies) are all influenced on intra-seasonal and longer time scales by many of the major modes of global climate variability. The most extensive of these is ENSO, and indeed, it has the largest influence on SEA climate variability. SSTs in the Indian Ocean and the MJO are other likely tropical influences on SEA climate, while extratropical variability involving the SAM and the subtropical high-pressure ridge also play a role.

4.1. El Nino - Southern Oscillation

It has long been recognized that the tropical Pacific Ocean has a significant impact on large-scale atmospheric circulation and Australian climate. The SOI, a measure of the pressure difference between Darwin (the western Pacific Ocean) and Tahiti (central Pacific) has been related to Australian rainfall since Gilbert Walker's work in the 1920s. Pacific Ocean SSTs are another manifestation of ENSO, an El Niño event sometimes being defined as persistently warm central Pacific SSTs that result in a shift in the Walker circulation and tropical convection moving away from Australian longitudes. Indeed, operational seasonal prediction schemes in Australia use either phases of the SOI (Stone *et al*., 1996) or patterns of SST variability in the Pacific and Indian Ocean (Drosdowsky and Chambers, 2001) to predict regional rainfall and temperature probabilities.

ENSO has been shown to modulate rainfall over most of Australia (Nicholls, 1989). One of the two principal modes of Australian inter-annual rainfall variability is directly related to equatorial Pacific SSTs and regionally it is centred on central eastern Australia. Rainfall is mainly affected by ENSO in the winter and spring months (McBride and Nicholls, 1983), but its impact has recently been shown to be asymmetric (Power *et al*., 2006). Australian annual mean rainfall has a linear in-phase relationship with positive values of the SOI (La Niña type conditions), but although negative SOI values (El Niño conditions) generally produce below mean rainfall over Australia, the actual magnitude of the SOI is a poor indication of the rainfall deficiency. The two most recent El Niño events illustrate this clearly (see Wang and Hendon, 2007). The 1997–1998 'El Niño of the century" had very large SST anomalies in the east Pacific Ocean, but only a minor impact on SEA rainfall, while the relatively weak 2002–2003 event was arguably the worst drought in Australian's recorded history, since rainfall was a record low and temperatures were very warm (Jones, 2002; Watkins, 2002). Wang and Hendon (2007) suggest that the region where positive Pacific SST anomalies are strongest determines the impact of an El Niño on Australian rainfall. They found that in 2002–2003 the warming was most pronounced near the dateline whereas it was much further east in 1997–1998. The shift in the Walker circulation in 2002–2003 that followed from this SST pattern produced more pronounced atmospheric descent over Australia and therefore a greater impact on rainfall than in 1997–1998. Potgieter *et al*. (2005) also found differences in the magnitude and spatial extent of inter-annual variations in Australian wheat yield (which integrates rainfall changes with other variables) between El Niño events, depending on the timing and location of SST anomalies.

As a simple demonstration of the modulation of Australian rainfall by ENSO, Figure 8 shows the mean rainfall deciles for 12 El Niño years (where the June–November mean SOI value was less than −8.0 in each year) in the winter/spring half of the year (June–November). It is clear that the east of the continent tends to have rainfall in the lowest tercile virtually everywhere bar the coast east of the Great Dividing Range. By contrast, for La Niña years (not shown; pattern over SEA essentially the opposite of that in Figure 8) rainfall over the same region tends to be in the upper tercile for these months. In summer, the mean El Niño response is weaker and the same is true for autumn. The limited impact of ENSO on SEA in autumn means that the trend toward a drier SEA climate is probably not related to changes in ENSO. The strength of the SOI-rainfall link has also been found to vary considerably with time. Nicholls *et al*. (1996) found that the SOI–rainfall relationship changed after the early 1970s and that the change was greatest in the southeast. Other work has shown that the ENSO influence on Australian rainfall varies substantially on inter-decadal time scales (Power *et al*., 2006).

Another demonstration of the limited ENSO impact in autumn is shown in the rainfall probabilities generated by the Australian Bureau of Meteorology's operational seasonal prediction scheme (Drosdowsky and Chambers, 2001). In autumn, the loadings of the first mode of SST variability (reflecting El Niño-like SST anomalies in the Pacific Ocean) do little to modulate the rainfall probabilities for SEA. However, the loading on the second mode in SSTs used (reflecting Indian Ocean SST variability) do modulate SEA rainfall probabilities in this season. Hence, it appears that, in autumn at least, SST variability in the Indian Ocean has a greater impact on SEA rainfall. This will be discussed in more detail below.

Temperature over much of Australia also responds to the state of ENSO. Part of this signal comes from the rainfall changes that occur, so that much of the inter-annual temperature variability can be explained by rainfall variations (Nicholls, 2003). There are two main mechanisms that provide this link (Power *et al*., 1998b; Timbal *et al*.,

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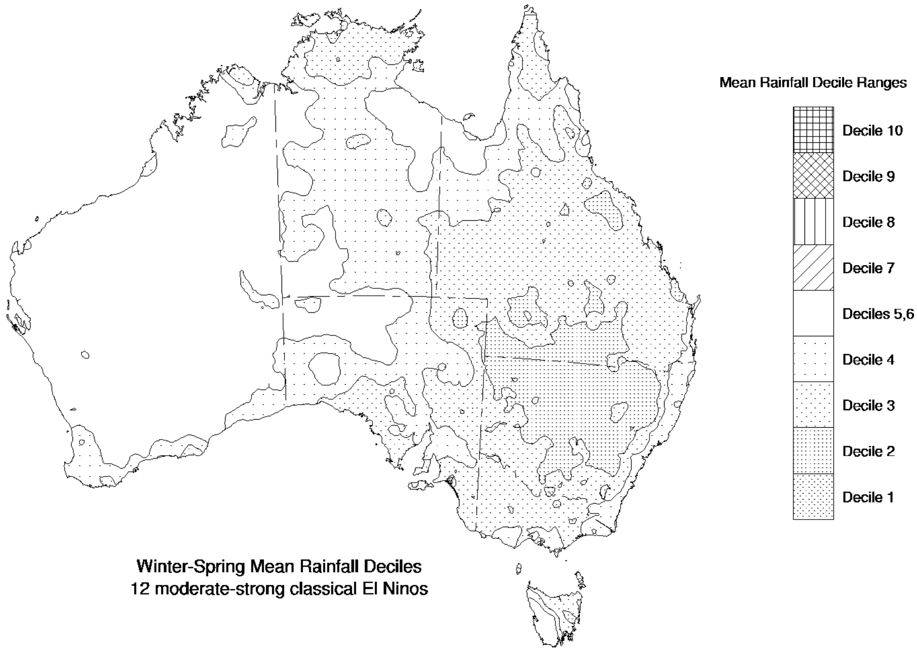

Figure 8. Rainfall deciles for winter/spring seasons in 12 El Niño years (where the SOI was less than −8.0).

2002). Lower rainfall is accompanied by less cloud, and hence daily Tmax increases with greater solar radiation. Also, decreased (increased) soil moisture during dry (wet) conditions means that evaporative cooling is reduced (enhanced) and mean temperatures are higher (lower). There are also some regions of Australia that show SOI-temperature correlations despite the lack of a SOI-rainfall relationship (Jones and Trewin, 2000). Such is the case in the southeast in summer due to temperature advection caused by the large-scale circulation anomalies linked to the Southern Oscillation. They also found that surface temperature shows the same asymmetry as rainfall relative to different signs of the SOI.

4.2. Tropical-extratropical interactions

Pittock (1975) found two main patterns of Australian rainfall variability, one covering the east of the continent that was the response to ENSO, and another that was concentrated in the southeast. He found that correlations between the latitude of the STR and rainfall showed a pattern very similar to this second mode of rainfall variability (see below). Nicholls (1989) identified Indian Ocean SST variability to be strongly correlated with a similar pattern in Australian winter rainfall, in a band stretching from the northwest to the southeast of the continent. The strength of this pattern had strong positive correlations with SSTs around Indonesia, and negative correlations with those in the central Indian Ocean. This pattern is essentially the second mode of global SST variability that is used in Australian seasonal prediction, as discussed above. Nicholls (1989) showed that its relationship with rainfall was largely independent of ENSO. He suggested that the gradient in SSTs from the east to central Indian Ocean may be related to the formation of cloudbands and, hence, the production of this important tropical-extratropical interaction rainfall mechanism for SEA. However, he did not determine whether the SST gradient forced the creation of the cloudbands.

Consequent work to better understand this mechanism included that of Simmonds (1990), who performed a modelling study where SST anomalies were imposed to the northeast and northwest of Australia. He found that rainfall over a large part of Australia was enhanced by higher SSTs off the northwest of the continent, with a pattern very similar to that uncovered by the previous work. Frederiksen and Balgovind (1994) had similar results when forcing a general circulation model (GCM) with an enhanced Indian Ocean SST gradient like the one uncovered by Nicholls (1989), with the response very sensitive to the strength of the gradient. Frederiksen and Frederiksen (1996) found that in a numerical model this SST gradient influences winter-time cloudband and extratropical cyclone formation in the Australian region. Watterson (2001) showed that one of the main patterns of low-level winds in a GCM induces winter rainfall anomalies over Australia that resemble NWCB as well as inducing a SST anomaly pattern in the Indian Ocean similar to the Nicholls (1989) SST dipole; the SSTs and rainfall anomalies appeared to be a response to the winds rather than the reverse. While the Indian Ocean impact on SEA rainfall can be explained by the formation of NWCB and is largely ENSO independent, this impact weakened when northeast SSTs were higher (Simmonds, 1990). These two modes of SST variability are largely independent, as they can be represented by the first two principal components in global SSTs, but it seems that they have competing impacts on rainfall. Wang and Hendon (2007) suggest that drought over Australia is most pronounced when there is a combination of SST

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anomalies that are positive in the central Pacific and negative in the eastern Indian Oceans.

Another representation of Indian Ocean SST variability involves equatorial SSTs only (Saji *et al*., 1999). The development of cold SSTs in the eastern Indian Ocean near Indonesia and warm SSTs in the west has become known as the Indian Ocean Dipole (IOD). The IOD causes heavy rains in eastern Africa and droughts over Indonesia, and it also has an impact on Australian rainfall. Figure 9 shows rainfall deciles for the March–November period for the 6 years of extreme positive IOD events (cool eastern Indian Ocean SSTs) as identified by Saji *et al*. (1999). Most of southern Australia (except the east coast) has below average rainfall, while in SEA virtually all of western and central Victoria exhibit the greatest rainfall deficiencies, being very much below average (decile 1). Ashok *et al*. (2003) show similar results. Meyers *et al*. (2007) used comprehensive classification methods to find IOD positive, negative and neutral years and similar ENSO classes, and they too showed the rainfall response over Australia in each group. According to their classification, three of the six years used in our calculations (1972, 1982 and 1997) were also El Niño years and three (1961, 1967 and 1994) were not (although others have classified 1994 as an El Niño). 1982 and 1967 were, respectively, the driest and second driest years on record for SEA. There are some differences in the rainfall response for these two subsets (El Niño and non-El Niño), but the pattern shown in Figure 9 is very similar over most of SEA for them both, except in the far northeast of the region.

Verdon and Franks (2005) related several of the above-mentioned Indian Ocean SST anomalies to eastern Australian rainfall. They found that the strength of both the Nicholls (1989) and Saji *et al*. (1999) dipoles modulate rainfall in SEA, but SSTs around Indonesia did so alone so that the western or central Indian Ocean SST forcing on rainfall was perhaps not as important as in the far east of the basin.

Indian Ocean SSTs, particularly those in the far eastern tropics, clearly have a relationship with SEA rainfall. It is not clear, though, whether these SSTs actually cause the rainfall anomalies. The IOD generally forms from May onwards in a given year, yet strong rainfall deficiencies are already evident over SEA in early autumn of IOD positive years, which is before the IOD forms. The IOD may, therefore, be a response to the same atmospheric forcing as the SEA rainfall anomalies, so that both may be caused by a third, preceding mechanism. This possibility was put forward by Nicholls (1989) to explain the link between eastern Indian Ocean SSTs and NWCB. Smith *et al*. (2000) showed that SWWA rainfall and southern Indian Ocean SSTs are linked via atmospheric forcing. England *et al*. (2006) found that high-pressure anomalies over Australia leading to low rainfall in SWWA create anomalous easterly winds over the eastern Indian Ocean that force upwelling and, hence, cool SSTs, thus providing a mechanism whereby the atmosphere induces a response in SSTs that may be relevant to SEA rainfall.

The above discussion and preliminary work on SEA rainfall declines by Wright and Jones (2003) suggest that the decade-long rainfall deficiencies appear to be independent of the ENSO-rainfall impact. Rainfall during the 1998–1999 La Niña, while a little above average, did little to relieve long-term deficiencies in SEA. Also, we have seen that the main fall in rainfall has occurred in autumn when the ENSO impact on rainfall is weak in SEA. Also, although there is a link between Indian Ocean SSTs and SEA rainfall, it is not clear whether SEA

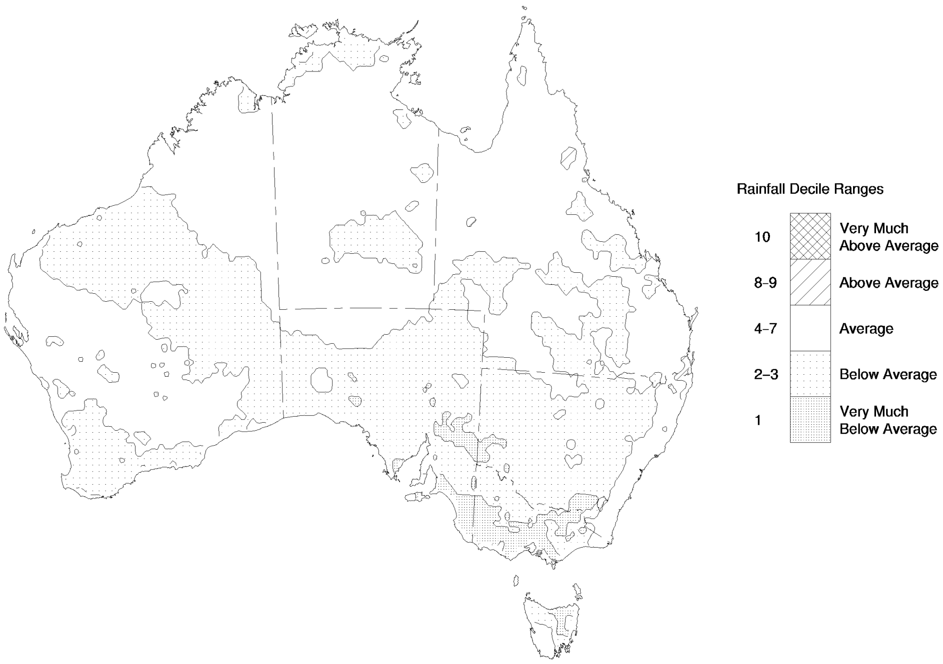

Figure 9. Mean rainfall deciles for March–November for the 6 years defined as extreme positive Indian Ocean Dipole years by Saji *et al*. (1999).

rainfall is actually a response to SST forcing, particularly in autumn.

4.3. Madden-Julian Oscillation

While ENSO is the major mode of variability in the Pacific Ocean on inter-annual time scales, the intra-seasonal timescale in the tropical atmosphere is dominated by the MJO (also known as the 30–60-day wave). The MJO is an eastward propagating region of enhanced tropical convection that has been shown to influence rainfall over Australia, particularly the north, and other regions of the globe on the intra-seasonal timescale. Phases of the MJO have been defined (Wheeler and Hendon, 2004) that essentially reflect the position of the region of enhanced convection. In the Australian tropics rainfall tends to increase when the MJO phase is in the local region, and decrease when it is more remote.

Donald *et al*. (2006) showed that there is a global rainfall response to the MJO phase. Wheeler and Hendon (2006) concentrated more on rainfall variability in Australia with season associated with the MJO. They found that significant circulation anomalies accompany different MJO phases that are consistent with the regional rainfall anomalies. Progression of the MJO from the western Indian to the eastern Pacific Ocean can produce large-scale changes to the atmospheric circulation that result in rainfall variations over different parts of Australia. Since MJO-related convective variations may produce atmospheric heating and cooling similar to Indian Ocean SST anomalies, the resulting circulation changes may be similar to the IOD impact. However, impacts of the MJO on SEA rainfall are not widespread and only occur at some locations and in some seasons.

4.4. Subtropical ridge

A ridge of high-pressure is detectable in daily mean sea level pressure fields over east Australian longitudes, as well as in monthly means. The latitude of this STR has long been suspected of influencing seasonal climate over the country, particularly in the east (Pittock, 1975; Drosdowsky, 2005, and references therein). It is generally expected that the position and strength of the STR will affect the mid-latitude storm track, either allowing systems to pass over the continent, thus bringing rain to southern districts, or forcing them to remain further south and hence promoting drier conditions. The STR has an annual cycle in latitude and strength, generally being farthest south in late summer and farthest north in early spring, strongest in winter and weakest in early summer.

Drosdowsky (2005) showed that in the post-1975 period, the annual cycle of the STR has changed in all months relative to pre-1975. After 1975, the STR was generally further north and stronger in all months except in autumn, particularly April and May. In this season, the normal behaviour is for the STR to move rapidly north, allowing mid-latitude storms to move north to bring more frontal systems and rain to SEA. Simmonds *et al*. (2001) have shown how Australian rainfall increases when the storm track moves north, and Leighton (1994) gave examples of the impact on rainfall of significant high- and low-pressure systems in the southeast. However, Drosdowsky (2005) found that in April and May this northward shift occurs more slowly in the post-1975 period. He also points out that along with the strengthening of the STR, this delay may well have had an impact in reducing rainfall over SEA in autumn. Certainly the largest rainfall decline since 1996 has been in this season, whereas in June rainfall has not fallen, and both the latitude and strength of the STR are essentially unchanged from pre- to post-1975. However, the correlation between SEA rainfall and the latitude of the STR has weakened, as has that between the SOI and SEA rainfall. The question as to why no rainfall decline occurred in SEA until the 1990s if the behaviour of the STR changed in the 1970s also remains unanswered. Also, the significance of the changes in the STR in these months and their impact on SEA rainfall need to be assessed in more detail.

4.5. Southern Annular Mode

The SAM has recently been shown to be linked to Australian rainfall. The SAM is the main mode of large-scale variability in the southern hemisphere extratropical circulation. It is a zonally symmetric varying exchange of mass between the polar regions and the mid-latitudes (Thompson and Wallace, 2000). Hendon *et al*. (2007) compared daily rainfall and surface temperatures over Australia during the high phase of the SAM index, which corresponds to a southward contraction of the mid-latitude storm track, to that during the low phase (equator-ward expansion of the storm track). They found that the high phase of SAM results in lower rainfall in the southeast and southwest of Australia in winter, and higher rainfall in summer in the southeast. They used data since 1979 and found a positive trend in the SAM index for summer that can account for up to half the observed positive trend in rainfall in southeast Australia in summer. Despite also finding a trend toward the positive phase in autumn, the lack of relationship between the SAM and autumn rainfall in the southeast precludes any direct attribution. Gillett *et al*. (2006) also found that the monthly means of both rainfall and temperature in SEA are below average during the positive phase of the SAM.

Other studies have found strong trends in the SAM index towards higher values (more southerly storm track) in summer and autumn. Thompson and Solomon (2002) showed that the resulting changes to the circulation are generally confined to the south polar regions and they attributed the bulk of the trend to variations in stratospheric ozone. Marshall *et al*. (2004) found similar trends but concluded that greenhouse gas increases have also played an important role. Arblaster and Meehl (2006) studied climate model simulations that showed that upper tropospheric and stratospheric trends in the SAM are

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mostly forced by ozone changes while near the surface both ozone and greenhouse gas forcings are responsible for the trends.

Meneghini *et al*. (2007) used an index of the pressure difference between 40 °S and 65 °S similar to a SAM index but only covering the Australian region (90°–180 °E). They found that this index was more closely linked to rainfall in the south of the country in winter (more so than the SOI), and in SEA north of the Great Dividing Range in summer. Little relationship was seen for autumn when the trend in their regional index was strongest. Their regional index may be closely aligned with the latitude of the Australian STR, which is not necessarily directly comparable to the hemispheric SAM index.

The SAM is one representation of the southern extratropical circulation of which the STR is another manifestation. Work on similar oscillations in this circulation goes back at least to Van Loon (1967) who diagnosed a semi-annual oscillation (SAO) in surface pressures at middle and high southern latitudes. The different annual cycles of heating and cooling in the high and mid-latitudes lead to a SAO in the meridional temperature gradient that influences the behaviour of extratropical cyclones (see Rind, 1986; Murphy *et al*., 2002). Van Loon *et al*. (1993) found that the SAO had weakened considerably after the late 1970s, particularly due to changes in the temperature cycles late in the year. Hurrell and Van Loon (1994) implicated declining stratospheric ozone concentrations. The recent work of Thompson and Solomon (2002) and Marshall *et al*. (2004) suggest that this is a problem that merits closer attention, as well as increasing greenhouse gases, so that any link with changes in the extratropical circulation that are affecting southwest and southeast Australian climate can be better qualified.

There is evidence that a shift in the atmospheric circulation in SEA in autumn has occurred. Figure 10 shows the autumn mean anomaly of mean sea level pressures in the last decade 1997–2006 relative to 1958–1996. These data come from the NCEP/NCAR reanalysis (Kalnay *et al*., 1996) and it should be kept in mind that the data over the high southern latitudes come from very sparse observations in the pre-satellite era. The ECMWF reanalysis data (not shown) reproduce a very similar pattern, so the changes in Figure 10 are not model dependent. Also note that mean sea level pressures over Antarctica have little physical meaning due to the high elevations of the continent. It is clear that pressures have been higher on average over and to the south of Australia in the recent decade. Pressures have obviously increased in the recent period in a band covering most of the mid-latitudes of the southern hemisphere, and they have decreased in the high latitudes. Indeed, the ‘annular’ pattern is similar in structure to the pressure difference between the high and low modes of the SAM and, therefore, suggests the trend toward the high mode of SAM reported previously (see above). It is evident that this pressure anomaly can explain some of the rainfall anomaly over SEA in the last decade as it suggests fewer low pressure and frontal systems in the region in autumn.

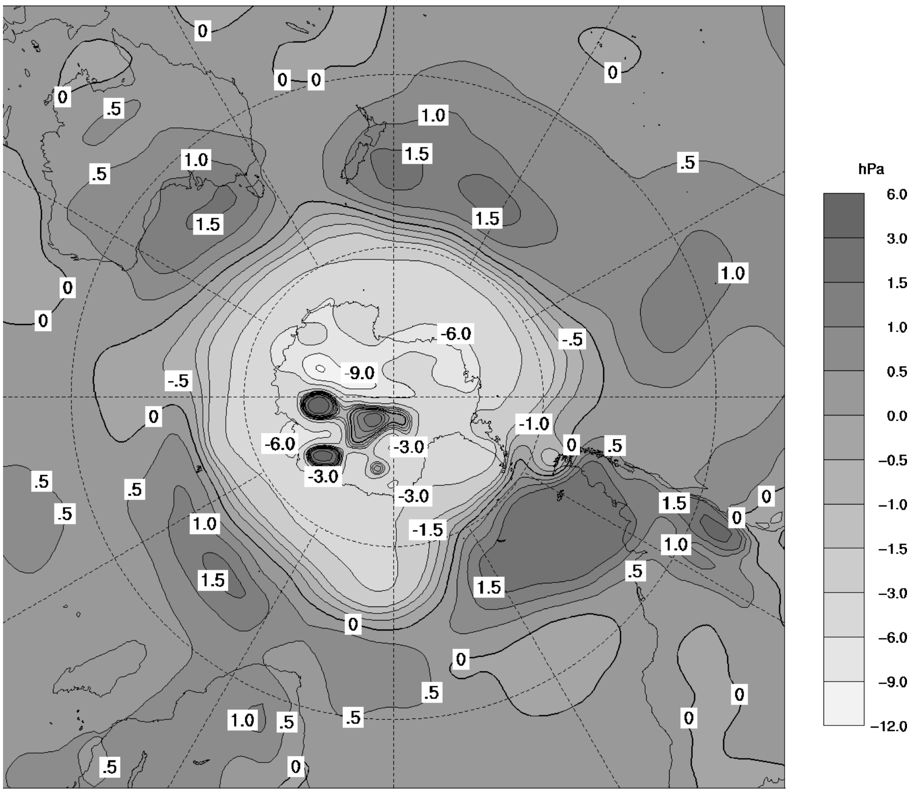

Figure 10. Autumn anomalous average mean sea level pressure for the period 1997–2006 from that for 1958–1996. Data are from the National Centres for Environmental Prediction Reanalysis.

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The trend in the SAM, reflecting a southward shift of the extratropical storm tracks, may be related. However, the impact of the SAM on autumn rainfall in SEA is weak, (Hendon *et al.*, 2007) so this problem is still to be resolved.

Two studies have used statistical downscaling models to relate the large-scale atmosphere to the climate at sites across SEA. Charles *et al.* (2003) uncovered a number of 'weather states' that explain rainfall variability across the Murrimbidgee River basin. They showed that there has been a fall in the number of winter-time approaching anti-cyclones and extratropical cyclone systems, in addition to an increase in anti-cyclone occurrences over the region, and a corresponding fall in rainfall. Timbal and Jones (2007) found that the recent rainfall decline at stations in SEA is related to higher pressure and reduced atmospheric water content. These studies provide further evidence that circulation changes are causing some of the rainfall decline in SEA, just as they have done in SWWA.

4.6. Extratropical SST

Whetton (1990) looked for relationships between SSTs around Australia and Victorian rainfall and found that SST variability in the western Pacific Ocean, the eastern Indian Ocean, west of western Australia and just south of Australia were important. Other studies have suggested that extratropical SSTs may impact on Australian rainfall, and there have been strong trends in SSTs in the Tasman Sea that may have a climate response over Australia. Figure 11 shows the linear correlation coefficient between monthly mean SSTs and SEA rainfall from 1950 to 2002. The tropical influence on SEA rainfall is clear with an ENSO pattern in the Pacific and the IOD in the Indian Ocean, as well as a dipole similar to those uncovered by Nicholls (1989) and Drosdowsky and Chambers (2001). There are also correlations that are just as strong in several extratropical regions, including positive correlations in the Tasman Sea and waters further east of Australia.

To better quantify these influences, we have calculated linear correlation coefficients between seasonal SEA rainfall and several SSTs 'indices' that cover the regions of strongest correlations in Figure 11. To assess their impact on temperature the correlations of these indices with maximum and minimum temperatures in SEA have also been calculated. These indices are the NINO4 index (mean SST over 160°E–150°W, 5°N–5°S) in the western Pacific Ocean, an Indian Ocean index (IOI) covering the ocean to the northwest of Australia representing the eastern arm of the IOD (110°–130°E, 20°–5°S), and a Tasman Sea index (TSI) for the waters directly to the east of SEA (150°–160°E, 40°–30°S). Smith and Reynolds (2004) extended reconstruction SST data are used and correlations are calculated for each season from 1900–2006 for rainfall and 1950–2006 for Tmax/Tmin. The results are shown in Table III with statistically significant correlations at the 5% level indicated in bold, determined using the method described in Power *et al.* (1999).

In autumn, only the local Tasman Sea SSTs have a statistically significant correlation with SEA rainfall, so that warmer SSTs lead to higher rainfall. While the NINO4 and IOI correlations are in the expected sense neither reach significance at 5% level. However, both have significant correlations with rainfall in winter and spring while the Tasman Sea SSTs correlations are not significant. The NINO4 correlation is strongest in spring while that of the IOI is strongest in winter. None of the indices has statistically significant correlations with SEA rainfall in summer. Correlations with both Tmax and Tmin are strongest with Tasman Sea SSTs, these being statistically significant in all seasons. NINO4 has positive correlations with Tmax in winter and spring and a negative correlation with Tmin in autumn. Conversely,

Table III. Linear correlation coefficients of southeast Australia rainfall (for 1900–2006), maximum (Tmax) and minimum (Tmin) temperature (for 1950–2006) with three SST indices for each season: the NINO4 index, Indian Ocean Index (IOI) and Tasman Sea Index (TSI). Correlations statistically significant at the 5% level are in bold.

	Index	Autumn	Winter	Spring	Summer
Rainfall	NIÑO4	−0.16	**−0.20**	**−0.37**	−0.18
	IOI	0.07	**0.30**	**0.26**	−0.09
	TSI	**0.25**	0.07	0.16	0.19
Tmax	NIÑO4	0.16	**0.27**	**0.33**	0.11
	IOI	**0.28**	0.08	0.00	0.24
	TSI	**0.32**	**0.39**	**0.40**	**0.43**
Tmin	NIÑO4	**−0.26**	−0.16	−0.11	−0.07
	IOI	0.11	**0.41**	**0.34**	0.19
	TSI	**0.49**	**0.30**	**0.60**	**0.55**

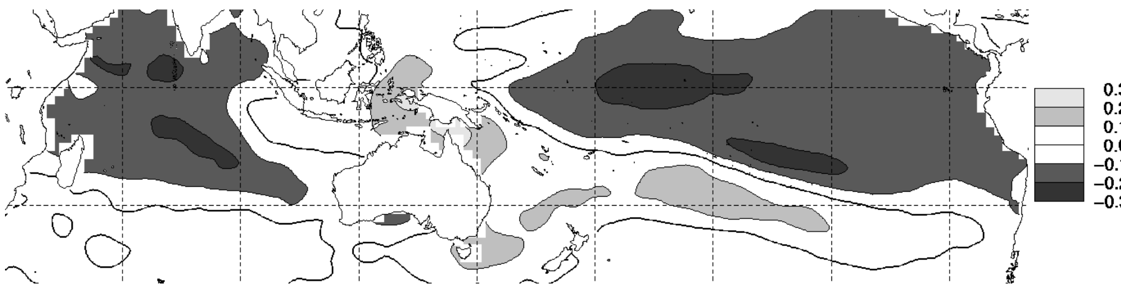

Figure 11. Linear correlation coefficients between monthly mean SSTs and south-eastern Australian rainfall from 1950 to 2002. SST data are from the Smith and Reynolds (2004) improved extended reconstruction.

Indian Ocean SSTs have significant correlations with Tmax only in autumn but with Tmin in winter and spring, all being positive.

These results reiterate those of previous studies and the discussion above on the lack of impact of ENSO and the IOD on SEA rainfall in autumn. Therefore, neither can be simply implicated in the rainfall decline in the southeast in autumn. Tasman Sea SSTs do have a statistically significant correlation in this season, but SSTs there have a strong warming trend and, hence, cannot explain the rainfall decline through the linear correlation between them.

For temperatures, the greatest effect comes from SSTs in the neighbouring Tasman Sea with positive SSTs leading to above average temperatures in all months. El Niño (La Niña) events are associated with warmer (colder) daytime temperatures in winter and spring, and colder (warmer) night-time temperatures in autumn. Thus, it appears that the cooling trend in Tmin in autumn over SEA is in spite of the warming of the Tasman Sea and is related to occurrences of ENSO events, as is the increase in winter/spring of daytime temperatures.

4.7. Land surface

The importance of soil moisture on climate variability in this region has been shown in the past. Timbal *et al.* (2002) suggested that rainfall and surface temperature persistence were related to soil moisture and that soil conditions retain some memory of the recent climate. Other studies (e.g. Simmonds and Hope, 1997) suggest that this rainfall persistence is due to persistence in the ENSO system, although Timbal *et al.* (2002) suggest that soil moisture levels are vital for maintaining the SOI-rainfall and SOI-temperature relationships. It, therefore, remains unclear whether soil moisture is an additional factor when considering prolonged rainfall and temperature anomalies.

In addition to Australian climate variability linked to the coupled ocean-atmosphere system and possibly reinforced by continental soil moisture, it is plausible that extensive land clearance across the Australian continent has contributed to some long-term climatic trends. For example, it has been shown (Timbal and Arblaster, 2006), by comparing climate model simulations with differing land cover, that the rainfall decline in SWWA attributable to large-scale circulation changes induced by greenhouse gas increases was further enhanced by land clearance through alterations to the large-scale rainfall.

How such an effect could be relevant to the more recent changes in SEA rainfall is unclear, given that land clearance was not significant in the preceding decades relative to earlier periods (AUSLIG, 1990). For example, Narisma and Pitman (2006) performed model experiments with two different levels of reforestation over Australia, but found no consistent differences in the simulations of January rainfall (they chose January because of earlier evidence of a response in this month).

4.8. Long-term trends in climate mechanisms

The processes that bring rain to SEA are reasonably well understood. While the effects on these processes from some of the climate mechanisms mentioned above have been well documented, some impacts are only being clarified with current or very recent research. In the preceding section we discussed these climate mechanisms individually, but they in fact interact in very nonlinear manners. Indian Ocean variability can complicate the ENSO effect on Australian rainfall (e.g. Simmonds, 1990), and there is now speculation that atmospheric intra-seasonal variability (the MJO) plays a role in the ENSO cycle. The STR and the SAM are intricately linked as the position of the ridge affects extratropical cyclone behaviour in the SEA region.

A number of studies (Power *et al.*, 1998a; Nicholls, 2003; Karoly and Braganza, 2005) collectively give strong evidence that the warming trends over Australia, including SEA, are likely to be due to enhanced greenhouse gas global warming. A link between global warming and SEA rainfall is not yet clear because of the relatively short duration of the dry period, but it has been shown to play a role in the longer rainfall decline in SWWA (Timbal *et al.*, 2006). Future projections from climate models under increasing greenhouse gas scenarios are for further, greater falls in rainfall in SWWA (Hope, 2006). Timbal and Jones (2007) and CSIRO (2001) project continued declines in rainfall over SEA.

5. Concluding remarks

There is no doubt that the southeast of mainland Australia has experienced significant climate anomalies over the decade since October 1996. Rainfall deficiencies of the magnitudes we are seeing have occurred before during the 20th century. However, the range of impacts is extraordinary due to the combination of consecutive dry years, high daily Tmax and cold night-time temperatures, and hence, frosts.

During the last decade, the mean rainfall over SEA has been 14.1% below the climatological (1961–1990) mean. The only time in the historical records that the 10-year mean SEA rainfall has been lower than this was during the 1936–1945 drought (17.0% below the mean). Drier than average autumns account for 61% of the current drop in rainfall and 53% of the trend since 1950. There has not been an 'autumn break' in SEA for the 7 years since 2000, and most observing stations across SEA have had significantly drier autumns, with fewer rain days and less intense rain than usual.

Maximum daily temperatures have been increasing across SEA to exacerbate the dry conditions, something not observed during previous prolonged drought events. The daytime warming is most likely related to global enhanced greenhouse gas induced warming. Minimum temperatures have fallen across much of western SEA in autumn, which is a direct consequence of lower cloud cover and soil moisture. Impacts of the climate anomalies of the last decade include more frosts in northwestern Victoria, significant reductions in water storage and allocations, increased stress on native trees, lower economic growth, less spring snow cover and increased bushfire risk.

An intriguing problem is that a similar rainfall decline occurred around 1970 in SWWA but the decline in SEA has not been evident until the mid-1990s. Both regions have had increasing trends in mean sea level pressure since around 1957. Rainfall is produced by similar mechanisms in the two regions, so it is reasonable to expect that the rainfall declines have some common characteristics and causes.

In SEA, rain is mostly produced by mid-latitude storms and fronts. Cloudbands stretching from northwestern Australia also bring rain through tropical-extratropical interactions. Cut-off lows are an important additional source of rain in northern SEA. Two features of the large-scale atmospheric circulation that impact on SEA climate have been considered here. Previous work shows that the SAM, a hemispheric-scale oscillation, has strong trends in most seasons, including autumn, when SEA rainfall has declined most. However, the SAM relationship with SEA rainfall has been shown to be weak in autumn. By contrast, the STR of high pressure that moves north and south over SEA throughout the year has been shown to have changed in autumn. Since 1975, the STR stays further south of SEA at the end of autumn compared to before 1975, which would have the consequence of impeding mid-latitude low-pressure systems from bringing rain to SEA.

The ENSO phenomenon impacts on rainfall over much of SEA. However, the impact of El Niño events is minimal in autumn and hence the rainfall deficiencies that have been caused by El Niño events in 1997, 2002 and 2006 are probably additional to the very low rainfall observed in autumn in SEA since 1997. Indian Ocean SST have been shown to have a strong relationship with SEA rain, particularly through their link to NWCB. Indian Ocean SST variability, such as the IOD, correlates strongly with SEA rainfall, but it appears the relationship is not causal since there is no evidence that SST anomalies precede those in rainfall: the dipole tends to form at the beginning of winter. Rather, the many studies carried out to date suggest that Indian Ocean SSTs and SEA rainfall are both responses to the same atmospheric circulation forcing, although there is some suggestion that SST off the northwest of Australia can help to persist the circulation and hence, rainfall anomalies. Local SST in the Tasman Sea affect autumn rainfall and temperatures in all seasons.

Detection and attribution studies have shown that temperature anomalies over Australia are forced to some degree by precipitation variability. They suggest that the rate of warming since the 1970s is greater than can be attributed to any rainfall decline. It is, therefore, highly unlikely that the maximum and mean temperature increases are due to natural variability alone. Decadal variability is a natural feature of the climate system and it can occur without any external forcing. However, we have shown that the mean autumn rainfall in SEA over the past decade is lower than would be expected by chance (less than 5% probability that it is a random occurrence). While no direct attribution of the rainfall decline to anthropogenic-forced climate change has yet been made, it cannot be ruled out. The latitude of the STR, the latitude of the mid-latitude storm track and the phase of the SAM have all altered, and it is to be expected that they are all inter-related and forced by the same mechanisms. We have shown that there has been a shift in the atmospheric circulation, with pressure increasing, in SEA in autumn, which is when the greatest rainfall declines have occurred. The recent trends in the SAM have been reproduced in climate model simulations that include trends in stratospheric ozone forcing over the high southern latitudes (Thompson and Solomon, 2002; Arblaster and Meehl, 2006). Further such simulations, using all natural and anthropogenic forcings, are necessary to reproduce the observed circulation and rainfall changes that we have seen in SEA.

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