An analysis of late twentieth century trends in Australian rainfall

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ABSTRACT: Trends in Australian precipitation from 1970 to 2006 are examined using a daily rainfall dataset. Results suggest a linkage between changes in the monsoon trough and rainfall trends over northwestern Australia. The late twentieth century drought observed along the Queensland coast is a response to changes in the atmospheric circulation that generates anomalous subsidence at high and middle levels of the atmosphere, thus inhibiting convection over the region. In addition, an anomalous anticyclonic circulation at low levels over Queensland tends to weaken the easterlies in the tropical western Pacific, thus diminishing the transport of moist air onto the coast. Trends in the frequency and magnitude of different rainfall events are also examined. This reveals that changes in total rainfall are dominated by trends in very heavy rainfall events across Australia. For example, some parts of western Australia reveal an increase in heavy rainfall events that are not accompanied by a rise in modest rainfall events, resulting in changes in the shape of the distribution towards a more skewed precipitation distribution. On the other hand, the frequency of extreme rainfall events along the Queensland coast has declined during summer and autumn consistently with the total rainfall decrease, indicating changes in the position of the precipitation distribution rather than its shape. Copyright © 2008 Royal Meteorological Society

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1. Introduction
Rainfall over Australia exhibits a very high degree of variability (Drosdowsky, 1993 and Smith et al., 2000). Understanding rainfall patterns is vital for managing agricultural and water resources. The recent drought over the eastern regions of the country has received much attention. Rakich and Wiles (2006) reported the period 2001–2005 as the driest years since 1968 and the warmest period ever recorded for NSW. Smith (2004) reported 2002 as the third driest year since 1900. The absence of heavy rainfall events in inland NSW is reflected by the reduced occurrence of flooding across the inland during the last few years.

The Australian climate is strongly affected by the surrounding oceans. In terms of air–sea interaction, one of the most expressive contributions to precipitation comes from the El Niño Southern Oscillation – (ENSO) (McBride and Nicholls, 1991; Lau and Nath, 2006). Previous studies provide evidence that warm El Niño events are generally accompanied by below-average rains over northern and eastern Australia, whereas wet conditions occur during cold events. A comprehensive description of the ENSO-related precipitation patterns in various parts of the Asian–Australian monsoon region is given by Ropelewski and Halpert (1987, 1989). Nicholls et al. (1996) found a decrease in the relationship between the Southern Oscillation Index (SOI) and Australian rainfall since mid 1970. Indeed, Power et al. (1999) showed that the Inter-decadal Pacific Oscillation (IPO) impacts notably on the Australian climate. Arblaster et al. (2002) suggested that inter-decadal changes in ENSO, shifts in the position of the Walker circulation, and variations in western Pacific sea surface temperature (SST) modulate correlations between the SOI and Australian rainfall. Suppiah (2004) also confirmed inter-decadal variations in the relationship between the SOI and Australian precipitation, thus corroborating the previous studies.

The impact of the Indian Ocean SST anomalies on Australian rainfall has been the subject of recent research (e.g. Nicholls, 1989; Ashok et al., 2001; Li et al., 2003; Saji and Yamagata, 2003a,b; England et al., 2006; Ummenhofer et al., 2008). The Indian Ocean Dipole (IOD) mode described by Saji et al. (1999) has been shown to impact upon Asian, African and Australian climates (Ashok et al., 2001, 2003, 2004; Li et al., 2003). England et al. (2006) investigated interannual rainfall extremes over southwest western Australia (SWWA) in relation to tropical and subtropical SST variability in the Indian Ocean. The SWWA has also experienced a reduction in rainfall since the mid 1960s, especially during austral winter (e.g. Allan and Haylock, 1993; Ansell et al., 2000; Li et al., 2003). This trend seems to be related...
to a combination of factors, including increased greenhouse gas concentrations (IOCI, 2002), natural climate variability (Smith et al., 2000; Li et al., 2005) and land use (Pitman et al., 2004).

Atmospheric variability over the Southern Ocean contributes to long-term rainfall fluctuations via the Southern Annular Mode (SAM). The SAM is a hemispheric mode of variability associated with a displacement in atmospheric mass between the southern high and mid latitudes. It has a large impact on surface winds, SST, sea ice, heat fluxes and oceanic transport (Hall and Visbeck, 2002; Sen Gupta and England, 2006). However, correlations between the SAM and Australian rainfall are only modest; explaining a fraction of Australia’s rainfall variability, and mostly constrained to the southern regions of the continent (Meneghini et al., 2006). Murphy and Timbal (2007) show that the rainfall decline in southern Australia during the past decade is associated with changes in the SAM and in the subtropical ridge that in turn reduce the number and impact of mid-latitude systems reaching this area.

A comprehensive review of the detection and attribution of Australian rainfall change was recently completed by Nicholls (2006). Rainfall changes over the SWWA region have been extensively studied. The same cannot be said for the northwest regions, with only a few studies addressing the increase in rainfall over the northwest of Australia. Wardle and Smith (2004) and Rotstain et al. (2007) suggest that the increased rainfall over northwest Australia is due to enhanced aerosols resulting from human activity, especially from Asia. However, there is still a lack of understanding of the atmospheric processes operating in this region. The highest priority for future studies, though, seems to be the east coast of Australia, where no work has yet attributed a cause to the large-scale rainfall decline observed along the eastern seaboard since the 1950s.

In this study, we investigate the trends in the Australian rainfall from 1970 to the present day. We choose this period to coincide with a time of relatively good data coverage, yet long enough to resolve multi-decadal timescales. A brief description of the observational datasets used in this study is presented in Section 2. Section 3 describes the trends in Australian precipitation and presents evidence of possible factors responsible for these changes. Section 4 focuses on the trends in extreme rainfall events across the continent. Discussions and conclusions are presented in Section 5.

2. The observational dataset

The dataset used in this study is based on the high-quality daily rainfall dataset from the Australian Bureau of Meteorology (Lavery et al., 1992). The data have been constructed using various spatial interpolation algorithms to estimate rainfall across Australia. The interpolated surface is displayed on a regular 0.5° grid extending from 10°S to 44°S and 112°E to 154°E. Daily rainfall is used instead of monthly data because the latter temporal resolution may alias important variations in individual rainfall events. For instance, Goswami et al. (2006) question the stability of the Indian monsoon rainfall over the past 50 years using a daily rainfall dataset. They found significant positive trends in the frequency and magnitude of extreme rain, and negative trends in the frequency of moderate events over central India. In other words, the monthly-to-annual trends can mask trends in distinct rainfall events. Variations in daily rainfall, in contrast, can be related directly to extreme events, which in turn have a very important impact on agriculture and other socioeconomic activities.

The choice of daily data limits our analysis to a shorter period due to the incompleteness of the rainfall measurement network. Due to the relatively low number of observations prior to about 1970, we focus this study on the 1970–2006 period. Prior to 1970, the rainfall network is generally too sparse for reliable analysis, particularly in terms of daily measurements. Therefore, we analyse daily rainfall records from 1 January 1970 to 3 February 2006. Furthermore, in order to explore the mechanisms of rainfall trends operating over Australia, other variables must also be analysed. In this sense, the introduction of satellite measurements since 1979 gives us more reliability in both temporal and spatial observations, especially over the Southern Hemisphere where the sparsity of records is large. Although the time series from 1970 to 2006 includes the first 9 years without satellite records, it is still important to maintain them for a period of over 30 years in order to capture multi-decadal modes. In this context, we use sea level pressure (SLP), outgoing longwave radiation (OLR), zonal winds, omega and specific humidity from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996), limited to the same period of the rainfall dataset, namely, 1970–2006.

3. Trends in Australian rainfall

The annual rainfall in Australia has exhibited trends in recent decades, as presented in Figure 1(a). In general, the spatial pattern of the trends in annual precipitation can be separated into two main regions: to the west where the rain is increasing (except along much of the coast line), and the east where precipitation has been decreasing (particularly along the northeast coast). Note that the trends, presented in Figure 1, were calculated based on standardized rainfall time series that facilitates the comparison of regions with different variances. The east–west pattern in annual precipitation (Figure 1(a)) is basically reproduced by trends in summer and autumn rainfall (Figure 1(b) and (c)). Winter and spring do not, in contrast, exhibit large trends around Australia. This is consistent with the findings of Smith (2004). A more detailed analysis of the annual and seasonal trends is separated below for two major regions: southern and tropical Australia, with emphasis on the latter.
3.1. Southern Australia
This section explores rainfall trends over SWWA, southern South Australia, southern NSW, Victoria and Tasmania. Several studies have shown that SWWA has experienced a reduction in rainfall since the mid 1960s, especially during austral winter (Allan and Haylock, 1993; Ansell et al., 2000; Smith et al., 2000; Li et al., 2003; Hope et al., 2006). Several mechanisms have been proposed as the cause of this trend, such as changes in SLP (Smith et al., 2000; Hope et al., 2006; Nicholls, 2006), a weaker African monsoon (Baines, 2005), a positive trend in the SAM (Li et al., 2005) and land clearance since the European settlement (Pitman et al., 2004).
Figure 1(a) shows a slightly negative trend in SWWA annual rainfall, resulting from the decline in spring (Figure 1(e)). Contrary to expectation, winter rainfall (Figure 1(d)) does not exhibit a significant reduction over this region. This is because the period analysed in this study (1970–2006) post-dates the sudden drop that occurred around the mid 1970s. Trends are sensitive not only to the temporal resolution of the data, but also to the length of the time series being considered. For this particular area, we extended the time series back to 1950 to assess the reduction in rainfall reported in previous studies. Figure 2 shows the time series of winter rainfall averaged over a localized region around Perth (115°W–120°W/south of 32°S). A breakpoint analysis yields a drop in SWWA rainfall around 1975, associated with a sudden reduction of mean rainfall during winter months. The decrease between the mean from 1950–1974 to 1975–2004 is approximately 13% or 17 mm. The post-1975 mean is statistically different from that of the earlier period at the 5% level based on a t-test, and is consistent with the decline found in June–July precipitation by Hope et al. (2006).

Tasmania exhibits an east–west pattern in the annual rainfall trends (Figure 1(a)). This zonal configuration in the annual trend arises due to an increase in winter and spring rainfall over western Tasmania (Figure 1(d) and (e), respectively) and by the decreasing signal in the eastern region especially during autumn (Figure 1(c)). Located in the mid latitudes between 40°S and 43.5°S, Tasmania is under the influence of westerly wind variations. Western Tasmania exhibits one of the highest rates of annual precipitation in the country (more than 2500 mm in a year), having most of its rainfall produced by moisture advected from mid-latitude storms and fronts constrained in the west by the mountainous topography. During winter, when the westerlies are strongest, western Tasmania receives more rain than the eastern regions, generating a prominent east–west variation. Therefore, it is likely that the negative trend over Tasmania is related in some way to changes in the magnitude of the westerlies via the SAM phenomenon. A similar relationship is also possible for the southern regions of Australia. In fact, southeastern Australia (southern NSW and VIC) also shows a significant decline in rainfall (Figure 1(a)) that is highest in autumn (Figure 1(c)). Murphy and Timbal (2007) showed that during the past decade the mean rainfall over southeastern Australia had been approximately 14% below the climatological mean in relation to the period 1961–1990.

Meneghini et al. (2006) showed that rainfall in southern Australia is negatively correlated to the SAM. The authors demonstrated that this relationship is even stronger during winter in western Tasmania when a regional SAM index is considered (using SLP data from 90°E to 180°E). It is well known that the SAM has exhibited a significant trend towards its high-index polarity over the past few decades (e.g. Thompson and Wallace, 2000; Thompson and Solomon, 2002; Marshall, 2003). While the NCEP/NCAR reanalysis shows that the greatest trend in the SAM occurs during winter, direct observational data reveal the largest increase is in summer (Marshall, 2003). On the other hand, Meneghini’s regional SAM index exhibits the highest trends in autumn, which could explain the large negative trend of autumn rainfall over Tasmania and southeastern Australia (Figure 1(c)). The positive phase of the SAM is associated with higher pressure at mid latitudes, and consequently, weaker westerlies. The weakening of the westerlies reduces the moisture transport to southern regions of Australia, resulting in less rainfall. Over southern Queensland and northern NSW, the anomalous high pressure at mid latitudes associated with the positive phase of the SAM may intensify the onshore winds, thus transporting more moisture and favouring enhanced precipitation during autumn time (Figure 1(c)). Nevertheless, the impact of the SAM on autumn rainfall in southeastern Australia is weak (Hendon et al., 2007). Murphy and Timbal (2007) show that the subtropical ridge over Australia has shifted further south over the southeast at the end of autumn in the last 10 years, compared to before 1975, thus inhibiting mid-latitude low-pressure systems from bringing rainfall to southeastern Australia.
In contrast to the above, certain regions in southern Australia and western Tasmania show a slight positive trend in precipitation during wintertime (Figure 1(d)). Also, Tasmania exhibits a positive trend in spring rainfall that is contrary to the observed positive trend in the SAM. However, Meneghini et al. (2006) found the highest correlations between the regional SAM index and rainfall over southern Australia to occur during wintertime, and not in summer and autumn when rainfall is largely reduced (Figure 1(b) and (c)). Therefore, we believe that the positive trends over southern Australia (including western Tasmania) during winter and spring cannot be explained solely by the SAM trends.

3.2. Tropical Australia

This section investigates rainfall trends over the northwestern, northern and northeastern regions of Australia. Annual precipitation over eastern Australia has experienced a prominent reduction equivalent to 0.3 SD/decade or approximately 102 mm/decade over the averaged region 12°S–24°S and 145°W–152°W (Figure 1(a)). This trend is persistent along the mid and south coasts of Queensland during summer, and along the northeast coast during autumn (Figure 1(b) and (c)) with a downward trend of 46 mm/decade. To date, there are no previous studies that have conclusively obtained a mechanism explaining the negative trend in rainfall seen along the Queensland coast (Nicholls, 2006).

Annual precipitation over western Australia shows an increase over most of the state, except for the west coast where trends are small and negative (Figure 1(a)). A centre of positive trend of 0.5 SD/decade (approximately 70 mm/decade) is located around 24°S/123°E (Figure 1(a)). The positive trend in annual rainfall across western Australia reflects the large increase in summer and autumn precipitation (Figure 1(b) and (c)). On the other hand, the slight negative trend in annual rainfall (Figure 1(a)) along the western coast is due to the reduction of winter and spring precipitation (Figure 1(d) and (e)).

There is an interesting point in the seasonal trends that needs to be highlighted. During austral summer (Figure 1(b)) northern Australia and northwestern Australia show a positive trend of approximately 0.25 SD/decade (50 mm/decade). In austral autumn, northern Australia, instead, exhibits a negative trend of −23 mm/decade or −0.1 SD/decade (Figure 1(c)). This trend is persistent along the mid and south coasts of Queensland during summer, and along the northeast coast during autumn (Figure 1(b) and (c)) with a downward trend of 46 mm/decade. To date, there are no previous studies that have conclusively obtained a mechanism explaining the negative trend in rainfall seen along the Queensland coast (Nicholls, 2006).

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contrasting trend from December to May could indicate a suppression of rainfall during autumn over northern Australia. Since this region is strongly influenced by the monsoon regime during summer time, these trends may be related to changes in the Asian–Australian monsoon; for example, via an earlier northward migration of the monsoon trough. This statement is supported by trends in the OLR as shown in Figure 3. Climatologically speaking, tropical latitudes usually exhibit low values of the OLR due to deep convection processes (Xie and Arkin, 1998). Generally, tropical convection is associated with OLR lower than 240 W/m² (Lau et al., 1997). Zhang (1993) suggests that OLR lower than 240 W/m² can be used as a measure for detecting areas of intense convection, associated with deep convective clouds that normally occur during the monsoon season.

Negative values of OLR in Figure 3 indicate a tendency in the position of the monsoon trough. Negative anomalies of the greatest magnitude are located over Indonesia in summer (Figure 3(a)). Note that northern Australia and northwestern Australia also exhibit negative OLR trends during summer, consistent with the positive trend of rainfall (Figure 1(a)). Trends in OLR averaged over the northern region 10°S–16°S/122°W–137°W exhibit a negative trend of −0.38 W/m²/month, indicating more convection during DJF. On the other hand, positive anomalies of OLR are found over northern Australia during autumn (Figure 3(b)), particularly over the north of Queensland. This is in agreement with the suppression of convection over the Queensland coast and consequent decreases in rainfall. The northern region 10°S–16°S/122°W–137°W shows a positive trend (0.17 W/m²/month) in OLR during late autumn which is related to the suppression of the convection in May.

As the OLR responds to alterations in atmospheric pressure, we have calculated trends in SLP, as shown in Figure 4(a) and (b). Tropical latitudes in the Indian Ocean and the western Pacific show a positive trend in summer and autumn SLP, since 1970. In contrast, there is a negative trend in summer SLP off the north and west coast of Australia (Figure 4(a)). This downward trend in SLP agrees with changes in OLR during the same season. In autumn (Figure 4(b)), the positive SLP trend indicates less convection and a suppression of precipitation over Australia.

Figure 4. Trends in monthly sea level pressure (SLP) over tropical Indian Ocean and Australia during (a) summer (DJF) and (b) autumn (MAM). Contour intervals are 0.005 hPa/month.
It is interesting to note that Australia has experienced a positive trend in SLP during the autumn season (Figure 4(b)), although a positive (negative) trend remains in precipitation (OLR) over the west as seen in Figure 1(c) (Figure 3(b)). Changes in OLR do not always reflect a direct effect of SLP anomalies, since the latter are usually dominated by variations at the surface level of the atmosphere, while the former can represent changes at higher altitudes. Thus, trends in SLP do not explain all of the variability in precipitation over Australia, particularly in the tropics. In addition, as the northwest coast of Australia is one of the regions most affected by tropical cyclones, part of the variability in precipitation may be due to changes in these sporadic yet extreme events. Changes in the frequency of rainfall extreme events will be investigated in Section 4.

In order to assess changes in circulation in the upper atmosphere, we calculate the divergence of the horizontal winds at 200 hPa (Figure 5). The divergence of the horizontal winds is a variable that indicates air convergence or divergence and consequent vertical motion across the atmosphere, according to mass conservation. A convergence (negative divergence) of the horizontal winds at lower levels of the atmosphere is associated with rising motion. At 200 hPa, the wind convergence generally indicates a downward motion of air (subsidence) and, thus, limited or no deep convection processes.

Figure 5(a) presents the distribution of the trends in wind divergence at 200 hPa during summer. The summer trend in wind divergence shows positive values over Indonesia, and at tropical latitudes over Australia (Figure 5(a)), indicating anomalous divergence at high levels of the atmosphere. This result agrees with Figure 3(a), suggesting a tendency towards greater convection over northern Australia and northwestern Australia during summer. In contrast, a convergence can be seen over the northeast coast of Australia, confirming the tendency towards subsidence in that region. Downward motion of air inhibits convection and thus produces the negative trend in summer rainfall seen over this region.

Figure 6 shows the mean and trend in omega along a section at 20°S over Australia. When displayed against the pressure in the atmosphere, Figure 6(a) shows that, for the mean summer conditions, air rises from the low to middle levels of the atmosphere, up to approximately 700 hPa. The associate trend, however, reveals an out-of-phase behaviour, with upward motion at middle and high levels of the atmosphere (reflected in the negative values between 600 and 200 hPa in Figure 6(b)). This trend suggests a tendency towards deep convection over northern Australia, corroborating the results shown for the OLR and wind divergence trends in Figures 3(a) and 5(a), respectively. The east coast exhibits a downward motion trend as seen in the positive values at...
eastern longitudes of Figure 6(b) (from 140°E to 150°E, approximately). This is also in agreement with the wind divergence trends depicted in Figure 5(a) and the overall reduced rainfall seen in this region during the late twentieth century.

The trends in wind divergence at 200 hPa and in omega at 20°S persist during autumn, as displayed in Figures 5(b) and 7, respectively. The distribution of wind divergence trends resembles that of summer, with anomalous convergence at high levels of the atmosphere over the east coast. Moreover, Figure 7(b) exhibits marked positive omega trends across the atmosphere over eastern longitudes (between 140°W and 150°W). This helps to explain the prolonged drought observed over the northeast coast of Australia, characterized by a trend towards subsidence of air that inhibits convection and suppresses precipitation.

The reduced summer rainfall along the Queensland coast is exacerbated by a decrease in moisture advection onto the land. The climatological behaviour in summer is shown in Figure 8(a), where the zonal winds flow onto the east coast. Trends in zonal winds over the West Pacific are shown in Figure 8(b). Positive values indicate westerly anomalies, while negative values represent anomalous easterlies. There is a weakening of the easterlies south of 20°S, and an enhancement of the easterlies at lower latitudes, as a result of the anomalous anticyclonic circulation at low and mid levels of the atmosphere over Queensland (see the integrated wind vectors in Figure 8(b)). The meridional dipole pattern in zonal wind trends over the West Pacific leads to less advection of moisture onto the Australian east coast, thus reducing the rate of orographic uplift, condensation and precipitation. This explanation corroborates the negative trends in summer rainfall seen in Figure 1(b). Rakich et al. (2008) also observed a reduction in the onshore moisture transport to the east coast of Australia. A closer view of the zonal wind and precipitation trends reveals a highly localized area in the extreme north of Queensland (Figure 1(b)) with enhanced rainfall due to an increase of the easterlies and the consequent advection of warm and moist air from the tropical western Pacific.

It is worth noting that changes in zonal winds during MAM (figure not shown) do not exhibit offshore anomalies (as in summer, Figure 9). Although there are
Figure 8. (a) Mean surface winds in summer (DJF). Maximum vector is 5.6 m/s. (b) The trend in zonal mean wind speed (contoured; m/s/month), overlaid by vectors showing trends in winds integrated from the surface to 500 hPa.

Figure 9. Time series of specific humidity anomalies at 850 hPa averaged over the northeast coast of Australia (16 °S/142 °W to 155 °W). The thick line represents the negative trend of −0.46 g/kg/10 years, which is significant at the 90% level according to a $t$ test.

no significant trends indicating offshore winds during autumn, the east coast of Australia has experienced a negative trend in moisture content at the 850 hPa level, as shown in Figure 10 indicating specific humidity at 16° S. This shows a gradual reduction in moisture content in the lower troposphere, although interannual variability is also large. The anomalous subsidence over the east coast seen in Figure 8(b) generates a tendency towards a more stable atmosphere, confining moisture to the surface levels. Although moisture is still present at near-surface levels of the atmosphere during autumn, this low-level moisture is not transformed into precipitation. The enhanced subsidence during MAM dries the mid troposphere, reducing the probability of moist convective rainfall. Therefore, it is possible that changes in MAM rainfall are driven by trends at higher levels of the atmosphere rather than by changes in atmospheric moisture advection at the surface.

During summer, the trend towards subsidence over the southeast Queensland coast (Figures 5(a) and 6(b)) is intensified by the reduction of moisture due to the anomalous offshore winds at low levels south of 20° S (Figure 6(b)). In other words, the negative trend in rainfall over the Queensland coast in summer is associated with changes in atmospheric circulation at low and mid levels, while during autumn it
Figure 10. (a) The Southern Oscillation Index (SOI). Method used by the Australian Bureau of Meteorology which is the standardized anomaly of the mean sea level pressure difference between Tahiti and Darwin (Troup SOI), multiplied by 10. (b) The NINO4 time series from 1970 to 2006. Sea surface temperature anomalies (°C) averaged over central Pacific 160°E to 150°W, 5°S to 5°N. Superimposed are the linear trend (thick line) and the 10-year running mean (thin smooth line).

is related to changes at the mid to high levels of the atmosphere.

The mechanisms generating the anomalous subsidence over Queensland are still unclear. As the Indian and Pacific Oceans influence tropical Australian rainfall, they are strong candidates to explain the long-term trends in precipitation. It is well known that the Indian Ocean has warmed markedly since 1970 (IOCI, 2002). This warming could be one of the factors responsible for the drought observed in summer and autumn over eastern Australia. Luffman et al. (2008) use a set of experiments from NCAR atmospheric model to demonstrate that the rise in tropical Indian Ocean SST drives enhanced convection throughout the troposphere, leading to a subsidence trend over northeastern Australia. The authors also show that the anomalous zone of subsidence is exacerbated by an anomalous anticyclonic circulation that induces an offshore trend in near-surface winds. The evidence of changes in atmospheric circulation showed in this study using observational data corroborates the findings of Luffman et al. (2008) based on idealized numerical simulations, suggesting an important role of Indian Ocean warming in changing climatic conditions over Australia.

The other factor explaining droughts over tropical Australia could be the long-term trends associated with ENSO. Simultaneous to the weakening of zonal winds along the east coast of Australia, this region is also likely impacted by the influence of a negative trend in the SOI. In fact, the weakening of the easterlies seen in Figure 8(b) may simply be symptomatic of changes in the SOI since 1970. It is known that during El Niño years, when the SOI is negative, the warm pool in the western Pacific is displaced to the east. Consequently, precipitation shifts eastward together with the anomalous warm waters. This anomalous configuration in the ocean alters the Walker circulation. As a result, convergence and rising air motion occur over the displaced warm pool, generating a compensating subsidence over Australia.

Figure 10 shows the raw SOI and NINO4 time series, and their associated linear trends and 10-year running means, for the period 1970–2006. A decadal oscillation is present in both the SOI and the NINO4 time series. Apart from the interannual-to-decadal variations, a marked linear downward (upward) trend is seen in the SOI (NINO4). The negative trend in SOI is even larger when the spring season index is assessed (figure not shown). While the monthly SOI trend is −0.16/month, the negative trend for springtime is −0.24/month. Considering the lagged response to changes in the Walker circulation, this will impact on precipitation during the ensuing summer season. A shift towards a lower mean SOI value has
recently been reported by Power and Smith (2007), who also claim 1977–2006 as a period of unprecedented El Niño dominance. Note also that the NINO4 region (averaged SST within 160°E to 150°W/S to 5°N) covers most of the region with warm anomalies related to the so-called El Niño Modoki (165°E to 140°W/10°S to 10°N) described by Ashok et al. (2007). This pseudo-El Niño event is characterized by warming in the central Pacific and colder SST anomalies in both eastern and western regions along the equator, with a tripolar SLP pattern during its evolution, analogous to the southern oscillation. Ashok et al. (2007) claim that the El Niño Modoki is not part of the traditional ENSO phenomenon, with distinct impacts on global climate. The authors showed the presence of two anomalous Walker circulation cells in the troposphere, instead of the single cell pattern in the typical El Niño case, with the joint ascending branch of these cells located in the central equatorial Pacific and the western descending branch over Indonesia and northern Australia. The positive trend in SST in the central Pacific revealed by the NINO4 time series (Figure 10(b)) therefore likely impacts Australian precipitation in the El Niño Modoki way. Ashok et al. (2007) observed a long-term increasing trend since 1979 in the El Niño Modoki pattern, which may be the mechanism forcing the drought trend over northeastern tropical Australia.

4. Extreme event trends

Most climate change analyses begin with an evolution of annual and seasonal trends. However, the long-term monthly averages can alias changes in extreme events. For instance, if moderate rainfall events decrease while heavy rainfall events become more frequent, there may be no apparent trend in annual or seasonal precipitation. In this case, the standard deviation of rainfall increases, indicating a climatic regime favoured by more frequent extreme events. Extreme rainfall events can cause crop damage and floods, having a significant impact on agriculture and, consequently, the national economy.

In order to analyse changes in the variations of rainfall, we show the spatial distribution of daily rainfall standard deviation computed per year and per season (left column) and the associated trends (right column) in Figure 11. Trends in the standard deviation show a pattern similar to the annual precipitation changes (Figure 1(a)) across Australia, with positive values in the west and negative values in the east. The increase of the standard deviation is marked over western Australia during summer and autumn (Figure 11(g) and (h)), and northern Australia during summer. On the other hand, the east coast reveals a decline in the standard deviation, particularly in DJF. However, a negative trend in the standard deviation does not imply that there is less variation among years if the annual mean also decreases. This misconception occurs because the standard deviation is based on the mean of the entire time series. As the mean can vary each year, the standard deviation is not a straightforward measure for a year-to-year comparison.

![Figure 11](image-url)
of rainfall averaged over four areas (indicated by the orange boxes in Figure 11) chosen according to the trends in DJF and MAM rainfall over the west and east coasts of Australia. The bootstrapped means reveal a marked change in the position of the PDF during both seasons, consistent with the decreased rainfall over the east coast and the increased precipitation over the west coast from the earlier to the posterior period. It is interesting to note how the precipitation has changed from 1970–1980 to 1990–2000. For example, Western Australia has experienced a larger spread in rainfall events compared to the Queensland coast. This increased spread affects not only the mean but more so, the tails of the distribution (Figure 12(a) and (c)). On the other hand, the PDF for the east coast (Figure 12(b) and (d)) has shifted towards a lower rainfall mean, but preserves its shape from one period to the next. Therefore, rainfall trends over the west are dominated by changes in the shape of the PDF, while over the east the trends have been driven by changes in the mean rainfall.

We also calculate the skewness, and the lower and upper deciles in the rainfall distribution of rainy days, as seen in Figure 13. The skewness is a measure of the asymmetry of the rainfall PDF. Generally, the rainfall distribution does not follow a Gaussian shape. In fact, precipitation is a climatic quantity that can be described by a skewed PDF, as it can only take positive values. Positive values in Figure 13(a) therefore indicate a change towards a more skewed distribution, while negative values represent a less skewed PDF. A positive (negative) skewness trend may thus be associated with an increase (decrease) in the intensity of extreme events.

The spatial distribution of the trends in the lower and upper deciles in Figure 13 measures the changes in the magnitude of the highest and lowest 10% of extreme events in the PDF. The red (blue) areas reveal a decrease (increase) in the intensity of lower rainfall events (Figure 13(b)). Figure 13(b) and (c) shows a decrease in the lowest and highest events along the east coast, whereas an increase is seen in the extreme events in the west, particularly the high rainfall events. This pattern is consistent with the trends in total rainfall (Figure 1(a)), particularly in the upper decile trend where the agreement is approximately 89% of spatial area. It is interesting to also note a region over the northwest coast around 20°S and 125°E that experienced a reduction in the skewness (Figure 13(a)), although the upper decile (Figure 13(c)) has increased. This is explained by the positive trend in the lower decile suggesting a displacement of the total rainfall mean and a shift towards a more symmetric PDF.

On the other hand, a centre of positive skewness around 22°S and 122°E is associated with an increase in the
used more complex indices to classify extreme events (more than 2 SD anomalies). Although some studies have (from 1 to 2 SD anomalies) and ‘very heavy rainfall’ rainfall (up to 1 SD from the mean), ‘heavy rainfall’ according to its deviation from the mean as ‘moderate events, we classified the daily precipitation lower decile range, resulting in a less symmetric PDF.

Figure 13. Trends in the (a) skewness, (b) lower decile and (c) upper decile, (millimetres per year) of the daily rainfall distribution from 1970 to 2005. Areas within the thin contours are statistically significant at the 90% level.

upper decile which is not accompanied by a rise in the lower decile range, resulting in a less symmetric PDF.

In order to further examine trends in the frequency of rainfall events, we classified the daily precipitation according to its deviation from the mean as ‘moderate rainfall’ (up to 1 SD from the mean), ‘heavy rainfall’ (from 1 to 2 SD anomalies) and ‘very heavy rainfall’ (more than 2 SD anomalies). Although some studies have used more complex indices to classify extreme events (e.g. Alexander et al., 2007), we have chosen a simple threshold based on the standard deviation because it allows a direct interpretation of the data. The number of moderate, heavy and very heavy rainfall events was calculated for each month and then the trend was fitted to each time series. The resulting spatial distribution of the annual and seasonal trends in extreme events is presented in Figure 14.

In general, the continent shows consistent trends between the annual rainfall and the extreme events, though trends in very heavy rainfall [Figure 14 (right column)] resemble the annual and seasonal trends more than the moderate and heavy events [Figure 14 (middle and left columns)]. The very heavy rainfall analysis reveals a general decrease over eastern Australia and an increase in the west, particularly during summer and autumn. This east–west structure is consistent with the trends in annual rainfall, which suggests that the extreme event trends may have an important influence on the annual mean changes. Indeed, Alexander et al. (2007) found that the trends in extreme events are highly correlated with trends in means for both temperature and precipitation in Australia, and suggest that the mechanisms driving the mean change are also driving changes in extremes. Groisman et al. (1999) used a simple statistical model of daily precipitation based on the gamma distribution to show that changes in mean monthly precipitation should be associated with large changes in the extreme events.

The strong and positive trend in annual, summer and autumn rainfall over northwest Australia is seen in all rainfall events, with the greatest resemblance to the very heavy rain [Figure 14 (right column)]. The increase in rainfall observed over the past 36 years in the northwest, particularly over northern Australia, therefore, largely comes from the higher number of very heavy rainfall events in summer and autumn. The increasing frequency of very heavy rainfall events in conjunction with a more modest upward trend in moderate rainfall suggests that the change in extreme events has been driven mostly by convective systems rather than large-scale precipitation. This is consistent with our previous analysis of changes in atmospheric dynamics over the region.

It is well known that a large amount of precipitation is brought to the western Australian coastline, from Broome (18°S) to Onslow (21.40°S), by tropical cyclones during January to March. For example, over half the total monthly precipitation received between 1939 and 1969 around Port Hedland (20.25°S) is from tropical cyclones (Milton, 1980). Furthermore, Broadbridge and Hanstrum (1998) found a significant increase in tropical cyclone frequency with positive SOI values, and a preference for severe cyclones to occur later in the season (April and May) following negative SOI years. Given the negative trend in the SOI since 1970, the rise in the frequency of very heavy rainfall events during MAM is likely therefore associated with a tendency towards more severe tropical cyclones reaching the western Australian coastline in autumn [Figure 14 (right column)].
Figure 14. Trends in the number of rainfall events per year from 1970 to 2006 in moderate rain (left column), heavy rain (middle column) and very heavy rain (right column). Definitions of these categories appear in the text. Units are in events per year and events per season for the annual and the seasonal plots, respectively. Areas within the thin contours are statistically significant at the 90% level.
5. Summary and conclusions

In this study, trends in the Australian rainfall have been investigated using daily rainfall records for the period 1970–2006. Australian rainfall changes over the past 36 years have been significant. These changes vary regionally, with a marked east–west gradient, and seasonally, with the largest changes occurring during summer and autumn. There have also been different trends in individual rainfall events when classified as moderate, heavy and very heavy rainfall.

Although the long-term changes in Australian rainfall are well established, there is insufficient understanding of the underlying causes of these trends. There is a lack of knowledge in particular about the negative trend along the east coast, and only a few studies to date on the increase over northwest western Australia. Recently, Nicholls (2006) summarized all the important findings regarding Australian rainfall trends. He advocated urgent priority for detection and attribution studies, particularly relating to the decline of rainfall along the east coast and the increased rainfall over the northwest.

Herein lies the significance of the present study. The main results from our analysis can be summarized as follows:

1. There are indications that the positive trend in annual and summer rainfall over northwest Australia is related to more intense deep convection caused by changes in the monsoon trough.
2. The negative rainfall trend over northwest Australia during autumn may be due to an earlier northward shift of the monsoon trough.
3. The SAM may explain the negative rainfall trends over Victoria, Tasmania, southern south Australia and southern NSW during DJF and MAM; and the positive rainfall trends over northern NSW and southern Queensland. However, the positive trend seen in the southern regions of Australia during winter and over western Tasmania both in winter and spring cannot be explained by the positive trend of the SAM.
4. The significant decline in summer rainfall over the Queensland coast is associated with changes in atmospheric circulation generating anomalous subsidence over the region, thus inhibiting the convective formation of clouds. In addition, there is evidence of weakened tropical easterlies that consequently reduce the moisture advection onto the coast.
5. Although there is no apparent reduction of moisture advection onto the east coast during autumn (MAM), major changes occur in the atmospheric circulation. In particular, the observed decline in autumn rainfall over Queensland is also related to anomalous downward motion over the east coast that increases the atmospheric stability and inhibits local convection, keeping moisture confined to low levels and reducing the specific humidity in the mid troposphere.
6. Changes in total rainfall reflect trends in the shape and position of the distribution, with a general increase of the extreme deciles and standard deviation in the west and a decrease in the east.

7. Trends in the distribution of total rainfall appear to be primarily a result of changes in very heavy rainfall events across Australia, particularly over the northwest, with a tendency towards a flatter precipitation distribution. Over the east coast, the rainfall distribution shows changes in the mean position rather than in the shape of the distribution.

Because changes in the frequency of very heavy rainfall events follow trends in total rainfall, particularly over eastern Australia, it is quite likely that the two trends are linked to the same mechanism. We suggest that the atmospheric changes observed over Queensland are associated with the positive trend in equatorial Pacific SST, and a consequent tendency towards more frequent ENSO and El Niño Modoki events (Ashok et al., 2007 and Power and Smith 2007).

In addition, it is possible that changes in convective rainfall events over eastern Australia could be, to a large extent, driven by the late twentieth century warming of the Indian Ocean (see also Luffman et al., 2008). Whether the warmed SST in the adjacent oceans is entirely due to the enhanced greenhouse effect, or also driven by atmospheric circulation changes remains unclear. Recently, several studies have reported a weakening of the Walker circulation under an enhanced greenhouse scenario (Vecchi et al., 2006; Power et al., 2007). Using numerical simulations forced by a double CO₂ scenario, Hennessy et al. (1997) found an increase in intense convective events and a reduction in moderate non-convective rainfall at mid and low latitudes. While rainfall change due to anthropogenic warming is beyond the scope of this study, the changes we note are consistent with the scenario of Hennessy et al. (1997). Future studies should focus on a clear detection and attribution of Australian rainfall change, especially along the east coast and over the northwest of Australia.

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