Trends in Australian rainfall: contribution of tropical cyclones and closed lows

Sally L. Lavender · Deborah J. Abbs

Abstract Over the past 40 years there have been significant changes in Australian rainfall with increases in the north-west and decreases in the east. Tropical cyclones (TCs) and other closed low pressure systems are important synoptic systems that provide a large proportion of Australia's annual rainfall. This study examines the proportion of rainfall that can be attributed to TCs over the 1970–2009 period, and to TCs combined with other closed lows over the 1989–2009 period. The contribution of these systems to Australian rainfall trends is also analysed. Tropical cyclones are found to have little influence on rainfall trends over the full time period. However, when the more recent 21-year period is considered, TCs and other closed low pressure systems can partially explain the positive rainfall trend in the north-west. Similarly, other closed low pressure systems, such as cut-off lows and east coast lows, can explain some of the negative rainfall trend in the south-east. The contribution of TCs and other closed low pressure systems to rainfall trends in the north and south-east is found to be predominantly due to respective increases and decreases in the rainfall producing efficiency of the systems. An understanding of the influence of these synoptic systems on Australian rainfall in the current climate is vital for evaluating how Australia's water budget may change in future climates.

Keywords Australian rainfall · Tropical cyclones · Rainfall trends

1 Introduction

Australian rainfall is highly variable on intra-seasonal to inter-annual timescales. Important drivers of Australian rainfall variability are known to include the El Niño-Southern Oscillation, the Indian Ocean dipole and the Madden Julian oscillation (Risbey et al. 2009). These drivers are known to have varying influences on different regions of the continent, allowing for regional rainfall variability and trends. Changes in Australian rainfall over the last 40 years show a significant increase in rainfall over north-western Australia and a decrease in the east (e.g. Taschetto and England 2009; e.g. Smith 2004). The influence of ENSO on Australian rainfall is well-known with El-Niño (La-Niña) years resulting in dryer (wetter) conditions, particularly in the east of the continent. There has been an increase in the proportion of El-Niño events in recent years which may explain some of the drying trend in the east, however the influence of ENSO is not as strong over north-west Australia and is unable to explain the positive rainfall trend over this region (Shi et al. 2008). The observed changes in rainfall have led to numerous studies on the rainfall trends over different regions of Australia suggesting a wide range of forcing mechanisms. For example, studies show that factors contributing to the increase in rainfall over north-west Australia include sea surface temperatures (Shi et al. 2008) and changes in the monsoon trough (Taschetto and England 2009), whilst the modelling study of Rotstayn et al. (2007) suggests that anthropogenic aerosols may also be contributing to the changes. Mechanisms controlling the decline in north-east Australian rainfall have been found to be sea surface temperatures (SSTs) north east of Australia (Li et al. 2011), the inter-decadal Pacific oscillation and the southern annular mode (Speer et al. 2011).

S. L. Lavender (✉) · D. J. Abbs
Centre for Australian Weather and Climate Research, CSIRO, Marine and Atmospheric Research, PMB1, Aspendale, VIC 3195, Australia
e-mail: Sally.Lavender@csiro.au

Although the large-scale forcings on north-west Australian rainfall have been examined, there is no knowledge of the synoptic-scale systems that are resulting in the changes in rainfall in this region and how these systems may change. Recent work by Berry et al. (2011) uses pluviograph records from four stations in north-west Australia to provide some background to the rainfall characteristics and rainfall producing mechanisms over this region. They point out that the observed increase in rainfall is likely due to changes in the synoptic weather systems rather than changes in the ocean state.

In other regions of Australia, particularly in the south, the synoptic systems contributing to rainfall are more fully understood. In a region of northwestern Victoria in southeastern Australia, cut-off lows are found to account for 50 % of April–October rainfall and 80 % of daily rainfall events (Pook et al. 2006). There is found to be large interannual variability in the cut-off lows and a decline in the amount of rainfall per cut-off low day was also evident, suggesting a decrease in the efficiency of these systems. Cut-off lows produce more of the heavier rainfall events in this region of southeastern Australia (Risbey et al. 2009) than other rainfall producing systems. Frederiksen and Frederiksen (2007) looked at the decrease in rainfall in southwest western Australia since the mid 1970s, finding this is due to a shift in storm tracks as well as a reduction in cyclogenesis, due to changes in the large scale circulation in the Southern Hemisphere. Risbey et al. (2009) found that the positive phase of the southern annualar mode results in more cut-off low systems which compensate for the decrease in rainfall due to the southward shift in storm tracks found by Frederiksen and Frederiksen (2007). Pook et al. (2012) also examined rainfall producing systems in the central wheat-belt of southwestern Australia, finding 50 % of rain producing systems are frontal, 33 % cut-off lows and 10 % warm- core low pressure systems. Both the fronts and cut-off lows were found to be contributing to the decline in rainfall over this region.

Over northern Australia the majority of annual rainfall falls during the summer monsoon season, which coincides with the tropical cyclone (TC) season. The contribution of TCs to rainfall has been analysed in a number of different basins and regions such as the North Pacific (Rodgers et al. 2000) and North Atlantic (Rodgers et al. 2001) as well as globally (Jiang and Zipser 2010). The latter study highlights three regions with the highest percentage of rainfall being due to TCs. These are the southwest of the Baja Californian coast, the region of the northwest Pacific around Taiwan and off the northwest of the Australian coast. Recent work analysing the contribution of tropical cyclones to rainfall over north-west Australia found TCs can contribute up to 45 % of the annual rainfall at individual stations e.g. Port Hedland (Ng 2010, refer to Fig. 1
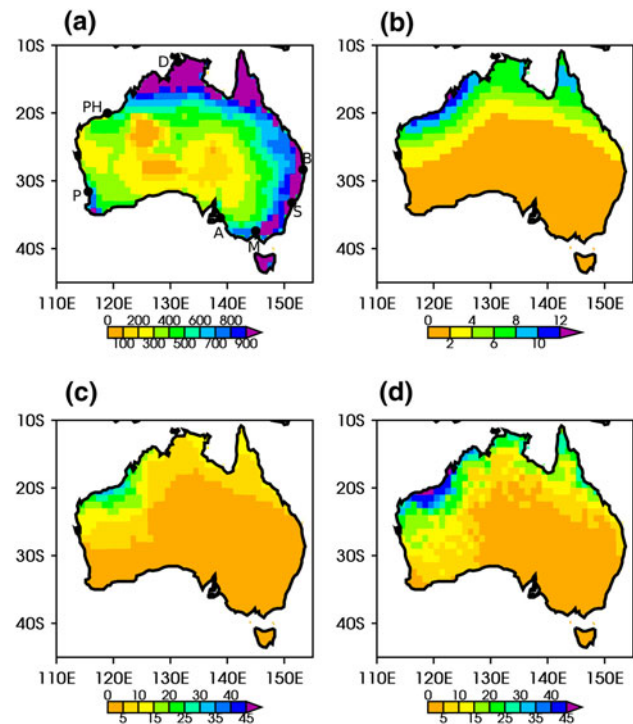
Fig. 1 Climatologies over 1970–2009 of **a** precipitation per year [mm year^{-1}], **b** number of tropical cyclone days per year (where a TC is assumed to influence a 5° × 5° *box*), and percentage of **c** annual precipitation and **d** extreme precipitation (above the 99th percentile) influenced by tropical cyclones. *Colouring* is shown by the legends. Locations of places referred to in the text and major Australian cities are marked on map (**a**), where *D* Darwin, *PH* Port Hedland, *P* Perth, *A* Adelaide, *M* Melbourne, *S* Sydney and *B* Brisbane

for location). Since this is the region where increases in rainfall are evident, it is intuitive to ask if these changes may be associated with changes in frequency or intensity of tropical cyclones. This is of particular interest due to the projected decrease in numbers of tropical cyclones under future climates (Lavender and Walsh 2011). Over the past 40 years there have been decreases in numbers of TCs over the Australian region, particularly in the east (Hassim and Walsh 2008), although Kuleshov et al. (2010) show that this decrease is not statistically significant. Over the northwest the numbers of tropical cyclones have remained approximately constant throughout the past 25 years (Hassim and Walsh 2008; Goebbert and Leslie 2010). TCs over north-west Australia are also not found to be largely influenced by ENSO, unlike in other regions and basins including north-east Australia where there is a decrease in land-falling cyclones in El Niño years.

Over regions where tropical cyclones do not have such a large influence, other synoptic low pressure systems are known to contribute to rainfall and produce extreme rainfall events. Over tropical (northern) Australia, a large proportion of rainfall can be attributed to the monsoon and

in particular monsoon lows. Over the east coast of Australia, east-coast lows (e.g. Lynch 1987, McInnes et al. 1992) can result in heavy rainfall, whilst other cut-off low systems (e.g. Qi et al. 1999) and extra-tropical cyclones (Lim and Simmonds 2007) influence the south of the continent. The influence of cut-off lows on rainfall over southern Australia has already been mentioned, with these systems providing a large amount of rainfall, particularly in the cool months (Pook et al. 2006, 2012; Risbey et al. 2009). These systems combined with TCs can all be defined as Australian region closed low pressure systems. The contribution of these systems to Australian rainfall and extreme rainfall will be examined here. Trends in the contribution of these lows to rainfall and extreme rainfall and in the precipitation efficiency of Australian region lows are analysed to determine if these systems can explain the observed rainfall trends. Understanding these processes in the current climate is vital for evaluating how Australia's water budget may change in future climates.

The following section gives an overview of the data and methodology used. Section 3 examines the influence of TCs on rainfall and rainfall trends. The influence of all Australian region closed low pressure systems combined is analysed in Sect. 4. This allows us to evaluate whether the rainfall trends can be, at least partially, attributed to changes in Australian region lows. Finally, Sect. 5 includes conclusions and future work.

2 Data and methodology

2.1 Precipitation data

Rainfall data were obtained from the Australian Water Availability project (AWAP; Raupach et al. 2009) database produced by the Australian Bureau of Meteorology. This is available as daily accumulated precipitation (prior to 9 am local time) at $0.05° \times 0.05°$ resolution (Jones et al. 2009). Data were obtained for the period 1970–2009. These were interpolated onto a $1° \times 1°$ grid. Extreme precipitation events were taken as the events above the long-term 99th percentile, as calculated for each $1°$ grid-box.

Initially these data were compared to $0.25°$ resolution daily data from the Tropical Rainfall Measuring Mission (TRMM, 3B42 v6; Kummerow et al. 1998; TRMM, 3B42 v6; Huffman et al. 2007) and the 1 degree daily Global Precipitation Climatology Project (GPCP, version 2; Huffman et al. 2001) data over the period 1998–2008 to ensure that contributions and trends were not dependent on the data set used. The three data sets were interpolated to $1°$ resolution and were found to have good agreement of the annual climatology of Australian rainfall over the 11 years. Over this relatively short length of time, trends are not particularly useful or significant, but the signs of the trends were the same in the three data sets.

2.2 Observational tropical cyclone data

Tropical cyclone (TC) best-track data were obtained from the International Best Track Archive for Climate Stewardship dataset (IBTrACS; Knapp et al. 2010) for the period 1970–2009. These were interpolated onto a $1° \times 1°$ grid and the region of influence of each TC was calculated using an effective radius of $5°$ longitude/latitude. The use of a $5°$ radius is consistent with a large number of studies on TC rainfall (e.g. Dare et al. 2012, Larson et al. 2005). Since the AWAP data is in local time for the 24 h previous to 9am and the TC data is in UTC, the location of the TC is averaged over the 4 locations of the TC over the previous 24 h from local time. Australia is between UTC+8 and UTC +11 depending on the state and time of year. For a particular day, the average TC location is calculated between 06Z the previous day and 00Z on the current day. On a certain day only one TC can influence a particular grid-box. Rainfall is considered to be TC influenced on a particular day if the track continues to exist in the IBTrACs data set even if it has undergone extra-tropical transition or no longer satisfies all the criteria for TCs. Here we are analysing the number of TC-days per grid-box, rather than actual numbers of TCs.

The precipitation efficiency of TCs is calculated based on the amount of rainfall per TC-day per grid-box.

2.3 Detection of closed-low pressure systems

Many of the studies highlighted in Sect. 1 are concerned with a certain type of closed low, cut-off lows. Even when just considering this one type of low, there is a large amount of variability in the definitions of these systems in the literature. For example, Pook et al. (2006) defined a cut-off low as a closed low at 500 hPa with a cold trough below or a closed low at the surface and cold trough aloft. Qi et al. (1999) studied cut-off lows over southern Australia using a definition of closed circulations at the surface and 500 hPa. A climatology of southern Hemisphere cut-off lows using NCEP-NCAR reanalyses was produced by Fuenzalida et al. (2005) at 500 hPa and Reboita et al. (2010) at three levels in the upper troposphere, 200, 300 and 500 hPa. Kentarchos and Davies (1998) used the 200 hPa level to produce a climatology of cut-off lows in the northern hemisphere whereas Smith et al. (2002) used the geopotential height at 500 hPa. Extra-tropical cyclones in the southern hemisphere have also been studied at various levels using the Melbourne University tracking scheme (e.g. Lim and Simmonds 2007, Simmonds and Keay 2000) which uses mean sea level pressure and the

methodology that the center of the low will be located close to the maximum in the laplacian of pressure (Murray and Simmonds 1991; Simmonds and Murray 1999; Simmonds et al. 1999).

In this study we want to include all types of closed lows, these will include some of the "other synoptic system" events as defined by Pook et al. (2006), such as warm cored cyclones. Many of the studies highlighted above (e.g. Fuenzalida et al. 2005, Kentarchos and Davies 1998, Smith et al. 2002) only consider closed low pressure systems at one atmospheric level. However, in some cases this results in rainfall-producing closed lows that are only evident at other levels in the atmosphere being excluded. Therefore, for this study we use a multi-level tracking scheme in which a closed-low is included if it is present at any level of the atmosphere analysed. ERA-Interim re-analysis data were obtained from the European Centre for Medium-range Weather Forecasts (ECMWF) on a 1.5° × 1.5° grid for the period 1989–2009 (Simmons et al. 2006). Twelve hourly values of mean sea level pressure, winds and temperature were obtained. The detection routine detects any closed low pressure system at five atmospheric levels: the surface, 850, 700, 500 and 300 hPa. Regions with cyclonic vorticity are checked for where the pressure or geopotential height is lower than the surrounding 24 grid-points. The multi-level detections were combined into multi-level tracks and discarded if the closed low exists for less than 48 h. The closed lows defined in this study are relatively long-lived compared to many studies.

To be consistent with the tropical cyclone analysis, these were interpolated to a 1° × 1° grid and assumed to influence a radius of 5° longitude/latitude. The percentage of Australian precipitation that can be attributed to closed lows is sensitive to the choice of radius. This is examined by varying the radius of influence from 2° up to 8° at 1° increments. Over the entire Australian continent, the average percentage of rainfall that can be attributed to closed lows using a 2°, 3°, 4°, 5°, 6°, 7° and 8° radius of influence varies between 8, 12, 17, 22, 26, 29 and 32 %. The largest changes in the percentage contribution occur between 2° and 5°, after which there is a slight leveling off. This is particularly evident in coastal regions where there is a large difference in the percentages at the smaller radii increments but after 5 − 6° there is only a small increase. Between 5° and 8°, it is mainly the inland regions where the percentage of closed low rainfall is increased (not shown). The choice of a 5° radius of influence in this study is therefore a compromise between a smaller radius, which may exclude rainfall from some of the larger systems, and a larger radius, which may include rainfall not related to a closed low i.e. background rainfall. There is little literature on closed lows, excluding TCs, and their influence on precipitation in the Australian region. This is further complicated by different types of lows having different sizes and influences on precipitation. Studies on cut-off lows in the Mediterranean (Jansa et al. 2001; Porcù et al. 2007) have shown the majority of rainfall occurs within 600 km of the low centre with the heaviest rainfall occurring within 300–500 km, similar to that from a TC. Pook et al. (2006, 2012) used a relatively large box for the analysis of synoptic systems with systems influencing rainfall over larger distances than allowed in the current study. A larger radius may be appropriate in this study, however, we do not want to be including background rainfall that is not related to closed lows in the results. The use of 5° here for all closed lows, including TCs, allows us to remove the influence of TCs from that of other closed low pressure systems on rainfall. A study on rainfall associated with closed lows would be useful in determining the most suitable radius for future studies on closed low rainfall.

Due to the difference in the definition of these closed lows and climatologies that have been produced for the Australian region, which are mostly only concerned with a particular type of low, we are unable to make any direct comparisons with other studies. However, when the percentage rainfall due to closed low systems is calculated, this is found to be comparable to that found by Pook et al. (2012) in their Fig. 8a. This will be evaluated in Sect. 4.

2.4 Trend and significance calculation

To calculate trends in the data, the mean for a particular grid point over each year was computed giving one value per grid point per year. The trends in the yearly data were then calculated for each grid point using a simple linear regression technique. A non-parametric Mann–Kendall test was used to test the statistical significance of the trends in the data. This method only compares the magnitude of the data rather than the actual data values, comparing each data value to the subsequent data values.

3 Trends in contribution of TCs to Australian rainfall and extreme rainfall

The climatology of annual rainfall based on the full 40 years of data (1970–2009) is shown in Fig. 1a. Largest rainfall totals occur over the north of the continent and along the east coast. Tropical cyclones (Fig. 1b) influence the north and north-west of the continent, with the largest numbers of TCs making landfall over north-west Australia. Analysing the contribution of TCs to Australian rainfall (Fig. 1c) shows that TC-days provide 20–35 % of the annual rainfall to parts of the north-western Australian coastline, around Port Hedland. These values are much
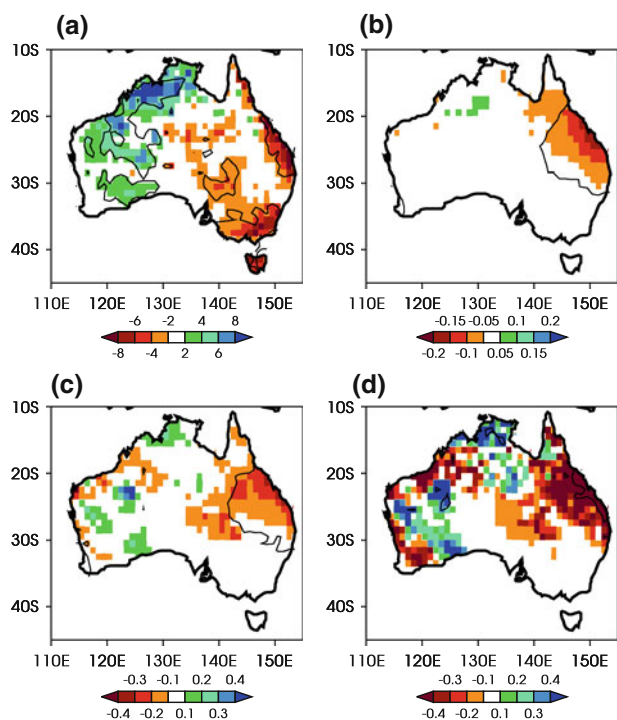
Fig. 2 Trends in **a** annual precipitation [mm year⁻¹] **b** tropical cyclone days and percentage of **c** annual precipitation and **d** extreme precipitation influenced by tropical cyclones over the period 1970–2009. *Colourings* are shown by the legend. *Black lines* highlight values significant at the 90 % level

lower than when the individual stations are considered (e.g. Ng 2010) due to coarser resolution. Further north the monsoon provides the majority of the annual rainfall and the TC contribution decreases to around 10–15 %. When extreme rainfall events, i.e. above the 99th percentile, are considered, over 40 % of these events are a result of tropical cyclones (Fig. 1d) over north-western Australia. The area of the west Australian coast north of 30°S,

extending inland to 130°E has relatively low annual rainfall (Fig. 1a) and up to 15 % of the extreme precipitation events occurring here are influenced by TCs.

The trend in annual rainfall over the whole of Australia for this 40 year period is shown in Fig. 2a and summarised according to broad regions in Table 1. The east–west split in the sign of the trend is evident, with a large and statistically significant decrease in annual rainfall along the east coast and in the southeastern corner. Over the west, excluding the southwestern coast, there is a significant increasing trend in annual precipitation as found in other studies (e.g. Taschetto and England 2009). This is particularly evident over the north-west, where there is an average increase of 2.85 mm yr⁻¹ over the whole north-west of the continent (Table 1). The majority of Australian cities (indicated on Fig. 1) lie in regions of decreasing rainfall trends which highlights the importance of this increase in the north-west to future water supply for the country's population.

The trend in annual number of TC-days (Fig. 2b) shows a decrease over the east coast over the last 40 years, consistent with a decreasing trend in the number of TCs over this region (Hassim and Walsh 2008). This decrease may be associated with more El Niño events than La Niña events in the second half of this time period. Over central north and north west Australia there are no significant trends in TC days, consistent with the findings of Goebbert and Leslie (2010). The decrease in rainfall over the east coast is partly a result of a decrease in TCs over this region with a significant decrease in the percentage of annual rainfall occurring as a result of TC-days (Fig. 2c) over the coast north of Brisbane. Over much of north-western Australia there is very little change in the percentage contribution of TCs to the annual rainfall with some areas showing a slight increase and some a slight decrease (not significant at the 90 % level). Further north, over Darwin,

Table 1 Summary of the trends in tropical cyclone (Fig. 2) and closed low (Fig. 4) rainfall, divided up according to regions of mainland Australia

Regions are split north–south at 25°S and east–west at 135°E, where *NW* north-west, *NE* north-east, *SW* south-west and *SE* south-east

Time period	Trend (per year) in	Region			
		NW	NE	SW	SE
TC years (70–09)	Rainfall (mm)	2.85	−1.91	0.92	−2.59
	TCs	−0.01	−0.09	−0.01	−0.02
	TC rain (mm)	0.60	−1.02	0.08	−0.34
	Non-TC rain (mm)	2.25	−0.89	0.84	−2.25
	Percentage of TC rain	−0.03	−0.16	0.02	−0.06
	Percentage of TC extreme rain	−0.06	−0.37	0.03	−0.12
Low years (89–09)	Rainfall (mm)	8.22	3.69	0.66	−4.59
	Closed lows	0.05	0.60	−0.08	0.31
	Low rain (mm)	5.79	3.22	0.64	−1.33
	Non-low rain (mm)	2.43	0.47	0.02	−3.25
	Percentage of low rain	0.33	0.33	0.10	0.10
	Percentage low extreme rain	0.73	0.21	0.35	−0.12

where a much smaller percentage of rainfall can be attributed to TCs there is a small and non-significant increase in TC related rainfall. When the average trend is taken for the whole north-west of the continent, there is found to be an increase in both non-TC and TC rain (Table 1) and a very small decrease in the percentage TC rainfall. When the percentage of extreme precipitation, greater than the 99th percentile, influenced by TCs is considered (Fig. 2d and Table 1) these trends are more pronounced. The increase in TC related rainfall in the north, near Darwin, with no associated increase in TC-days suggests a possible change in the efficiency of TCs, i.e. the amount of rainfall associated with each storm. This will be discussed in more detail later. These results suggest that the positive trend in rainfall over this region is a result of synoptic systems other than TCs. Since these possible systems include other closed low pressure systems, the following section will analyse the contribution and influence of Australian region lows on the rainfall and trends.

4 Trends in contribution of TCs and closed lows to rainfall

Lows associated with the monsoon will be picked up by the closed low detection routine, as will TCs, east coast lows and higher latitude cut-off lows. Over the 21 years where ERA-Interim data (1989–2009) are available, closed lows account for approximately 30–50 % of annual rainfall over the majority of Australia (Fig. 3a), with some regions in the north having almost 60 % of their rainfall due to these systems. When extreme precipitation events are considered the majority of the coastline, with the exception of south-western Australia, has over 50 % of its extreme rainfall as a result of closed lows (Fig. 3b). This highlights the importance of these closed low pressure systems to Australian rainfall and extreme rainfall.

The influence of all Australian lows on the rainfall trends is now examined. The total annual rainfall trend is shown again in Fig. 4a, but over the shorter 21 year period that is concurrent with ERA-Interim availability. This shows quite a different trend over northern and eastern Australia than when the full 40 years were considered (Fig. 2a, note different scale). The increase in rainfall over much of the west, apart from the south, is still evident but this now extends across north-east Australia where previously a decrease was evident. Table 1 summarises these results by region, with an average positive trend of 8.2 mm yr^{-1} in the north-west and a positive trend of 3.7 mm yr^{-1} in the north-east, compared to a decrease of 1.9 mm yr^{-1} over the full 40-years. This is consistent with the 1970s having above average rainfall so most of the drying trend is evident when this earlier rainfall data is
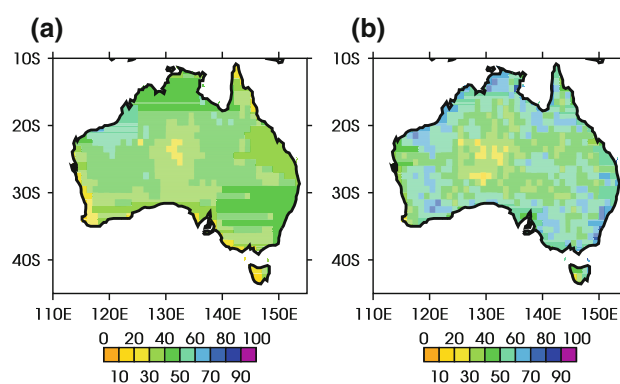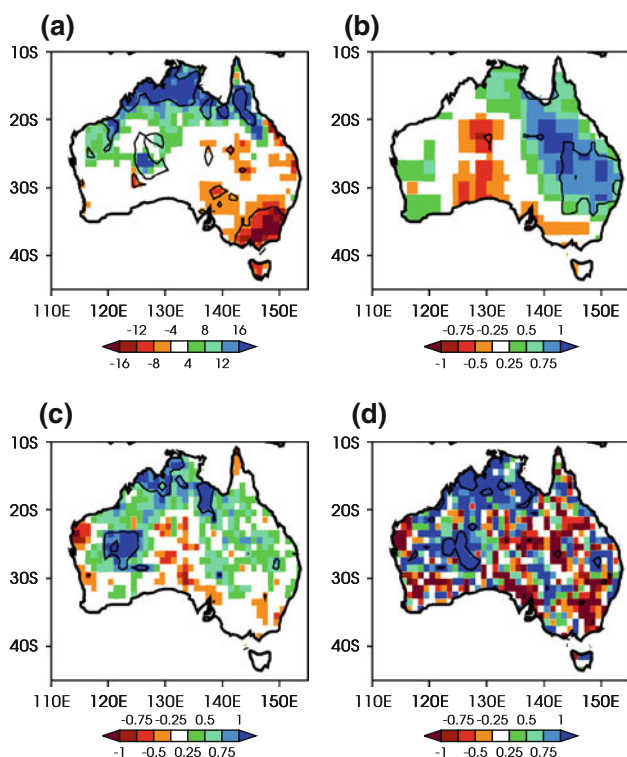

Fig. 3 Percentage of **a** annual precipitation and **b** extreme precipitation due to closed low pressure systems, detected from ERA-interim data over the period 1989–2009. *Colouring* is shown by the legends

included in the analysis. A recent study has found increases in north-east Australian rainfall since 1979 may be related to ozone depletion (Kang et al. 2011). The drying trend over south-east Australia is still prominent, to an even larger extent than shown previously (Table 1). Trends in extreme rainfall events (not shown) were found to be similar to those of annual rainfall (Fig. 2a), consistent with other work on extreme rainfall that includes data post 2000 (e.g. Taschetto and England 2009, Gallant et al. 2007).

Although a decrease in the number of TC-days since 1970 over east Australia was shown (Fig. 2b), there has been a significant increase in the number of closed low-days over this region since 1989 (Fig. 4b). This increase may be associated with an increase in inland trough lows as found and defined by Speer et al. (2009) and heat lows. The trend in numbers of closed low days is not so apparent in the west with the central-western region showing a decrease and the far west a slight increase.

Table 1 splits the trend in rainfall into closed low and non-closed low influenced rainfall trends. Over the whole north-west there has been an increase in closed low influenced rainfall of 5.8 mm yr^{-1}. With the exception of the south-east, closed lows explain the largest portion of the rainfall trend when split into these broad areas. Spatially, over north-west Australia there is a positive trend in the percentage rainfall influenced by closed lows (Fig. 4c). This positive trend extends to other regions where a positive rainfall trend is evident. Much of this increase in the percentage closed low rainfall occurs where there is little or no change in the number of closed low days, suggesting a change in the efficiency in the closed low pressure systems. This is investigated later. The increase in closed low-days in the east does not have a large influence on the closed low associated rainfall in this region (Fig. 4c). In fact, when extreme events are considered (Fig. 4d) there is a decrease in closed low associated extreme events over the south-east
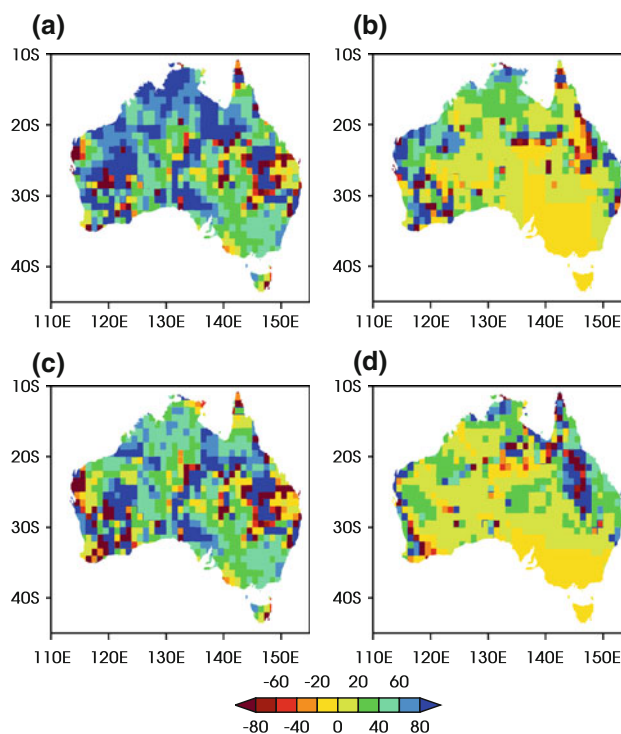
Fig. 4 Trends in **a** annual precipitation [mm year^{-1}] **b** closed low pressure systems and percentage of **c** annual precipitation and **d** extreme precipitation influenced by closed low pressure systems over the period 1989–2009. *Colourings* are shown by the legend. *Black lines* highlight values significant at the 90 % level

Fig. 5 Percentage of the trend in rainfall shown in Fig. 4a that is attributed to **a** closed low pressure systems, **b** TC days only and **c** closed low (minus TC) days. **d** Percentage of the 40 year trend in rainfall (Fig. 2a) that is attributed TCs. *Colourings* are shown by the legend

(Table 1). This may explain some of the negative trend in rainfall in the south-east, although non-closed low rainfall is found to have a larger negative trend when averaged over the whole of the south-east.

The contribution of closed lows to the trend in rainfall over this 21-year period is now analysed in more detail. Figure 5a shows the percentage of the rainfall trend in Fig. 4a that can be attributed to the trend in rainfall associated with closed low pressure systems. If the sign and magnitude of the trend are equal the contribution is 100 %, if the signs of the trends are opposite the value will be negative. Over 40 % of the rainfall over the entire northwest Australian region is a result of closed lows and regions where the rainfall trend was largest over 80 % is a result of closed lows. Rainfall trends over the majority of the Australian continent can at least partly be attributed to closed lows, with the largest exception being the central east coast region. This region of the east coast is where we have seen the largest increase in closed-low days (Fig. 4b) and there is an associated small increase in closed low rainfall, however the overall rainfall trend in this region is slightly negative.

These closed lows, as per the definition in Sect. 2.3, will include TCs. Days where there is a TC are now separated

from the closed low days to determine the effect the inclusion of TCs is having on the results. The percentage of the rainfall trend that is associated with only TCs is shown in Fig. 5b and closed lows (minus TCs) in Fig. 5c. The high percentage of the rainfall trend associated with all closed lows is a contribution of both TCs and other closed low pressure systems. Tropical cyclones help to explain the rainfall trend in the far north of the continent and around Port Hedland. Other closed low systems explain over 40 % of this positive rainfall trend and also explain up to 60 % of the negative rainfall trend in south-east Australia. In the far west TCs have the largest effect, although this has little relevance since there is little to no trend in rainfall in this region. In regions where the largest trends in rainfall occur (Fig. 4a) these are mostly due to changes in closed low rainfall, excluding TCs. Figure 5d shows the percentage of the rainfall trend over the full 40-year period (1970–2009) that can be attributed to TCs. This corroborates the findings of Sect. 3, showing that the increase in rainfall over northwest Australia is not associated with TCs. Similarly, as found for the longer time period, decreases in rainfall over the east coast can be related to a decrease in TC-rainfall.

The increase in the closed low related rainfall in regions of the north-west where there has been little change in the number of closed low days suggests that a change in the
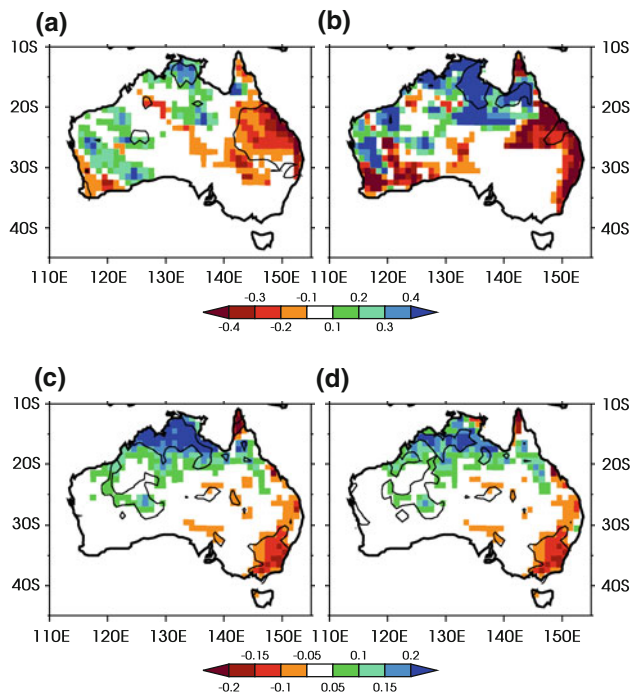
Fig. 6 Trend in the amount of precipitation [mm] per tropical cyclone day per year over the period **a** 1970–2009 and **b** 1989–2009 and **c** precipitation [mm] per closed low pressure system influenced day per year over the period 1989–2009. *Colourings* are shown by the legend. *Black lines* highlight values significant at the 90 % level

efficiency of closed lows, i.e. the amount of rainfall per closed low day. This will now be investigated.

Figure 6 shows the trend in rainfall per TC-day per year over the full 40-year period (Fig. 6a), the 21-year period (Fig. 6b), all closed lows (21 years, Fig. 6c) and closed lows minus TCs (21 years, Fig. 6d). All systems and periods show an increase in the amount of rainfall per system per day in the north of the continent. Over the full 40 years the increase in efficiency of TCs in the north helps to explain the increase in extreme rainfall events due to TCs over this same region. Over the shorter period this trend in efficiency is much more pronounced, suggesting that much of the trend in Fig. 6a is a result of the inclusion of data from the later half of the period. This increase in rainfall associated with TCs is consistent with future projections of TCs which suggest an increase in intensity of the strongest storms, resulting in further increase in rainfall with each system.

The spatial pattern of the trend in precipitation per closed low bears a striking similarity to the total rainfall trend over the same period (Fig. 4a). Since there are not large changes in the number of closed low days over the regions with the highest rainfall trends, we can conclude that it is the change in the rainfall-producing efficiency of these systems that is resulting in the majority of the rainfall trends. This is a combination of the changes in efficiency of

both TCs and other closed lows over this period. In southeast Australia it is the decrease in the efficiency of closed lows (excluding TCs) contributing to the decreasing rainfall trend. This decrease in efficiency is consistent with the results of Pook et al. (2006).

5 Discussion and conclusions

This study has analysed the contribution of tropical cyclones and other closed low pressure systems to Australian rainfall. TCs are found to have the most influence on annual rainfall over north-western Australia (greater than 30 %), and account for only 10 % of rainfall over most of the north of the continent. When all closed low pressure systems are considered, over 30 % of rainfall over the majority of the continent, and over 40 % of rainfall north of 20°S can be accounted for. These values are greater when only extreme events are considered.

Over the past 40 years an increase in rainfall over northwest Australia and a decrease over the east of Australia has been evident. The decrease in rainfall in the east is associated with a decrease in the number of TC-days over this region. However, in the north-west, with the exception of the far north, TCs are unable to explain any of the increases in rainfall. All closed lows, including TCs were detected using ERA-interim data from 1989 onwards. These closed low systems explain over 60 % of the trend in rainfall over this period. This is a combination of both TCs and other closed low-pressure systems, although the closed lows (excluding TCs) have the largest influence. In south-east Australia, where there is a negative rainfall trend, over 40 % of the decrease in rainfall can be attributed to closed lows. To understand this further we need to examine what type of closed low, i.e. monsoonal/east coast/cut-off lows, is controlling the trends in the particular regions. It is of interest to note that if the length of track criteria is removed from the closed low definition and any closed low that occurs at any time in the 12-h data is included, these contributions to the rainfall trends are not evident. These short-lived systems that may be present at only a single time are likely to be weak with low precipitation totals. Therefore, much of the rainfall that occurs on one of these weak low days is likely to be background rainfall. This further emphasises the importance of these longer-lived closed low pressure systems on Australian rainfall trends.

The sensitivity of the percentage of Australian rainfall attributed to closed lows was acknowledged in Sect. 2.3. When the contribution of closed lows to the trends in rainfall (Fig. 5a) are analysed using various radii of influence, the spatial distribution of the contribution to the trends stays fairly constant, with some changes at inland areas at larger radii (not shown). However, the magnitude

of the trend contribution does vary. Using a radius of influence of just 2°, closed lows can explain over 40 % of the positive rainfall trend in the far north and the coast of north-western Australia. In the southeast, over 20 % of the rainfall trend can be attributed to closed lows with this small radius of influence. As the radius of influence is increased so are the magnitudes of the trends. This further highlights the importance of closed lows as well as the need for a study on the most appropriate radius of influence when analysing rainfall associated with these systems.

When the precipitation efficiency of these systems was analysed, changes in the amount of rainfall per system per day is found to be the largest contribution to these rainfall trends. Changes in the dynamics and structures of these systems to help understand changes in the rainfall producing efficiency will be investigated in a future study.

Projections of TCs over the Australian region in future climates show there is likely to be a decrease in the number of these systems (e.g. Lavender and Walsh 2011). Based on the present study, this will result in a decrease in precipitation over north-west Australia. In this study we have shown the influence of other closed low pressure systems on Australian rainfall and hence, changes in these systems under future climate conditions also need to be understood. This will help us to evaluate how Australia's water budget may change in the future.

References

Berry G, Reeder MJ, Jakob C (2011) Physical mechanisms regulating summertime rainfall over northwestern Australia. J Clim 24:3705–3717

Dare R, Davidson N, McBride J (2012) Tropical cyclone contribution to rainfall over Australia. Mon Weather Rev. doi:10.1175/MWR-D-11-00,340.1 (in press)

Frederiksen JS, Frederiksen CS (2007) Interdecadal changes in southern hemisphere winter storm track modes. Tellus 59A:599–617

Fuenzalida HA, Sánchez R, Garreaud RD (2005) A climatology of cutoff lows in the Southern Hemisphere. J Geophys Res 110: D18,101. doi:10.1029/2005JD005,934

Gallant AJE, Hennessy KJ, Risbey J (2007) Trends in rainfall indices for six Australian regions: 1910–2005. Aust Meteorol Mag 56:223–239

Goebbert KH, Leslie LM (2010) Interannual variability of northwest Australian tropical cyclones. J Clim 23:4538–4555

Hassim MEE, Walsh KJE (2008) Tropical cyclone trends in the Australian region. Geochem Geophys Geosyst 9(7):Q07V07. doi:10.1029/2007GC001,804

Huffman GJ, Adler RF, Morrissey M, Bolvin DT, Curtis S, Joyce R, McGavock B, Susskind J (2001) Global precipitation at one-degree daily resolution from multi-satellite observations. J Hydrometeorol 2:36–50

Huffman GJ, Adler RF, Bolvin DT, Gu G, Nelkin EJ, Bowman KP, Hong Y, Stocker EF, Wolff DB (2007) The TRMM multi-satellite precipitation analysis: quasi-global, multi-year, combined-sensor precipitation estimates at fine scale. J Hydrometeorol 8:38–55

Jansa A, Genoves A, Picornell MA, Campins J, Riosalido R, Carretero O (2001) Mediterranean cyclones and heavy rain. part 2: statistical approach. Meteorol Appl 8:43–56

Jiang H, Zipser EJ (2010) Contribution of tropical cyclones to the global precipitation from eight seasons of TRMM data: regional, seasonal and interannual variations. J Clim 23:1526–1543

Jones DA, Wang W, Fawcett R (2009) High-quality spatial climate data-sets for Australia. Aust Meteorol Oceanogr J 58:233–248

Kang SM, Polvani LM, Fyfe JC, Sigmond M (2011) Impact of Polar ozone depletion on subtropical precipitation. Science 331:951–954

Kentarchos AS, Davies TD (1998) A climatology of cut-off lows at 200 hPa in the Northern Hemisphere, 1990–1994. Int J Climatol 18:379–390

Knapp KR, Kruk MC, Levinson DH, Diamond HJ, Neumann CJ (2010) The international best track archive for climate stewardship (IBTrACS): unifying tropical cyclone best track data. Bull Am Meteorol Soc 91:363–376

Kuleshov Y, Fawcett R, Qi L, Trewin B, Jones D, McBride J, Ramsay H (2010) Trends in tropical cyclones in the South Indian Ocean and the South Pacific Ocean. J Geophys Res 115:D01,101. doi:10.1029/2009JD012,372

Kummerow C, Barnes W, Kozu T, Shiue J, Simpson J (1998) The tropical rainfall measuring mission (TRMM) sensor package. J Atmos Ocean Technol 15:809–817

Larson J, Zhou Y, Higgins RW (2005) Characteristics of landfalling tropical cyclones in the united states and mexico: climatology and interannual variability. J Clim 18:1247–1262

Lavender SL, Walsh KJE (2011) Dynamically downscaled simulations of Australian region tropical cyclones in current and future climates. Geophys Res Lett 38:L10,705. doi:10.1029/2011GL047,499

Li J, Fend J, Li Y (2011) A possible cause of decreasing summer rainfall in northeast Australia. Int J Clim. doi:10.1002/joc.2328

Lim EP, Simmonds I (2007) Southern Hemisphere winter extratropical cyclone characteristics and vertical organisation observed with the ERA-40 data in 1979–2001. J Clim 20:2675–2690

Lynch AH (1987) Australian east coast cyclones III: case study of the storm of August 1986. Aust Meteorol Mag 35:163–170

McInnes KL, Leslie LM, McBride JL (1992) Numerical simulation of cut-off lows on the Australian east coast: sensitivity to sea-surface temperature. Int J Clim 12:783–795

Murray RJ, Simmonds I (1991) A numerical scheme for tracking cyclone centres from digital data. Part I: development of meteorology. Aust Meteorol Mag 39:155–166

Ng B (2010) Tropical cyclones and northwestern Australian rainfall. Honours thesis. School of Earth Sciences, University of Melbourne

Pook MJ, McIntosh PC, Meyers GA (2006) The synoptic decomposition of cool-season rainfall in the southeastern Australian cropping region. J Appl Meteorol Clim 45:1156–1170

Pook MJ, Risbey MJ, McIntosh PC (2012) The synoptic climatology of cool-season rainfall in the central wheatbelt of western Australia. Mon Weather Rev 140:28–43

Porcù F, Carrassi A, Medaglia CM, Prodi F, Mugnai A (2007) A study on cut-off low vertical structure and precipitation in the mediterranean region. Meteorol Atmos Phys 96:121–140

Qi L, Leslie LM, Zhao SX (1999) Cut-off low pressure systems over southern Australia: climatology and case study. Int J Clim 19:1633–1649

Raupach MR, Briggs PR, Haverd V, King EA, Paget M, Trudinger CM (2009) Australian Water Availability Project (AWAP):

CSIRO Marine and Atmospheric Research Component: Final report for phase 3. Tech. Rep. 013, CAWCR

Reboita MS, Nieto R, Gimeno L, da Rocha RS, Ambrizzi T, Gerraud R, Kruger LF (2010) Climatological features of cutoff low systems in the Southern Hemisphere. J Geophys Res 115:D17,104. doi:10.1029/2009JD013,251

Risbey J, Pook M, McIntosh P, Wheeler M, Hendon H (2009a) On the remote drivers of rainfall variability in Australia. Mon Weather Rev 137:3233–3253

Risbey JS, Pook MJ, McIntosh PC, Ummenhofer CC, Meyers G (2009b) Characteristics and variability of synoptic features associated with cool season rainfall in southeastern Australia. Int J Clim 29:1595–1613

Rodgers EB, Adler RF, Pierce HF (2000) Contribution of tropical cyclones to the North Pacific climatological rainfall as observed from satellites. J Appl Meteorol 39:1658–1678

Rodgers EB, Adler RF, Pierce HF (2001) Contribution of tropical cyclones to the North Atlantic climatological rainfall as observed from satellites. J Appl Meteorol 40:1785–1800

Rotstayn LD, Cai W, Dix MR, Farquhar GD, Feng Y, Ginoux P, Herzog M, Ito A, Penner J, Roderick ML, Wang M (2007) Have Australian rainfall and cloudiness increased due to the remote effects of Asian anthropogenic aerosols? J Geophys Res 112:D09,202. doi:10.1029/2006JD007,712

Shi G, Cai W, Cowan T, Ribbe J, Rotstayn L, Dix M (2008) Variability and trend of North West Australia rainfall: observations and coupled climate modeling. J Clim 21:2938–2959

Simmonds I, Keay K (2000) Mean Southern Hemisphere extratropical cyclone behaviour in the 40-year NCEP-NCAR reanalysis. J Clim 13:873–885

Simmonds I, Murray RJ (1999) Southern extratropical cyclone behaviour in ECMWF analyses during the FROST special observing periods. Weather Forecast 13:878–891

Simmonds I, Murray RJ, Leighton RM (1999) A refinement of cyclone tracking methods with data from FROST. Aust Meteorol Mag (special issue), pp 35–49

Simmons A, Uppala S, Dee D, Kobayashi S (2006) ERA-interim: new ECMWF reanalysis products from 1989 onwards. ECMWF Newsl 110:26–35

Smith BA, Bosart LF, Keyser D, Jean DS (2002) A global 500 hPa cutoff cyclone climatology: 1953–1999. In: 19th conference on weather analysis and forecasting, 12–16 August, San Antonio, TX, p P1.14

Smith IN (2004) An assessment of recent trends in Australian rainfall. Aust Meteorol Mag 53:163–173

Speer MS, Wiles P, Pepler A (2009) Low pressure systems off the New South Wales coast and associated hazardous weather: establishment of a database. Aust Meteorol Oceanogr J 58:29–39

Speer MS, Leslie LM, Fierro AO (2011) Australian east coast rainfall decline related to large scale climate dynamics. Clim Dyn 36:1419–1429

Taschetto AS, England MH (2009) An analysis of late twentieth century trends in Australian rainfall. Int J Clim 29:791–807