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The influence of changes in synoptic regimes on north Australian wet season rainfall trends

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[1] Precipitation over the north of Australia mainly falls during the wet season and is associated with the Australian monsoon. Recent studies have shown that precipitation in the north and northwest of Australia during the wet season has increased over the past 50 years. In previous work, daily radiosonde data at a single site (Darwin) were used to identify five distinct wet season regimes, each associated with a characteristic synoptic circulation pattern and rainfall probability distribution. Here the five regimes are used to decompose the 50-year precipitation trend at Darwin from 1957/1958–2007/2008 into two contributions; that due to changes in the regime relative frequency of occurrence, and that due to changes in the within-regime precipitation. Over the entire wet season from September to April, the within-regime precipitation does not change significantly for any of the regimes. However, the relative frequency of occurrence decreases significantly for the driest regimes, and increases significantly for one of the wettest regimes, suggesting that changes in the large-scale circulation are a more important contributor to the precipitation trends than are thermodynamic changes. During December to March, the largest contributions to the total precipitation trend come from changes in all three of the wettest regimes. During November and April, when the average precipitation is lower, there is a large relative contribution to the precipitation trend from the increase in frequency of a wet regime and a decrease in frequency of the dry regimes. This contributes to the significant lengthening of the north Australian wet season.

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1. Introduction

[2] Much of the rain that falls in the tropical north of Australia is associated with the wet season, with 90% of annual rainfall occurring between November and April [*Nicholls et al.*, 1982]. This seasonality is associated with the Australian summer monsoon, where a reversal of the zonal wind from easterly to westerly directions results in moist air being transported over the north of Australia, however a substantial proportion of the total rainfall does occur outside this monsoon period [*Nicholls*, 1984].

[3] Recent studies have shown that precipitation in the north and northwest of Australia (NWA) increased over the last half century, particularly during the summer months [e.g., *Smith*, 2004; *Taschetto and England*, 2009; *Berry et al.*, 2011]. *Taschetto and England* [2009] investigated December, January, February (DJF) season rainfall trends in the north of Australia and found that increases in precipitation may be due to more intense deep convection embedded in the monsoon trough, and that very heavy rainfall events contributed the most to the increased total precipitation. They linked these changes to changes in tropical Pacific and Indian Ocean sea surface temperatures (SST), but were not able to say whether these SST changes have been caused by anthropogenic warming or atmospheric circulation changes. Trends in NWA precipitation have also been attributed to increased anthropogenic aerosols [*Rotstayn et al.*, 2007], however *Shi et al.* [2008] found that the strong link between aerosols and increased rainfall was most likely due to an incorrect relationship between Indian Ocean SSTs and NWA rainfall in the model used in that study. *Shi et al.* [2008] also found that despite the strong relationship between ENSO and Australian rainfall, changes in the frequency of ENSO events could not explain the increase in precipitation in NWA, consistent with the decreasing strength of the relationship between the Southern Oscillation Index and Australian rainfall [*Nicholls et al.*, 1996].

[4] A major question arising throughout these previous studies is whether the increased precipitation in northern

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Australia is due to changes in the frequency or intensity of precipitation events. *Taschetto and England* [2009] found an increasing trend in the upper decile of precipitation from 1970–2005 over the western half of Australia (including Darwin), accompanied by an increase in the number of very heavy rain events during DJF. This suggests an increase in intensity of precipitation events, but it is unclear whether this is due to changes in circulation producing the flow in which heavier rain occurs, or if the circulation has remained the same, but associated precipitation events have increased in intensity, e.g. through increased humidity. *Berry et al.* [2011] found that moisture transported from the Gulf of Carpentaria into the NWA region was a precursor for rainfall in the heat low region, which could imply that circulation changes are an essential ingredient in the observed rainfall trends.

[5] The variability of the north Australian wet season was classified into 5 regimes by *Pope et al.* [2009] (hereafter P09), who also showed that regimes other than the active monsoon contribute significantly to the wet season rainfall. The regimes were defined using K-means clustering applied to daily radiosonde data (temperature, winds, moisture) at Darwin. Despite being identified using data from a single location, P09 demonstrated that all of the regimes show distinct large-scale circulation patterns (see P09, their Figure 7). P09 also showed that the regimes are associated with distinct precipitation probability distributions. The aim of the present study is to investigate the trend over the past 50 years in Darwin precipitation during the wet season in the context of the regimes of P09. The particular question this work aims to address is if the increase in wet season rainfall is due to increases in the precipitation associated with each regime (i.e., the intensity of precipitation), or due to changes in the frequency of occurrence of the regimes (i.e., the circulation). This question will be investigated by examining trends in the regime occurrence and in the precipitation associated with each regime as calculated from the Darwin International Airport station data.

[6] The paper is organized as follows. Section 2 will describe the data and methodology used, including a detailed description of the regimes from P09. The results relating to the frequency of occurrence of the regimes, the within regime rainfall, and changing season length will be given in section 3. A discussion of how these results relate to previous studies and the conclusions of the study are given in section 4.

2. Data and Methodology

[7] The study of P09 used K-means clustering on the wind and temperature data at 16 levels and moisture data at 12 levels from daily radiosonde ascents at Darwin, for the months September to April, to separate days into one of five regimes of north Australian wet season atmospheric conditions. In P09 the clustering was applied to the data from years 1957/58 to 2005/06, excluding 1992/93 because of problems with the data during this season. Subsequently each day from the seasons of 2006/07 and 2007/08 were allocated to their closest cluster. The five regimes defined by P09 are labeled Deep West (DW), Shallow West (SW), Moist East (ME), East (E) and Dry East (DE). The regimes have quite distinct vertical profiles which, as shown in P09, are each associated with a characteristic synoptic pattern (and different rainfall characteristics). The DW regime is indicative of an active monsoon over Darwin, with westerly zonal winds up to 400 hPa and a very moist troposphere. The composite synoptic pattern shows anomalously low pressure over the Australian region and strong west to northwesterly surface winds over the north. The SW regime represents an active monsoon further to the east of Darwin, with westerly winds up to 800 hPa and easterly winds above that. The ME regime represents a monsoon break period and its composite vertical structure shows easterly winds throughout the depth of the troposphere, and the synoptic pattern shows these cover the whole of northern Australia. This regime brings moist air from the ocean and was identified by P09 as the regime with the second largest values of precipitable water after the DW regime. The E and the DE are similar in their vertical wind profiles but differ in their moisture profiles. The synoptic situation during the DE is such that the air is advected into the Darwin region mainly from dry continental Australia, whereas during the E regime the flow is more south-easterly. The quite distinct profiles and synoptic conditions of the five regimes makes them a potentially useful tool for understanding recent changes in precipitation patterns in the north of Australia in the context of the large-scale synoptic flow, and the daily regime classifications calculated by P09 have been directly applied in the present study.

[8] The precipitation associated with each regime has been calculated using the 24-hour rain gauge data from the Bureau of Meteorology Darwin International Airport station. Readings from this station are available from 1941 onwards and they are continuous and of good quality. Darwin International Airport was chosen to correspond to the approximate location of the radiosonde data used in the generation of the regimes. On a daily timescale the precipitation at Darwin would vary from other stations in the northern part of Australia; however for the December–February seasonal rainfall, the correlation between Darwin precipitation and precipitation for the whole of north Australia (north of 26 degrees south) is 0.67. This suggests that for the wet season timescale on which the current focus is, Darwin can be used as an indicative station. For each wet season day from September 1st 1957 until April 30th 2008, the 24 hour precipitation is attributed to the daily regimes as classified in P09. This gives wet-season (Sep–Apr) mean values of precipitation associated with each regime. It is important to highlight that the regime classifications were calculated and applied independently of the precipitation information.

[9] An analysis of the variability of the vertical profiles of the regimes reveals that the DE and E regimes are difficult to distinguish. Since these two regimes have the lowest associated values of precipitation (P09; their Figure 5), for much of the following analysis, they have been combined. As documented in P09, there were problems with the radiosonde data for the wet season of 1992/1993, and so this season has been excluded from the analysis in this study.

3. Results

[10] The precipitation evolution during the wet season (September to April) at Darwin over 51 years (from 1957/1958–2007/2008) is shown in Figure 1. It is evident that the

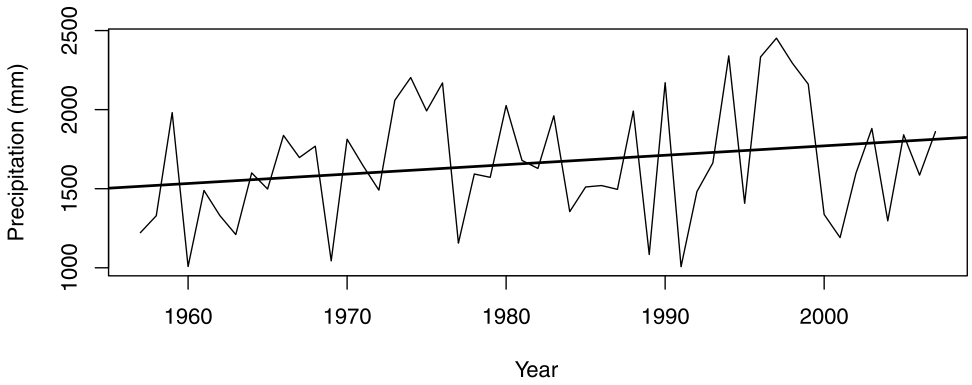

Figure 1. Total wet season (September to April) precipitation (mm) from 1957/1958 to 2007/2008 using the rain gauge data from Darwin International Airport. The least squares linear trend is overlaid.

wet season precipitation has increased over the last 50 years by approximately 6 mm per year (using a simple linear regression; $p = 0.099$), consistent with the earlier studies cited in the introduction. Having confirmed the existence of a positive precipitation trend the P09 regimes are now used to decompose this trend into contributions from changes in the frequency of occurrence of different synoptic conditions and changes of the within-regime precipitation amounts.

3.1. An Overview of Annual Regime Occurrence

[11] To begin the examination of the relationship of precipitation and synoptic regimes, a visual assessment of the occurrence of each of the different regimes is performed using a Hovmöller-type plot of regime occurrence in Figure 2. Each regime is color-coded and the corresponding color for each day of the wet season (horizontal axis) is shown for each of the seasons (vertical axis). This "genetic map" of the Australian wet season reveals several interesting well-known and also new features of the wet season behavior. A typical wet season (Sep–Apr) begins with mostly dry regimes (DE/E). The number of days with each of these two regimes varies with year, and the length of the period before the wetter regimes become frequent also varies. For instance, in the wet season of September 1982 to April 1983, only the DE and E regimes occur until well into December. In other years there are some instances of the moist regimes (ME or DW) occurring as early as September. Generally the DW regime occurs mostly in the summer months (December, January, February; DJF), often for more than a week at a time signifying active monsoon periods. In between the active monsoon periods, the ME and the SW regimes occur. From around the beginning of April the dry regimes become increasingly more prevalent and the wet regimes less so. One of the important aspects of the variability of the north Australian wet season that this figure reveals is the dependence of wet season start on ENSO [*Nicholls et al.*, 1982; *Holland*, 1986]. In the seasons of 1965, 1972, and 1982 there is a clear delay in the occurrence of the wetter regimes (DW, SW and ME) associated with the strong El Niño events, and during 1964, 1975 and 1998 there are earlier occurrences of the wet regimes associated with La Niña.

[12] An intriguing feature revealed by Figure 2 is an apparent lengthening of the period during which the wettest regimes occur. It is evident that the later years of the record show a higher frequency of occurrence of the wet regimes in November and April than is apparent in the earlier years. This will be investigated in more detail below.

3.2. Regime Frequency of Occurrence

[13] The relative frequency of occurrence (RFO) of the regimes for each wet-season from 1957/1958 to 2007/2008 is shown in Figure 3, and the mean and standard deviation are given in Table 1. As was evident in Figure 2 the RFO of each of the regimes is quite variable from season to season. The DW regime occurs the least frequently of all the regimes on average with a mean relative frequency of occurrence of 9.7%, although the variability as a percentage of its mean is 48% which is the highest of all the regimes. This is an indication of the well-known inter-annual variability of the Australian summer monsoon. The SW regime also has low mean RFO of 16% and a fairly high variability of 35% of its mean. The combined dry regimes (DE and E) together occur more than any other regime at 43.3%, with the ME regime occurring 30.9% of the time over the analysis period. These regimes show the lowest relative inter-annual variability with 18% and 25% of their means respectively.

[14] Figure 3 shows the time evolution of the season-mean RFO for each of the regimes as well as a least squares linear trend fit to the data. It is evident that the dry regimes (DE/E) are decreasing in their RFO, compensated by a strong increase in the RFO of the ME regime. A more rigorous statistical analysis of the linear regressions for the RFO of the different regimes reveals no significant trend in either the DW or SW RFO (using an F test and significance of 95%). The negative trend in the dry regimes is found to be significant with a value of 0.2% per year. A corresponding significant increase in the RFO of the ME regime of the same value is also established. These results provide a first hint that the overall rainfall trend in Darwin might be strongly influenced by a change in the RFO of the synoptic states affecting the region as represented by the P09 regimes. However, before being able to draw firmer conclusions, the within-regime precipitation behavior must be investigated.

3.3. Within Regime Precipitation

[15] Figure 4 shows the time-evolution of the wet-season average precipitation within each regime. The overall means and variability for each regime are again summarized in

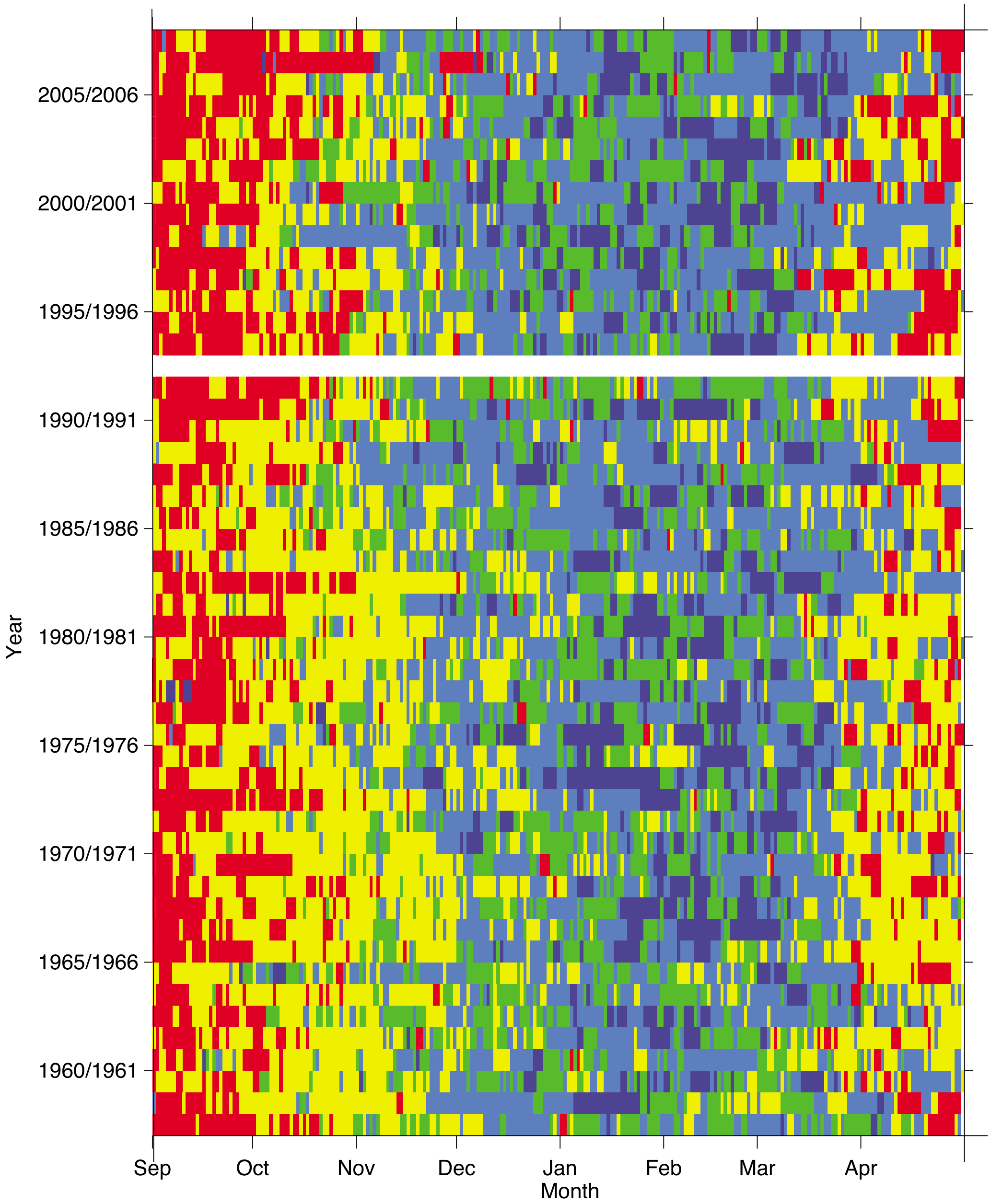

Figure 2. Regime occurrence by day and season from 1957/1958 to 2007/2008. The season labels are below the relevant line. DE regime is red, E regime is yellow, SW regime is green, ME regime is light blue, DW regime is dark blue. Season 1992/1993 is missing due to problems with the radiosonde data during that season (P09).

Table 1. As expected, the joint DE/E regime is the driest with an associated average precipitation of only 1.8 mm/day but with quite large relative variability around this very low mean. The SW regime has an average precipitation of 6.8 mm/day and shows the most inter-annual variability of all the regimes. The ME is the second wettest regime with an average associated precipitation of 10 mm/day, and shows the lowest relative variability. The DW regime is associated with the largest precipitation amounts of 21.6 mm/day. This regime also displays a large relative inter-annual variability, with values for the ratio of the standard deviation to the mean similar to those for the combined DE/E regime.

[16] As for the RFO, least squares linear fits to the data are calculated and the best fit lines shown in Figure 4. Statistical testing reveals that there are no significant (F-test at the 95% level) trends in the amounts of precipitation associated with any of the five regimes. There are also no significant trends in the within regime precipitation when each month is investigated separately. This indicates that changes of the within regime precipitation (which may be caused by changes in sea surface temperatures, moisture or local effects) are not a significant contributor to the trends in the total wet season precipitation seen at Darwin. In particular the wet regimes, such as the ME and DW

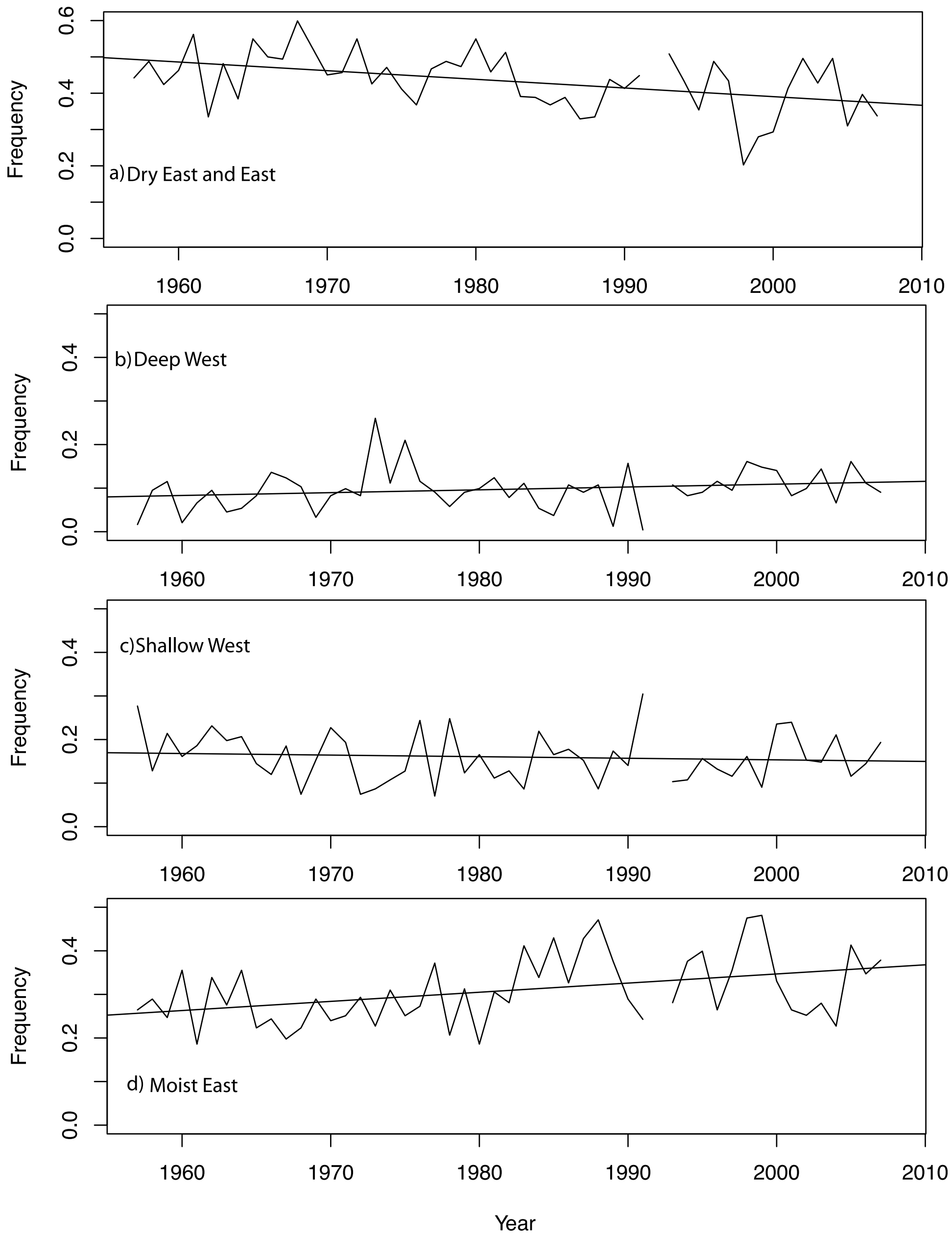

Figure 3. Relative frequency of occurrence of the regimes for (a) DE and E combined, (b) DW, (c) SW, and (d) ME, for each wet season from 1957/1958 to 2007/2008. The least squares linear trend is shown for each regime which has been calculated excluding the 1992/1993 season.

regimes, do not show any trend in their precipitation behavior throughout the last 50 years.

3.4. Season Length

[17] When discussing Figure 2 an apparent lengthening of the wet season was noted, with earlier onsets and longer persistence of the 3 wet regimes (DW, ME, SW) in recent years. Here, several objective definitions of "season length" are applied to test if this visual impression can be confirmed. First, the start and end of the wet season are defined as the first and last occurrence of a certain number of consecutive days of any of the 3 wet regimes (DW, ME, SW). Then the season length is calculated as the number of days between the first and last day of the season. Figure 5 shows the season length for each year and the least squares linear trend fit to the data using the definition of the wet season start and end to be 5 consecutive days in one of the three wet regimes (DW, ME and SW). Using this measure of the season length, the mean length is 147 days, with a standard deviation of 26.6 days. Over the 50 year period, the season length has increased significantly (at the 95% level) by 0.66 days per year. The calculations were repeated using a definition of 2, 3, and 7 consecutive days of the three wet regimes, and 3 or 5 consecutive days of only the ME regime. All of these ways to define the wet season result in an increase in the length of the season over the last 50 years, with only the choice of 2 and 3 consecutive days of 3 wet regimes not showing significance at the 95% level.

Table 1. Statistics for Relative Frequency of Occurrence (RFO) and Within Regime Precipitation (WRP) for Each of the Regimes

	DE + E	SW	ME	DW
Mean RFO	43.4	16.0	30.9	9.7
Standard deviation RFO	8.0	5.6	7.7	4.7
SD/Mean	18%	35%	25%	48%
Mean WRP	1.8	6.8	10.0	21.6
Standard deviation WRP	0.80	3.9	2.1	9.7
SD/Mean	45%	58%	21%	45%

[18] The trends in the monthly RFO for the regimes show that the increases in the ME regime, and the corresponding decrease in the combined dry regimes (DE/E) are greatest in November and April. In November the ME increases by 0.46% per year, and in April by 0.40% per year. The DE/E regimes decrease by 0.45% per year in November and 0.33% per year in April. This confirms that there is a lengthening of the wet season in terms of the onset and persistence of the wet regimes.

3.5. Seasonal and Monthly Trends

[19] Many previous studies of north Australian rainfall have focused only on the summer season (DJF). So far in this study the focus has been on the entire wet season. In this section the trends in rainfall and the regimes are analyzed by month with the specific goal to provide more insight into which part of the season is contributing to the large trend in Darwin precipitation. The analysis is performed

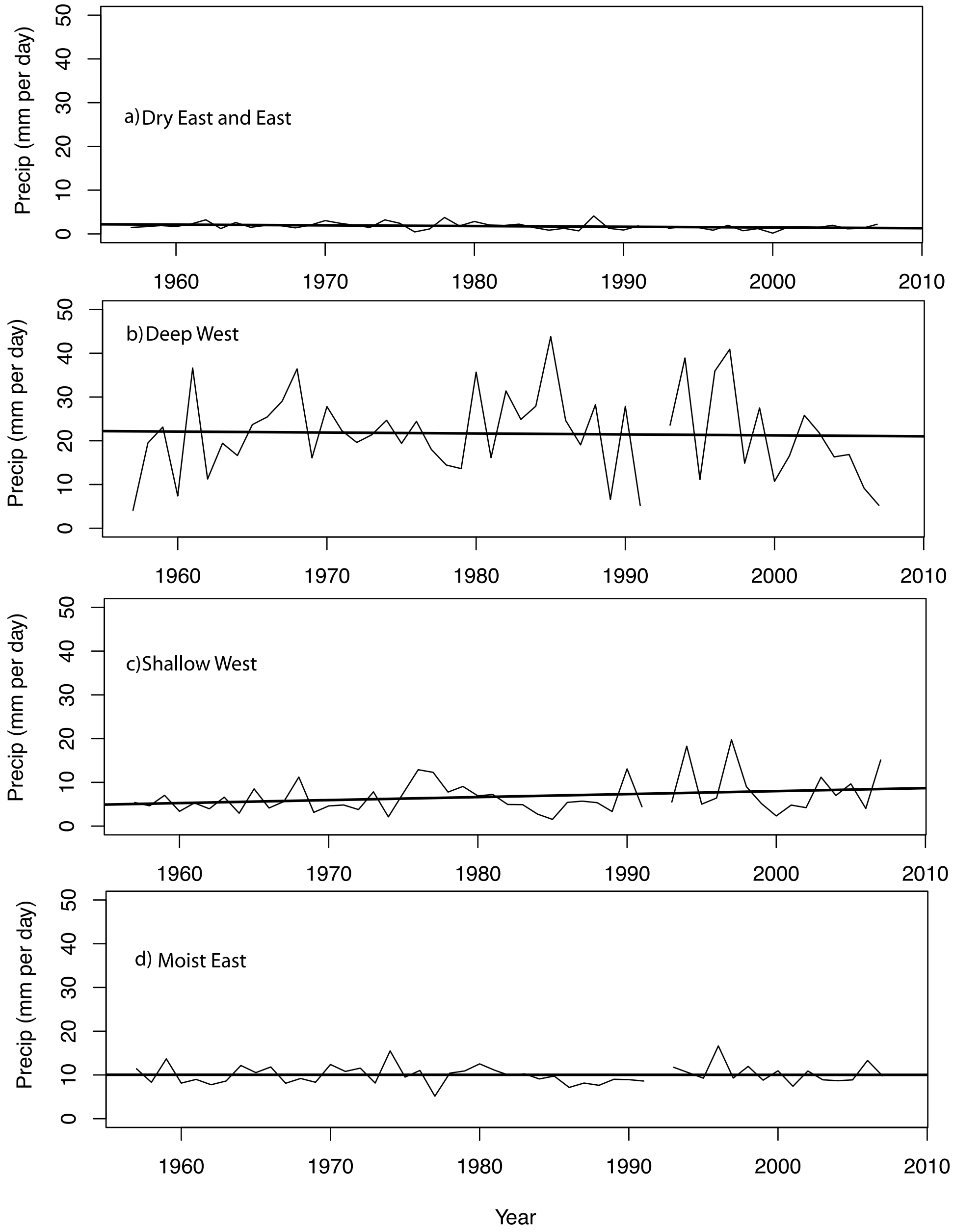

Figure 4. Average within regime precipitation (mm per day) for (a) DE and E combined, (b) DW, (c) SW, and (d) ME, for each wet season from 1957/1958 to 2007/2008. The least squares linear trend is shown for each regime which has been calculated excluding the 1992/1993 season.

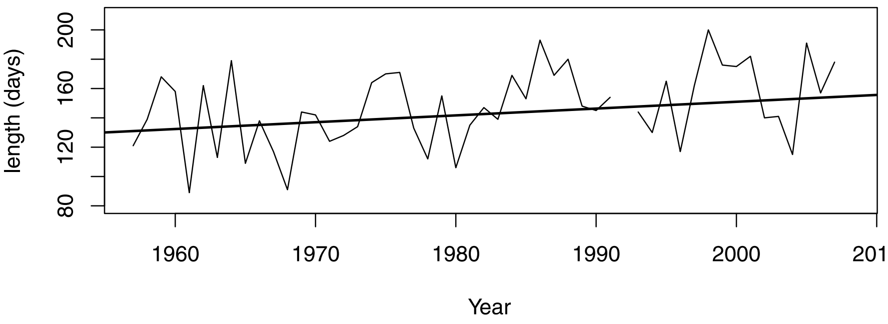

Figure 5. Season length (days) calculated using the definition of the start and end of the season as 5 sequential days of one of the wet regimes (SW, DW, ME) for each wet season from 1957/1958 to 2007/2008. Overlaid is the line of best fit using least squares method calculated excluding 1992/1993. The trend is 0.66 days per year (significant at the 95% level).

by decomposing the total rainfall trend (ΔR) into trends in the RFO of the regimes and the within-regime precipitation as follows:

$$\Delta R = \sum_{i=1}^{4} N_i \Delta P_i + \sum_{i=1}^{4} P_i \Delta N_i + \sum_{i=1}^{4} \Delta N_i \Delta P_i \qquad (1)$$

where N_i is the frequency of occurrence of regime i, P_i is the within regime precipitation, and ΔN and ΔP represent the linear trends in these two measures.

[20] Figure 6 shows the total monthly trend in Darwin precipitation (black bars), along with the contribution to these trends from each regime by the first two terms in the above equation (colored bars). The third term in equation (1) was found to be small for all regimes. It is evident that the largest overall positive trends in precipitation occur in February and March, followed by December and January. Small positive trends exist in November and April with small negative overall trends in September and October. The decomposition of the observed trends shows the influences

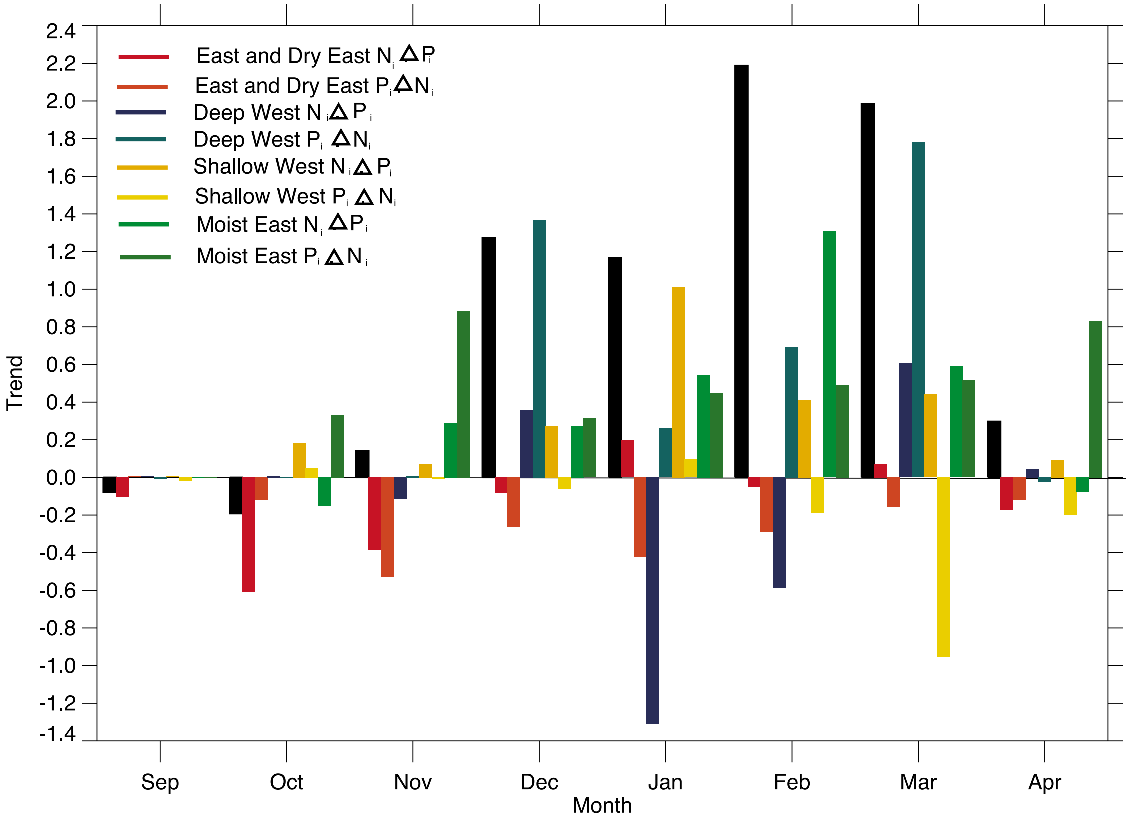

Figure 6. Bar plot showing the linear trend in Darwin precipitation by month. The black bars show the total trend at Darwin, and the colors show the contribution to this trend from each of the regimes. For each regime, there is a component from the trend in precipitation associated with the regime ($N_i.\Delta P_i$) and a component from the trend in the frequency of occurrence of the regime ($P_i.\Delta N_i$).

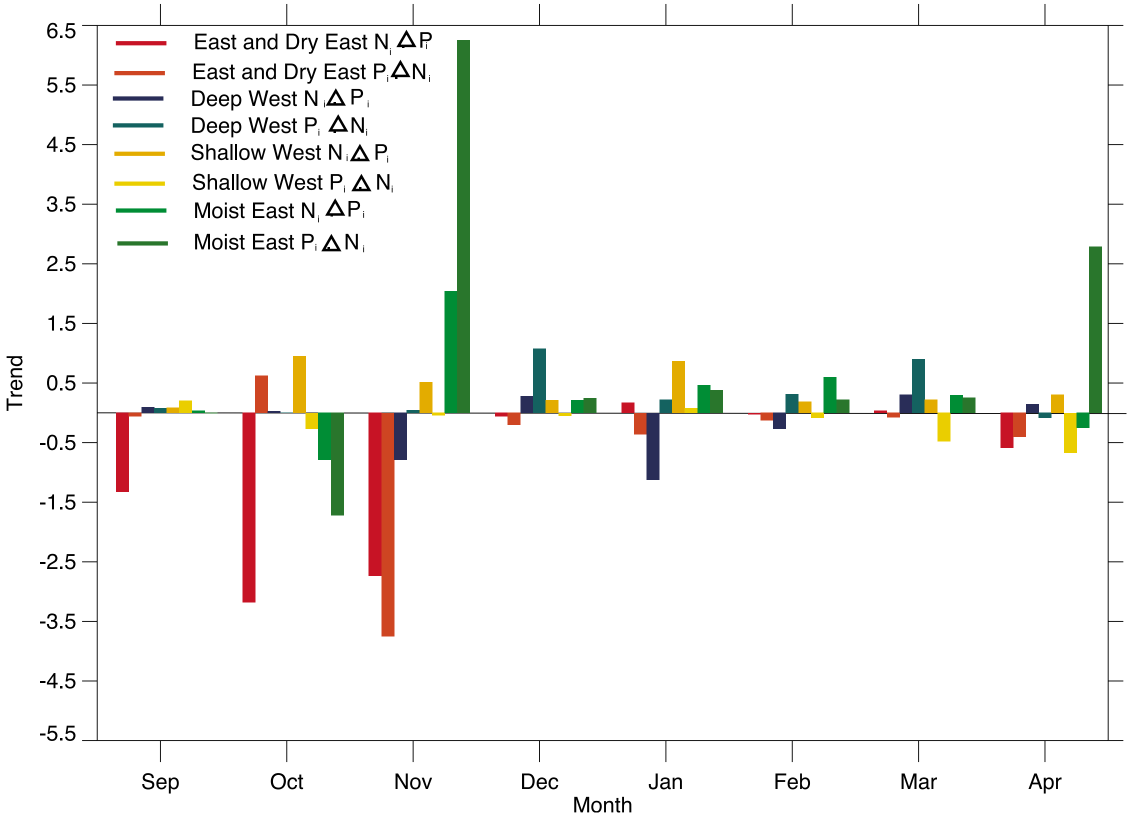

Figure 7. Bar plot showing the relative contributions of each regime and month to the total trend. For each regime, there is a component from the trend in precipitation associated with the regime ($N_i.\Delta P_i$) and a component from the trend in the frequency of occurrence of the regime ($P_i.\Delta N_i$).

from the different regimes. The negative trends in September and October are associated with a decline in the within-regime rainfall in the DE/E regimes. While the within-regime rainfall trends were not statistically significant (cf. Figure 4), the large RFO of the DE/E regimes in September/October means that even small within-regime rainfall trends contribute to the overall trend. The small positive overall trends in November and April are largely associated with an increase in the RFO of the ME regime. During the months of December to March (the peak of the wet season) the situation is more complex. In December and March the positive overall trends result largely from an increase in the RFO of the DW regime, indicating an increased occurrence of monsoon conditions at the beginning and end of the monsoon season. In January there are compensating effects with an increase in within-regime rainfall in the SW and ME regimes as well as an increase in the RFO of the ME regime counteracted by a decrease in the within-regime rainfall in the DW regime. The positive February trend is dominated by an increase in both RFO and within-regime rainfall in the ME regime, while for the other wet regimes the RFO and within-regime rainfall effects compensate.

[21] While Figure 6 shows that the trends are largest in December to March, it needs to be kept in mind that the rainfall amounts are also the largest in those months. In a relative sense those months might therefore not show the largest changes. This is confirmed by Figure 7, which shows the *relative* contribution of each regime to the overall trends. It is clear that the largest relative contributions to the observed trends occur in November with the ME regimes RFO providing a positive contribution partially compensated by the combined DE/E regime.

4. Summary and Conclusions

[22] The goal of this study was to provide new insights into the potential mechanisms contributing to the observed positive trends in wet-season precipitation in northern Australia. Specifically, using observations at Darwin the rainfall trends were decomposed into contributions from changes in the frequency of occurrence of the main wet-season synoptic regimes and contributions from changes in within-regime rainfall. Here, to first order, changes in regime frequency are interpreted as changes in the large-scale flow (since P09 showed the regimes to have distinct associated synoptic conditions), while changes in within-regime rainfall are interpreted as changes in the thermodynamic conditions or local effects within the regime. Using the synoptic regimes defined by P09 the study has demonstrated that such a decomposition can in fact provide additional information on the likely mechanisms involved in causing the observed precipitation changes.

[23] For the wet season as a whole the regime-decomposition revealed that most of the observed trend in precipitation is due to an increase in the frequency of occurrence of rain-bearing regimes at the expense of the occurrences of dry regimes. In particular it was shown that there is a significant increase of the ME regime, a regime in which north-easterly

flow transports moist air into the north Australian region. This regime is usually associated with the buildup and decay as well as breaks in the Australian summer monsoon (P09). Not surprisingly, much of the increase in the ME regime occurrence therefore happens on the ends of the main monsoon season, namely in November and April, leading to a significant lengthening of the wet season in the Darwin region. The within-regime rainfall changes for the entire season have been shown to be small for all regimes. Consequently, the main influence on wet-season rainfall trends is a change in the large-scale circulation rather than in the local thermodynamics.

[24] Applying the regime decomposition to individual months, while more difficult due to poorer sampling of the regime occurrences, reveals an interesting and rich picture of influences on the rainfall trends. The largest absolute precipitation trends occur from December to March and are associated with changes in all of the three wet regimes. Changes in the occurrence of the DW regime are dominating the changes in December and March, indicating a lengthening of the season with active monsoon occurrences. While the trends are largest in the summer months, so are the rainfall amounts themselves. When normalizing the trends by the mean monthly precipitation, it emerges that the largest relative changes occur in November and April and are mainly due to an increase in the occurrence of the ME regime, consistent with the findings when considering the wet season as a whole.

[25] While there are still many open questions on the mechanisms that lead to the observed rainfall increases in northern Australia, this study has contributed important new insights. First, it was shown that the decomposition into synoptic regime occurrence and within-regime precipitation provides a useful framework for the study of precipitation changes that could likely be applied to other regions. Second, it was shown that the trends in northern Australian wet-season precipitation are mainly a result of circulation changes, in particular in the early and late part of the season. A significant lengthening of the wet-season has occurred over the last 50 years. Finally, it was shown that while the largest absolute changes occur in the main monsoon season, perhaps the most important relative changes occur on either end of it, with a large change in the flow conditions from south easterly to more easterly and north-easterly flow as evidenced by the increase in frequency of the wet ME regime at the expense of the dry DE and E regimes. With this important new insight, future research will focus on elucidating the potential dynamical reasons for this change in the large-scale flow.

[26] **Acknowledgments.** This work was supported by the Australian Research Council through the Linkage Project grant LP0883961 and the Discovery Project grants DP0985665 and DP0877417. The 24-hour rainfall from Darwin International Airport was obtained from the Bureau of Meteorology. The authors are very grateful to Mick Pope for providing the daily regime classifications.

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