Characteristics of the Northern Australian Rainy Season

I. N. Smith
Marine and Atmospheric Research, CSIRO, Aspendale, Victoria, Australia

L. Wilson
School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia

R. Suppiah
Marine and Atmospheric Research, CSIRO, Aspendale, Victoria, Australia

(Manuscript received 19 June 2007, in final form 9 January 2008)

ABSTRACT

A trend of increasing rainfall over much of north and northwest Australia over recent decades has contrasted with decreases over much of the rest of the continent. The increases have occurred during the summer months when the rainy season is dominated by the Australian monsoon but is also affected by other events such as tropical cyclones, Madden–Julian oscillations, and sporadic thunderstorms. The problem of diagnosing these trends is considered in terms of changes in the timing of the rainy season. While numerous definitions for rainy/monsoon season onset exist, most are designed to be useful in a predictive sense and can be limited in their application to diagnostic studies, particularly when they involve predetermined threshold amounts. Here the authors define indices, based on daily rainfall observations, that provide relatively simple, robust descriptions of each rainy season at any location. These are calculated using gridded daily rainfall data throughout the northern Australian tropics and also for selected stations. The results indicate that the trends in summer rainfall totals over the period from 1950 to 2005 appear to be mainly the result of similar trends in average intensity. Furthermore, the links between the September–October average Southern Oscillation index indicate that ENSO events affect season duration rather than average intensity. Because duration and average intensity are derived as independent features of each season, it is argued that the trends in rainfall totals are largely unrelated to trends in ENSO and most likely reflect the influence of other factors. Finally, diagnosing these features of the rainy season provides a basis for assessing the confidence one can attach to different climate model projections of changes to rainfall.

1. Introduction

The northern Australian rainy season starts sometime between September and December, peaks during the austral summer, and ends rapidly in March or April (Suppiah and Hennessy 1996). The remainder of the year is virtually dry. During the wet season, rainfall at most stations north of about 30°S is affected by active and break periods of the monsoon, the presence of tropical cyclones, and local thunderstorms. The monsoon refers to that time during the summer when the tropics are subject to both rainfall and large-scale changes in the pressure and wind regime, whereas the wet (or “rainy”) season refers specifically to that period when significant rainfall occurs and can vary from point to point. Cook and Heerdegen (2001) refer specifically to the transitional period that precedes the onset of the monsoon and the fact that “extramonsoonal” rainfall events can account for up to 30% of the seasonal rainfall totals. Thus, the rainy season starts earlier and lasts longer than the monsoon season and its behavior tends to be uncorrelated with that of the monsoon (Nicholls et al. 1982). Intraseasonal or 30–60-day (or Madden–Julian) oscillations (MJO) modulate the active-break cycle of the monsoon (Suppiah 1992, 1993; Wheeler and McBride 2005).

Suppiah and Hennessy (1996, 1998) analyzed daily rainfall records at stations in northern Australia and showed that trends of increasing total summer (November–April) rainfall over the period 1910–90 at many
stations tended to be accompanied by similar trends in the frequency of rainfall events exceeding the long-term 90th percentile values. They noted that this tendency was consistent with the notion that a warmer atmosphere can hold more moisture and can lead to more intense events but concluded that there were insufficient numbers of these significant trends to prove a link to the enhanced greenhouse effect. Goswami et al. (2006) noted that Indian monsoon rainfall, although relatively unchanged over past years, has been characterized by an increase in the frequency of and magnitude of extreme rain events. Smith (2004) drew attention to the fact that increases over much of northern and western Australia have dominated the all-Australian rainfall totals over recent decades and that these could be regarded as unusual in a historical context. This was apparent in an analysis of rainfall data up to the end of 2002 and has been reinforced by rainfall over the subsequent 4 years (2003–2006). These trends, which are most evident post-1950, have occurred at the same time that global temperatures and Australian average temperatures have increased rapidly compared to the previous period, 1900–50 (cf. Nicholls 2004). Whatever the reasons, the nature of the changes in rainfall over northern Australia deserves closer scrutiny simply because of the possibility that they may indicate the direction of climate change into the future. Not only are trends in total amounts of interest but so, too, are any trends in the timing of the rainy season, including any trends in intensity.

The onset and end (retreat) dates of the monsoon and/or rainy season can be defined using a wide range of criteria that include rainfall, surface and upper-level winds, outgoing longwave radiation (OLR) indices, upper-tropospheric water vapor brightness temperature, etc. However, Wang et al. (2004) note that defining the onset date (of the South China Sea monsoon) “has been noticeably controversial” and that “the lack of a universally accepted definition . . . is a major roadblock for studying interannual variability.” In fact, they list 17 different definitions before proposing another based on 850-hPa zonal winds.

The same issues apply to the Australian monsoon/rainy season. Rainfall-only definitions are discussed in Nicholls et al. (1982) and Nicholls (1984), while rainfall and wind-based definitions are discussed in Cheang (1987), Hendon and Liebmann (1990), and Drosdowsky (1996). Wheeler and McBride (2005) compare onset dates from a sample of years using some of these while, more recently, definitions have also been suggested that involve indices of total precipitable water (Zeng and Lu 2004). Pope et al. (2007) show how regimes of the monsoon can be defined according to rainfall, MJO, El Niño–Southern Oscillation indices, OLR, and model reanalysis fields. The definition proposed by Nicholls (1984) is based on the date when the accumulated seasonal rainfall reaches a prescribed threshold (15% of annual rainfall). Nicholls used this definition to define a large-scale onset date for the northern Australian rainy season (mainly for predictive purposes) based on the average of 10 stations. Cook and Heerdegen (2001) described the rainy season over northern Australia based on long-term daily rainfall observations and the probability of dry spells. This method helps to specify the mean season onset and end (retreat) dates for any station, which, in turn, allows an investigation of the dependence on latitude and ENSO events.

It is apparent that there is no globally accepted single index that can be used to completely describe the rainy season, but it is also apparent that most indices are not suitable for simultaneously describing onset and end dates for individual stations for individual years. Here we define the onset of any rainy season as the date when 15% of the end of season total is accumulated and the end date as the date when 85% of the end of season total is accumulated. In other words, we focus on the two dates between which 70% of the seasonal rainfall is accumulated, independent of the actual total. This may seem of limited value because it does not necessarily distinguish between a season with high rainfall and a season with low rainfall, but it does have the advantage of unambiguously providing information about any rainfall season for any station in any year where there are reasonably good quality observations. The two dates define the duration (in days) over which 70% of the seasonal rainfall (in millimeters) fell and therefore leads to a measure of average rainfall intensity for that particular season. Consequently, by using these indices in combination, it is possible to diagnose key features of the rainy season in both space and time and to diagnose any long-term trends and relationships with ENSO events. We demonstrate this by analyzing rainfall data for northern Australia and addressing several questions: Are the rainfall increase/decreases due to an increase/decrease in the length of the rainy season? Or are they due to a change in the intensity of rainfall falling within the season? Are any changes in season length due to changes in onset dates or end dates? Is there a coherent spatial pattern to these changes? What is the role of ENSO events in driving these changes? These questions are regarded as vital, not simply because we need to better understand current climate change, but also because they provide quite specific benchmarks for assessing any climate and regional models that attempt to simulate future climate changes in response to anthropogenic and natural forcings.
2. Data and methodology

The rainfall data analyzed here were provided by the National Climate Centre (NCC) of the Bureau of Meteorology and consist of gridded data on a \(0.25^\circ \times 0.25^\circ\) grid. These are described by Lo et al. (2007), who indicate their confidence in the validity of the data over northern Australia after 1948. We have sampled this gridded data onto a \(2^\circ \times 2^\circ\) grid, which is more than sufficient to capture the spatial variability across the region. The available data enable us to analyze seasonal rainfall for each year between 1950/51 and 2003/04. We analyze daily rainfall data for dates between 1 September [Julian day (JD) 243] and 30 April (JD 484)—corresponding to eight months or 242 days.

In addition, we have analyzed individual station records from 11 sites across northern Australia, which enable similar analyses to be performed for all seasons between 1950/51 and 2005/06. Figure 1 shows the locations of these stations, which were selected on the basis that they also provided a reasonable sample across the region and also provided continuous, reliable records. Features of the rainy seasons for these stations, summarized in Table 3, show that Tempe Downs in the south and Roebourne in the far west have the lowest mean seasonal rainfall totals (218 and 220 mm, respectively) while Darwin has the highest (1632 mm).

3. Definition of onset and end dates

One of the traditional definitions of rainy season onset is the date when the first relatively heavy rainfall occurs. Figure 2 shows the daily rainfall amounts recorded at Darwin during 1968/69 (a time of neutral ENSO conditions). If 25 mm in one day is regarded as a heavy rainfall event, then the onset date could be defined as early as JD 287. However, it can be seen that this event was followed by an extended period of about 60 days before another similar event occurred. If the threshold is increased to 50 mm in one day, then the onset date occurs nearly a month and a half later on JD 369. Likewise, if 100 mm is adopted as the threshold, then onset occurs another month later on JD 400. Similarly, if the end date is defined as the last occurrence of a heavy rainfall event, then, in this case, the season effectively ended on JD 428 since, irrespective of the threshold, no heavy rainfall events occurred after this date. Therefore, depending on the threshold chosen, the duration of the rainy season was either 142, 60, or only 29 days. As has been pointed out by others, this type of index is not satisfactory since the dates are very sensitive to the subjective choice of threshold. Furthermore, if the threshold is relatively large, it is possible in some wet seasons characterized by frequent but moderate rain events that no onset date can be defined. (e.g., if 100 mm is chosen as a threshold, then in some years where no daily rainfall totals ever reached this value, no dates can be defined).

This shortcoming associated with threshold-based definitions is well recognized and a more useful index is
one that defines the onset date as that date when the accumulated rainfall exceeds some threshold amount. Lo et al. (2007) considered that 50 mm of accumulated rainfall from 1 September at any site provided a very useful index since it required no prior knowledge of long-term average rainfall, is easily measured, and yields information in real time. These advantages are counterbalanced by the fact that 50 mm can represent a relatively large total for some stations and a relatively small total for other stations, as there is a strong spatial variation in rainfall over tropical Australia. These difficulties can be mostly avoided by defining the accumulated threshold in terms of each station’s long-term mean seasonal rainfall. According to Nicholls (1984), an accumulation of about 15% of mean annual total rainfall appears to provide a good indicator of onset date. If we use the Darwin long-term average seasonal total (1673 mm), then this method suggests an onset date when accumulated rainfall exceeds 243 mm. A corresponding end date would be one when the accumulated rainfall reached 85% of the long-term average seasonal rainfall (1422 mm).

This method works well in most situations, but prescribing fixed thresholds for onset and end dates based on long-term average accumulated rainfall can also suffer from the problem that, in very dry years, these may never be reached—thereby leaving the season undefined. Conversely, in a very wet year, thresholds for end dates may be exceeded far too early, leading to a meaningless indication of the season duration. Figure 3 illustrates the problem for Darwin in two contrasting years: 1989/90 and 1996/97. On both occasions the 243 mm accumulated rainfall threshold appears to provide a reasonable onset date. However, using 1422 mm accumulated rainfall does not define an end date for the dry year and appears to underestimate the end date in the wet year. These situations can sometimes be dealt with on a case by case approach (Lo et al. 2007) but, in general, are unsatisfactory.

Here we propose that onset and end dates can be determined using individual end-of-season totals rather than long-term average totals. The advantage is that the onset and end dates are always defined no matter how abnormal the season. The obvious disadvantages are that the dates are unknown until the end of the season, so they provide no predictive information nor do they convey any information about seasonal rainfall totals. For example, if the onset date is defined as the date when the accumulated rainfall exceeds 15% of the end-of-season total, then, in the case of the dry 1989/90 season (Fig. 3), the onset date was JD 346. Likewise, adopting an 85% threshold defines the end date as JD 435 and the season duration as 90 days; that is, 70% of the season’s total was accumulated over this period. In the case of the wet 1996/97 season, onset occurred on JD 343 and the end occurred on JD 426—a total duration of 84 days. The major difference between the two seasons is the fact that rainfall events were more intense in 1996/97 compared to 1989/90.

In the case of the 1968/69 season, the end-of-season total was 1810 mm (approximately 10% more than the long-term average value of 1623 mm). Fifteen percent of this was accumulated by 5 January (JD 370) and 85% by 4 March (JD 428), yielding an estimate for the season duration of 59 days. Table 1 compares onset and end dates for the Darwin 1968/69 season based on different indices, while Table 2 compares long-term average values for these dates (and durations) according to various methods. According to the definition adopted here, the long-term (1950/51–2005/06) average mean onset date (JD 341) is identical to that based on 15% of
Table 2. Estimates of the mean features of the Darwin rainy season.

<table>
<thead>
<tr>
<th>Source</th>
<th>Onset (mm)</th>
<th>Retreat (JD)</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nicholls (1984)</td>
<td>339</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hendon and Liebmann (1990)</td>
<td>359</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Murakami and Matsumoto (1994)</td>
<td>328</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drosdowsky (1996)</td>
<td>372*</td>
<td>431*</td>
<td>60*</td>
</tr>
<tr>
<td>Cook and Heerdegen (2001)</td>
<td></td>
<td></td>
<td>186</td>
</tr>
<tr>
<td>Zeng and Lu (2004)</td>
<td>341*</td>
<td>461*</td>
<td>121*</td>
</tr>
<tr>
<td>Janowiak and Xie (2003)</td>
<td>335*</td>
<td>465*</td>
<td>131*</td>
</tr>
<tr>
<td>Lo et al. (2007)</td>
<td>297</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>341</td>
<td>436</td>
<td>96</td>
</tr>
</tbody>
</table>

* Estimates of monsoon dates.

The long-term average seasonal total but has the added advantage of also yielding estimates for long-term average values for the end date (JD 431) and season duration (96 days). Another advantage of the current method lies in the fact that the dates are affected by rainfall events throughout the entire season, whereas other definitions are independent of events before or after the defined dates. In this sense the current indices better describe the season as a whole.

The long-term averages can be compared with those of other stations in Table 3. The onset dates range from as early as JD 315 at Tempe Downs to as late as JD 387 at Roebourne, while end dates range from JD 422 at Tennant Creek to JD 447 at Booby Island. The range in values for the onset dates (72) is almost three times the range of the end dates (25). This implies a rather slow, but variable, onset to the season across the region followed by a rather abrupt end everywhere. A feature of these indices is that the shorter the season, the sharper or more abrupt is the corresponding accumulated rainfall profile. For example, a station with uniform rainfall throughout the 8-month window will, based on this definition, have a season duration of close to 170 days (i.e., 70% of 243 days). Stations to the south and east are less seasonal than those in the west. The season is only 54 days long at Roebourne, but twice as long (113 days) at Rockhampton. The standard deviations of the season durations indicate that Darwin and Coen (17) are far less variable than, say, Roebourne (36) or Winton (32). However, the average duration at Winton (88) is much longer than at Roebourne (54). In percentage terms, variability of season duration can be said to increase from north to south and from east to west.

4. Average intensity

The conventional definition of rainfall average intensity (Ic) is total seasonal rainfall (T) divided by the total number of raindays (N), or

\[ T = N I_c. \]

The definition of a rainday can be somewhat arbitrary depending on the choice for the critical minimum
amount: $N_R$, and therefore $I_c$, can suffer from the problems associated with threshold definitions. A related problem with counting raindays is that the results can be particularly sensitive to data quality, particularly with records containing occasions where 2- or 3-day rainfall amounts were reported rather than the individual daily amounts. This has much less effect on indices defined in terms of accumulated rainfall.

Here we define season average intensity ($I_A$) as the ratio of accumulated rainfall between the onset and end dates ($T$) divided by the duration ($D$):

$$T = DI_A.$$

This effectively represents the average amount of rain falling per day during the peak of the season (or between the onset and end dates when 70% of the end-of-season rainfall falls).

As such, $I_A$ represents the average gradient of the accumulated rainfall profile. However, $I_A$ does not necessarily equal $I_c$ but provides a useful, relatively simple, descriptor of each season.

From Fig. 3, the average intensity for Darwin in 1989/90 was about 9 mm day$^{-1}$ whereas in the much wetter 1996/97 season the average intensity was more than double at 20 mm day$^{-1}$. [In the case of 1968/69, 1267 mm was accumulated over 59 days (Table 1) yielding an average intensity of 21 mm day$^{-1}$.] The long-term average intensity (1950/51–2005/06) is 12 mm day$^{-1}$, which can be compared with the long-term average values from the other stations in Table 3. Booby Island, Coen, Darwin, and Broome experience the most intense rainfall while the least intense rainfall is experienced at Tempe Downs (1.7 mm day$^{-1}$).

5. Interannual variations of Darwin and Rockhampton indices

Figure 4a shows the interannual variation of Darwin onset dates, end dates, and duration for each season from 1950/51 to 2005/06. While the mean duration is 96 days, in some years it can extend to nearly 4 months while in others last only about 2 months (e.g., 1968/69, which, in fact, was wetter than average, implying a relatively short but intense rainy season). There was a slight increase in the onset dates over the full period (trend correlation $r = +0.07$, Table 3) and almost negligible change in end dates ($r = -0.002$), suggesting a very slight ($r = -0.09$) decrease in season duration. These results contrast with those for Rockhampton on the east coast where Fig. 4b indicates a significant ($r = -0.30$) trend toward earlier onset dates, a trend ($r = +0.11$) toward later end dates, and a consequent significant ($r = +0.29$) increase in season duration.

Interannual variations in seasonal rainfall and average intensity for both Darwin and Rockhampton are shown in Fig. 5. These clearly show the contrasting and significant trends in seasonal rainfall totals at both stations. While Darwin rainfall total trends have been positive (trend correlation $r = +0.36$), the season duration trend is slightly negative ($r = -0.09$), thereby resulting in a significant positive trend in average intensity over time ($r = +0.28$). In the case of Rockhampton, the total trend is negative, ($r = -0.29$), yet the duration trend is positive ($r = +0.29$), thereby resulting in a significant negative trend in average intensity over time ($r = -0.25$).

6. Large-scale results

The same analyses performed on the individual station records have also been performed on the $(2° \times 2°)$ gridpoint data. Figure 6 shows contoured values for mean onset date, mean end date, and mean season duration for the period 1950/51–2003/04. The onset dates, end dates, and season duration are expressed relative to
the values for Darwin (JD 341, JD 496, and 96 days, respectively). Figure 6a indicates that the rainy season, as defined here, tends to start earliest in the south, then at central and northern stations, followed by relatively late onsets on the far northeast and northwest coasts. Note that this picture is different from that presented by a traditional definition based on rainfall amounts, whereby the season tends to start earliest in the north, and later inland and farther south. This occurs because the dates are defined to indicate the times when percentage accumulated rainfall is changing most rapidly. The more concentrated the season, the closer will be the two dates, while the more uniform the season (as is the case with more southern locations), the farther apart the dates will be. This means that a well-defined peak in the rainfall, as is the case with the more northern locations, will yield a later onset date than the more southern locations. Therefore, these indices are not meant to be compared with traditional indices, which are designed to indicate when heavy rainfall events first start and end. The end dates (again relative to Darwin, Fig. 6b) follow a slightly different pattern with the season tending to end earliest in the south and later toward the north and eastern coastal regions and the southwest. However, the major feature, as already noted, is the relatively uniform pattern of values. As a consequence, the pattern of mean season duration (Fig. 6c) tends to follow the pattern for mean onset dates. The longest (i.e., more uniform) seasons occur in the south while the shorter (i.e., more “abrupt”) seasons occur farther north.

Figure 7 shows the pattern of total rainfall accumulated between the onset and end dates and mean average intensity. While there is a close correspondence between rainfall totals and intensity, it can be seen that in the far west there is a relatively small dry region with relatively high average intensity. This may reflect the fact that seasonal rainfall in this region is more affected by intermittent trigger events such as tropical cyclones.

7. Trends

Table 3 indicates recent trends in the various indices for each station by showing the trend correlation coefficient \( r \) associated with each time series. Values significant at \( P < 0.1 \) (i.e., \( |r| > 0.22 \)) are indicated by boldface type, while those significant at \( P < 0.05 \) (\( |r| > 0.27 \)) are both boldfaced and underlined. All stations bar Ayr and Rockhampton in the far east have experienced increases in total rainfall. Of these, five (Booby Island, Broome, Darwin, Fitzroy Crossing, and Tennant Creek) exhibit significant increases. With the exception of Broome, these increases are associated with significant increases in average intensity. At Ayr and Rockhampton, decreases in total rainfall are associated with decreases in average intensity. Only at Roebourne is the sign of the total rainfall trend different from the sign of the average intensity trend, but neither is significant. Other than at Rockhampton, there is little evidence of any consistent larg-scale pattern of significant long-term trends in these indices (not shown). Figure 8, however, shows the pattern of trends for both seasonal rainfall and average intensity. The trends in seasonal rainfall mirror those identified by Smith (2004) with significant increases throughout much of the north and west of the continent contrasting with significant decreases in the far east. It can be seen that these trends are closely associated with similar trends in average intensity.

8. Relationship between ENSO and rainfall indices

Joseph et al. (1994) noted that the onset dates for the Indian summer monsoon tend to be delayed during El Niño years. Previous studies have demonstrated that positive (negative) values of the Southern Oscillation...
The Southern Oscillation index (SOI) tends to be associated with early (late) onsets of the rainy season over northern Australia (Nicholls 1984; Suppiah and Hennessy 1996). In addition, positive values of the SOI have also been linked to an extended duration of the wet season both in northern Australia and Indonesia (Hendon 2003). Table 4 summarizes the results of correlating the seasonal mean values for the Southern Oscillation index over the spring, September–November (SON), season with the new indices defined in this study. No significant correlations were found between any of the indices and the February–March (i.e., late season) average SOI.

At all stations, the SON SOI is significantly positively correlated with seasonal rainfall totals. It is also negatively correlated with onset dates at all stations, but there is no consistent relationship with end dates. As a
result, a positive SOI value tends to be associated with increased season duration, sometimes significantly. However, the relationship with intensity is less uniform. While the tendency is toward greater intensities, none of the relationships is significant.

This is illustrated in Fig. 9, which shows the accumulated rainfall profiles for Darwin from contrasting consecutive seasons 1987/88 (an El Niño year) and 1988/89 (a La Niña year). In the first season, when the SON SOI was $-15.9$, the seasonal total was 1532 mm and the onset and end dates were JD 348 and JD 442. In the following season, the SON SOI had increased to $+11.5$, the seasonal total was a substantially higher 2049 mm, the onset date (JD 325) much earlier, but the end date (JD 442) was identical. As a consequence, the average intensities were almost equal (16.1 versus 17.5 mm day$^{-1}$). In other words, the totals differed mainly because one season was 22 days longer than the other.

Figure 10 shows the large-scale correlation patterns between SON SOI and onset dates, duration, and seasonal totals (There is very little evidence of a consistent pattern of significant correlations between SON SOI and end dates.) This confirms that there is a strong link between the SOI and onset dates for much of northern Australia (Fig. 10a), which translates into a strong link with season duration (Fig. 10b). There is little evidence of a strong link with average intensity, except in the southeast corner (Fig. 10d). The net result is that the SOI is strongly linked to total rainfall throughout much of far-north Australia (Fig. 10c) apparently because it is associated with early onset dates and longer seasons for most regions. In the far southeast, the SON SOI is not strongly linked to season duration (Fig. 10b) but does
appear to affect the rainfall total by its link with average intensity.

9. Discussion and conclusions

There are advantages and disadvantages with most onset and end date indices depending on whether the index is required to monitor the monsoon season or the rainy/wet season, whether it is required for prognostic or diagnostic purposes, and whether it is required to describe local versus larger-scale features. In the case of northern Australia, there have been a number of studies based on a variety of variables that can be used to indicate the onset of either the monsoon or the rainy season. In some cases these are not always applicable to individual stations or individual years and in most cases are not suitable for indicating end dates and therefore season duration. Here we make use of relatively simple indicators of onset and end dates that, although purely diagnostic and largely independent of rainfall amount, provide values for any station for any year. Apart from being relatively simple to calculate, these dates are relatively robust with respect to missing data. The onset and end dates, on their own, do not completely describe any particular rainy season. This is true of most indices that attempt to characterize features of the monsoon/rainy season. However, in conjunction with actual rainfall amounts, they also provide measures of average rainfall intensity.

### TABLE 4. Correlation between the time series for mean SOI (SON) and time series of the rainy season indices. Values significant at $P < 0.05$ are light italic font and those at $P < 0.01$ are bold italic.

<table>
<thead>
<tr>
<th>Location</th>
<th>Total</th>
<th>Onset date</th>
<th>Retreat date</th>
<th>Duration</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ayr</td>
<td>+0.52</td>
<td>−0.31</td>
<td>−0.03</td>
<td>+0.27</td>
<td>+0.15</td>
</tr>
<tr>
<td>Booby Island</td>
<td>+0.55</td>
<td>−0.52</td>
<td>+0.13</td>
<td>+0.48</td>
<td>−0.016</td>
</tr>
<tr>
<td>Broome</td>
<td>+0.30</td>
<td>−0.23</td>
<td>+0.04</td>
<td>+0.14</td>
<td>−0.12</td>
</tr>
<tr>
<td>Coen</td>
<td>+0.40</td>
<td>−0.44</td>
<td>+0.22</td>
<td>+0.53</td>
<td>−0.12</td>
</tr>
<tr>
<td>Darwin</td>
<td>+0.33</td>
<td>−0.26</td>
<td>+0.14</td>
<td>+0.29</td>
<td>+0.02</td>
</tr>
<tr>
<td>Fitzroy Crossing</td>
<td>+0.22</td>
<td>−0.24</td>
<td>−0.14</td>
<td>+0.16</td>
<td>−0.01</td>
</tr>
<tr>
<td>Rockhampton</td>
<td>+0.50</td>
<td>−0.17</td>
<td>−0.14</td>
<td>+0.02</td>
<td>+0.28</td>
</tr>
<tr>
<td>Roebourne</td>
<td>+0.30</td>
<td>−0.12</td>
<td>−0.31</td>
<td>−0.008</td>
<td>+0.11</td>
</tr>
<tr>
<td>Tempe Downs</td>
<td>+0.35</td>
<td>−0.17</td>
<td>−0.22</td>
<td>−0.04</td>
<td>+0.27</td>
</tr>
<tr>
<td>Tennant Creek</td>
<td>+0.43</td>
<td>−0.12</td>
<td>+0.28</td>
<td>+0.27</td>
<td>+0.06</td>
</tr>
<tr>
<td>Winton</td>
<td>+0.49</td>
<td>−0.15</td>
<td>−0.05</td>
<td>+0.09</td>
<td>+0.14</td>
</tr>
</tbody>
</table>
Another significant feature revealed by this analysis is that, where rainfall has been either increasing or decreasing in the long term, so too has the average intensity. There is no evidence that trends in seasonal rainfall amounts are associated with either longer or shorter seasons. Furthermore, the relationship between rainfall and ENSO events is relatively strong across much of the region. However, unlike the relationships revealed between the long-term trends, in the far north, a relatively wet (dry) season associated with La Niña (El Niño) years occurs because the seasons tend to be longer (shorter). In the far north of Australia La Niña years are associated with wetter and longer rainy seasons than El Niño years. ENSO affects the monsoon over both the Indochina Peninsula and the South China Sea similarly (Zhang et al. 2002; Wu and Wang 2000). Consequently, the fact that the SOI has tended to decrease over recent time (Power and Smith 2007) suggests that, if anything, the rainy season there should have become shorter. There is no evidence for this, and the fact that the significant long-term trends in rainfall amount noted by Smith (2004) are mainly associated with trends in average intensity suggests that changes in ENSO cannot explain the trends for most of the far north: It is likely that trends in both are the result of other factors. On the other hand, in the far southeast of the region, the SON SOI is mainly linked to average intensity and the recent tendency toward negative values is consistent with reductions in both average intensity and total amount.

What, then, are the factors driving the observed changes in northern Australian rainfall? Suppiah and Hennessy (1996, 1998) noted that increased summer rainfall at many stations tended to be accompanied by increases in the frequency of the more extreme rainfall events and that this was consistent with predictions that global warming may lead to increases in atmospheric moisture content. However, for those regions where both rainfall amount and average intensity have decreased, it is likely that atmospheric moisture content has decreased, so the role of global warming is unclear. Wardle and Smith (2004) postulated that increasing surface temperatures over much of the continent drive a stronger summer or “monsoonlike” circulation, with increased rainfall, cloud cover, and therefore cooler temperatures in the far north. This is plausible because model simulations of climate change typically predict that land surfaces warm faster than the oceans, not only because of different transient responses, but also at equilibrium because of feedback processes (Joshi et al. 2007). Another hypothesis is that increased Asian aerosols may be implicated in disturbing the hydrological cycle leading to remote effects such as an increase in
Fig. 10. Correlation between the time series for SON SOI and time series for (a) onset dates, (b) duration, (c) seasonal total, and (d) average intensity.
rainfall over northern Australia (Rotstayn et al. 2007). Krishnakumar et al. (1999) proposed that an apparent weakening of the ENSO–South Asian summer monsoon may be due to global warming; yet Annamalai et al. (2007) found little evidence for this in an analysis of the results of numerous climate model simulations produced for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report (FAR). In the case of the South Asian summer monsoon, Annamalai et al. (2007) focused on the results from just six of the climate models that best simulated monsoon precipitation and noted that they all predicted an increase in the mean and variability in response to enhanced CO₂ without describing whether this reflected an increase in average intensity or an increase in season length. In the case of northern Australia, the FAR models yield a range of results: some simulating increases for later this century; the majority indicating decreases. Sun et al. (2007) noted that the FAR multimodel ensemble-mean result for future global annual precipitation changes is characterized by increases over all equatorial regions including northern Australia. Furthermore, this tends to be associated with an increase in both frequency and intensity of heavy precipitation events. This is not apparent in the eastern part of the region where rainfall has decreased.

Other than noting that the recent pattern of trends in northern Australian summer rainfall has been accompanied by an increase in global mean temperatures, it is still difficult to explain the factors behind their occurrence. Future work, focusing on this question and prompted by these results, will be to apply the same methodologies to simulated daily rainfall from various climate models since this appears to provide a useful “fingerprinting” technique for this particular aspect of climate change in this particular region.

Acknowledgments. The authors thank Jozef Syktus, William Wang, and Ian Watterson for their assistance in accessing daily rainfall data, and Harvey Davies for providing software support used to analyze the data. We also thank David Karoly, Leanne Webb, and Mathew Wheeler for their constructive comments on an earlier version of this paper, and are appreciative of the constructive comments of anonymous reviewers. This research was made possible through the Water for the Healthy Country Flagship of CSIRO.

REFERENCES


