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SPATIAL VARIATION IN THE DURATION OF THE RAINY SEASON IN MONSOONAL AUSTRALIA

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ABSTRACT

Climatological research in the tropics of northern Australia has focused particularly on the Australian summer monsoon. However, the timing of many ecologically important processes is determined not by the monsoon but by extra-monsoonal rainfall events. These events produce a temporal pattern of wet and dry spells that is at least as important ecologically as the amount of rain. We defined the rainy season as that period when the probability of 10-day dry spells was less than 0.5, and the wet season as that period within the rainy season when the probability of dry spells was less than 0.1. We applied these criteria to seven stations along a strong north–south rainfall gradient spanning more than 12° of latitude in tropical north Australia. The duration of the rainy and wet seasons in northern Australia decreases with increasing latitude. The timing and duration of these seasons were also affected by the El Niño–Southern Oscillation (ENSO). The relative contribution of temporally isolated rainfall events to both the duration of the rainy season and the amount of rainfall increases with latitude. The geographic variation in these seasons corresponds to many patterns occurring in natural ecosystems. We argue that understanding the extra-monsoon rainfall events is critical to understanding how climate variation affects natural ecosystems. Copyright © 2001 Royal Meteorological Society.

KEY WORDS: dry season; El Niño/La Niña; ENSO; monsoon; Northern Australia; rainfall gradient; tropical savannas; wet season

1. INTRODUCTION

Central north Australia has a classic monsoon climate pattern with reversal of flow from low-level continental-origin easterlies during winter to low-level westerly flow during summer (December–March) (Suppiah, 1992). The monsoon has been the subject of much research because it brings a high proportion of the annual rainfall and is associated with important phenomena, such as tropical cyclones (e.g. Holland, 1986; Hendon and Liebmann, 1990; Manton and McBride, 1992; Drosdowsky, 1996; Suppiah and Hennessy, 1996; Suppiah *et al*., 1998). The monsoon onset usually corresponds to a sudden transition from scattered random convection to large-scale spatially organized convection (McBride, 1987). Holland (1986) defined the onset and withdrawal of the monsoon based on 850 hPa zonal winds at Darwin (12°26′S, 130°52′E), and demonstrated that the period of the monsoon shows considerable interannual variability. The mean dates of onset and withdrawal for 1952–1982 were 24 December and 7 March respectively (Holland, 1986). Slightly later dates were found by Drosdowsky (1996) for 1957/1958–1991/1992.

A transitional period usually precedes the onset of the monsoon. Rains during that period have a diversity of origins (Keenan and Carbone, 1992), and can account for up to 30% of the total wet season

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rainfall (Nicholls *et al*., 1982). They also show strong interannual variability but this variability is not correlated with the behaviour of the monsoon (Nicholls *et al*., 1982). Nicholls (1984) defined the north Australian wet season onset as the date of accumulation of 15% of a climate station's mean annual rainfall. He found that there was considerable spatial coherence in the dates of wet season onset across ten north Australian climate stations. The median onset date of the ten stations was then selected as an index of the onset of the north Australian wet season. The median date of the wet season onset for 1950/1951–1973/1974 was 21 December. Thus, the onset of the wet season as defined by Nicholls is generally only several days before the monsoon onset (McBride, 1987).

By the onset of Nicholls' wet season, nearly 250 mm of rain would have fallen at Darwin but less than 50 mm at Barrow Creek (21°32′S, 133°53′E). Because plants respond to the absolute amounts of rain, growth would be at very different stages across north Australia by the wet season onset. The annual speargrasses, *Sorghum* spp., can germinate after the first rainfall event of 15 mm or more, which can occur in early October in Darwin (Andrew and Mott, 1983). Native deciduous trees flush with new leaves from October to December (Williams *et al*., 1997). Interannual variations in rainfall timing can have profound effects on wildlife breeding and plant species composition (Taylor and Tulloch, 1985). Abrecht and Bristow (1996) note that the rate and number of leaves initiated in cereals and lower grain yields all result from water deficits during establishment. Thus, rains trigger many ecological processes well before the onset of both the wet season and the monsoon as defined by Nicholls.

Many ecological variables, including the height, basal area, cover and species diversity of trees, decrease with decreasing rainfall southwards through the Northern Territory (Williams *et al*., 1995). It is likely that the ecosystems are responding as much to growing season length as to mean annual rainfall. Therefore, knowledge of the dates of the monsoon (Holland, 1986; Drosdowsky, 1996) and definitions of the wet season that use a single date for all of north Australia (Nicholls, 1984) can contribute little to understanding how climatic variation affects terrestrial ecosystems in north Australia.

Rather than applying a single date for the wet season onset across north Australia, McCown (1981) recognized the importance of variation in the commencement, cessation and duration of the growing season. He used a simple water balance model to define the green season. For Darwin and Katherine (14°28′S, 132°16′E) median dates for the green season were 19 October to about 7 June and 2 November to about 17 May, respectively. Kamara and Jackson (1997) adopted a similar approach for Sierra Leone. In a recent paper on the monsoon in West Africa, Omotosho *et al*. (2000) defined the date of onset of the rainy season as 'the beginning of the first two rains totalling 20 mm or more, within 7 days, followed by 2–3 weeks each with at least 50% of the weekly crop-water requirement' (i.e. 4 mm/day at Kano). This followed an earlier definition: 'the first three or four rainfalls of at least 10 mm with not more than 7 days between them'. Like McCown, these definitions recognize the need for a continuing supply of available moisture for sustained plant growth.

Although McCown (1981) showed that native pasture growth and liveweight gain of cattle corresponded well with the green season and the converse dry season, an earlier cessation date might be more appropriate for many natural ecosystem processes that appear to be more closely related to rainfall than soil moisture. Annual speargrasses generally set seed in Darwin and Katherine 2–3 months, respectively, before the end of McCown's green season (Andrew and Mott, 1983). Similarly, leaf fall of native deciduous trees commences in early April in Darwin (Myers *et al*., 1998). Traditional Aboriginal burning was carried out in this region from the time when speargrass senesced in mid-March through until December (Braithwaite, 1991).

An index of the duration of the rainy period that is relevant to terrestrial ecosystems in central north Australia is required to predict the ecological impacts of climate change. The monsoon can be defined on the basis of objective meteorological observations, but the choice of criteria to define the period of isolated rainfall events before and after the monsoon will be arbitrary (see Mollah and Cook, 1996). The dates of the first and last significant falls of rain could provide a simple index of the duration of the rainy season. However, such an index would fail to capture important variations in the temporal patterning of rainfall events. The start and finish of these events can, perhaps, best be described probabilistically.

The patterns of dry spells and wet spells at the start and end of the rainy season are critical to crop establishment, growth and harvest (Mollah *et al.*, 1991; Chapman *et al.*, 1996; Mollah and Cook, 1996) and should also be important to natural ecosystems. Although the temporal patterns of rainfall events may be highly correlated with mean annual rainfall in north Australia, these relationships do not necessarily hold across continents (Jackson, 1988) and may alter under climate change. In the wet/dry tropics of the world, ecological properties may be more fundamentally related to the temporal patterning of rainfall than the amounts (Cook and Mordelet, 1997). Heerdegen and Cook (2000) have developed an index of the duration of the rainy period based on the temporal patterns of rainfall events in central north Australia. We expand on that paper here to show how important are the variations to natural ecosystems.

2. THE PATTERNS OF RAINFALL EVENTS IN DARWIN AND ELLIOTT

We determined the frequency of dry spells and wet spells between the first and last falls of 5 mm or more after 1 September and before 31 May over the period under investigation. We used a 5-mm threshold to define a rainday, since daily evapotranspiration generally exceeds this amount. Although raindays tend to be clustered in north Australia (McCaskill and Kariada, 1992), this analysis showed that dry days are also clustered. Sequences of 3 raindays or fewer accounted for more than 60% of total raindays in Darwin (Figure 1), while sequences of 8 raindays or fewer accounted for more than 95% of raindays in Darwin. The length of dry spells was much more variable than the length of wet spells, with sequences of 8 dry days or more accounting for about 50% of dry days (excluding the annual dry season) in Darwin and about 75% in Elliott.

The sequence of wet and dry spells in Darwin in 1978/1979 is shown in Figure 2. It also includes the timing of important ecological events (McCown, 1981; Andrew and Mott, 1983; Williams *et al.*, 1997; Myers *et al.*, 1998) and the monsoon and wet season onset for that year (Nicholls, 1984; Holland, 1986). During the 1978/1979 rainy season, the onset of the monsoon resulted in no marked discontinuity in the patterns of dry spells and wet spells (Figure 2). Although daily rainfall amounts are usually higher during the monsoon period, much of the rain will exceed plant requirements in terrestrial systems and be lost through either runoff or deep drainage. It is clear from Figure 2 that the first and last rains of the wet season have greater relevance to terrestrial ecosystems than the timing of the monsoon.

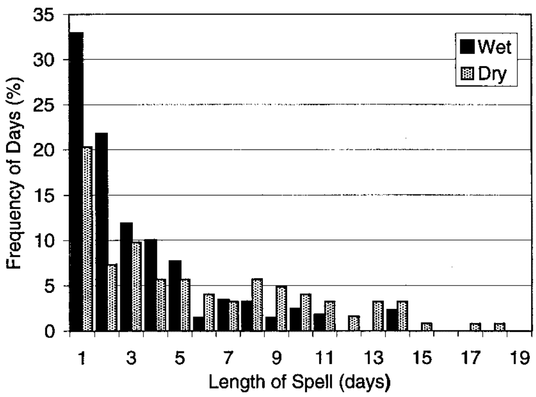

Figure 1. The relative frequency of spells of consecutive wetdays (≥ 5 mm) and dry days (< 5 mm) of 20 days or less in Darwin for the period 1976–1996. Dry spells > 19 days long are omitted. The annual longest dry period, which ranged from 88 to 254 days, is omitted from the calculations

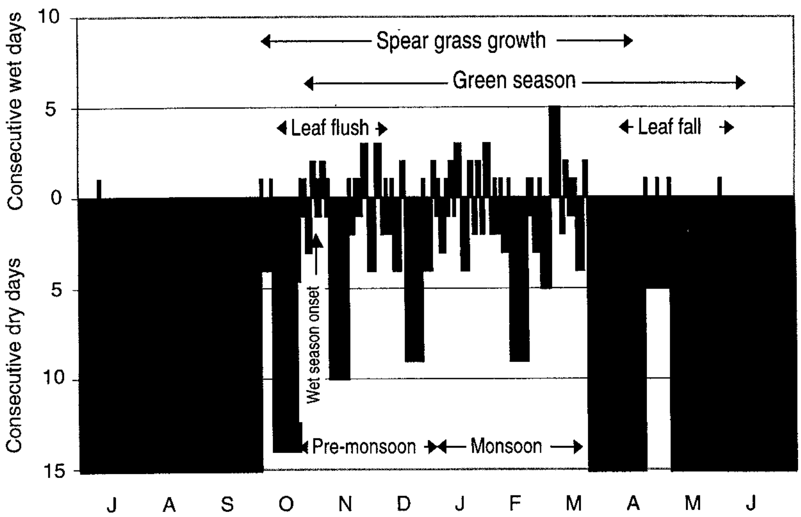

Figure 2. The sequence of dry days (< 5 mm) and wet days (≥ 5 mm) in Darwin in 1978/1979 showing the period of the monsoon for that season (Holland, 1986), Nicholls (1984) wet season onset for that year, McCown (1981) green season and the timing of some important ecological events—speargrass growth, leaf flush and leaf fall (Andrew and Mott, 1983; Myers *et al*., 1998)

3. DEFINING AN INDEX OF THE RAINY SEASON AND THE WET SEASON

3.1. Study sites

For our analyses, we chose seven climate stations from Pirlangimpi on Bathurst Island in the north of the Northern Territory to Alice Springs in the south (Figure 3). Although Alice Springs is not within the monsoonal tropics (Gentilli, 1971, cited in Suppiah, 1992) it was included for comparative purposes. The stations represent the North Australian Tropical Transect (NATT) in Australia's Northern Territory. The NATT is one of a series of sub-continental scale terrestrial transects that have been established along major environmental gradients around the globe to understand better the ecological impacts of global change in climate, atmospheric composition and land use (Koch *et al*., 1995). It traverses about 12° of latitude along the gradient of decreasing precipitation southwards from the north Australian coastline to central Australia. This rainfall gradient is largely unaffected by relief. The north–south gradient in mean annual rainfall in the Northern Territory varies from approximately 200 mm per degree of latitude in the north to about 100 mm per degree in the south. Tropical savanna vegetation dominates this region. The major land-uses are tourism, pastoralism, conservation, mining, military training and subsistence living.

3.2. Data analysis

For each climate station, we calculated the probability of 10-day dry spells commencing on each day of the year, expressed as a percentage of the 20-year record, using official data provided by the Australian Bureau of Meteorology. We defined raindays as any day having greater than 5 mm rainfall because the mean daily potential evaporation during the summer months is about 5 mm along the NATT (Muller, 1982). For Darwin, Larrimah, Elliott, Tennant Creek and Alice Springs, we used 21 years of daily rainfall records from 1 June 1975 to 30 May 1996. We chose this 21 years because most of the ecological research in this region dates from this period. For Pirlangimpi, we used records from 1980 to 1996. For Katherine, we used a much longer record of 71 years of complete records between 1915 and 1990 (we excluded 1922/1923, 1985/1986 and 1986/1987 because of incomplete data). This allowed us to calculate the probability of 10-day dry spells in 20 El Niño years from 1905 to 1982 and 20 La Niña years from 1892 to 1988 (Suppiah, 1993) using data from Lavery *et al*. (1992). It should be noted that the 20-year probability distributions for dry days differed little from longer periods, such is the strength of the monsoon signal in the rainfall record.

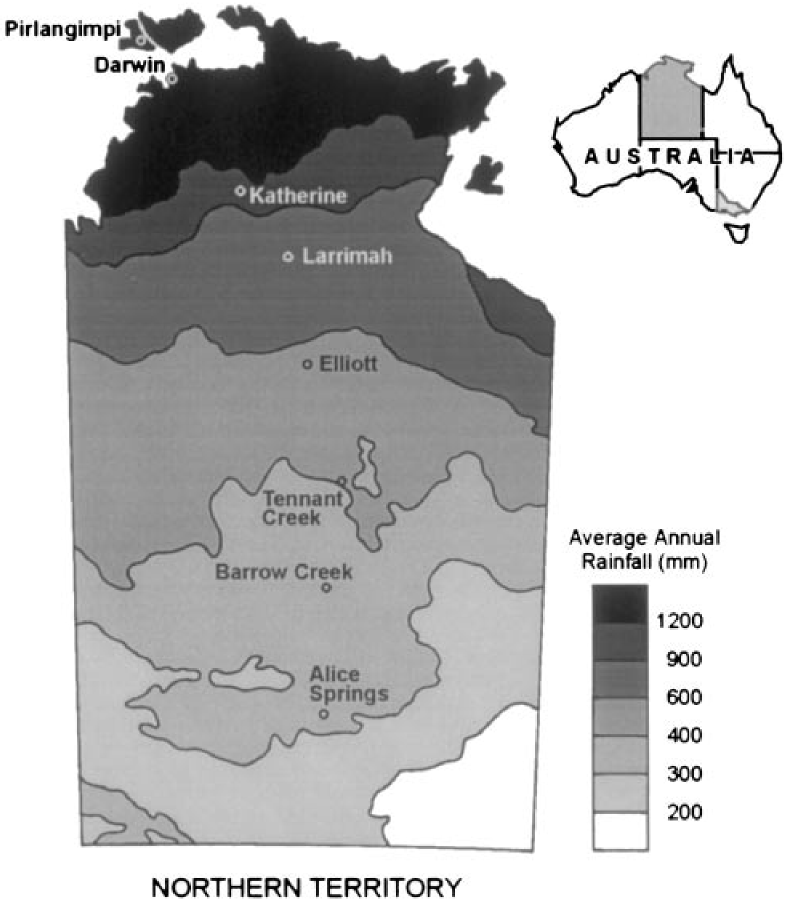

Figure 3. Location of eight climate stations and annual rainfall isohyets (mm) for the Northern Territory, Australia

Using a 10-day running mean, we defined the dry season as being that time of year when the probability of 10-day dry spells was greater than 0.5. The rainy season was the period when the probability of 10-day dry spells was less than 0.5. Within the rainy season, we defined the period of monsoonal influence (or 'the wet') as the period between the first and last dates that the probability of 10-day dry spells fell below 0.1 (Figure 4). Further sub-categories as indicated are self-explanatory.

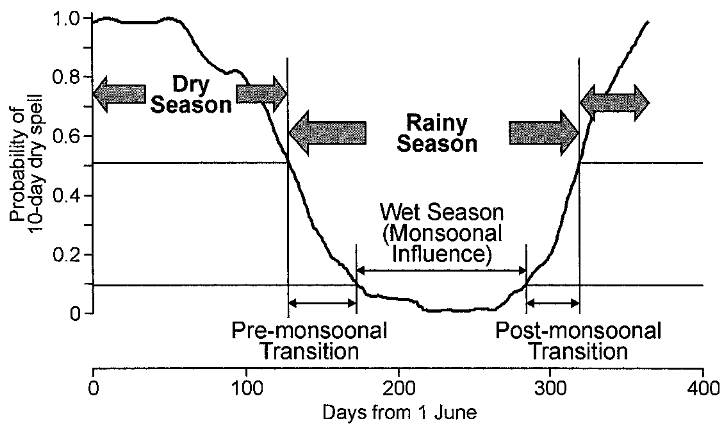

Figure 4. The probability of 10-day dry spells in Darwin, together with the temporal extent of the terms used in the analysis

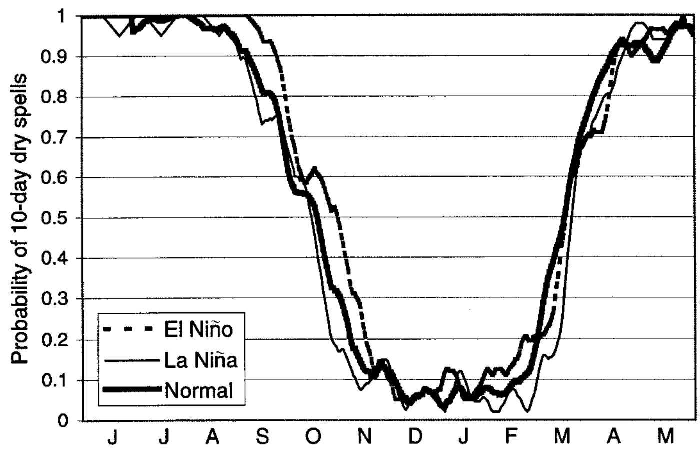

Figure 5. Ten-day running means of the probability of 10-day dry spells starting on a particular date in Katherine. El Niño and La Niña years are shown together with 71 years (normal) between 1915 and 1990

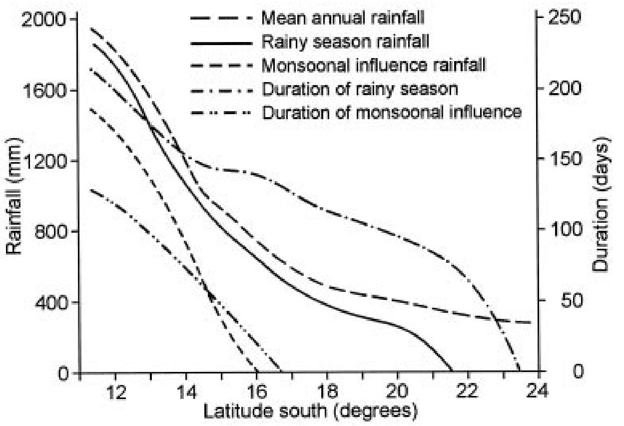

Figure 6. The relationship of the various attributes of the monsoon to latitude

4. RESULTS

4.1. Effects of ENSO

For 71 years of records, the average duration of the rainy season at Katherine was 150 days (Figure 5; Table I). The duration was shorter during El Niño years and longer during La Niña years and this was reflected in the mean rainfall totals. The start of the rainy season was, on average, 15 days later during El Niño years than La Niña years, while the end was only 4 days earlier in El Niño years. The wet season started similarly in both El Niño years and La Niña years, but this period of less than 10% probability of 10-day dry spells finished 31 days earlier in El Niño years.

4.2. Comparisons of stations

Over the 8° of latitude from Pirlangimpi to Tennant Creek, the duration of the rainy season decreased from 221 days to 110 days (Figure 6; Table I). Thereafter the duration decreased more rapidly with increasing latitude, being just 6 days at Alice Springs, approximately 4° of latitude further south. The decreasing duration of the rainy season with increasing latitude is accounted for by both later starting dates and earlier finishing dates. The rainy season at Tennant Creek starts 50 days later and ends 65 days

Table I. The timing and amounts of rainfall in the rainy season and the wet season for seven climate stations along a rainfall gradient in the Northern Territory, Australia

Station	Mean annual rainfall (1 June–31 May) (mm)	Rainy season				Wet season			
		Start date	End date	Duration (d)	Mean rainfall (mm)	Start date	End date	Duration (d)	Mean rainfall (mm)
Pirlangimpi 11°24′S, 130°25′E[a]	1963	21 Sept	30 Apr	221	1898	3 Nov	6 Apr	154	1657
Darwin 12°26′S, 130°52′E[b]	1718	13 Oct	17 Apr	186	1623	21 Nov	14 Mar	113	1254
Katherine 14°28′S, 132°16′E[c]	961	25 Oct	24 Mar	150	874	10 Dec	25 Feb	77	555
Katherine 20 La Niña years 1892–1988	1048	22 Oct	28 Mar	157	982	10 Dec	6 Mar	86	643
Katherine 20 El Niño years 1905–1982	854	6 Nov	24 Mar	138	757	8 Dec	1 Feb	55	396
Larrimah 15°35′S, 133°13′E[b]	806	31 Oct	24 Mar	144	721	26 Dec	22 Feb	58	394
Elliott 17°31′S, 133°32′E[b]	517	6 Nov	5 Mar	119	403	—	—	—	—
Tennant Creek 19°38′S, 134°11′E[b]	413	8 Nov	26 Feb	110	288	—	—	—	—
Barrow Creek 21°32′S, 133°53′E[b]	314	19 Nov	9 Feb	83	133				
Alice Springs 23°49′S, 133°53′E[b]	261					—	—	—	—

[a] For 1980/1981–1995/1996.
[b] For 1976/1977–1995/1996.
[c] For 1915/1916–1989/1990, excluding 1922/1923, 1985/1986 and 1986/1987.

earlier than at Pirlangimpi. The start of the rainy season corresponds to an accumulated total rainfall from 1 June of 30–40 mm for all stations from Pirlangimpi to Tennant Creek.

The wet season follows a similar pattern to that of the rainy season, decreasing in duration from 154 days at Pirlangimpi to 58 days at Larrimah (Table I). South of Larrimah the region becomes arid and dry spells are so common throughout the year that a wet season is not registered using our method. The period between the start of the rainy season and the start of the wet season is about 1–4 weeks longer than the post-wet season period.

At Pirlangimpi, the rainy season and wet season account for 97% and 84%, respectively, of the annual rainfall (1 June–31 May; Table I). The duration of the wet season is 70% that of the rainy season. At Larrimah, the rainy season still accounts for 90% of the annual rainfall, but the wet season only accounts for 49%, while the duration of the wet season is only 40% that of the rainy season.

5. DISCUSSION

We have developed an index of the start and finish of the rainy season in central north Australia. The rainy season as we have defined it corresponds approximately to the period in Darwin during which native deciduous trees are in leaf (Williams *et al.*, 1997; Myers *et al.*, 1998), annual speargrass is growing (Andrew and Mott, 1983) and frillneck lizards are at their peak activity (Griffiths and Christian, 1996).

Although there are scant phenological data for sites further south, it is reasonable to assume that the decreasing of tree biomass and diversity along the north–south rainfall gradient reflect the progressive shortening of the rainy season with increasing distance inland. This season rapidly decreases in length south of Tennant Creek. This is approximately where the tree stratum of native vegetation changes from *Eucalyptus* and deciduous species to *Acacia* and the grass stratum changes from tussock grasses with ephemeral leaves to hummock grasses with evergreen and sclerophyllous leaves (Wilson *et al.*, 1990; Williams *et al.*, 1995).

We also devised a complementary probability based definition of the wet season. The wet season as we defined it does not occur south of 15°–16°S. This roughly corresponds to the southern limit of monsoon tall-grass savannas, where the tree stratum is typically dominated by *Eucalyptus miniata*, *E. tetrodonta* or *E. tectifica*, and the herbaceous stratum is often dominated by annual speargrasses (Wilson *et al.*, 1990).

The use of sub-continental scale transects to study global change issues assumes that space can be used as a surrogate for time (Koch *et al.*, 1995). Examining historical variation in rainfall amounts and temporal patterns can be used to test whether that assumption is justified. In Katherine, the amounts of rainfall and their temporal patterns respond similarly to the ENSO. In El Niño years, duration of the rainy and wet seasons and the amount of rain received in those seasons became more similar to those of Larrimah, about 1° of latitude further south (Table I). Although the starting date of the wet season was little affected by El Niño, in general the rationale for using space as a surrogate for time appears well founded, at least on historical grounds.

By defining rainfall seasonality as a function of the probability of an n-day dry spell, we have moved away from definitions based on accumulated rainfall or meteorological phenomena towards one that is more relevant ecologically. Our selection of criteria to define the rainy and wet seasons corresponds with some important ecological patterns in the Northern Territory. Nevertheless, the exact dates should be taken as indicative only as they will vary with the choice of criteria and are affected by our use of records from 1976 to 1996, which had below-average rainfall. Users of this methodology could easily construct a probability function from other periods of daily rainfalls using whatever length of dry spell and whatever critical probabilities they deem appropriate.

We conclude that the temporal patterning of isolated rainfall events that occur before and after the monsoon are critical determinants of ecosystem function and their importance increases with increasing latitude. The timing of these events is affected by the ENSO. Although the annual number of dry days has been decreasing over much of Australia during this century (Suppiah and Hennessy, 1998), north Australia has much more concentrated rainfall than elsewhere in the tropics of the world (Jackson, 1988).

Changes to the patterns of wet and dry spells during the extra-monsoonal period could be a major climatic driver of ecosystem change in north Australia. Understanding the temporal and spatial variation in the extra-monsoonal rain producing systems will be critical to predicting the effects of climate change on ecosystems.

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