Variability of the Australian Summer Monsoon at Darwin: 1957–1992

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ABSTRACT

The variability of the Australian summer monsoon is reexamined using data covering 35 monsoon seasons. A new, easily applied objective definition of active and break phases of the monsoon, based solely on the zonal wind at Darwin, is proposed. Attempts to define "wet westerly" onsets are shown to be misleading, since no clear relationship is found between westerly winds and rainfall, on the timescales associated with the transition between active and break phases. The resulting dates of monsoon onset at Darwin differ from those reported in some recent studies, resulting in significantly different relationships with the Southern Oscillation. In particular, the date of monsoon onset is shown to be significantly related to, and hence predicted from, prior values of the Southern Oscillation index. Also in contrast to a number of recent studies that have highlighted the so-called 40–50-day oscillation in the Australian summer monsoon, no dominant timescales are found in the length of the active periods or in the recurrence time between active phases.

1. Introduction

A number of authors (Troup 1961; Holland 1986; Hendon and Liebmann 1990a) have examined the onset of the Australian summer monsoon and published lists of dates of onset for various years. The initial intention of this research was to extend the Holland (1986) or Hendon and Liebmann (1990a) record of onset dates up to the 1991/1992 season and then to examine the variations in the large-scale Southern Hemisphere circulation and Australian rainfall associated with monsoon onset and active monsoon periods. For a variety of reasons (discussed in section 2), neither the Holland (1986) nor the Hendon and Liebmann (1990a) onset dates and active/break periods could be reproduced. Their definitions, therefore, could not be applied with confidence regarding the consistency of the dates to the independent data available for the period 1987/1988 to 1991/1992 and beyond.

This paper therefore begins with an examination of some of the research on intraseasonal variability and monsoon onset in section 2. New definitions of active/break cycles and the onset and retreat of the monsoon are developed in section 3, and the results compared with those of the previous studies. In section 4 the interannual and intraseasonal variability of the onset/retreat and active/break cycles are examined. Finally, in section 5 these results are discussed and conclusions presented. In the remainder of this section we (a) describe the datasets to be used and (b) briefly note some relevant aspects of the climatology of the upper wind at Darwin and rainfall over northern Australia.

a. Data

Two main datasets are used in this study. The first consists of four times per day soundings of zonal and meridional wind components at 16 standard levels from the surface to 50 hPa from Darwin (12.5°S, 130.9°E). The second dataset consists of daily rainfall records from the six stations used by Troup (1961), including the Darwin Airport rawinsonde site. The period of record for both these datasets is the 36-yr period from January 1957 to December 1992, spanning 35 complete monsoon seasons. The location of the rainfall stations and the Darwin upper-wind observation site are shown in Fig. 1. All data were obtained from the National Climate Centre (NCC) of the Australian Bureau of Meteorology. Wind data up to June 1987 were obtained from a quality controlled dataset, the final five years from archives of real-time messages. All rainfall data were obtained from digitized monthly station returns.

For the wind data some missing values were filled by two applications of a three-stage linear interpolation procedure. First, single missing levels within a flight were filled by interpolation between the adjacent levels. Second, gaps over two or more levels were filled by interpolation in time, using the previous and following observations at the same local time as the missing observation, in order to preserve the diurnal cycle. Finally, another interpolation in time using the immediately (six hourly) prior and following observations was

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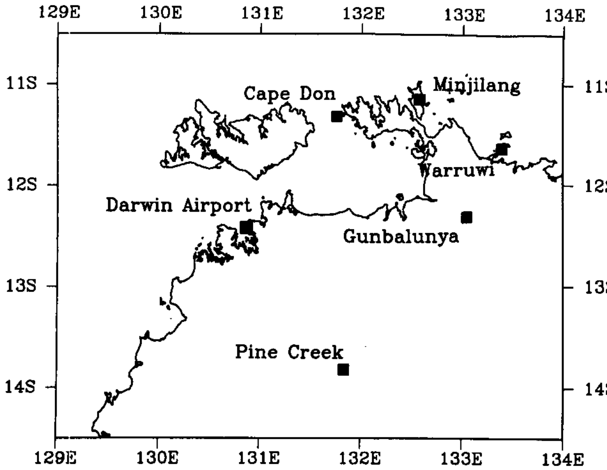

FIG. 1. Location of six daily rainfall stations used in this study, including the Darwin Airport upper wind station.

applied. This process was then repeated to reduce the data gaps further by utilizing some of the interpolated values. The number of missing values was reduced from about 5% in the low levels and 15% in the upper troposphere to around 2% for all level below 100 hPa. Only one flight per day regularly reached the 100-hPa level and the interpolation had little effect at and above this level. Rainfall data were used only as averages of a number of stations, and no replacement of missing values was attempted.

b. Climatology

The time–height sections of the 35-yr (July 1957 to June 1992) mean zonal and meridional winds at Darwin are shown in Figs. 2a and 2b, respectively. All available data have been used in the construction of these means, with the four flights per day averaged to produce a mean daily observation. These figures show a typical monsoonal structure. In the upper levels two distinct northwesterly maxima occur, in September–November and April–June, with weaker westerlies in midwinter (July–August) and strong southeasterlies during summer (December–March). The low levels are dominated by strong southeast trades. These are most intense, and at lowest levels from April to July the maximum then moves to higher levels, reaching 700 hPa during October and remaining at this level until early December. During this "transition" period surface westerlies associated with the north Australian summer heat low develop. These low-level westerlies reach a maximum strength of over 4 m s^{-1} at 950–900 hPa in late January–early February and extend up to the 500-hPa level.

The 35-yr mean rainfall (Fig. 2c), averaged over the six stations shown in Fig. 1, also shows a marked annual cycle. The daily rainfall rate increases steadily from near zero in mid-October to 8 mm/day at the end of December, this period producing about 25% of the mean annual rainfall. This is followed by a sharp increase to 10–12 mm/day during the first few days of January, before reaching a peak at around 14 mm/day in late January–early February. The 2.5-month period from early January to mid-March accounts for about 61% of the mean rainfall. The return of the dry season is more rapid, with the mean daily rate dropping from 12 mm/day in mid-March to near zero by the end of April. The premonsoon season rainfall is mainly due to convective activity in the form of both large-scale organized systems and random-scattered thunderstorms, but early season tropical cyclones may also contribute. The rapid increase in daily rainfall rate in early January suggests that mean monsoon onset should occur around

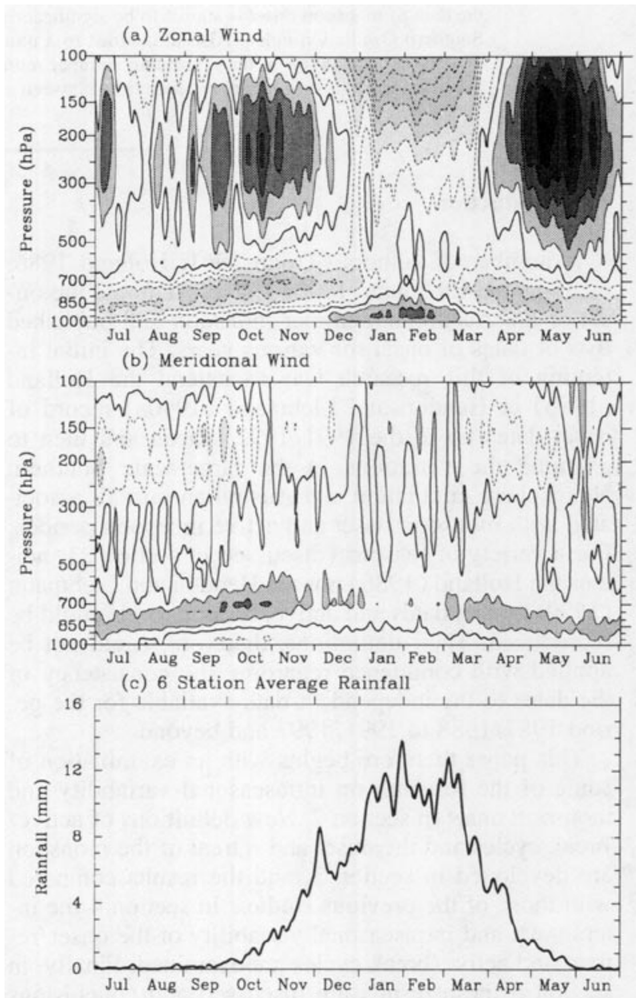

FIG. 2. Time–height section of 35-year mean (a) zonal and (b) meridional wind at Darwin and (c) rainfall for the six station composite in Fig. 1. Contour interval in (a) and (b) is 2 m s^{-1}, the zero contour is a heavy solid line, and negative (easterly or northerly) contours are dashed. Positive (negative) values greater (less) than one contour interval (2 m s^{-1}) are heavy (light) shading. Data have been smoothed over time using a 9-point binomial filter.

this time. This is consistent with the results of Nicholls (1984) and Nicholls et al. (1982), who used the date of the accumulation of a certain threshold or percentage of annual rainfall to define onset, if their highest percentage (30%) is used to define onset.

2. Review of previous research

A number of studies have already been performed on the onset and intraseasonal variability of the Australian and, especially, the Indian summer monsoons. The criteria used to define variability and onset can be grouped into four categories:

(a) wind-only definitions (e.g., Holland 1986),

(b) rain-only definitions (e.g., Anantharkrishnan and Soman 1988; Nicholls 1984; Nicholls et al. 1982; Lough 1993),

(c) combined wind and rain definitions (e.g., Troup 1961; Hendon and Liebmann 1990a),

(d) large-scale circulation (e.g., Davidson et al. 1983; Murakami and Sumi 1982).

The most comprehensive sets of published onset dates are those of Holland (1986) for the period 1952/1953 to 1982/1983 and Hendon and Liebmann (1990a) for the period 1957/1958 to 1986/1987. Troup (1961) presented results for four seasons, 1955/1956 to 1958/1959, while Davidson et al. (1983) list onsets for six seasons between 1971/1972 and 1979/1980. They were unable to define onset during the other three seasons in this period. Nicholls et al. (1982) give mean dates of "onset" based on accumulation of various amounts of rainfall at Darwin, while Nicholls (1984) lists onset for a mean over ten stations for 32 seasons from 1950/1951 to 1981/1982.

Hendon and Liebmann (1990a) examined the relationship between their set of onset dates and those of Holland (1986) and found a correlation of 0.74. While this is *statistically significant,* it actually represents a poor relationship, explaining only about 55% of the variance, given that both sets of dates are meant to represent the same event and are derived from essentially the same set of data. Of the 26 years common to both sets of dates, only one-half differ by 2 days or less. In five cases the difference is more than 15 days, with an extreme difference of 38 days for the 1969/1970 season. To determine the reasons for these large differences, the observed zonal winds at Darwin around both sets of onset dates were examined. Some serious discrepancies were noted between both sets of dates and the observed winds. In particular it was found that many of the onsets occur during periods of substantial low-level easterly flow or during very short and/or shallow bursts of westerlies at Darwin.

This problem, which appears to be worse in Holland's (1986) dates, appears to arise from two sources: the use of a single-level wind, subjected to low-pass filtering, in both studies. Holland (1986) chose the 850-hPa level to minimize the effect of the sea breeze; however, the circulation associated with the heat low often extends up to this level, although mean westerlies do not appear until late December (Fig. 2a). Some onsets in both of these studies are therefore associated with low-level (below 800 hPa) westerly flow, while the lower midtropospheric (800–600 hPa) zonal wind remains strong easterly.

The low-pass filtering of the daily wind data, as produced by Holland's (1986) cubic spline or Hendon and Liebmann's (1990a) 1–2–3–2–1 filter, leads to more serious discrepancies. Active bursts of the Australian summer monsoon are associated with deep westerly flow, extending up to between 400 and 200 hPa, overlain by strong easterly flow, as noted by Manton and McBride (1992) and earlier authors (see Troup 1961 and references therein). The onset of these bursts is characterized by a relatively rapid change from easterly or weak shallow westerly flow to strong deep westerly flow [see Gunn et al. (1989) and Hendon et al. (1989) for an analysis of the 1986/1987 onset during the Australian Monsoon Experiment, AMEX]. Any form of low-pass filtering spreads this abrupt change over several days. The amount of spreading depends on the magnitude of the wind before and after onset and the actual threshold used to define onset, but the date assigned to onset will generally be a day early when the unfiltered wind is still easterly. In some cases the difference may be up to 2 days.

This shifting of the onset date due to filtering of the zonal wind time series is clearly illustrated by the example shown in Fig. 3. Examination of the time–height section of zonal wind (Fig. 3a) shows that onset in this year (1957/1958) clearly occurred between 0000 UTC (0900 LST) 27 December 1957 and 0000 UTC 28 December 1957, when the zonal wind component in the lower troposphere increased from near zero to a peak of approximately 12 m s^{-1}. Figure 3b shows the time series of the 6-h 850-hPa zonal wind, the daily average wind (with respect to a local day), and the smoothed daily wind, using the Hendon and Liebmann (1990a) filter. The filtered curve shows a smooth increase with zero crossing between 26 and 27 December 1957. The even earlier date of 25 December 1957 given by Hendon and Liebmann (1990a) is difficult to explain but may be due to the removal of the annual cycle from their dataset (it is not clear whether this has been done), as well as their incorporation of a rainfall criterion. This westerly burst was preceded by, and overlapped the end of, a rain event, as will be shown in the following section. This imperfect overlap between westerly winds and rainfall suggests that use of a rainfall criterion may introduce a certain amount of subjectivity into the selection of onset date.

The cubic spline used by Holland (1986) also acts as a low-pass filter. Experiments with time series of periodic signal plus white noise suggest a cutoff period of the order of 30 days. This cutoff period appears to depend on the length of the time series to which it is applied (McBride, personal communication 1992) and can give different results when run over different lengths of data. The initial analysis was performed on 1-yr segments from October to September. In many years different onset dates can be obtained merely by using a 6-month time series from October to March. In either case one needs to wait till the end of the season before determining the onset date and the active and break periods.

The example discussed here is typical of a large proportion of the onsets in the 1957/1958 to 1986/1987 period and highlights the major problem with the Holland (1986) and Hendon and Liebmann (1990a) onset dates; this is the difficulty in reproducing their results from the description of their techniques and datasets.

3. Active/break cycles and onset

a. Spectral analysis

Various authors (Hendon and Liebmann 1990a,b; Suppiah 1993) have commented on the appearance of the so-called 40–50 day oscillation during the Australian summer monsoon. To examine this signal in the present datasets, power spectra of the Darwin zonal winds and area-averaged rainfall were calculated. The 36-yr time series were broken into 12 consecutive, nonoverlapping segments of length 1024 days, and the periodogram estimates were obtained with a fast Fourier transform (FFT). The segments of 1024 points have a frequency resolution of 1/1024 day^{-1} and are sufficiently long to resolve the harmonics of the annual cycle. The squared periodogram estimates from each of the 12 segments were then averaged to produce the final power spectrum.

While the annual and semiannual cycles dominate the variance spectra of the zonal wind (Fig. 4) and also the area-averaged rainfall (Fig. 5a), there is substantial broadband power in the intraseasonal (20–70 day) range, especially in the upper troposphere. In order to assess the significance of this broad peak, an appropriate null hypothesis is necessary. While the background may be a red noise or Markov process, the discrete spectral lines at the one year and subharmonic periods are not part of this process. If the annual cycle, including the first four harmonics, is removed, the rainfall spectrum (Fig. 5b) shows enhanced variance in the intraseasonal range but not at a significant level against a red noise background. Similar results are found with the 150-hPa zonal wind, as shown in Fig. 5d. At the 850-hPa level, one spectral estimate at 37 days exceeds the 95% a priori confidence level. This result is similar to that of Hendon and Liebmann (1990a), who concluded that the peak at 33 days in their spectrum of the Darwin 850-hPa zonal wind was significant against a subjectively determined red noise background.

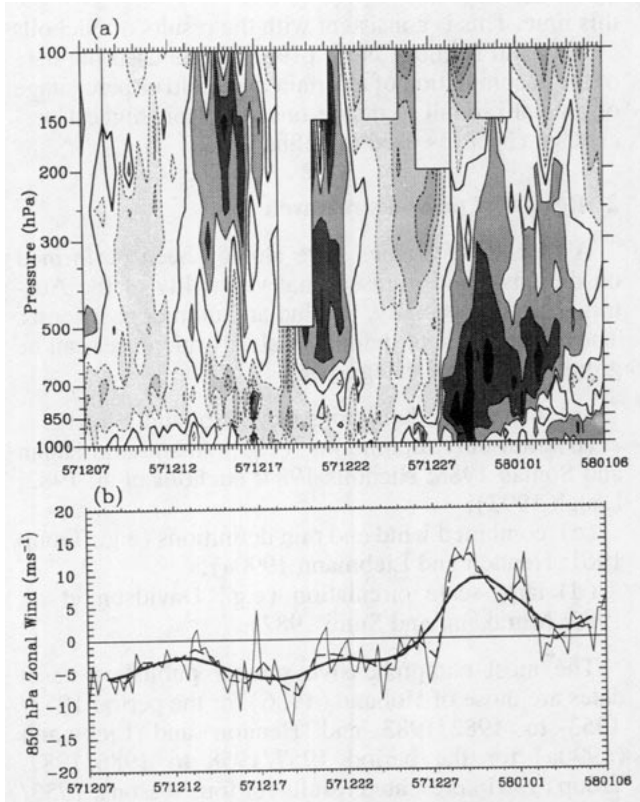

FIG. 3(a). Time–height section of 6-h zonal wind at Darwin for period 7 December 1957 to 6 January 1958. Contours and shading as in Fig. 2, except that contour interval is 4 m s^{-1}. Major tick marks are at 0000 UTC (0900 LST). (b) Time series of the 6-h 850-hPa zonal wind (light solid curve), the daily average wind (with respect to a local day) (heavy dashed curve), and smoothed daily wind, using the Hendon and Liebmann (1990a) 1–2–3–2–1 filter (heavy solid curve) for same period as in (a).

b. Westerly wind events

To identify active monsoon periods a subjective examination of the time–height section of unfiltered Darwin zonal winds similar to Fig. 3a for the October to April period in every season from 1957/1958 to 1986/1987 was performed. These periods, characterized by deep low-level westerly flow (zonal wind speed at least 5 m s^{-1} extending up to at least the 700-hPa level) overlain by strong upper-level easterlies, generally occurred between mid-December and mid-March and were generally easily distinguished. Monsoon onset was then defined as the beginning of the first active period.

A number of low-level westerly bursts were also identified during November and early December. Figure 2a shows that upper-level westerlies persist at Darwin until mid-December. In many of the early (late November–early December) westerly wind bursts, the strongest westerlies occurred in the mid- and upper troposphere. This suggested that they were in fact associated with deep midlatitude westerly troughs and were

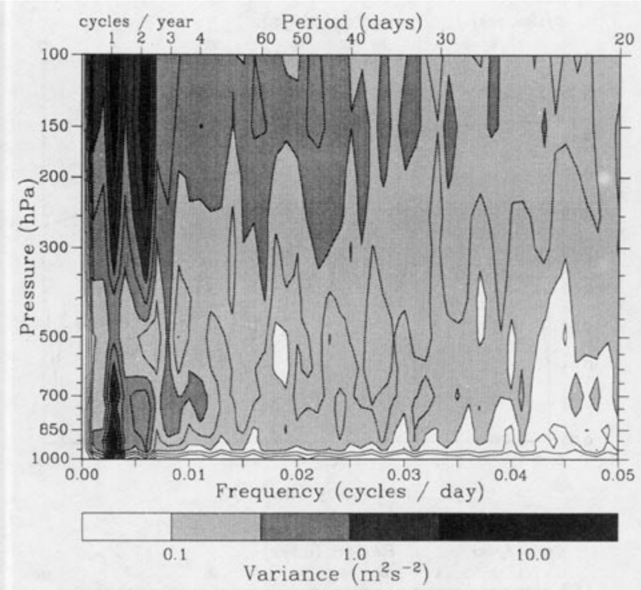

FIG. 4. Frequency–height section for frequencies less than 0.05 cycles per day (periods greater than 20 days) of variance of zonal wind at Darwin. See text for details of calculation of the spectral amplitudes.

therefore excluded by the requirement for upper-level easterly. The monsoon onset was then identified as the beginning of the next westerly wind burst.

To remove as much as possible of the subjectivity in the definition of active and break periods described above, the following objective procedure was devised. First, a pressure-weighted deep-layer mean (DLM) zonal wind was calculated over the available data in the eight lowest levels of the dataset (surface to 500 hPa) for each wind observation in the time series. Since transitions from break to active phases (and also from active to break) can occur extremely rapidly (within one day), no smoothing was applied to the DLM values. Instead the Troup (1961) procedure of defining west wind spells or bursts was applied. To ensure consistency with a similar analysis of daily rainfall, to be described later, only one flight per day (at 2300 UTC) was used. A westerly monsoon spell of N days occurs when the actual DLM zonal wind is westerly on each of the N days, the average DLM zonal wind over the N days exceeds $U(N + 1)/N$ m s^{-1}, and the upper-tropospheric wind (in the 300–100-hPa layer) is easterly. Various values of U were tried, with generally similar results for values up to 4 m s^{-1}. Troup (1961) applied this procedure to the 3000 ft (approximately 910 hPa) zonal wind with U = 10 knots (5.15 m s^{-1}). The active periods defined in this manner for the 35 seasons from 1957/1958 to 1991/1992 are shown in Fig. 6. The minimum length of a burst was set to two days, this excluded two single days. Similarly, the minimum break between bursts was set to three days, so that westerly wind bursts separated by one or two days were concatenated.

Monsoon onset (retreat) is defined as the first (last) day of the first (last) active period. This procedure reproduced 27 of the 30 subjectively determined onset dates; in the remaining three years the onset occurred gradually and was therefore difficult to define. In these years the objectively determined dates have been preferred. A number of the early season midlatitude-type westerly bursts are also selected by this procedure, suggesting that some subjective assessment cannot be avoided in determining the onset date. The onset dates for the five years from 1987/88 to 1991/92 were determined completely objectively. The actual onset and retreat dates, the total length of season, and the number of active days are given in Table 1.

This procedure can easily be applied in real time and should produce consistent results in future years. Once a two-day westerly burst has occurred, the monsoon onset can be defined. Unlike the situation where filtered winds are used, prior or subsequent events, such as a strong easterly flow produced by the presence of a tropical cyclone, will not change the analysis. Westerly bursts associated with deep midlatitude westerly troughs can also be easily recognized by examination of synoptic analyses.

A composite time–height section of zonal wind relative to the onset date (Fig. 7a) shows a much sharper transition from easterly to westerly flow than a similar composite using the Hendon and Liebmann (1990a) or Holland (1986) dates. This is especially true in the midtroposphere (700–300 hPa) but also at the low levels. The six station area-averaged rainfall over the top end of the Northern Territory (Fig. 7b) shows a gradual increase (from 6–10 mm/day to 16–20 mm/day) at onset, similar to that found using either the Holland (1986) or Hendon and Liebmann (1990a) onset dates.

c. *Rain events*

Using a similar process applied to area-averaged rainfall, Troup (1961) also defined rain events. An additional constraint was the requirement for rainfall to be recorded at four or more of the six stations used in the area average, to remove large rainfall events at a single station. In an analysis of four seasons from 1955/1956 to 1958/1959, Troup found a close relationship between wind and rain based on onset dates in just two of the years. This analysis has been repeated using the same six stations for the same period as the wind analysis, that is, 1957/1958 to 1991/1992. These analyses are less robust than the wind, being sensitive to the number of stations required to record rainfall on each day of a rain event, and the threshold rainfall amount. Troup (1961) used a value of 0.75 inches (equivalent to 19 mm) and rainfall at four of the six stations; the results for a threshold of 15 mm and rainfall at least at 50% of Troup's six station composite are shown as the

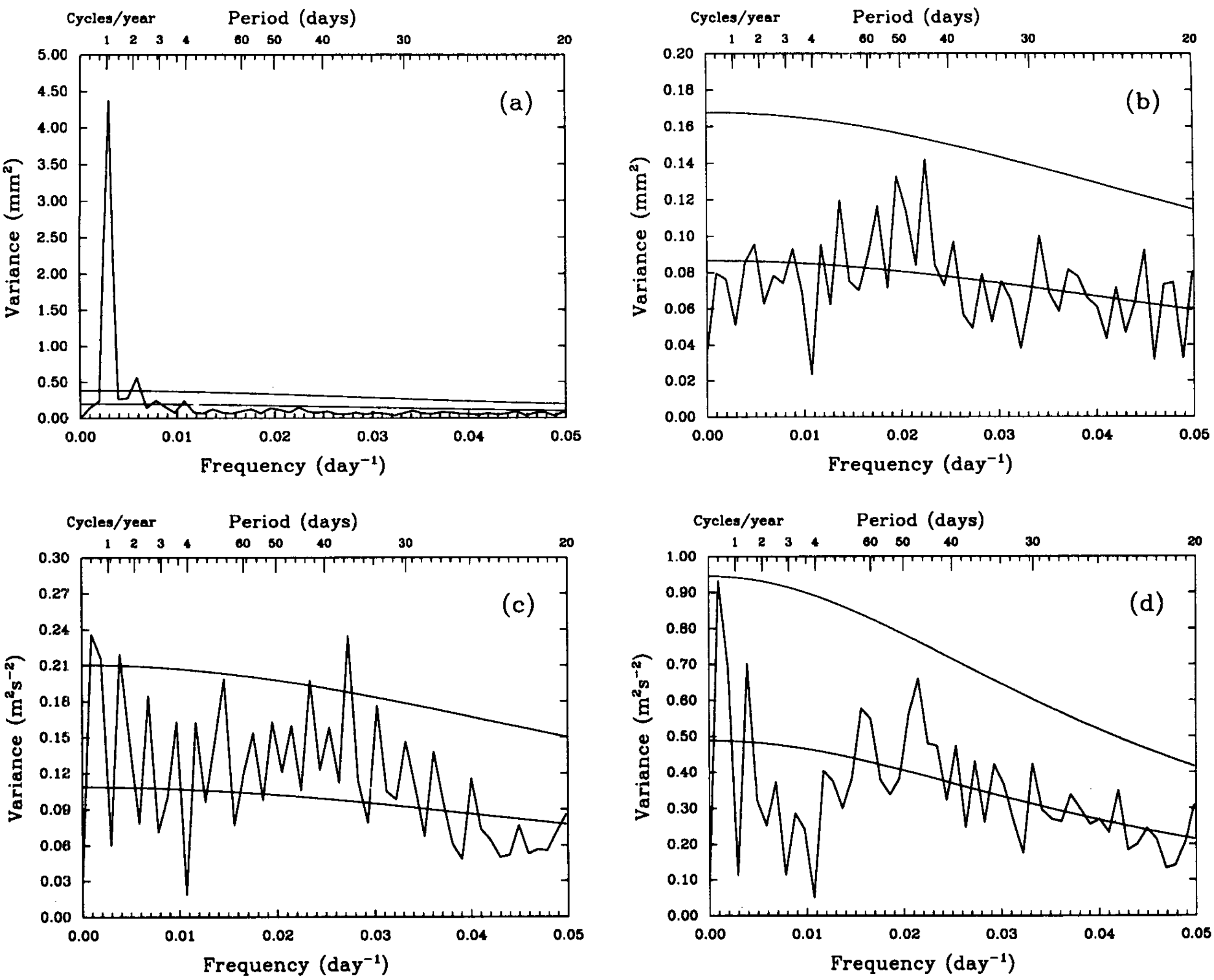

FIG. 5. Spectra of six station composite daily rainfall for frequencies less than 0.05 cycles per day (periods greater than 20 days), calculated by the segment averaging procedure: (a) mean only removed from each segment, (b) mean and first four harmonics removed from each segment, (c) as for (b) but for the Darwin 850-hPa zonal wind, and (d) as for (b) but for the Darwin 150-hPa zonal wind. Dashed lines show background red noise spectrum (lower) and 95% confidence limit (upper).

open bars in Fig. 6 and the number of rain days given in Table 1.

d. Wind–rain relationship

On the annual timescale there is an obvious relationship between westerly winds and rainfall as shown in Fig. 2. On the shorter timescales of interest here the relationship is less obvious, as shown by the overlap between wind and rain events in Fig. 6 and Table 1. As noted previously, the first wind and rain events during the 1957/1958 season do not coincide, highlighting the difficulty in using a wet-westerly onset definition. Troup (1961) recognized this problem and decided that "... it appears preferable to state that the monsoon commenced over the period(s) ... 19–28 December 1957."

The coherence between the zonal wind and rainfall for frequencies less than 0.05 cycles per day (periods greater than 20 days) is shown in Fig. 8. The major feature, as expected, is the significant (95% confidence level is at 0.22) coherence associated with the annual and semiannual cycles. On these timescales there is a strong, largely in-phase relationship between rain, low-level westerlies, and upper-level easterlies. Significant coherence is found on the intraseasonal timescale in the lower troposphere, between about 900 and 600 hPa, where the rain leads the wind maximum (westerly) by one-eighth of a cycle (4–8 days). In the upper troposphere there is less coherence but the phase is consistent, suggesting that maximum zonal wind leads rainfall by one-quarter of a cycle. An alternative, and probably more accurate, interpretation is that rain leads zonal wind minimum

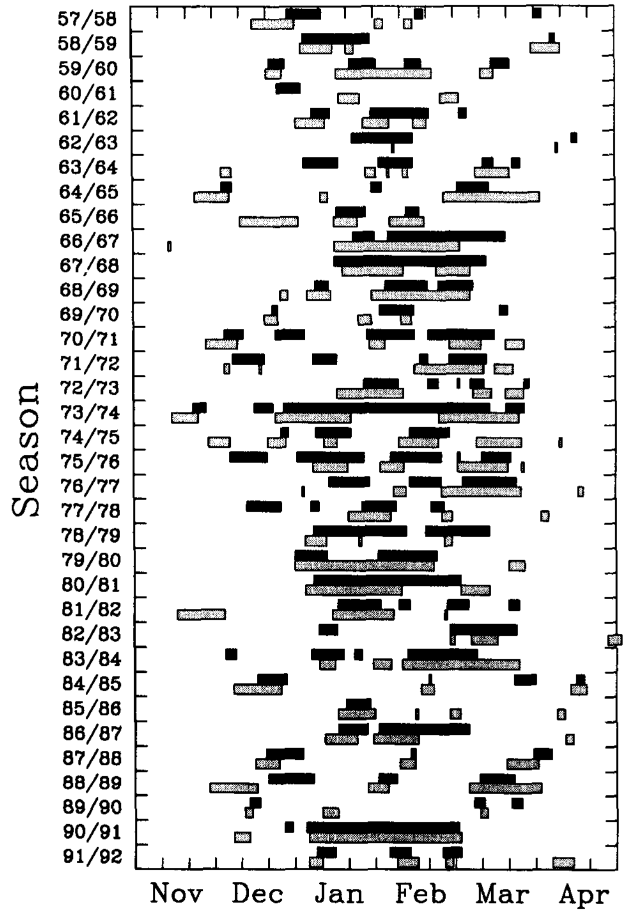

FIG. 6. Active westerly periods with $U = 2.5$ m s^{-1} (solid filled bars) for the 35 seasons from 1957/1958 through to 1991/1992 and rain periods with $R = 15$ mm and rainfall recorded by at least 50% of stations (hollow bars). See text for definitions of westerly wind and rain periods.

(maximum easterlies) by one-quarter of a cycle. This is consistent with the analysis of Hendon and Liebmann (1990a), who demonstrated coherence between the 850-hPa zonal wind and rain on all timescales beyond the synoptic.

Table 1 lists the number of active westerly days, the number of rain days, and the number (about 50% of either) satisfying both criteria (wet and westerly) during the 35 seasons. While most of the rainfall during the monsoon season is associated with westerly winds, the synoptic-scale processes that produce rainfall during the premonsoon season also operate during the "break" or nonwesterly periods after monsoon onset. Some of the heaviest individual daily rainfall totals in the vicinity of Darwin have occurred during periods of strong easterly winds associated with tropical cyclones, particularly at the end of a season. The 1980/1981 season ended abruptly, in terms of the westerly wind at Darwin on 2 March 1981, when the monsoon trough moved off the north coast. Over the next ten days widespread heavy rainfall was experienced along the north coast, culminating with Tropical Cyclone Max, which passed just north of Darwin on 11 March 1981 (Rooney 1981).

The extent of the relationship between wind and rain can also be examined by stratifying the rain days into west wind and nonwest wind days. Figure 9 clearly shows that rainfall occurs under two significantly different vertical zonal wind profiles, the strong deep westerly monsoon regime and also a deep easterly regime. This easterly profile is found on the poleward side of the monsoon trough or tropical cyclones and is also similar to that following tropical squall lines. This deep easterly profile can be seen in Fig. 7, one to three days prior to onset, and is consistent with the coherence analysis that shows rainfall leading westerly winds by a few days on most timescales.

4. Monsoon variability

a. Interannual variation

Mean onset date for the 35 seasons listed in Table 1 is 28–29 December, three to five days later than that found by Holland (1986) or Hendon and Liebmann (1990a), with mean retreat on 13 March, seven days later than Holland (1986). Based on the dates in Table 1, the mean season has a length of 75.5 days, of which the mean number of active days is 39, giving over 50% of the season under active conditions. The distribution of onset dates is significantly negatively skewed, with a much longer tail of early onsets and with some suggestion of a bimodal distribution. The 8-day period from 29 December to 5 January contains only three onsets, compared with six and seven for the previous and following 8-day periods, respectively.

The extreme dates for onset are 22 November 1973 for the 1973/1974 season (earliest) and 25 January 1973 for the 1972/1973 season (latest). While the latter date is in general agreement with Holland (1986) and Hendon and Liebmann (1990a), the earliest onset differs significantly and will be discussed in some detail in later sections. The extreme retreat dates are 2 January 1961 (earliest) and 17 April 1985 (latest). This last date is associated with the landfall of Tropical Cyclone Gretel southwest of Darwin producing a brief revival of deep westerlies. The shortest seasons are 1960/1961 and 1985/1986, both consisting of a single 10-day westerly wind burst. The longest (125 days) and most active (100 west wind days and 71 rain days) season was 1973/1974.

Correlations between the monsoon onset and retreat dates, length of season, number of active days, total seasonal rainfall, and prior Southern Oscillation Index (SOI) are shown in Table 2. Onset date is significantly related to the SOI in preceding months, with the largest value of −0.56 found with spring (September–Octo-

TABLE 1. Dates of monsoon onset and retreat and (a) length of season (number of days from onset to retreat), (b) number of active (deep westerly) days, (c) number of rain days, and (d) number of days satisfying both the wind and rain criteria, for the 35 seasons from 1957/58 to 1991/92.

Season	Onset	Retreat	(a)	(b)	(c)	(d)
1957/58	28 December 1957	2 April 1958	96	22	25	4
1958/59	3 January 1959	7 April 1959	95	29	29	19
1959/60	21 December 1959	20 March 1960	91	33	50	26
1960/61	24 December 1960	2 January 1961	10	10	17	0
1961/62	6 January 1962	5 March 1962	59	35	29	20
1962/63	21 January 1963	15 April 1963	85	27	4	2
1963/64	3 January 1964	24 March 1964	82	36	29	10
1964/65	3 December 1964	13 March 1965	101	23	55	17
1965/66	15 January 1966	15 February 1966	32	18	47	15
1966/67	21 January 1967	19 March 1967	58	54	50	37
1967/68	14 January 1968	11 March 1968	58	58	38	38
1968/69	7 January 1969	7 March 1969	60	37	52	36
1969/70	22 December 1969	20 March 1970	89	21	17	8
1970/71	4 December 1970	15 March 1971	102	65	41	26
1971/72	7 December 1971	11 March 1972	96	42	40	20
1972/73	25 January 1973	28 March 1973	63	30	42	20
1973/74	22 November 1973	26 March 1974	125	100	71	55
1974/75	25 December 1974	26 February 1975	64	34	59	21
1975/76	6 December 1975	20 March 1976	106	75	46	33
1976/77	12 January 1977	23 March 1977	71	50	44	22
1977/78	12 December 1977	24 February 1978	75	38	26	14
1978/79	6 January 1979	13 March 1979	67	61	15	12
1979/80	30 December 1979	21 February 1980	54	36	60	35
1980/81	6 January 1981	2 March 1981	56	56	49	35
1981/82	15 January 1982	24 March 1982	69	36	45	18
1982/83	8 January 1983	23 March 1983	75	34	19	14
1983/84	4 December 1983	7 March 1984	95	49	60	34
1984/85	16 December 1984	17 April 1985	123	27	32	16
1985/86	18 January 1986	27 January 1986	10	10	26	10
1986/87	15 January 1987	5 March 1987	50	47	35	24
1987/88	19 December 1987	4 April 1988	108	26	30	12
1988/89	20 December 1988	22 March 1989	93	40	56	19
1989/90	13 December 1989	25 March 1990	103	15	15	5
1990/91	26 December 1990	1 March 1991	66	62	65	57
1991/92	7 January 1992	1 March 1992	55	25	28	13
Means	28/29 December	13 March	75.5	39	38	21

ber–November, SON) values of the SOI. The number of active days, total length of season, and annual rainfall (July to June) are also significantly related to the previous spring SOI. Retreat date is not related to the SOI, in agreement with Holland (1986). Total seasonal rainfall is most strongly related to the number of active westerly days during the season. Other significant correlations are between the length of the season and both onset and retreat date, although these are themselves not related. Correlations between the onset dates derived here and those of Holland (+0.44) and Hendon and Liebmann (+0.61) are statistically significant at least at the 5% level, but, as with the correlation between the Holland and Hendon and Liebmann dates themselves, the percentage of variance in any one set of dates accounted for by any other is small.

The significant correlation between onset date and SOI in the following spring reported by Holland (1986) is not found. This relationships between onset dates and prior and subsequent SOI is sensitive to the influence of a few extreme outliers. The earliest onset determined by Holland (1986) and Hendon and Liebmann (1990a) is 23 November 1981 for the 1981/82 season, which was followed one year later by the strong ENSO event of 1982–1983. The data on which this onset is based are shown in Fig. 2 of Holland and Nicholls (1985) and show a very short duration of minimal westerlies. Examination of synoptic charts and satellite data clearly show that this westerly burst of late November 1981 was associated with a deep midlatitude system and had none of the characteristic features of the monsoon. As discussed earlier, similar events have occurred in a number of other years; in these cases the upper-level flow at Darwin is generally westerly and these "bursts" are excluded from Fig. 6. Removing this particular event in November 1981 shifts the onset to the later than average date of 15 January 1982.

On the other hand, the earliest onset in the present work is 22 November 1973 during the extremely active 1973/74 season. This onset is associated with Tropical Cyclones Ines and Beryl (Lourensz 1981) off the northwest coast of Australia. These cyclones produced

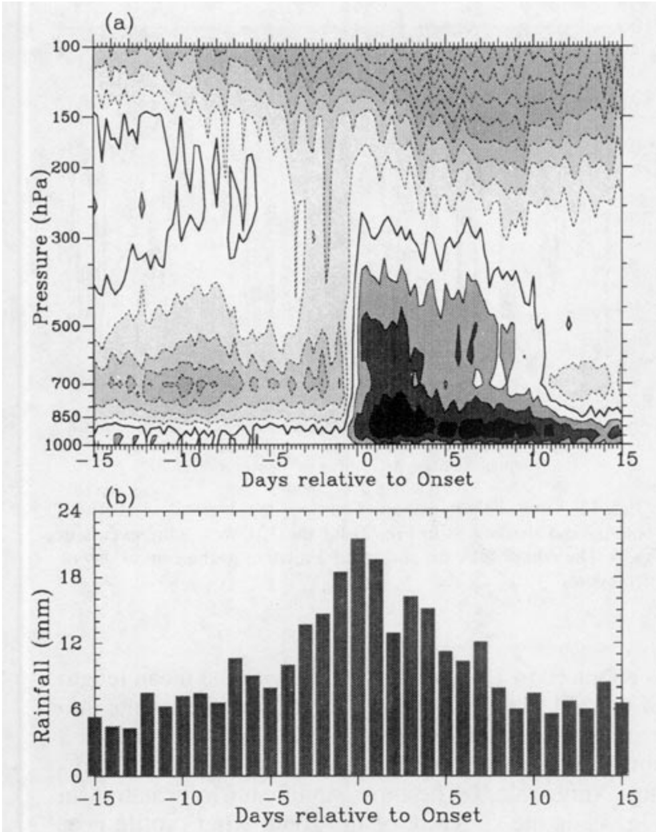

FIG. 7. Composites about onset dates for the 35 seasons given in Table 1 of (a) time–height section of 6-h Darwin zonal winds (with contours and shading as in Fig. 2) and (b) six station area-average rainfall.

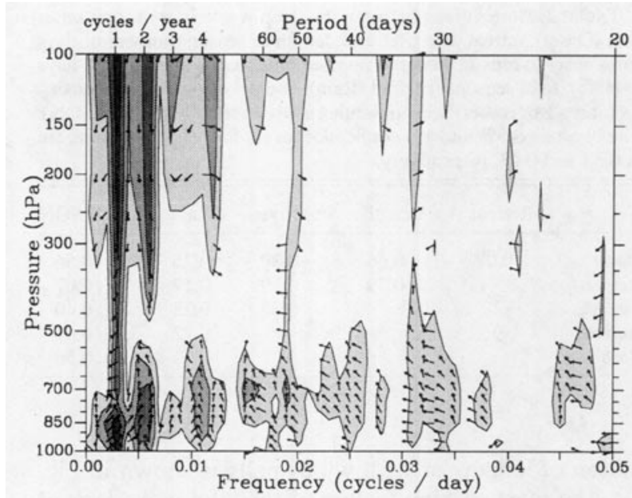

FIG. 8. Frequency–height section of coherence squared between zonal wind at Darwin and six station rainfall time series. Phase shown only where coherence exceeds 0.2 (contour interval is 0.2, 95% confidence level is at 0.22). For northward-pointing vector rain and west wind are in phase, for eastward-pointing vector wind leads rain by one-quarter of a cycle.

a 6-day burst of westerlies at Darwin but with strong easterlies before and after the event. The cubic spline employed by Holland (1986) severely filters this burst, and while a local maximum is produced, it does not reach the zero line. The lighter filter of Hendon and Liebmann (1990a) does produce a westerly maximum in this period; however, the rainfall peak appears to occur prior to the onset of westerlies during the strong easterly as cyclone Ines passed north of Darwin on an east–west track, although Fig. 6 does show the rain and west wind bursts, as defined in this study, to overlap. This season was then followed by the aborted 1974–75 El Niño event.

Taken together these two changes are sufficient to change the correlation between the onset date and next spring SOI to a nonsignificant negative value. This does not necessarily imply that the relationship described by Holland (1986) and Holland and Nicholls (1985) between westerly winds north of Australia in spring and sea surface temperatures in the east Pacific one year later is not valid. This relationship is implicit in the composites of Rasmussen and Carpenter (1982) and may be better quantified by a direct measure of the *equatorial* zonal wind rather than the date of monsoon onset at Darwin.

b. Intraseasonal active–break cycles

During the 35 seasons from 1957/58 to 1991/92, 101 west wind events can be identified in Fig. 6. These range in length from a minimum (by definition) of two days (three events) to a maximum of 78 days during the extremely active 1973/74 season (this event contains three breaks of less than two days). The distri-

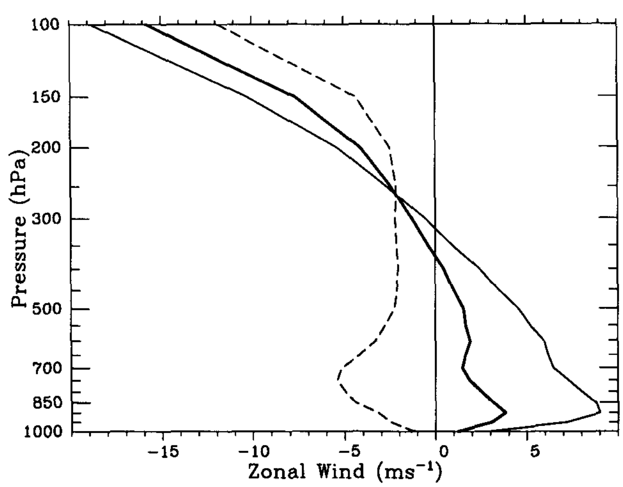

FIG. 9. Vertical profiles of zonal wind at Darwin for all rain days (heavy solid curve), rain and westerly wind days (light solid curve), and rain and nonwesterly wind days (light dashed curve) based on wind and rain spells shown in Fig. 6 and Table 1.

TABLE 2. Correlations between the deep westerly monsoon onset data (Onset), retreat date (Retreat), length of season (number of days from onset to retreat, Length), number of active, westerly wind days (Active), total seasonal rainfall (Rain), and prior spring (September–October–November) season Southern Oscillation index (SOI SON). The two-tailed 5% and 1% confidence levels for 35 observations are at 0.33 and 0.43, respectively.

	Retreat	Length	Active	Rain	SOI SON
Onset	−0.07	−0.66	−0.30	0.25	−0.56
Retreat		0.79	0.19	0.17	0.07
Length			0.32	0.28	0.40
Active				0.72	0.41
Rain					0.56

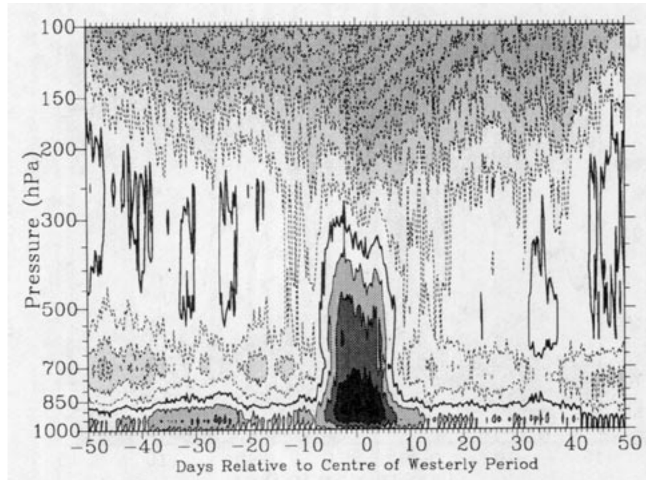

FIG. 11. Time–height section of composite 6-h zonal winds (with contours and shading as in Fig. 2) for the 101 west wind events in Fig. 6. The composites are constructed relative to the central day of each event.

bution of lengths of west wind spells is shown in Fig. 10. The most striking feature of this plot is the lack of a single preferred timescale or period range. Rather, there appear to be at least three peaks at 4 to 5, 8, and 14 days, with a long tail beyond 20 days. The mean length is 13.5 days, with a standard deviation of 12.8 days. Similar results are obtained if westerly bursts separated by two or less days are not joined. The total number of events increases to 126, and while the number of extremely long events decreases, the distribution for lengths less than 20 days remains roughly similar.

The structure of many atmospheric phenomena have been elucidated through the use of compositing. This procedure involves averaging a number of cases or events to extract the common features, for example, the canonical El Niño event of Rasmussen and Carpenter (1982). An underlying assumption of this technique is that the events being composited have a basic similarity in the spatial and temporal scales and structures. In the construction of Fig. 7a there is an implicit assumption that the zonal wind profile around the time of onset has a similar structure in all years. This assumption of a common timescale is not valid for the 101 west wind events as shown by Fig. 10. Compositing all these events about their central dates (Fig. 11) produces a composite event similar to that of Hendon and Liebmann (1990b), who composited about the date of maximum west wind in a bandpass filtered time series. This figure shows that the timescale for westerly wind events is about 10 to 15 days, consistent with the mean length of the 101 events. However, stratifying the events into groups about each of the peaks in Fig. 10 produces a similar composite event for each group but with a varying "timescale." The most significant information in Fig. 11 is the structure of the zonal wind profile near the central day of the burst, and this is similar to the wet westerly wind days profile in Fig. 9.

The period between west wind spells can be measured from the central day of one spell through to the central day of the next spell. Excluding the long dry season break from the end of one season to the beginning of the next, there are 66 such intervals, ranging from 7 to 84 days, with a mean of 31.7 days and standard deviation of 15.7 days. Their distribution is shown in Fig. 12. As with the length of the westerly spells, and in agreement with the spectral analysis (Figs. 4 and

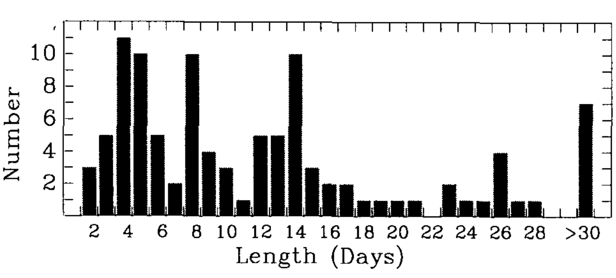

FIG. 10. Frequency distribution of length of active spell, in days, for the 101 westerly events shown in Fig. 6.

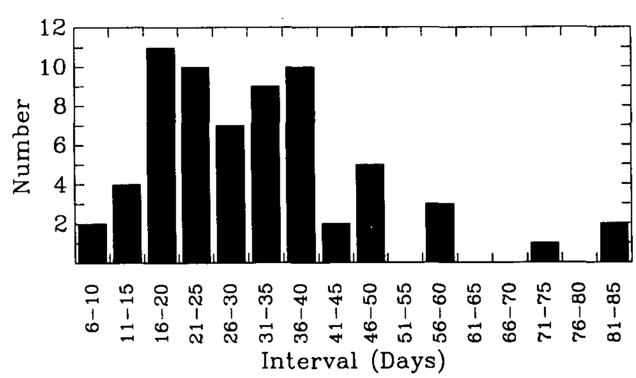

FIG. 12. Frequency distribution of intervals between active spells, measured as number of days between the midpoints of the 101 westerly wind events shown in Fig. 6 but excluding the long "dry season" break from one season to the next.

5), there is no strongly preferred period between spells with a fairly flat distribution from 20 to 40 days. Again this result is not due to the concatenation of events, in fact the distribution shifts toward shorter gaps if these are included. This lack of a preferred timescale is also evident in Fig. 11, where there is little sign of the prior or subsequent event.

This result would appear to be in conflict with the results of Holland (1986), who stated that active periods had a 40-day recurrence, with 10-day standard deviation. Repeating Holland's analysis on the 2300 UTC observations from the present dataset, we find a mean recurrence interval of only 36 days but, more importantly, a very flat distribution from approximately 20 to 40 days, similar to Fig. 12. As noted earlier, Holland's cubic spline acts as a low-pass filter with cut off at approximately 30 days. When applied to a red noise sequence, the lowest period (highest frequency) found will be close to (but above) the filter cutoff. Hendon and Liebmann (1990b) used a Butterworth bandpass filter to find the peak of the active (maximum west wind) period. This procedure does isolate events with a recurrence interval centered about the midpoint of the passband, as should be expected.

5. Conclusions

An attempt has been made to produce an objective, wind-only definition of the onset, active, and break phases and retreat of the Australian summer monsoon. This definition uses the procedure described by Troup (1961) to determine westerly wind or rain periods, based on an average zonal wind speed or rainfall over a number of days. In contrast to Troup (1961) and most subsequent authors (e.g. Holland 1986; Hendon and Liebmann 1990a), the procedure is applied to a lower-tropospheric, pressure-weighted deep-layer (surface to 500 hPa) mean zonal wind rather than a single low-level wind. An additional requirement, not previously considered, is for the low-level westerly to be overlain by upper-tropospheric (300–100 hPa) easterlies. Although some subjective assessment is still required in cases where the westerly bursts are due to deep midlatitude westerly troughs, the procedure should be easily applied in an operational environment and produce consistent results on new and independent data.

A complex relationship is found between rainfall and westerly wind bursts. Cross spectral analysis shows that there is significant coherence between the lower-tropospheric winds and rainfall, with a phase relationship such that rainfall leads maximum west wind by one-quarter of a cycle. A consistent result is found in comparing the overlap between westerly wind and rainfall bursts. While the average number of westerly wind and rainfall days per season are comparable, these do not, in general, overlap. A substantial portion of the rainfall therefore occurs with strong, deep easterly zonal winds, associated with tropical squall lines, tropical cyclones, or the poleward side of the monsoon trough. These results suggest that it is not a useful procedure to combine rainfall and wind into a single "wet westerly" monsoon onset definition.

Much of the interannual variability in monsoon onset and intensity of the monsoon season (e.g., length of the season, number of active days, total seasonal rainfall) is significantly related to the El Niño–Southern Oscillation phenomenon. In particular, and in contrast to the results of Holland (1986), the monsoon onset date is strongly correlated with the SOI in the prior spring (SON) season but not with the SOI in the following spring.

While there is considerable intraseasonal variability in the summer monsoon, no dominant timescales were found in the spacing of the active/break periods or in the length of the active spells. The broad band of recurrence intervals between active periods suggests that the predictability of the intraseasonal variations may be limited to 10–15 days; that is about the average length of an active spell and not from the peak of one event to another. Further work is needed to determine if there is more predictability within a season, that is, if the periodicity is relatively constant within a season and with the influence of longer term (interannual) variations, especially the Southern Oscillation. Finally, these results are based solely on Darwin winds and rainfall in an area within five degrees of Darwin. The extent to which events at Darwin are representative of conditions to the east and west and the connections with the Southern Hemisphere midlatitudes also need to be examined.

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