Interannual Variability of the Australian Summer Monsoon at Darwin: 1952–82

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ABSTRACT

Fluctuations in the Australian summer monsoon over the period 1952–82 are described. The basis of the study is an objective definition of the major summer monsoon components based on the low-level zonal winds at Darwin; this is shown to be in good agreement with other large-scale indicators. Statistics are presented and discussed for the interannual variation in summer monsoon onset, extent, active and break conditions, circulation strength, and vertical structure.

Some relationships with the Southern Oscillation are also described. These indicate that the Southern Oscillation Index (SOI) is highly correlated with the intensity and degree of convergence in the low-level monsoonal shear zone, and with the mean daily rainfall rate over northern Australia. There is also a significant correlation between the summer monsoon onset date and the SOI in the *following* spring, which has implications for El Niño teleconnections.

1. Introduction

Following the FGGE/WMONEX observing period in 1978/79 there has been a considerable degree of interest in the Australian summer monsoon, its intrinsic features, and teleconnections with, for example, the Southeast Asian winter monsoon and the El Niño sea surface warming off South America. The published studies have generally been in three main areas: 1) observational studies which have utilized advanced analysis schemes and the FGGE/WMONEX data to examine the monsoon onset conditions, monsoon surges, and the large scale forcing and response to convection (for example, Murakami and Sumi, 1982a,b; Sumi and Murakami, 1981; Davidson et al., 1983, 1984; McBride, 1983); 2) climate and teleconnection studies which have examined the relationship between the Southern Oscillation and parameters such as rainfall and tropical cyclones, together with the Australasian region's teleconnections with the El Niño phenomenon (for example, Nicholls et al., 1982; Nicholls 1984a,b); and 3) more theoretical studies which have utilized simple numerical and analytical models to examine the response of the regional circulation to sources of heat and momentum (for example, Matsuno, 1966; Webster, 1972; Chang, 1977; Gill, 1980; Lau and Lim, 1982). A comprehensive review of the major findings on the summer monsoon may be found in McBride (1985).

Although these works have increased our knowledge of the summer monsoon, they also raise questions as to how typical the FGGE year was, and how much summer monsoon variability there is on both intraseasonal and interannual time scales. The aim of this study is to utilize single station analyses extending over the full period of available data to answer some of these questions. Information is presented on the scale of circulation changes and the correlation between wind, rain, cloud and a Southern Oscillation Index. Section 2 contains a discussion of the available data and their utility. In section 3 an objective summer monsoon definition is proposed, which can be applied to the long period of record. Some of the spatial and temporal fluctuations in the summer monsoon are then described.

2. Data and analysis technique

Data from the stations shown in Fig. 1 were utilized in this study. Six-hourly (2300, 0500, 1100, 1700 GMT) upper air data from Darwin and Alice Springs (radar winds), and Cocos Island and Honiara (radiotheodolite) were extracted from Australian Bureau of Meteorology archives. Rainfall statitistics were derived from Bureau of Meteorology archives of daily rain totals from all available rainfall stations across northern Australia (indicated by the heavy dots in Fig. 1). These data were reduced to daily mean values for all of northern Australia by the following process. First the average rainfall for each rainfall district (shown in Fig. 1) was calculated for each day. These were used to calculate an area-weighted daily mean for northern Australia. A seasonal average of these daily mean rainfalls was then used for interseasonal comparisons. Cloud data consisted of 0000 GMT digital equivalent black body temperature (TBB) data with 5 km subpoint resolution from the Japanese *Geostationary Meteorological Satellite* (GMS) as routinely archived by the Bureau of Meteorology.

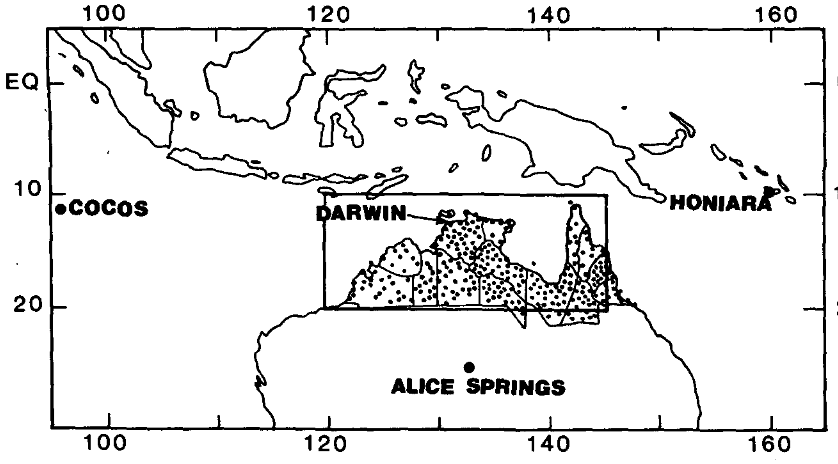

FIG. 1. Map of the Australian/Indonesian region containing the stations and place names used in this paper. Upper air stations are located at Darwin, Alice Springs, Honiara, and Cocos Island; rainfall stations are indicated by the heavy dots together with outlined rainfall districts; and the heavy rectangle indicates the region from which the north Australian cloud statistics were derived.

High cloud was arbitrarily defined as being colder than 238 K; the raw data were then converted to percent area coverage for the north Australian area shown in Fig. 1. Webb and Reid (personal communication, 1984) provided monthly mean values of Troup's SOI (Troup, 1967), which is the difference between the Papeete (17.5°S, 149.6°W) and Darwin MSL pressures normalized by the standard deviations of these differences.

The period 1952–82 was chosen as the longest usable period of regular observations to at least 100 mb at Darwin. The upper air stations represent the best available overall coverage of the Australian summer monsoon regime. As may be seen by the January mean gradient level wind analysis in Fig. 2, Darwin is located in the middle longitudes of the major westerly zone, and just equatorward of the monsoonal shear zone. Alice Springs is in the easterlies on the poleward side of this shear zone. Honiara lies near the eastern extremity of the westerly winds, and Cocos Island is near the longitude at which the narrow band of Indian Ocean equatorial westerlies broaden into the Indonesian/Australian monsoon regime.

Levels of significance given in this paper have been derived using the Student's t distribution; no serial correlation corrections were necessary. Unless otherwise indicated, only those correlations that are significant at the 0.05 or better level are discussed.

3. Summer monsoon definition

A number of wind, rainfall and cloud-based definitions have been proposed to describe the Australian summer monsoon.

Wind-based definitions were proposed by Troup (1961), Ramage (1971), Murakami and Sumi (1982b) and Murakami et al. (1984). Ramage used a global

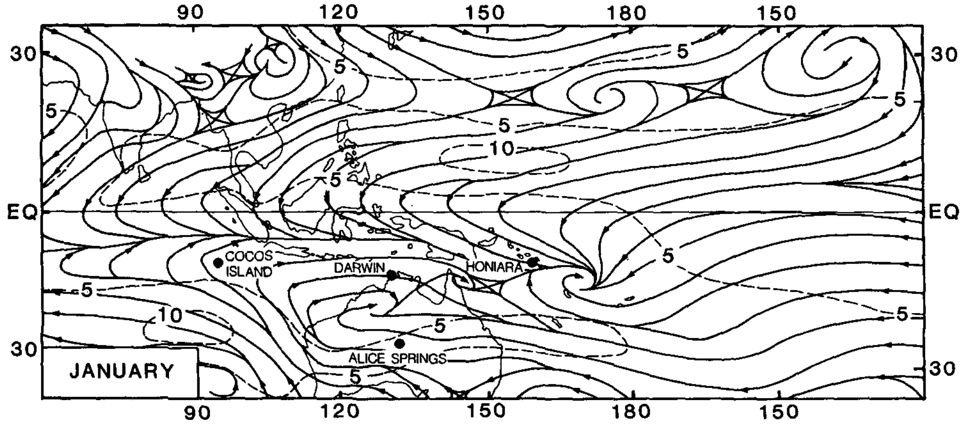

FIG. 2. January mean gradient-level streamline/isotach (m s^{-1}) analysis (after Atkinson, 1971), indicating the general extent of the Australian summer monsoon in relation to the stations described in this paper.

definition based on the constancy and strength of the low-level winds to define the area in which a reversal between summer and winter monsoonal circulations occurred. Troup described the summer monsoon in terms of west wind spells at the 1 km level at Darwin. Murakami and Sumi used the mean 850 mb zonal wind averaged along 10°S from 100 to 180°E. They defined the summer monsoon onset by the first appearance of mean westerly winds and a summer monsoon break as a period in which mean easterlies displace the westerly regime.

Rainfall definitions have been suggested by Troup (1961), and Nicholls et al. (1982). Troup described the summer monsoon by rain spells in which the cumulative rainfall totals averaged over six stations in the vicinity of Darwin exceeded 19 mm d^{-1}. Nicholls et al. defined the summer monsoon onset by the date at which a specified amount of rain fell at Darwin Airport. They found that about 500 mm (or as much as one-third of the season total at some stations) corresponded best with the onset defined by other techniques. Nicholls (1984a) then used a number of stations across northern Australia to define a series of wet season onsets for the period 1950–82.

Davidson et al. (1983, 1984) noted that the summer monsoon during FGGE was characterized by periods of active tropical convection on a very large scale interspersed with suppressed conditions. They therefore defined the monsoon onset by the first flare-up of tropical convection over northern Australia. Subsequent periods of suppressed convective activity were defined as monsoonal breaks. McBride (1983) further showed that, although there were large-scale convective bursts, the convection at any one location was also modified by slow longitudinal movement across the monsoon regime.

The Murakami and Sumi and Davidson et al. definitions, or variations thereon, provide a good broad-scale description of the summer monsoon and its fluctuations. However, they can only be used over the past few years for which suitable data are available. A rainfall-based definition was rejected because of the need to account for the large, and variable proportion that falls in the transition season (i.e., before any large scale circulation change occurs). A wind index based on the three stations of Cocos Island, Darwin, and Honiara was also considered. Cocos and Honiara lie at the extremities of the monsoon regime (Fig. 2), however, and seemed to introduce more noise than useful signal.

A single station definition based on the 850 mb zonal winds at Darwin therefore was chosen as being the most objective and generally representative. Since Darwin has upper wind observations four times daily, diurnal influences were first damped by averaging over each day. Minor synoptic or smaller scale variations were then smoothed by fitting cubic splines to yearly time sequences of daily mean winds. The result for 850 mb zonal winds in the 1978/79 season is shown in Fig. 3.

The onset, retreat, active, inactive and break phases of the summer monsoon—also illustrated in Fig. 3—were defined, then, as follows: The onset and retreat are the first and last occurrences of a westerly wind in the smoothed 850 mb zonal wind time sequences at Darwin, regardless of intervening easterly reversals. The long period (ten days or more) fluctuations, which also occur typically with the summer monsoon period, are defined as active and inactive periods (Fig. 3). An inactive period in which a wind reversal to easterlies occurred is further referred to as a break period. The terms active, inactive and break were chosen to agree with those used in the references quoted above.

Two exceptions were taken to the above definitions during the 31 years used in this study: Short period westerly bursts during October 1952 and July 1978 were not considered to be associated with a large-scale monsoonal reversal and were disregarded. Synoptic-scale features, such as a tropical cyclone or monsoonal depression are generally embedded in a vigorous monsoonal circulation (e.g., McBride, 1983) and therefore do not seem to produce unrepresentative signals in this single station analysis.

Indeed, although these definitions were of necessity based on a single station, Darwin, they do appear to provide an excellent indication of the overall broad summer monsoon features. An indication of this representativeness is given in Fig. 4, which contains the same Darwin 850 mb zonal wind sequence as in Fig. 3, together with the Darwin 100 mb zonal wind (top); the percentage coverage of high cloud and rainfall amount over northern Australia (center); and the Alice Springs 850 mb and 100 mb zonal wind time sequence (bottom). The curves are derived using the same cubic spline fit used in Fig. 3. It is clear that the summer monsoon, as defined, is associated with dramatic large-scale circulation, cloud, and rainfall variations. For example, the onset is accompanied by a sudden establishment of upper easterlies at Darwin, a considerable increase in convection and rainfall over northern Australia, and, at Alice Springs, by a weakening of the upper westerlies and strengthening of the lower easterlies. Further, the FGGE year break defined by Murakami and Sumi (1982b) and by Davidson et al. (1984) corresponds closely to the inactive period in Fig. 3.

These FGGE year results are generally typical of all other years in this study. In addition, the derived onset dates from this technique agree to within a few days with those proposed by Troup (1961), Davidson et al. (1983), Murakami and Sumi (1982b) and Murakami et al. (1984). The wet season onset dates for northern Australia defined by Nicholls (1984a) are also consistent with the wind-based definition. The correlation between the two is 0.49 (significance level 0.01). However, this correlation is provided mainly by a strong relationship between the early wind and rainfall onset dates. In many of the seasons with late circulation changes there is still a general increase in scattered

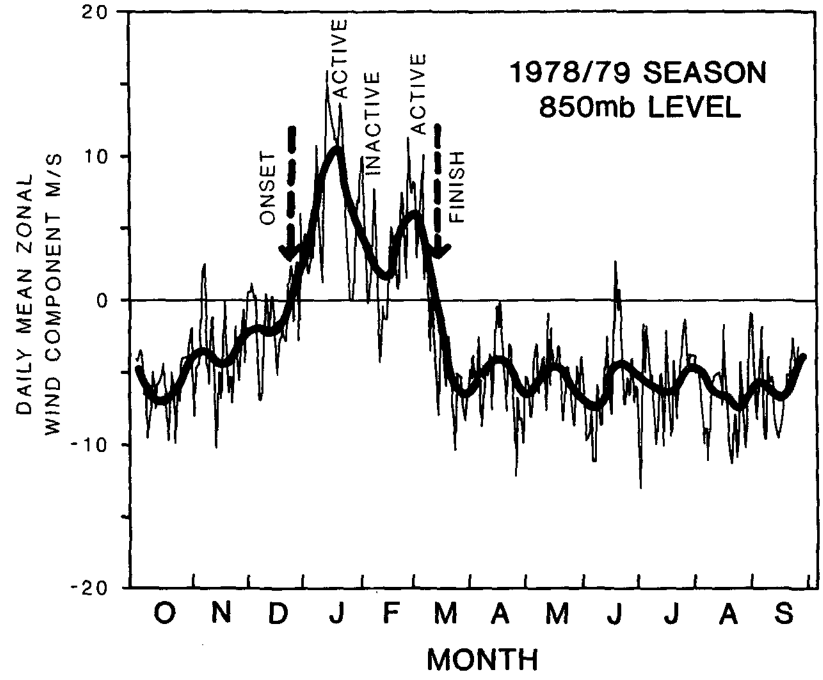

FIG. 3. Time sequence of daily mean zonal winds at Darwin for the 1978/79 summer and winter monsoon seasons. The light curve is a line joining all data points and the slightly smoothed heavy curve is comprised of a set of cubic splines. The summer monsoon onset and retreat, and active and inactive periods are indicated.

convective rainfall after October and the accumulation of this rainfall may exceed the predefined limit before the circulation change occurs. The actual circulation change, however, is generally accompanied by a sharp increase in rainfall over northern Australia similar to that shown in Fig. 4.

4. Interannual variability of the summer monsoon

a. Seasonal extent

The interannual variability of the extent of the summer monsoon season at Darwin is shown in Fig. 5, together with statistics for the onset and retreat dates, and the length of the season. This seasonal extent includes all active, inactive and break periods and should not be confused with the circulation strength, which is treated in subsection 4b. There is obviously a considerable season to season variability. The onset is generally in late December but has occurred from late November to mid-January. Though the retreat is generally toward the end of February or in early March, the observations show a spread over a two-month period. And the length of the season (including all active, inactive and break periods) has varied from two weeks to four months with a mean of approximately two months.

There is no significant correlation between the summer monsoon onset and retreat dates. This supports independent conclusions by, for example, Nicholls (1984b) and Nicholls et al. (1982) that the amount of early-season tropical cyclone activity and rainfall over northern Australia bears little relation to the degree of late season activity.

The onset, retreat and length of the FGGE/WMONEX year (highlighted in Fig. 5) were close to the long-term mean. Also, there was no significant trend in any of the parameters from year to year, though the late 1960s were characterized by a series of late and short monsoon seasons.

b. Circulation strength

The interseasonal variability in the overall monsoon circulation is illustrated by the vertical time sections of monthly mean zonal winds in Fig. 6. These show extreme (1973/74), weak (1974/75) and near-average (1975/76) summer monsoon seasons, interspersed by the easterly winter monsoon periods.

The 1973/74 summer monsoon season had record or near-record rainfall over much of northern and central Australia and unbroken overcast skies at Darwin for most of January. As can be seen in Fig. 6, there was also a vigorous circulation during this season. A deep layer of westerlies with monthly mean values exceeding 10 m s^{-1} was overlain by a strong easterly jet near 100 mb. Also notable are the 200–300 mb subtropical westerly maxima which precede and follow this summer monsoon circulation.

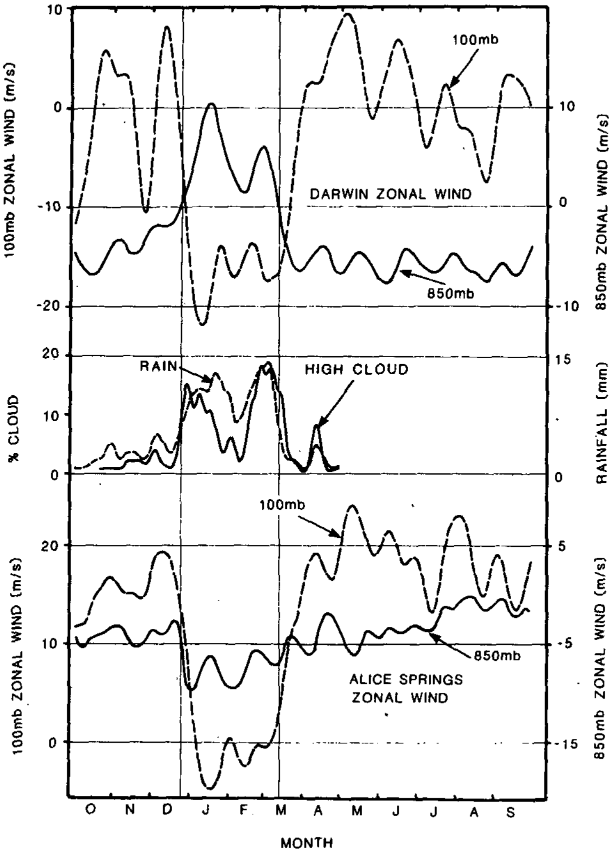

FIG. 4. Time sequences of daily mean 100 and 850 mb zonal winds at Darwin (top) and Alice Springs (bottom) for the 1978/79 summer and winter seasons, together with percent coverage of high cloud (black body equivalent temperature ≤238 K) and daily mean rainfall over northern Australia (center). The vertical lines indicate the onset and retreat dates of the summer monsoon.

By comparison, the 1974/75 season was quite weak. Although there were occasional bursts of westerly winds, easterly winds became established over Darwin for a large part of the season. The result was a weak mean low-level westerly flow and no distinct upper tropospheric easterly jet. Lying between these two extremes is the slightly above average 1975/76 season. This circulation was less vigorous but otherwise contains similar features to the 1973/74 season.

A good indicator of the interannual variability in the circulation strength at Darwin may therefore be obtained from the mean and variance of the lower and upper tropospheric zonal winds. This is shown by the seasonal mean 850 and 100 mb zonal winds in the top two panels of Fig. 7. These statistics cover the periods from 10 days before the summer monsoon onset to 10 days after its retreat (as shown in Fig. 5) and were obtained by first averaging over each day to remove diurnal effects. The 10 day extension of either side of the summer monsoon season was chosen to include the full onset and retreat periods in our statistical analysis.

Also shown for comparison in the bottom two panels of Fig. 7 are the north Australian daily mean rainfall for the same period, and the December to February mean SOI.

Figure 7 shows that there is a considerable interannual variability in all these parameters. There is little coherence from season to season, but individual decades can be biased toward good or poor monsoon seasons. For example, the late 1950s and early 1960s were characterized by weaker and drier summer monsoon circulations than were the 1970s. The daily variance in the wind and rain observations (not shown) was also smallest in the early decade.

It is also clear from Fig. 7 that the upper- and lower-level winds, the north Australian rainfall, and the SOI are distinctly correlated. The SOI relation is discussed in section 5. The coherence of the other parameters is shown explicitly by the vertical profiles of zonal wind correlations in Fig. 8. The wind to wind correlations show that mid- to lower tropospheric zonal wind fluctuations from season to season are strongly out of phase with those in the upper troposphere. The correlation coefficients are around −0.7 and it is notable that the 100–150 mb zonal wind is more closely coupled to winds in the 700–900 mb layer than to nearby layers,

	MIN	MEAN	MAX	SD
ONSET DATE	NOV 23	DEC 24	JAN 27	15
FINISH DATE	JAN 1	MAR 7	APR 6	18
LENGTH	11	74	119	25

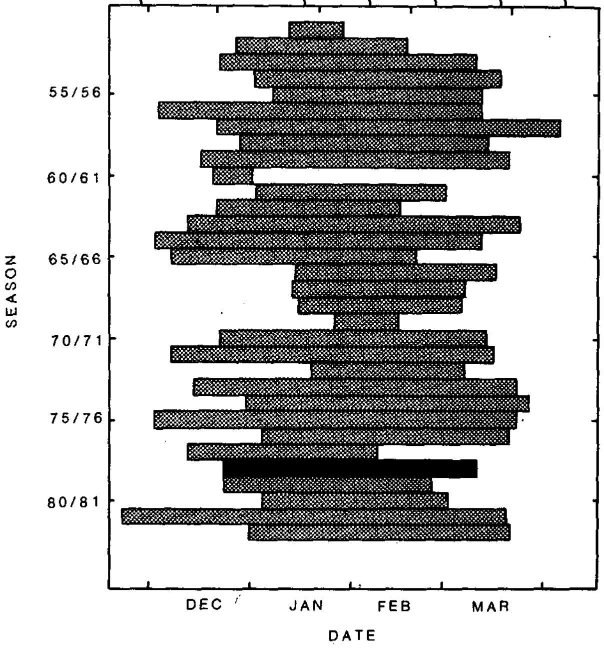

FIG. 5. Summer monsoon periods at Darwin, 1952–83 (stippled), together with onset, retreat and length statistics. The standard deviation (SD) and length are in days, the FGGE/WMONEX season is highlighted, and the 1982/83 season has been included.

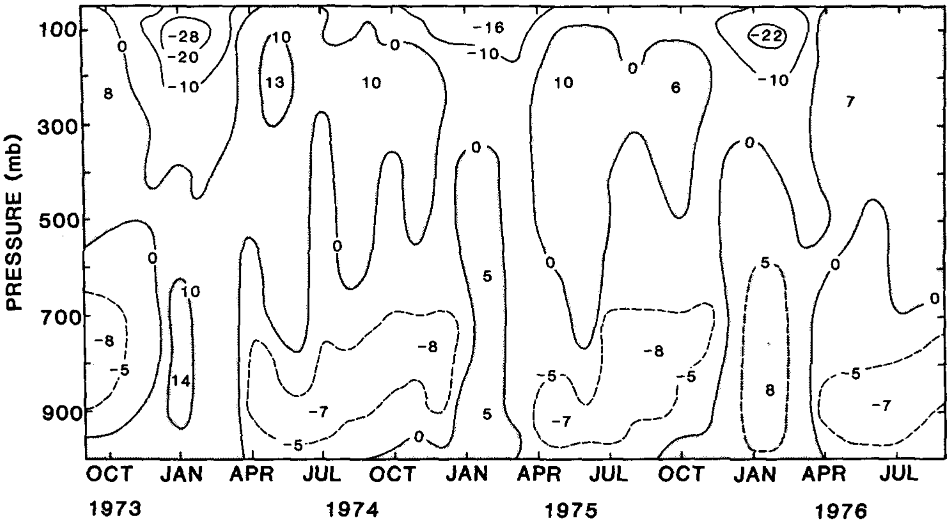

FIG. 6. Time/height section from 1973 to 1976 of Darwin zonal winds (m s^{-1}; westerlies are stippled).

such as 250 mb. The upper and lower tropospheric winds are also highly correlated with the rainfall over northern Australia (−0.63 at 100 mb and 0.84 at 850 mb); and the vertical profile of correlation coefficients between mean zonal wind and rainfall is nearly coincident with that of the mean zonal wind and the 850 mb wind profile (as shown in Fig. 8). This indicates that the upper to lower tropospheric coherence is largely due to a mutual coherence with the north Australian rainfall. Indeed, when the linear rainfall relation is removed from the winds, the correlation between the 850 mb and 100 mb zonal winds drops to 0.01. This is consistent with a Rossby mode response to deep moist convection over northern Australia (e.g., note the zonal wind changes equatorward of the major heating region in Fig. 4 of Silva Dias et al., 1983).

These wind and rain correlations also support an early finding by Troup (1961) that spells of low-level west wind and rain at Darwin were accompanied by strengthened upper tropospheric easterlies.

c. *Active, inactive and break periods*

The circulation strength, as defined, implicitly contains the effects of inactive and break periods in the summer monsoon (e.g., Fig. 3). Indeed, those years with a mean easterly wind in Fig. 7 are examples of seasons in which the break period easterlies exceeded the active period westerlies in strength and/or persistence. The distributions of active and break periods for the 1952–82 period are shown in Fig. 9. The percentage of the season under break conditions (Fig. 9a) has varied from zero to nearly 60%, with a mean of around 20%. The number of active bursts (which is one more than the inactive periods for the same season) has varied from one to four, but most seasons experience two or three. The rainfall records are slightly noisier (e.g., Fig. 4, center) but generally provide similar statistics.

The mean period between active bursts (taken as the time from peak to peak in the smoothed wind sequences as shown in Fig. 3) is 40 days, with a standard deviation of 10 days. This is in agreement with the ubiquitous tendency of the tropical atmosphere toward a natural oscillation frequency of around 40 days (e.g., Madden and Julian, 1971, 1972). It also agrees with observations by Julian and Madden (1981), Krishnamurti and Subrahmanyam (1982), and others, that active and inactive phases of the Asian summer monsoon are related to the 40-day oscillation. Some intraseasonal details of this feature within the Australian summer monsoon are described in McBride (1985).

5. Summer monsoon variability and the Southern Oscillation

The Southern Oscillation is a remarkable negative correlation between pressure anomalies over Indonesia and the southeastern Pacific Ocean (e.g., Walker, 1923; Troup, 1967; Bjerknes, 1969). The corresponding fluctuations in zonal pressure gradient are closely related to changes in the zonal Walker circulation across the equatorial Pacific. As a result, the Southern Oscillation is associated with a variety of atmospheric and oceanic phenomena, particularly over Indonesia, Australia and the equatorial Pacific. A survey of some relevant studies may be found in McBride and Nicholls (1983) and Philander (1983). The intensity of this oscillation is usually measured by one of a number of SOIs. As noted in section 2, the Troup SOI is used here; this is a normalized Papeete minus Darwin sea level pressure difference.

No significant correlation was found between the seasonal parameters described in section 4a and the SOI in the year leading up to the summer monsoon season. In particular, the length of the season is quite

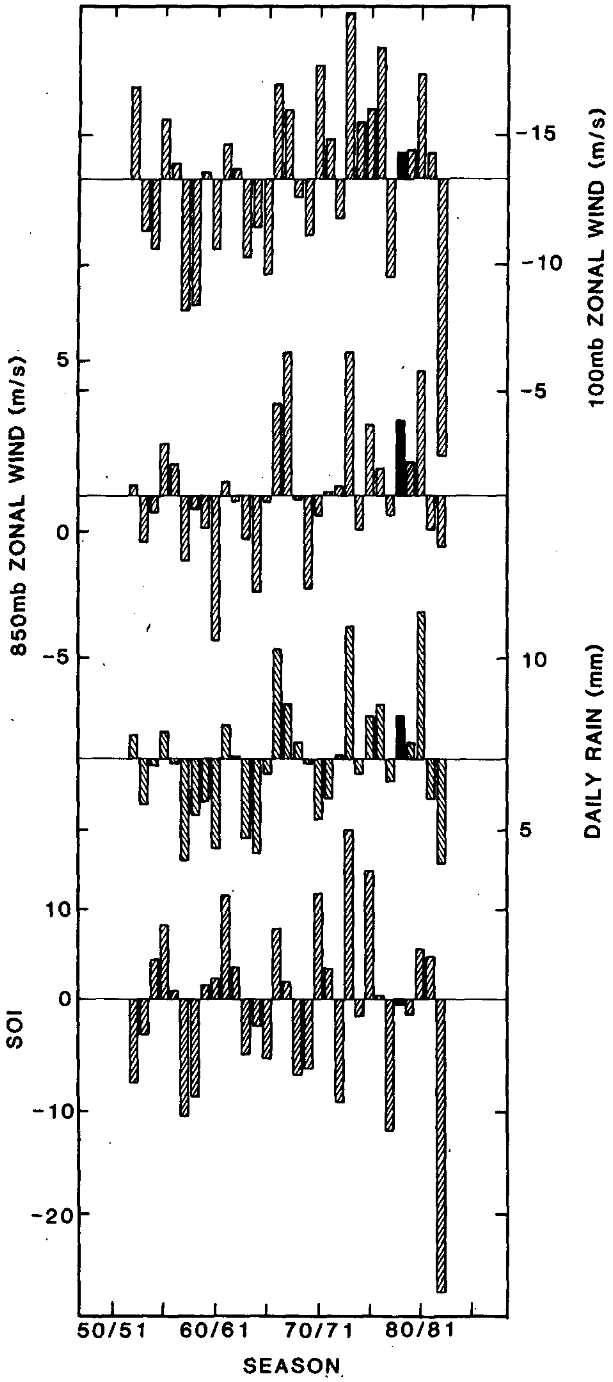

FIG. 7. Variability from 1952–83 of the seasonable mean Darwin 100 mb zonal winds (top; note reverse scale), the Darwin 850 mb zonal winds (second from top), the seasonal mean daily rainfall (mm) over northern Australia (second from bottom), and the Dec.–Feb. mean SOI (bottom). All data are shown as departures from the long-term mean, the FGGE/WMONEX year is highlighted, and the highly anomalous 1982/83 season is included for comparison.

poorly related to the SOI. The onset, however, is strongly related to the SOI in the *following* year. The maximum correlation coefficient was 0.54 (significance level 0.01) for the onset date and SOI in the following Southern Hemisphere spring (i.e., about nine months after the onset). This correlation is supported by the El Niño composites of Rasmusson and Carpenter (1982) in which anomalous westerly winds appear in the Indonesian and north Australian region as early as the October prior to the El Niño onset (their Figs. 17, 18, 22).

An example of the implications for the El Niño onset is shown in Figs. 10 and 11. Figure 10 shows the time-lagged correlations of monthly mean east equatorial Pacific SST with onset date of the summer monsoon at Darwin. The general span of monsoon onset times is indicated by the solid bar, and the time-lagged correlations extend from the previous January to the following December. Figure 11 contains a scatter diagram of the summer monsoon onset dates (days after October 1) against the east equatorial Pacific sea surface temperature (SST) anomalies in the following September. (The El Niño years are highlighted.)

The summer monsoon onset date is correlated positively with east equatorial Pacific SST anomalies in the months prior to onset (Fig. 10). That is, a warm East Pacific tends to indicate that the subsequent summer monsoon will be late. A much stronger relationship is observed, however, between the onset date and these SST anomalies up to 12 months later. An early summer monsoon onset tends to precede anomalously warm equatorial Pacific SSTs in the following July to December, the time of maximum El Niño. Figure 11 shows that these correlations are largely due to the El Niño years. The six earliest summer monsoon onset dates were each followed by an El Niño in the following year and, conversely, all El Niño years were preceded by early onsets of the summer monsoon in the previous year. A similar relationship is observed with the early wet season onsets as defined by Nicholls (1984a).

These observations suggest that there is a large-scale teleconnection from the north Australian region during the summer monsoon transition season to the eastern Pacific in the following year. Clearly this contains some predictive information for El Niño events. Substantial questions remain, however, on why there are early summer monsoon bursts, and how they can affect distant regions such as the eastern Pacific. This is a topic of further work at the Bureau of Meteorology Research Centre, a preliminary review of which has been presented in Holland and Nicholls (1985).

A marginal, though significant, relationship was also found between the summer mean SOI and the percentage of the season under break conditions (coefficient −0.42, significance level 0.05). This means that seasons with higher sea level pressure at Darwin tend to have longer, or more periods of easterly reversals.

As has already been indicated in Fig. 7, there is a high correlation between north Australian rainfall, the SOI, and Darwin zonal winds. The correlation between the northern Australian daily mean rainfall averaged

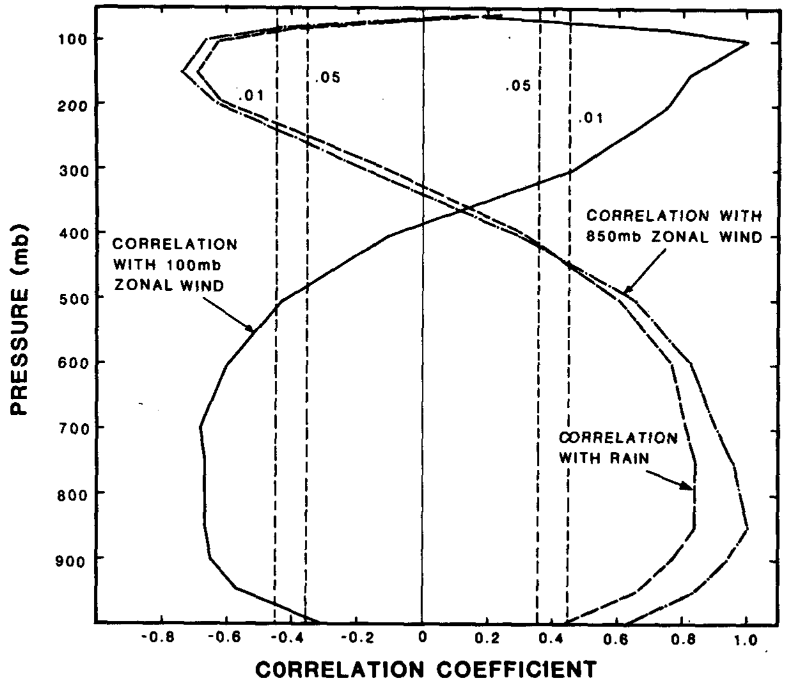

FIG. 8. Vertical profile of correlation coefficients for the seasonal mean zonal wind components with those at 850 and 100 mb, and with the daily mean rainfall. Vertical dashed lines indicate the 0.05 and 0.01 significance levels.

over the summer monsoon season and the SOI averaged over December–January is 0.5 (significance level 0.01). This result is distinctly different from previous work (e.g., McBride and Nicholls, 1983) which has indicated a small and insignificant correlation between these parameters. The difference is due to the different methodologies: the McBride and Nicholls study used December–January total rainfall at individual districts (indicated in Fig. 1); this study uses the daily mean rainfall for all of northern Australia averaged over the summer monsoon season as defined in section 2. This indicates that

1) the amount of rainfall within a localized area, such as a rainfall district, is subject to meso- to synoptic-scale events that individually are not well related to the SOI, but when averaged over a large enough area become coherent with the SOI; and

2) the rainfall rate (as indicated by the daily means) is related to the SOI, but the accumulation over a season is not well related.

The latter conclusion is consistent with the above observation that there is no significant correlation between the SOI and the length of the summer monsoon season.

The wind relationships with the SOI are illustrated in Fig. 12. This figure contains vertical profiles of correlation coefficients between the summer mean SOI, the seasonal mean zonal winds at Darwin and Alice Springs, and the Darwin–Alice Springs zonal wind shear and meridional wind divergence. The most notable features are

1) The nearly coincident upper tropospheric negative SOI/zonal wind correlations at both Darwin and Alice Springs. This shows that both stations have a relatively stronger easterly wind in the upper troposphere during seasons of higher than normal SOI (that is lower Darwin, and/or high Papeete MSL pressures). The strong relationship between upper tropospheric winds in the Australian tropics and the SOI has been noted by previous authors (e.g., Troup, 1967; Tanaka, 1981). The interesting feature here is that the coherent relationship extends to winds at Alice Springs, on the other side of the monsoonal shear zone. A similar finding may be found in Selkirk (1984, Fig. 5).

2) The poor relationship between the upper tropospheric zonal wind shear and meridional wind divergence with the SOI. This poor SOI relationship is also found with the meridional winds (not shown; see for example Selkirk, 1984; Fig. 6).

3) The remarkable change in all these features below 500 mb. The SOI correlations with lower tropospheric winds are of opposite sign at Darwin and Alice Springs. There is also a significant cyclonic wind shear and meridional wind divergence correlation with the SOI. This implies that during periods of high SOI (low Darwin, and/or high Papeete MSL pressures), Alice Springs has stronger easterlies, Darwin has stronger westerlies, and the monsoonal shear zone has greater cyclonic shear

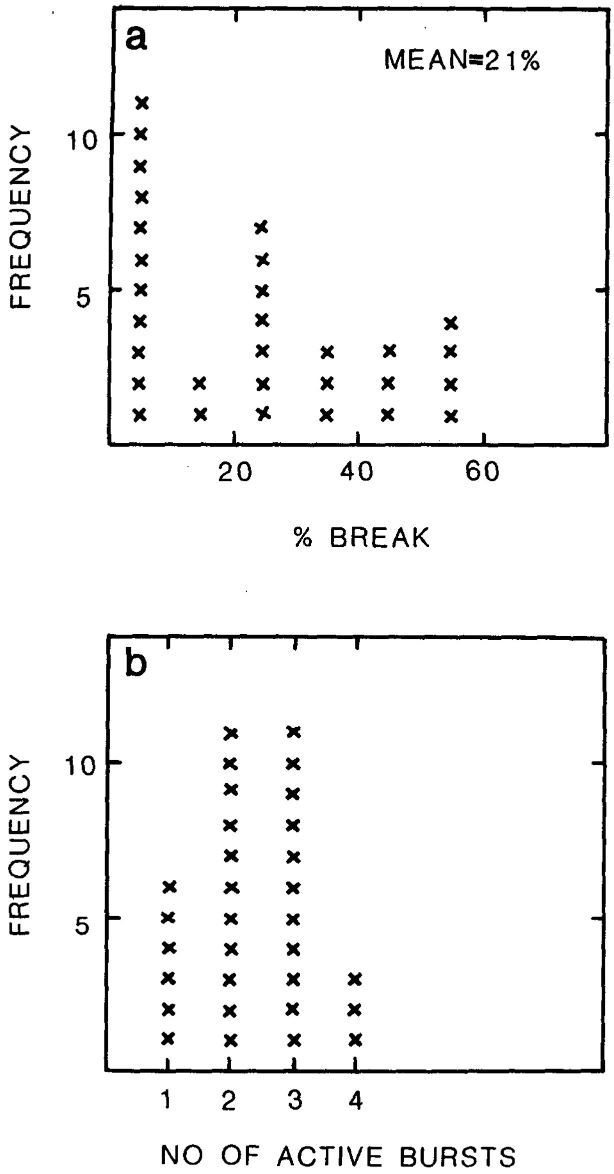

FIG. 9. Frequency distributions for the 1952–82 summer monsoon seasons of (a) percentage of the season under break conditions, and (b) the number of active monsoonal bursts during the season.

and more convergence. This is consistent with the corresponding higher daily rainfall rate over nothern Australia noted above.

6. Conclusions

Some features of the interannual variability in the Australian summer monsoon over the period 1952–82 have been described. The basis for determining these fluctuations has been an objective wind-based definition of the summer monsoon and its intraseasonal fluctuations using slightly smoothed 850 mb winds at Darwin. The onset and retreat of the summer monsoon have been defined as the first and last days of westerly wind in this smoothed sequence. Within this summer monsoon period, maxima and minima in the westerly flow have been defined as active and inactive periods,

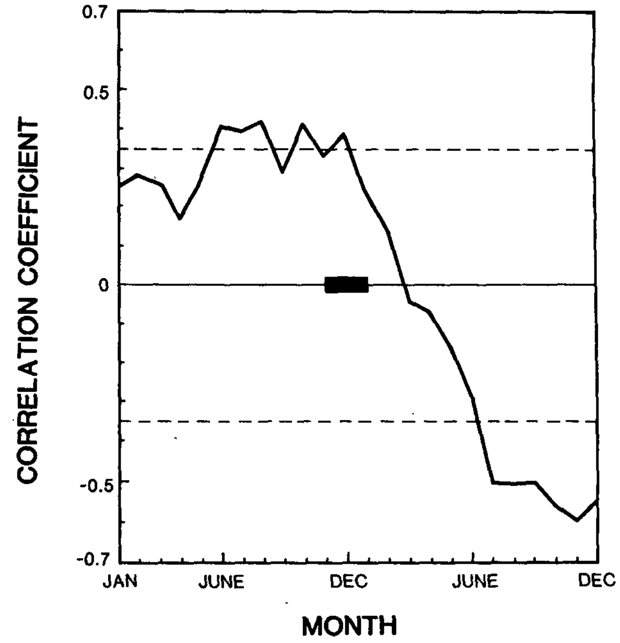

FIG. 10. Correlations of monthly east equatorial Pacific SST with onset date of the summer monsoon at Darwin. Data from 1950/51–1981/82 (1954/55 missing). This solid bar indicates the approximate time of the monsoon onset and 0.05 significance levels are shown as dashed lines.

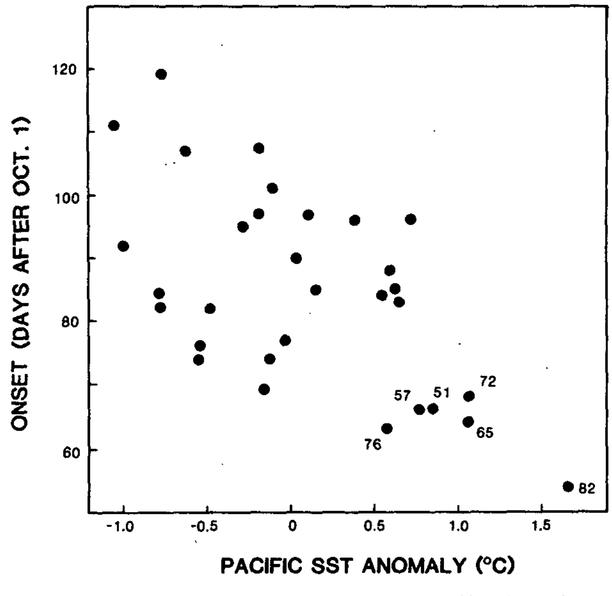

FIG. 11. Scatter diagram of equatorial east Pacific November to September SST anomalies against the Australian summer monsoon onset (days after October 1) for the previous year. The six earliest onsets, which were all followed by El Niño events in the following year, are labeled (72, for example, indicates the 1972 El Niño).

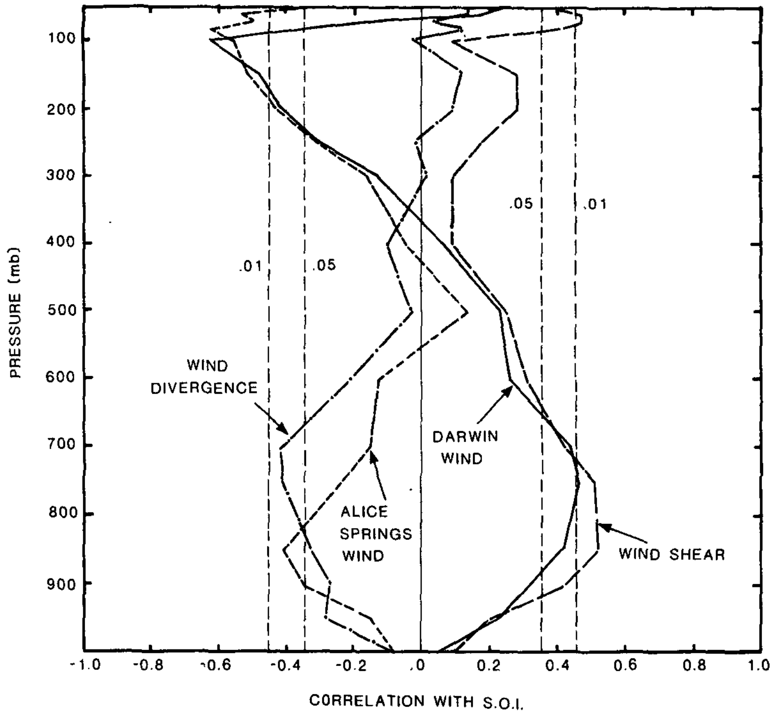

FIG. 12. Vertical profiles of correlation coefficients between the summer mean SOI and the summer monsoon mean zonal winds at Darwin and Alice Springs, and the mean Darwin–Alice Springs zonal wind shear and meridional wind divergence. Vertical dashed lines give the 0.01 and 0.05 significance levels.

and any periodic reversal to an easterly flow is referred to as a break period. The parameters from this simple, single station definition have been shown to be in good agreement with large-scale variations in wind, cloud and rainfall.

There is a considerable interannual variability in the onset, retreat, seasonal extent, percentage of break conditions, seasonal mean daily rainfall, and strength of the summer monsoon. A short period oscillation of 2–4 years is evident and this may be modulated by a longer period cycle: in the early 1960s the summer monsoons were weaker, shorter and drier; in the 1970s they were stronger, longer and wetter. Taken over all seasons the mean period between active bursts in the summer monsoon is around 40 days; this is yet another example of the tendency of the tropical atmosphere toward a 40-day oscillation. Break conditions occupy about 20% of the summer monsoon period and their variation is significantly correlated with the SOI. In terms of these seasonal parameters, the well-documented 1978/79 FGGE and WMONEX season is quite close to the long-term mean.

Vertical profiles of zonal wind correlations at Darwin clearly indicate a coupled two-layered atmosphere in the summer monsoon regime. This coupling is almost entirely due to an out-of-phase correlation of the upper and lower tropospheric winds with the rainfall over northern Australia; when the linear rainfall regression is removed from the Darwin zonal winds the strong vertical correlations disappear. This feature, which is indicative of a convectively driven regime, is the topic of further investigation.

In relation to the SOI, a distinct in-phase variation in upper tropospheric zonal winds at both Darwin and Alice Springs has been noted. This contrasts with an equally distinct out-of-phase relationship between the SOI and the lower tropospheric winds at these two stations. In essence, a more positive SOI (lower Darwin, and/or higher Papeete MSL pressure) is associated with stronger upper tropospheric easterlies at both Darwin and Alice Springs, and with a more intense, and convergent, monsoonal shear zone over northern Australia. This monsoon trough relationship is supported by a concomitant high correlation between the SOI and mean daily rainfall rate over northern Australia.

The observed high correlation between the date of summer monsoon onset and the SOI and east Pacific SST in the *following* year is of considerable interest for further investigation. This indicates both a teleconnection between the summer monsoon regime and the eastern Pacific and may contain some predictive capability for El Niño onset.

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