A Composite Study of Onset of the Australian Summer Monsoon

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(Manuscript received 1 September 1989, in final form 10 April 1990)

ABSTRACT

Onset of the Australian summer monsoon is identified each year (1957–87) using the wind and rainfall record at Darwin. Onset is defined as the first occurrence of wet, 850 mb westerly winds. Composites of atmospheric fields at stations in and about the Australian tropics are constructed relative to the onset date at Darwin.

The composite onset is accompanied by the development of a convectively driven, baroclinic circulation over northern Australia. Upper tropospheric easterlies expand about the equator and the subtropical jet shifts poleward at onset. This behavior is interpreted as a transient southerly shift of the local Hadley circulation concurrent with the development of an upper level anticyclone over northern Australia.

The composite onset coincides with the arrival of an eastward propagating convective anomaly. The anomaly originates in the southern Indian Ocean, propagates eastward at 5 m s^{-1} and is detectable as far east as the date line. An eastward propagating zonal wind anomaly also is detectable at tropical stations east and west of Darwin. These features are indicative of the 40–50 day oscillation and thus the composite onset is concluded to coincide with the traversal of the oscillation across northern Australia. The composite onset is further shown to coincide with the first occurrence of the convectively active 40–50 day oscillation during each southern summer.

1. Introduction

While having received less attention than its northern counterpart, the Southern Hemisphere summer monsoon, at longitudes near Australia, is recognized now as one of the major elements of the global climate. Fluctuations of the intensity and location of the monsoon convection affect the global circulation over a wide range of scales. For example, longitudinal shifts of the austral summer mean convective center, from near 135°E to the dateline during an ENSO event, result in dramatic seasonal circulation anomalies in both hemispheres (e.g., Rasmusson and Wallace 1983). This present study, however, will be concerned with the impact of a much shorter time scale phenomenon, onset of the summer monsoon.

Troup (1961) was the first to point out that the monsoon in the Australian region exhibited many similar features to that of the Asian monsoon including that of a distinct onset. In particular he showed, using only four seasons of data, that onset occurred in a matter of 2–5 days and was accompanied by a poleward shift of the subtropical jet and expansion of the upper level tropical easterlies.

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Since this pioneering study, little attention was paid to the onset phenomenon until FGGE/WMONEX 1978–79 (Murakami and Sumi 1982; Davidson et al. 1983, 1984) and AMEX 1987 (Hendon et al. 1989). These studies dealt in detail with the synoptic scale circulation changes associated with particular onset events. In general, their findings concerning the large-scale circulation corroborate the earlier findings of Troup (1961). These studies examined only a limited number of onset events, however, and thus it is difficult to determine the common and essential elements (if any) of the onset phenomenon.

The interannual variation of onset date was examined by Holland (1986) for the years 1952–82. The relationship between onset dates identified by Holland and the seasonal cycle of outgoing longwave radiation (OLR) were further studied by Murakami et al. (1986) for the years 1974–82. While significant relationships between onset date and various measures of the anomalous state of the general circulation were demonstrated in both of these studies (i.e., the southern oscillation index and the phase of intraseasonal OLR fluctuations), the circulation changes that accompany onset were not addressed.

In the present study these circulation changes that accompany onset will be documented by means of a composite study for the years 1957–87. A composite approach was chosen with the underlying assumption that onset is similar each year and is governed by the same mechanism each year. Thus, 30 seasons should be sufficient to extract signal from noise. Of course it is very unlikely that onset each year evolves in the same manner and that it occurs due to the same mechanism, but this composite approach is adopted as a first means of examining the circulation changes. The underlying assumptions regarding a composite are reexamined in section 5.

A crucial aspect of this study will be the ability to identify the onset for each of the 30 seasons. The success of identifying the onset is clearly shown in Section 3, though in a limited number of years (3 or 4), onset was not well defined. We thus feel our description of the tropical and extratropical circulation anomalies that accompany onset are quite general yet subject to a degree of synoptic variability.

2. Data

The primary data analyzed are the upper air record at Darwin (12°S, 130°E) and the daily record of area averaged rainfall for stations north of 15°S in Australia; Holland (1986) used a similar record for stations north of 20°S. These records are available for 1957–87. The intent of this study is to document the large-scale circulation changes that accompany onset over northern Australia. Thus, selected stations covering Australia and surrounding oceans are also examined. In particular, a line of stations north–south and east–west relative to Darwin is emphasized to examine the longitudinal and latitudinal structure of the onset. Table 1 lists these stations and their record length while their locations are identified in Fig. 1.

TABLE 1. Locations and record length for stations examined in composite study. All records were averaged to produce winds, temperature and moisture variables once per day. Missing data were created by linearly interpolating in time.

Station	Location	Record length
Darwin	12°S 130°E	1957–87
Koror	7°N 134°E	1957–87
Alice Springs	23°S 133°E	1957–77
Adelaide	34°S 138°E	1957–77
Singapore	1°N 104°E	1957–85
Cocos Is.	12°S 96°E	1957–77
Honiara	9°S 159°E	1957–77
Pago Pago	14°S 170°W	1966–87
Truk	7°N 151°E	1957–87
Norfolk	29°S 167°E	1957–77
Lord Howe	31°S 159°E	1957–77
Brisbane	27°S 153°E	1957–77
Charleville	26°S 146°E	1957–77
Cloncurry	20°S 140°E	1957–77
Perth	31°S 115°E	1957–77
Pt. Hedland	20°S 118°E	1957–77
Woomera	31°S 136°E	1957–77
Hobart	42°S 147°E	1957–77
Townsville	19°S 146°E	1957–77

Additionally, 12 years of polar orbiting outgoing longwave radiation (OLR) measurements are employed (1974–87 with the 1978/79 season missing). Gridded, initialized analyses from ECMWF are also available for the period 1980–87. These data are used to surmise the horizontal characteristics of the monsoon convection and to corroborate circulation changes identified in the much longer record of station data. Daily data, on a 2.5° grid, were formed from twice daily observations.

3. Onset definition

The extent of persistent monsoon convection is about equator–10°S, 110°–165°E during January (Fig. 1). The region of most intense convection, however, barely extends into northern Australia. Twin anticyclones in the upper troposphere straddle the equator at the longitude of Australia with easterlies covering that portion of the continent affected by the monsoon convection and westerlies covering the remaining majority. Distinct meridional outflow (both equatorward and poleward), interpreted as representative of the local Hadley circulation, occurs from the region of time mean convection. At lower levels, the circulation is cyclonic with westerlies over the northern portion of the continent (not shown; e.g., see Hendon 1988).

The seasonal cycle of the monsoon convection and 200 mb circulation are shown in Fig. 2 for Australian longitudes. The daily climatology for the OLR record (1974–87) and ECMWF record (1980–87) were created at each grid point and then harmonically analyzed. Shown are the first three harmonics (annual, semiannual, terannual) averaged between 130° and 145°E. The peak in the annually varying convection (negative OLR) occurs at about 15°S during January with easterlies extending from the equator to about 30°S. At this time seasonal westerlies cover the Australian subtropics (poleward of 30°S). During austral winter, seasonal westerlies cover most of Australia along with suppressed tropical convection. The OLR variation over the Australian subtropics does not reflect convective variation, but rather, the annual variation of surface temperature.

Essentially the reverse occurs north of the equator with peak convection and easterlies during northern summer and minimum convection and westerlies during northern winter. A distinct semiannual variation of the equatorial zonal wind is accompanied by meridional outflow from the convective center in the Northern Hemisphere and from the convective center in the Southern Hemisphere during their respective summers. Again, this is interpreted as the local Hadley circulation.

A closer inspection of the seasonal cycle of zonal wind and rainfall over northern Australia reveals the monsoonal nature of the circulation (Fig. 3). This average seasonal cycle was made by first creating a daily

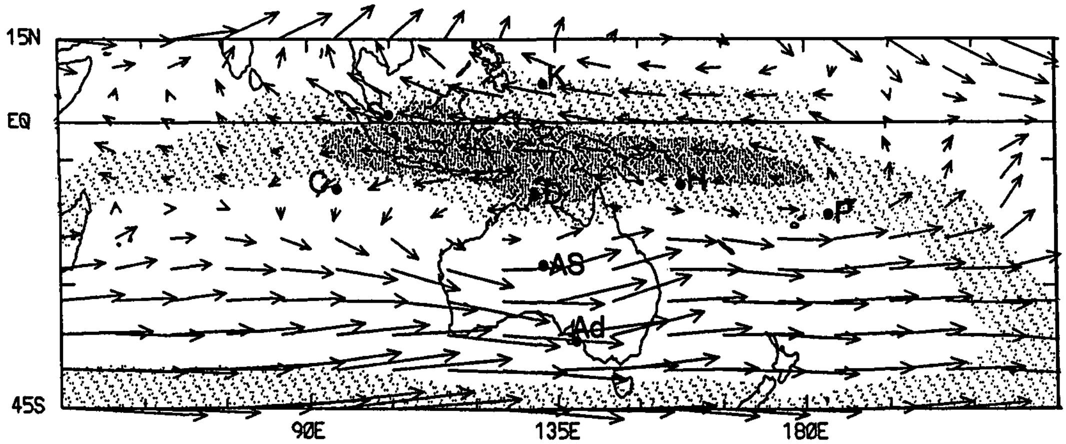


FIG. 1. Thirteen year (1974–87) mean OLR and eight year (1980–87) mean ECMWF 200 mb winds for January. Light shaded regions are radiances less than 235 W m^{-2} while dark regions are less than 210 W m^{-2} (indicative of very deep time mean convection). Maximum westerly winds have magnitude 35 m s^{-1} and maximum easterlies have magnitude 15 m s^{-1}. The locations of selected key stations used in the composite study are Darwin (D), Koror (K), Alice Springs (As), Adelaide (Ad), Singapore (S), Cocos Island (C), Honiara (H) and Pago Pago (P).

climatology for the 31-year record of zonal wind at Darwin and area averaged rainfall. The climatology was then low-pass filtered (high frequency cutoff at 30-day period). During the wet season, lower tropospheric westerlies are coherent with upper tropospheric easterlies, typical of a tropical monsoon. The average transition from dry-easterly to wet-westerly regimes occurs on 4 January, and the wet season lasts until late March. Individual seasons (e.g., 1959/60, Fig. 4), however, show a much more dramatic transition with wet, low-level westerlies developing in a matter of days. The break-active cycles, typical of the Australian monsoon (Holland 1986), are also evident.

A variety of methods have been used to identify the monsoon onset (Nichols et al. 1982). Since we are concerned with circulation changes that accompany onset, the low-level wind based definition of Holland (1986), refined to include rainfall, will be employed

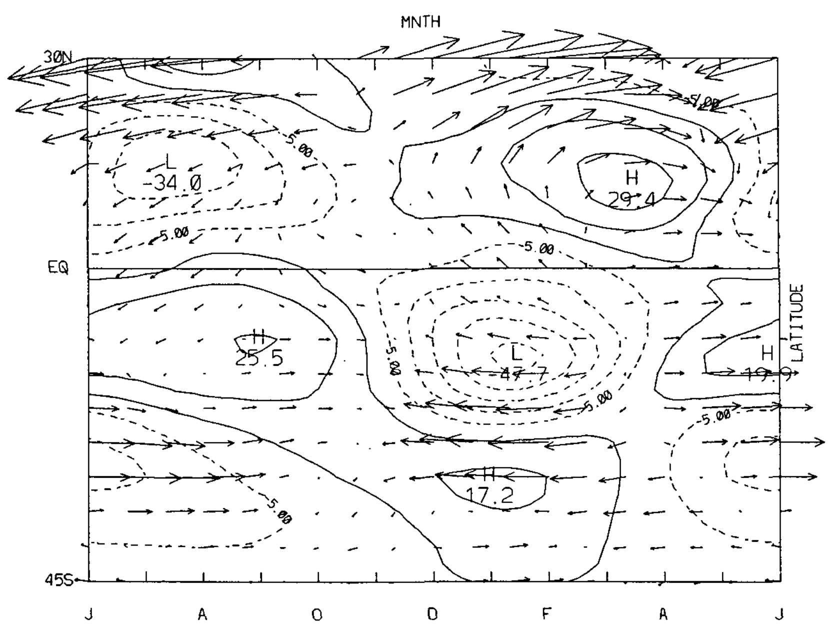


FIG. 2. First three harmonics of the annual cycle (annual, semiannual, terannual) of OLR (contoured) and ECMWF 200 mb winds (vectors) averaged between 130–145 E. Contour interval is 10 W m^{-2} (first contour at ±5 W m^{-2}) and maximum vector wind has magnitude 30 m s^{-1}. See text for details.

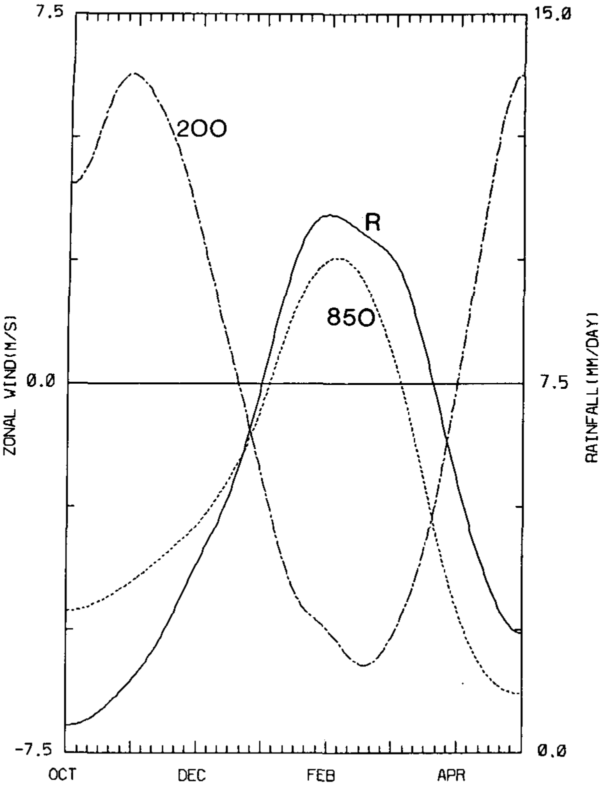


FIG. 3. The 31-year mean seasonal cycle of rainfuall over northern Australia (solid line) and zonal wind at Darwin; 850 mb (dotted); 200 mb (dashed).

here. As per Holland, the 850 mb zonal wind at Darwin is filtered to remove synoptic fluctuations. The filter, a running 1–2–3–2–1 mean, passes fluctuations with periods greater than approximately seven days. The first occurrence of wet westerlies is identified as monsoon onset. Wet is arbitrarily defined as a rainfall rate of at least 7.5 mm day^{-1}. This rainfall rate is approximately that which occurs at the zero crossing of

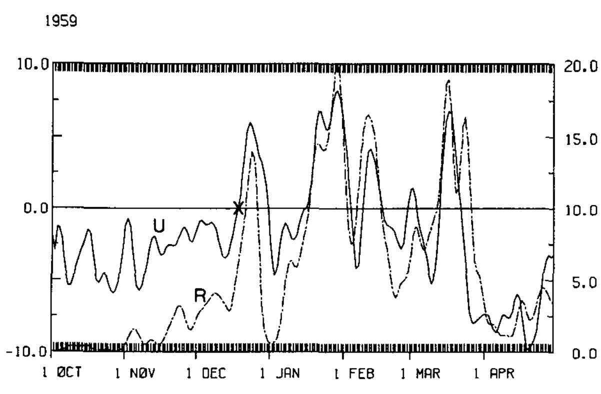


FIG. 4. A representative low-pass filtered (see text) daily time series of 850 mb zonal wind (solid) at Darwin and north Australian rainfall (dotted). The time series were filtered with a running 1-2-3-2-1 mean. The scale for zonal wind is at left (m s^{-1}) and rainfall at right (mm day^{-1}). Onset for this year, 1959, is indicated by the cross.

TABLE 2. Onset dates and the mean and standard deviation derived from 30 years of wind and rainfall at Darwin. For comparison, Holland's (1986) results are included. See text for description of seasonal mean date.

Season (mo/day/yr)	Season (mo/day/yr)
1957–58: 12/25/57	1972–73: 1/23/73
1958–59: 12/31/58	1973–74: 12/13/73
1959–60: 12/17/59	1974–75: 1/4/75
1960–61: 12/22/60	1975–76: 12/1/75
1961–62: 1/4/62	1976–77: 12/9/76
1962–63: 12/25/62	1977–78: 12/11/77
1963–64: 1/1/64	1978–79: 12/22/78
1964–65: 12/3/64	1979–80: 12/29/79
1965–66: 1/3/66	1980–81: 1/4/81
1966–67: 1/17/67	1981–82: 11/23/81
1967–68: 1/5/68	1982–83: 1/7/83
1968–69: 1/7/69	1983–84: 1/5/84
1969–70: 12/20/69	1984–85: 12/10/84
1970–71: 12/2/70	1985–86: 1/16/86
1971–72: 12/6/71	1986–87: 1/14/87

	Present study	Holland (1986)	Seasonal mean
Mean onset date	25 December	24 December	4 January
Standard deviation	16 days	15 days	—

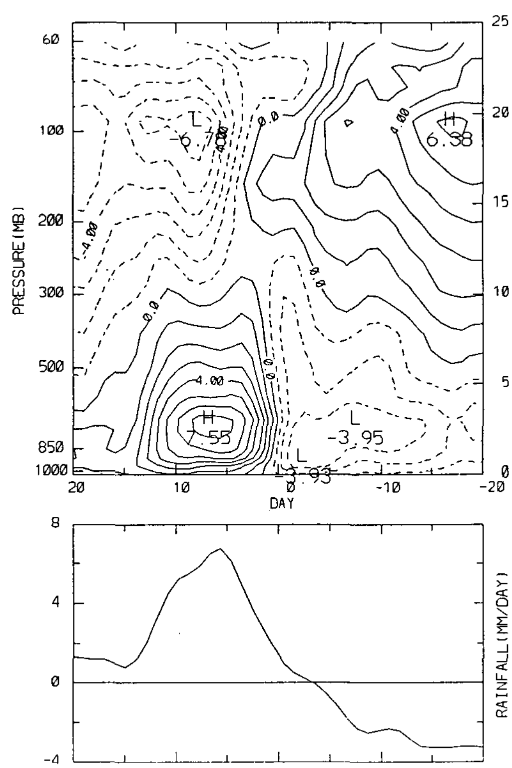


FIG. 5. The 30-season composite onset of zonal wind at Darwin (top), and north Australian rainfall (bottom). Day zero corresponds to the zero crossing of the 850 mb zonal wind. Note time runs from right to left and spans 20 days before and after onset. Contour inteval in a) is 1 m s^{-1}.

the 850 mb zonal wind in the average seasonal cycle (Fig. 3).

Onset date for all 30 seasons, 1957–86, was determined in the above manner. Table 2 lists the dates, the average onset date, and the standard deviation. Holland's (1986) results are included for comparison. The slight difference between results is due to the higher frequency filter employed here along with the incorporation of rainfall into the onset definition. The date derived from the average seasonal cycle is approximately one week later, resulting from averaging together of the active-break cycle of each typical wet event. All methods, however, yield generally similar results.

An underlying assumption is that identification of the large-scale onset can be achieved by examining a single station wind record. Troup (1961) and Holland (1986) both showed this to be the case. Our inclusion of area averaged rainfall into the onset definition should emphasize the large-scale component. Nevertheless, the only guarantee is to examine the composite onset at various stations and ascertain the degree that the large-scale circulation is coherent. As will be shown in section 4, onset as defined here is indeed a large-scale event.

4. Composite onset

The basis for the remainder of this study is to composite the time evolution of various atmospheric fields relative to the onset date at Darwin. In general, composite 40-day cycles of the onset event, running from 20 days prior to 20 days after, will be made. For all fields the multiyear seasonal mean (December–March) is removed prior to compositing. Unfiltered anomalies are composited, but in some cases slight smoothing of the composited field is used for plotting clarity.

The 30-event composite of zonal wind at Darwin and northern Australian rainfall (Fig. 5) indeed reveals onset to be a dramatic event. (Note, time runs right to left in Fig. 5). Within a matter of 5–10 days low-level, dry easterly anomalies are replaced by wet westerlies. The peak-to-peak amplitude is about 10 m s^{-1} and 10 mm day^{-1}. The zonal wind fluctuation in the lower troposphere develops out of phase with the upper troposphere, typical of convectively driven regimes. Maximum amplitude aloft occurs right at tropopause level with an evanescent perturbation extending into the lower stratosphere.

The duration of the wet-westerly event is about 15–20 days, with an implied period of 35–40 days for the entire event. This agrees with Holland's (1986) finding that the average time between active periods (onset included) is 40 days. The significance of this 40-day period is further explored below.

The meridional extent of the onset event is seen in the composite zonal winds at Koror, Alice Springs, and Adelaide (Fig. 6). Day zero refers to the zero crossing of the 850 mb zonal wind at Darwin. Troup's (1961) observations, that the subtropical jet shifts southward while the equatorial upper level easterlies expand symmetrically *about* the equator, are wholly confirmed in the present multiyear composite. The equatorial easterlies expand at least as far north as Koror (~7°N) and as far south as Alice Springs (23°S). The subtropical jet shifts poleward to at least Adelaide (~35°S) where the sense of the upper level anomalies is opposite that at Darwin (Fig. 5) and Alice Springs. These developments are consistent with the mean annual cycle (Fig. 2) but occur over a much shorter time scale.

Contrary to the deep baroclinic development at Darwin (Fig. 5), indicative of a convectively driven regime, low-level easterlies predominate north of the equator (Fig. 6a). As will be shown below, this is consistent with all of the convection shifting south of the equator (again consistent with the mean annual cycle but occurring over a much shorter time scale). A hint

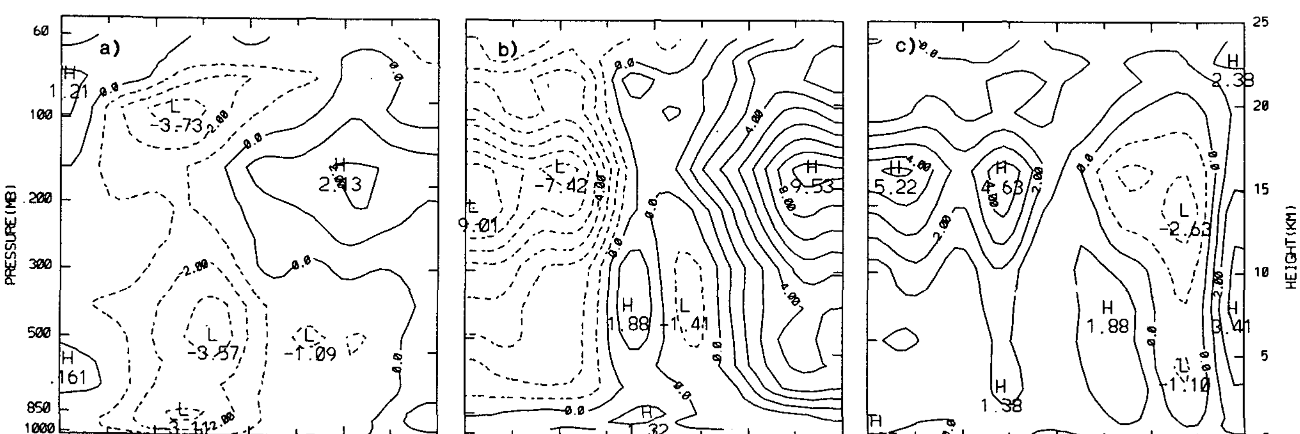


FIG. 6. Composite zonal wind at (a) Koror, (b) Alice Springs, and (c) Adelaide relative to onset at Darwin. Plotting convention is as in Fig. 4.

of the monsoonal westerlies is evident at Alice Springs (Fig. 6b), but in general, the wet-westerly event is confined north of approximately 20°S.

This poleward shift of the subtropical jet and development of the convectively driven, baroclinic regime over northern Australia is interpreted to be a manifestation of a southward shift in the local Hadley circulation and the development of the upper level anticyclone over Australia (Fig. 1). The sense of the local Hadley circulation is inferred here from the upper tropospheric meridional wind and lower tropospheric moisture fields. Prior to onset, upper northerlies extend from the Northern Hemisphere (Koror, Fig. 7a) across the equator, past Darwin (Fig. 7b) to at least Alice Springs (not shown but similar to Darwin) while southerlies occur at Adelaide (Fig. 7c). Implied upper level convergence (sinking motion) occurs south of Alice Springs with upper level divergence (rising motion) north of the equator. At onset, a southward shift in this circulation occurs with upper level southerlies developing at Koror (outflow *from* the Southern Hemisphere) and northerlies (outflow *from* the north) developing as far south as Alice Springs. At Adelaide, pre-onset southerlies shift to northerlies. Implied upper level divergence occurs between Darwin and Alice Springs, with upper level convergence occurring south of Adelaide and north of the equator. Careful examination of Darwin's and Alice Springs' composite reveals that this implied upward branch temporarily traverses south past both Darwin and Alice Springs. Three to four days after onset, it recovers to its climatological position just north of Darwin, apparently because the convection has shifted back to its mean position north of Darwin.

This interpretation of a transient poleward migration of the Hadley cell at onset is confirmed by examining the composite moisture fields (Fig. 8). Prior to onset, Koror (Fig. 8a) exhibits anomalous moist conditions, typical of the upward branch of the Hadley circulation lying north of the equator. Meanwhile, Darwin (Fig. 8b) and Alice Springs (Fig. 8c) exhibit drier than normal conditions. Just prior to onset Darwin becomes moist; two to three days later Alice Springs becomes moist while Koror dries out. This moist event lasts about 10 days at Darwin, consistent with the duration of upper level divergence inferred from the meridional wind (Fig. 7b).

This transient shift of the local Hadley circulation and jet streams is coherent across the entire breadth of Australia and the tropical oceans to its north (Fig. 9). Here 700 mb relative humidity anomalies are used as a proxy for active tropical convection. The 150 mb winds are used to represent the upper branch of the Hadley circulation and jet streams. Stations north of the equator exhibit a transition from moist, northwesterlies prior to onset (day −12, Fig. 9a), to dry southeasterlies after onset (day +16, Fig. 9c). Across the breadth of tropical Australia, dry, pre-onset westerlies evolve to moist southerlies (with the upward branch of the Hadley cell centered in central Australia) at onset (day +2, which is near the time of maximum rainfall at Darwin; Fig. 9b) and then to more normal post-onset easterlies. The intensification of the subtropical jet is apparent from Woomera (31°S, 136°E) southwards. Also evident is the switch from cyclonic circulation prior to onset (Fig. 9a) to anticyclonic circulation after onset (Fig. 9c). Thus, the overall picture is that onset is associated with a southward transient shift of the local convectively driven Hadley circulation, a poleward expansion (in both hemispheres) of the equatorial easterlies, a poleward shift in the subtropical jet and increased anticyclonic circulation over Australia. All of this is in agreement with the mean seasonal cycle but occurs in a matter of days rather than months.

The horizontal extent of the convection associated with onset is examined using OLR, which is a proxy

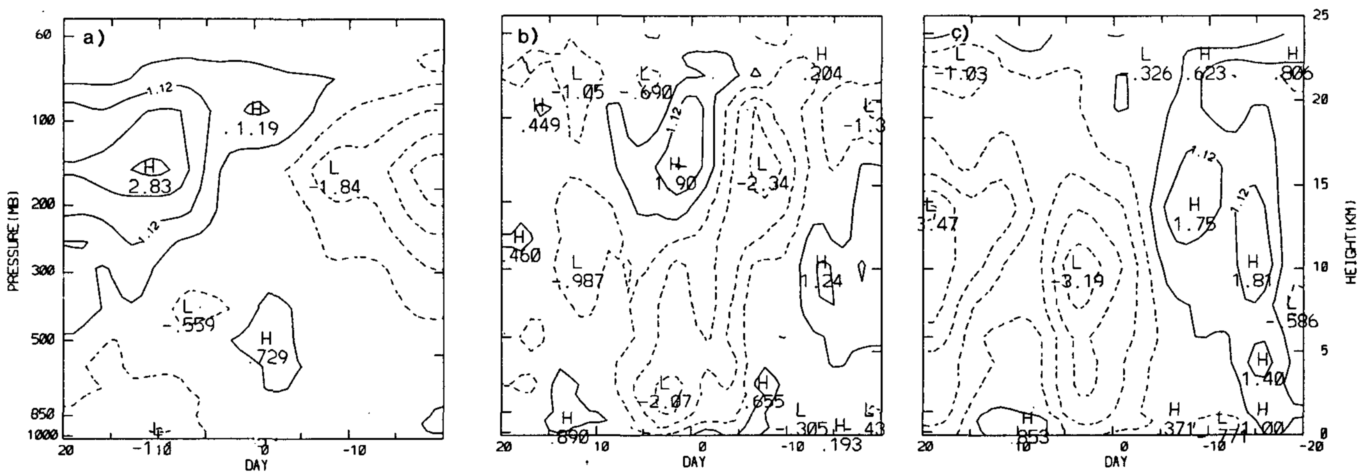


FIG. 7. Composite meridional wind at (a) Koror, (b) Darwin, and (c) Adelaide relative to onset at Darwin. Plotting convention is as in Fig. 4. Contour interval 0.75 m s^{-1} with first contour at ± 0.375 m s^{-1}.

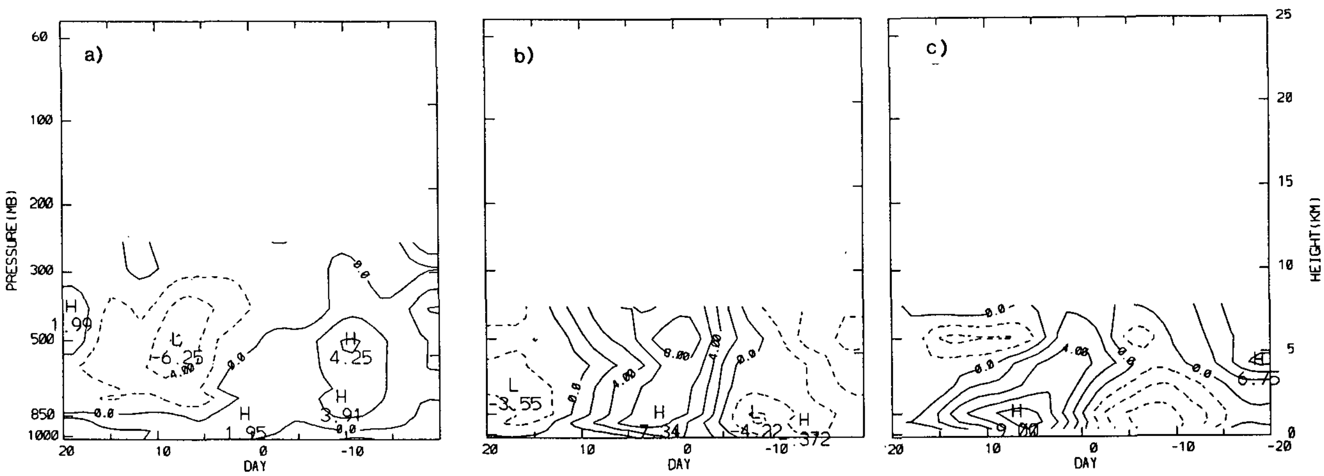


FIG. 8. Composite relative humidity at (a) Koror, (b) Darwin, and (c) Alice Springs relative to onset at Darwin. Plotting convention is as in Fig. 4. Contour interval is 2%.

for tropical convection. Near onset (day +2), an extensive region of enhanced convection (low OLR) covers Northern Australia (Fig. 10b). Weak positive anomalies (suppressed convection) are evident south of the equator in the Indian Ocean and near the dateline. Prior to onset (day −8; Fig. 10a), this enhanced convective region appears to have originated in the southern Indian Ocean while by day +12 (Fig. 10c) it has translated northeastward towards the dateline.

The relationship between the convection, local Hadley circulation, and anticyclones at onset is examined further with the gridded ECMWF analyses at 200 mb. Here the total composite wind field (mean included) is shown for day +2 (Fig. 11b) along with the composite OLR (mean included). At onset a well developed anticyclone is centered over northern Australia with pronounced outflow from the convective region into the Northern Hemisphere. The temporal development of those features is depicted by subtracting composite day +2 from day −8 (Fig. 11a) and day +2 from day +12 (Fig. 11c).

A cyclonic tendency at day −8 (Fig. 11a) is replaced by an anticyclonic tendency further to the east at day +12 (Fig. 11c). Note that the tendency is for tropical westerlies and subtropical easterlies to be replaced by tropical easterlies and subtropical westerlies as the anticyclone moves southeastward in agreement with the composited station data (Fig. 9). Along with this, a tendency for suppressed convection over and to the east of northern Australia prior to onset evolves to suppressed convection over and to the west of Australia with enhanced convection to the east after onset.

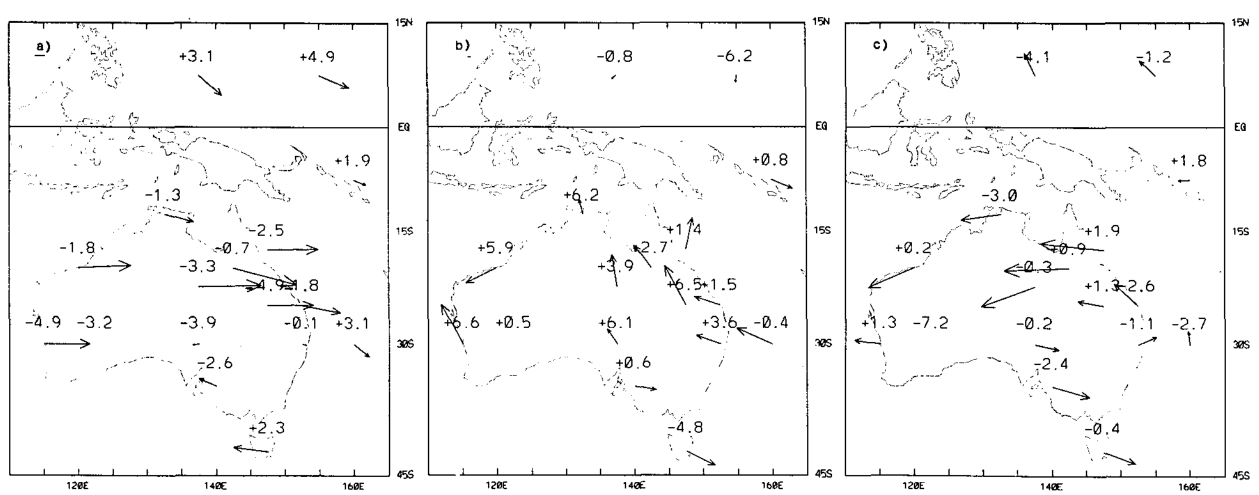


FIG. 9. Composite 150 mb winds (vectors) and 700 mb relative humidity (percent) at various stations in and around Australia. (a) is day −12, (b) day +2, and (c) day +16 relative to onset at Darwin. The maximum vector wind is 10 m s^{-1}.

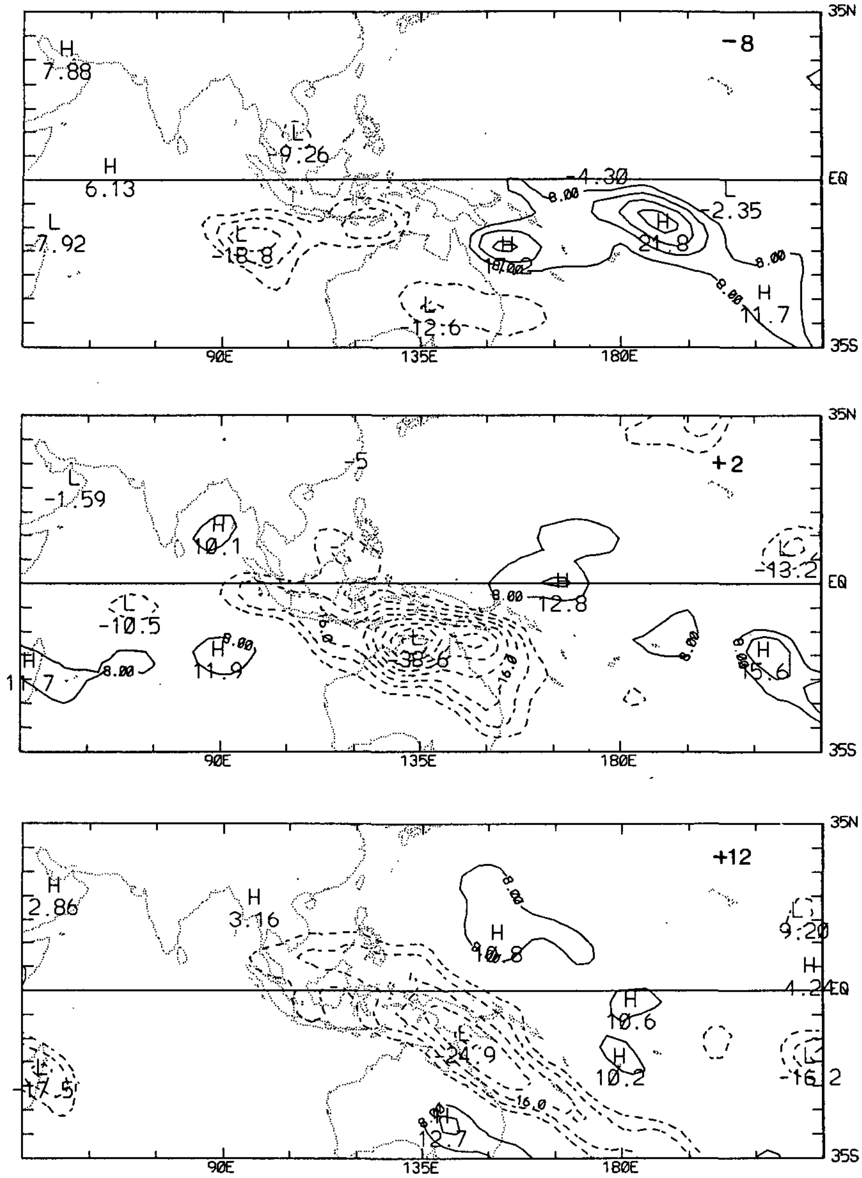


FIG. 10. Composite plan view of OLR relative to onset at Darwin. Contour interval is 5 W m^{-2} with first contour at ±10 W m^{-2}. The sequence is (a) day −8, (b) day +2, and (c) day +12.

The eastward migration of the convective anomaly that accompanies onset is further elucidated from the composite OLR Hovmöller diagram (Fig. 12a). Because the convective anomalies are maximum south of the equator, OLR anomalies are averaged between 5° and 15°S. In fact, if averaged between 5°N and 5°S (as is common practice), very little eastward propagation can be detected.

The composite onset is associated with the slow eastward migration (about 5 m s^{-1}) of a convective anomaly, which is detectable as far back as day −20 over the southern Indian Ocean. The structure and phase propagation of this convective anomaly is typical of the so-called 40–50 day oscillation (Madden and Julian 1972) in the Indian–West Pacific oceans (Lau and Chan 1985; Knutson and Weickmann 1987). Bear in mind that the present composites were made with unfiltered anomalies and with no expectation of a 40–50 day periodicity.

An interesting feature of this composite is the tendency for the convective anomaly (negative OLR) to temporarily stall at Australian longitudes (day −5 to day +5). Negative convective anomalies (positive OLR), however, steadily propagate eastward. This stalling of the positive convective anomaly over northern Australia, also evident in the 40–50 day composite study of Knutson and Weickmann (1987), may be indicative of the interaction of the propagating 40–50 day oscillation with the stationary monsoon.

Further evidence that onset is accompanied by the poleward expansion of the slow eastward moving convective anomaly as it traverses Australian longitudes is gained by examining the latitude–time composite of the OLR anomaly averaged about Australian longitudes (Fig. 12b). The anomaly is initially equatorially symmetric (day −10 to −5) but then rapidly develops southward over northern Australia. Subsequently, after onset, the convection retreats northward. This behavior is also evident in the 40–50 day composite study of Knutson and Weickmann (1987) but is much more apparent here. This poleward expansion–equatorward retreat of convection is much different than poleward propagating convective bands observed during the Indian summer monsoon (Yasunari 1979).

Using the wind records at Cocos Island and Pago Pago, the eastward migration of the convective onset event is examined east and west of Darwin. At Cocos Island (Fig. 13a, 35° west of Darwin) the upper tropospheric reversal from westerlies to easterlies occurs 5 days prior to that at Darwin (Fig. 13b). At Pago Pago (Fig. 13c, 60° east of Darwin) the reversal occurs 10 days after that at Darwin. This is equivalent to a 5 m s^{-1} eastward phase speed. At Pago Pago, the reversal from lower tropospheric trade easterlies to monsoon westerlies occurs only about 3 to 4 days after onset at Darwin, while at Cocos Island it is nearly simultaneous. The peak lower tropospheric westerlies at Pago Pago, however, do occur about 10 days after those at Darwin. This simultaneous development of westerlies across the entire Australian tropics is consistent with the stationary signal seen in the OLR composite near day 0 (Fig. 12a). Furthermore, at Pago Pago the zonal wind disturbance is basically confined to the upper troposphere, indicating little, if any, convective activity. This, too, is consistent with the plan-view OLR composites (Fig. 10) which show the convective anomaly to be weaker and to be south of Pago Pago at day +12. Taking both the OLR and zonal wind composites, the onset then appears as the manifestation of a slow eastward propagating, convectively driven disturbance as it traverses Australian longitudes. This composite disturbance exhibits many of the features of the so-called tropical 40–50 day oscillation.

That the 40–50 day oscillation may indeed influence onset is not surprising considering the well known impact it has on Australian monsoon activity. For example, Holland (1986) showed the mean period of active break cycles to be 40 days. Furthermore, the only significant out-of-phase coherence, in the 40–50 day band, between 850 and 200 mb zonal wind at Darwin occurs during the summer monsoon season (Madden 1986).

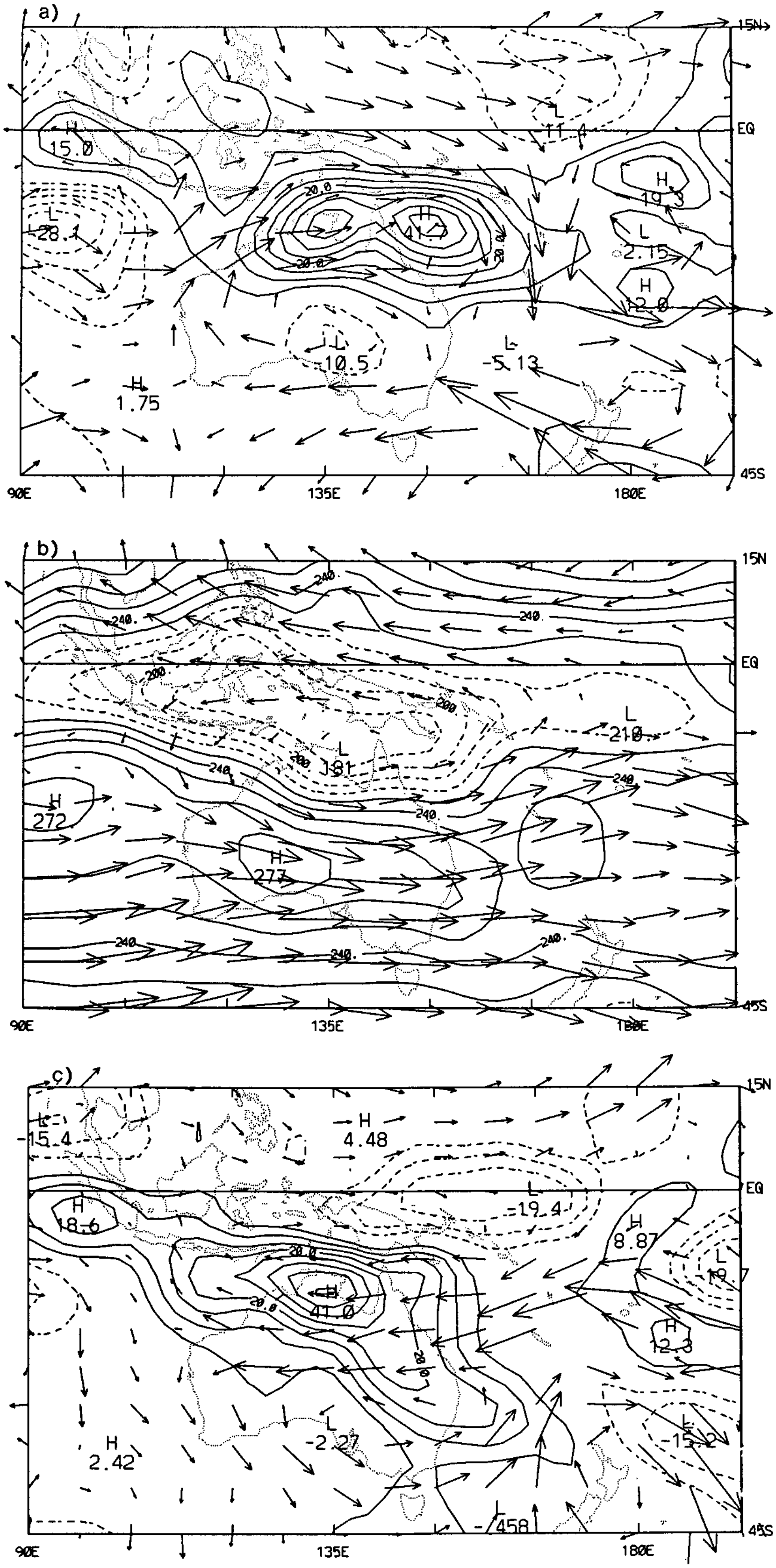
Further evidence of the substantial impact of the 40–50 day oscillation on monsoon activity is seen by considering the power spectra of rainfall and 850 mb wind at Darwin along with their coherence. Two hundred 12-day segments, beginning 1 October each year, were analyzed. The 30-year mean seasonal cycle was removed and a Hanning window was applied as per Hartmann and Gross (1988). Each time series was "padded" with zeroes to 256 days. A FFT was used to compute the spectral coefficients (bandwidth 1/256 $days^{-1}$). The power spectra for each year were averaged together (yielding 60 degrees of freedom), as were the co-spectrum and quadrature-spectrum prior to computing coherence squared and phase.

Despite the fact that the rainfall spectrum (Fig. 14b) is markedly red, the most outstanding subseasonal spectral peak of the 850 mb wind at Darwin (Fig. 14a) is in the 30–50 day band. The coherence squared between the two series (Fig. 14c) also exhibits a substantial peak at these frequencies, though the rainfall and wind are significantly coherent for all periods longer than about 20 days. In the 30–50 day band the rainfall leads the wind by 1/10 cycle (~4 days), but its exact lag is not clear due to the large spatial separation of the rainfall stations (see Holland 1986). Nonetheless, the rainfall leads the wind by roughly the same amount as seen in the composite onset (Fig. 5).

This substantial spectral peak at 30–50 days in the wind and its strong coherence with rainfall at these frequencies, along with the remarkable resemblance of the composited wind and OLR anomalies to the 40–50 day oscillation, lead us to hypothesize that onset (as defined here) results from the passage of a 40–50 day oscillation during Australian summer. We further hypothesize that the composite onset results from the first passage of a convectively active 40–50 day oscillation south of the equator. That is, numerous 40–50 day events are detectable throughout the year at upper levels (presumably forced elsewhere), but they remain uncoupled with the lower tropospheric winds (due to the lack of convection) until onset occurs. Prior to onset both the mean convection and that associated with 40–50 day events remain north of Australia.

This hypothesis is substantiated by compositing all identifiable 40–50 day events in the two month period *preceding* onset each year at Darwin. The time series of zonal wind at Singapore were bandpass filtered (30–60 day halfwidths, Murakami 1979) and all out of phase 40–50 day oscillations between the 850 mb and 200 mb zonal wind were identified. Singapore was chosen because it is near the equator and would be expected to be influenced by all 40–50 day events regardless of season (Madden 1986). Only events detectable at both 850 mb and 200 mb are chosen because we assume they are indicative of active coupling via convection.

Unfiltered composite winds and OLR were made, as before, using the dates of the peak 40–50 day 850 mb westerlies at Singapore. A clear 5 m s^{-1} eastward propagating baroclinic zonal wind disturbance is re-


a)
15N
EQ
45S
90E
135E
180E
H
15.0
L
28.1
L
11.4
H
19.3
H
41.7
20.0
L
2.15
H
12.0
L
10.5
L
-5.13
H
1.75
b)
15N
EQ
45S
90E
135E
180E
240.
200
L
210.
L
181
H
272.
H
277.
c)
15N
EQ
45S
90E
135E
180E
L
-15.4
H
4.48
L
-19.4
H
18.6
H
8.87
L
19.7
20.0
H
41.0
H
12.3
H
2.42
L
-2.27
L
-15.2
L
-458

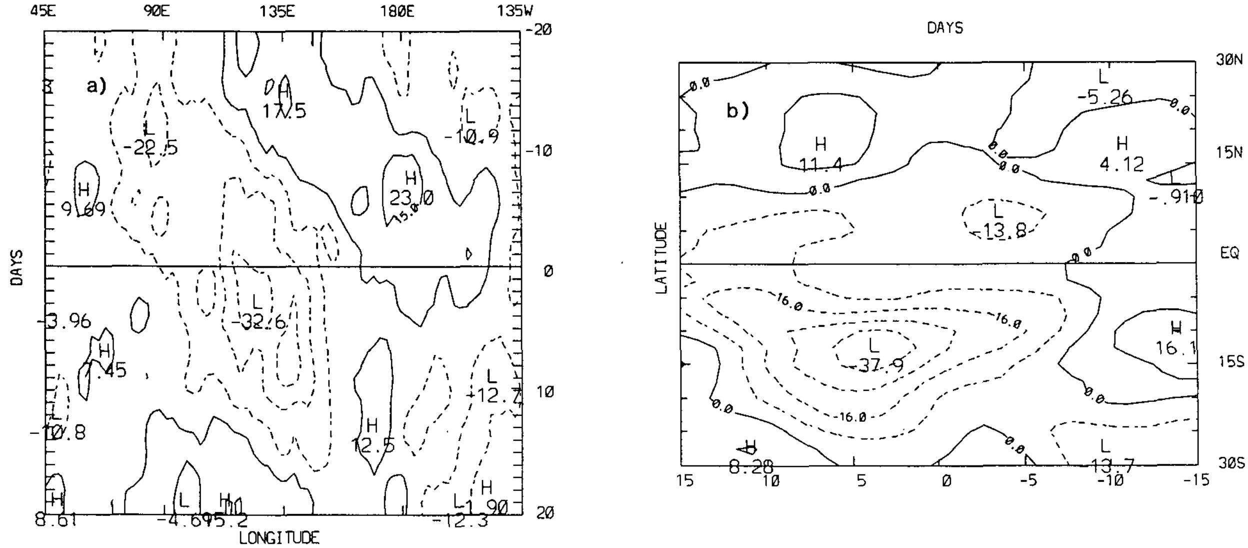


FIG. 12. Composite OLR displayed as (a) Hovmöller diagram averaged between 5°S and 15°S and (b) as latitude versus time averaged between 130°E and 145°E. The contour interval is 10 W m^{-2} in (a) and 8 W m^{-2} in (b). The first contour is at ±5 W m^{-2} in a) and at 0 W m^{-2} in (b). Day zero refers to onset at Darwin. Note time runs down in a) and from right to left in (b).

vealed at all stations along and to the north of the equator; very little activity is seen south of the equator (not shown). This eastward propagation, confined north of the equator, is best seen in the OLR composites (eight events for the years 1974–87). Here the longitude–time plot (Fig. 15a) is formed by averaging between the equator and 10°N; little propagation is observed if averaged south of the equator. A distinct convective anomaly propagates from the Indian Ocean out to about 160°E. At Australian longitudes, however, this eastward propagating convective anomaly is confined essentially to the Northern Hemisphere (Fig. 15b). Thus, while propagating 40–50 day oscillations exist at longitudes near Australia prior to onset, the convective anomalies remain north of Australia until after onset.

5. Conclusions

Circulation changes associated with onset of the Australian monsoon were examined by means of composites relative to the first occurrence of wet, 850 mb westerlies at Darwin. The composite OLR anomaly at day +2 (Fig. 10b) clearly indicates the utility of this single station index. Troup (1961) was the first to realize that, despite the active monsoon being composed of numerous synoptic-scale events, the shift from dry to wet regimes was a large-scale phenomenon and was easily detectable at a single station. Holland (1986) was able to exploit this feature to study the interannual variability of the monsoon.

Troup's (1961) observations that onset is accompanied by a large poleward shift of the subtropical jet and an expansion of the equatorial, upper tropospheric easterlies were clearly confirmed in this multiyear study. These developments were shown to accompany the development and eastward migration of an upper level anticyclone similar to the seasonal cycle but occurring on a much shorter time scale. An added element of this transition is the tendency for the subtropical jet and easterlies to overshoot their climatological poleward positions right at onset. A few days after onset they recover equatorward to their more normal positions. This adjustment was speculated to be related to the local Hadley circulation driven by the monsoon convection, shifting from north of the equator (5–10 days prior to onset) to south just past Alice Springs (~20°S) right at onset, and then recovering back to just north of Darwin (~10°S) 5–10 days after onset.

The composite onset was shown to be dominated by a slow, eastward migration of a deep-baroclinic, convective circulation displaced south of the equator. This propagating, Walker-type circulation exhibited many features of the so called 40–50 day oscillation (e.g., Madden and Julian 1972) including an upper

FIG. 11. Composite ECMWF winds at 200 mb (7 events, 1980–87) and OLR (13 events, 1974–87) for onset relative to Darwin. Panel (b) displays the total winds and OLR (mean included) for day +2. Panels (a) and (c) are the difference fields between day −8 and day +2 and day +12 and day +2, respectively. Contours less than 220 W m^{-2} (indicative of deep convection) are dashed in b). Contour interval in b) is 10 W m^{-2} and in a) and c) is 5 W m^{-2}. Maximum vector wind has magnitude 35 m s^{-1} in b) and 20 m s^{-1} in a) and c).

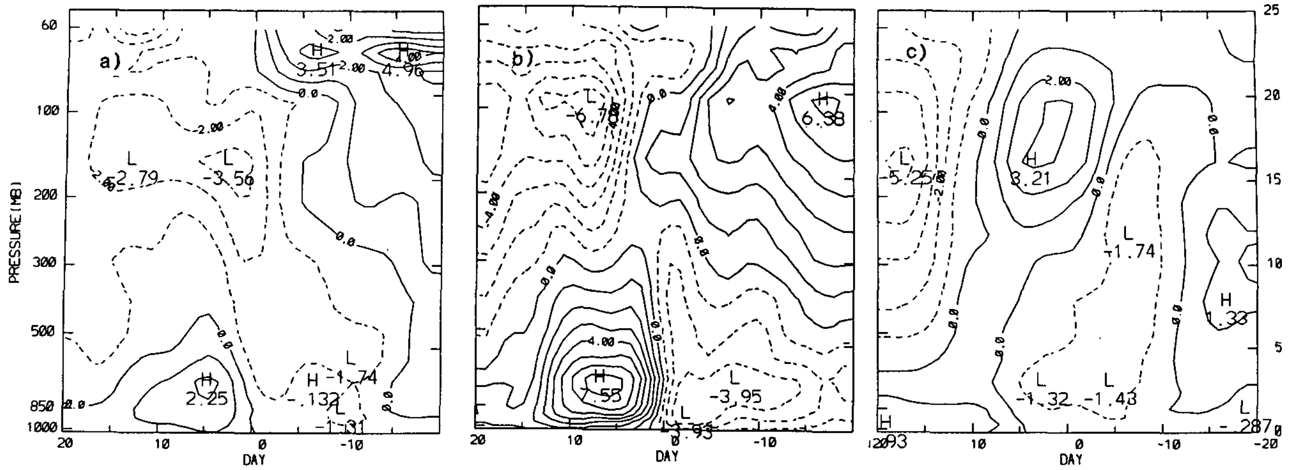


FIG. 13. Composite zonal wind at (a) Cocos Island, (b) Darwin and (c) Pago Pago relative to onset at Darwin. Plotting convention is as Fig. 4.

level anticyclone that accompanies the convective anomaly. The convective anomaly is detectable as far west as the Indian Ocean 15 to 20 days prior to onset; it propagates eastward at about 5 m s^{-1} and is discernible as far east as the dateline. It is interesting that Davidson et al. (1983, 1984) detected essentially this same behavior of the poleward shift of convection and development and eastward migration of the anticyclone during the onset of 1978/79. They ascribed this behavior, however, to midlatitude cyclogenesis.

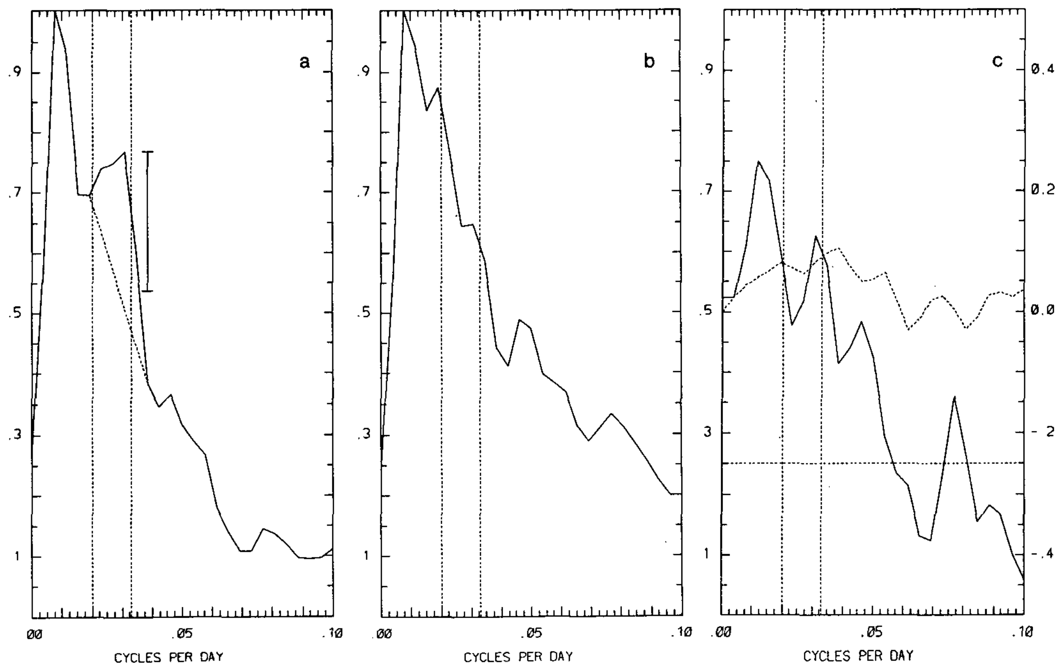


FIG. 14. Power spectra of (a) 850 mb zonal wind at Darwin and (b) north Australian rainfall. Only periods longer than 10 days are shown. The vertical lines indicate the 30–50 day period band. The maximum power has been normalized, arbitrarily, to unity. The bandwidth (1/256 days^{-1}) and 95% confidence level, assuming a chi square distribution with 60 degrees of freedom, are indicated in (a) for the peak spectral estimate at 32 day period. A subjective estimate of the background zonal wind spectrum is given by the linear fit (dotted line) between the adjacent spectral estimates outside of the 30–50 day band. (c) Coherence squared (solid) and phase (dotted) between rainfall and 850 mb zonal wind. The scale for the coherence squared is on the left and the phase on the right (cycles). The horizontal line indicates the 95% confidence limit for the coherence squared. A positive phase indicates rainfall leads wind.

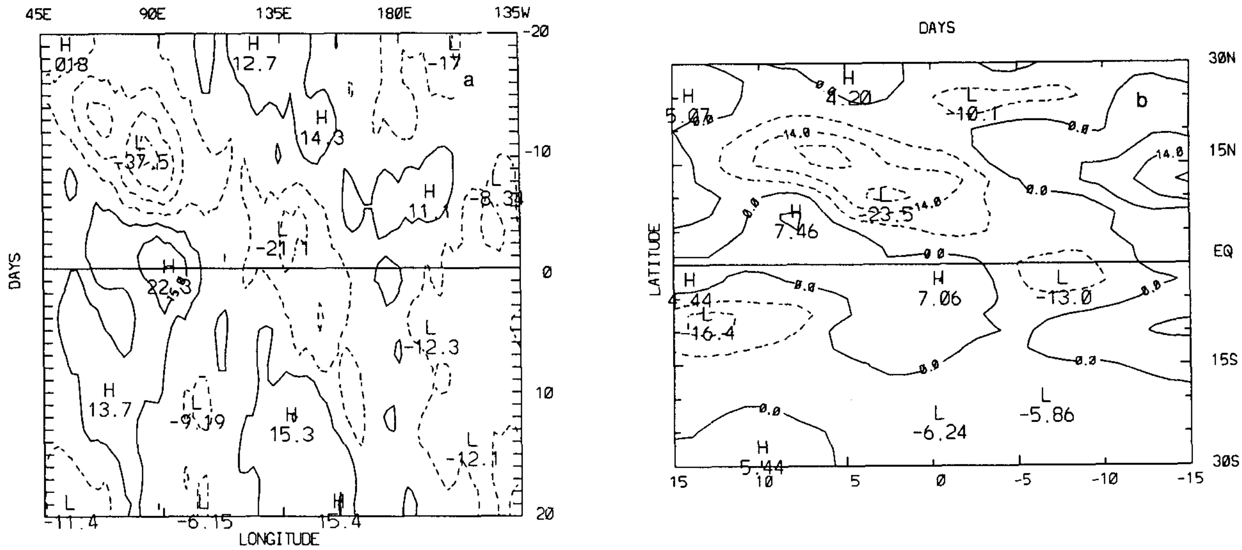


FIG. 15. (a) Composite OLR averaged between the equator and 10°N for all identifiable 40–50 day events at Singapore in the 60 day period preceding onset at Darwin each year (1974–87). (b) Latitude versus time of the composite OLR averaged between 130°E and 145°E. The plotting convention is as in Fig. 12.

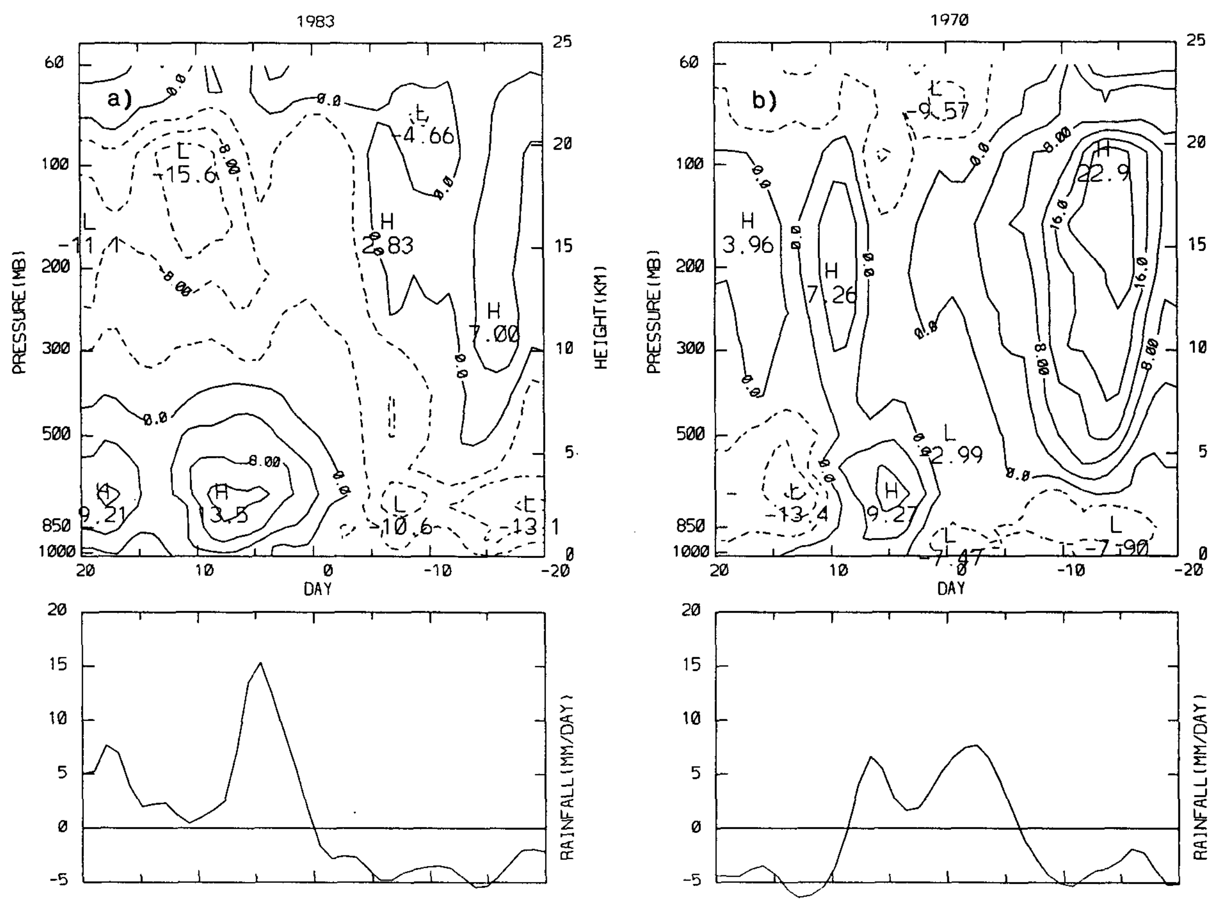


FIG. 16. Zonal wind at Darwin and north Australian rainfall time series for onset in individual years (a) 1983/84 and b) 1970/71. Note time runs from right to left. Day 0 (onset) 5 January 1984 in a) and 2 December 1970 in b). Contour interval is 4 m s^{-1}.

The hypotheses that onset is strongly influenced by the 40–50 day oscillation and is in agreement with Murakami et al. (1986) who also found that onset, in general, occurred in phase with the first intraseasonal OLR fluctuation during southern summer. Murakami et al. also showed that the Australian summer monsoon is highly variable and that onset date reflects this variability. Further comparison to results of Murakami et al. is difficult because only OLR averaged over northern Australia was examined in their study.

Determination of how representative the composite onset is for any given year is difficult. The standard deviation of the composite zonal wind at Darwin is as large as the wind itself (not shown), thus indicating an extremely variable onset evolution. Examination of individual years shows that some years look remarkably like the composite (e.g., 1983, Fig. 16a) while others do not (e.g., 1970, Fig. 16b). We estimate that approximately half of the years closely resemble the composite onset while the other half exhibit variable time scales. Nonetheless, the 30-year composite is remarkably clear, suggesting the dominance of one particular mechanism. With regard to the 40–50 day oscillation, onset during 27 out of 30 years falls within 4 days of the transition of the oscillation as determined by bandpass filtering the zonal wind and rainfall with a 30–60 day half-width filter. This sort of analysis concurs with results from Murakami et al. (1986) but gives no information regarding horizontal structure. Nonetheless, the dominant signal from the composite suggests that onset reflects the passage of the 40–50 day oscillation. Whether or not every onset occurs due to the oscillation is not evident, but the 40–50 day oscillation is clearly an important component of the Australian summer monsoon.

Acknowledgments. Greg Holland kindly supplied the Australian station data. We are grateful to Jackie Gratrix for preparing the manuscript and to the two reviewers for their critical comments. This work was supported in part by NASA Grant NAGW-1138.

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