The tropical circulation in the Australian/Asian region — November 1987 to April 1988

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In this paper a broad summary of the tropical circulation between 70°E and 180°, for the period November 1987 to April 1988, is presented. Analyses of tropospheric flows, sea surface temperatures, tropical cyclone tracks, circulation indices and rainfall data are discussed.

The 1987 El Niño-Southern Oscillation (ENSO) warm event was in decline at the beginning of the period and the Southern Oscillation Index (SOI) remained small through the period. Despite this, some of the circulation anomalies associated with the ENSO event persisted well into the season. The monsoon in the southern hemisphere was weaker than normal, resulting in below average rainfall over north Australia. The weakness of the monsoon was also undoubtedly linked to the historically low level of tropical cyclone activity in the southern hemisphere. The monsoon was characterised by low frequency oscillations in intensity linked to the main weather events.

Over India and the Bay of Bengal the northeast monsoon was weaker than normal; in the southeast Asian sector its onset was later than usual and low frequency oscillations characterised its intensity. Northeastery surges and near equatorial vortices, major weather-producing mechanisms over South-East Asia and the South China Sea, were important elements of the monsoon circulation, the occurrence of northeasterly surges being above the long-term mean.

Introduction

This seasonal summary discusses the tropical circulation in the area of synoptic analysis responsibility of the Darwin Regional Meteorological Centre (RMC). This area ranges from 70°E to 180°. The time-period covers November 1987 to April 1988; that is, the austral late spring to early autumn. As in past seasonal summaries in this series (Kingston et al. 1987; Dixon et al. 1988; Garden et al. 1989) the focus is to identify circulation features which differed significantly from long-term mean flows, which were described by Dixon et al. (1988). Relationships are identified between these anomalies and other abnormalities, and some implications for regional climates discussed.

Firstly Southern Oscillation Index (SOI) values are examined and related to a broadscale description of the monsoon circulation for the season. This is followed by discussions of sea surface temperature (SST) analyses, seasonal flows and anomalies, tropical cyclone occurrences, and the northeast monsoon of South-East Asia. Particular reference is made to low-frequency oscillations and their effect on north Australian and South-East Asian rainfall.

Data sources

Mean wind and mean sea level pressure (MSLP) analyses for the period November 1987 to April 1988, and diagnostic fields derived therefrom, were obtained from the Australian Bureau of Meteorology's automated tropical analysis scheme (Davidson and McAvaney 1981). This produces 12-hourly real-time univariate analyses from surface synoptic, conventional upper air and aircraft observations, and satellite-observed upper wind measurements. Pseudo-observations
are inserted by Darwin RMC where necessary. Climatological mean charts, used as the basis for the wind anomaly charts, were derived from those produced by Atkinson and Sadler (1970) and Sadler (1975). The SST analyses were produced manually from ship and satellite observations and SST anomaly charts were produced by comparison with climatological data from Reynolds (1983). MSLP anomalies were based mainly on charts published in the monthly Darwin Tropical Diagnostic Statement.* These are manually analysed from monthly CLIMAT messages. Where no CLIMAT data were available grid-point anomaly data from Monthly Report on Climate System† and anomaly analyses from Climate Monitoring Bulletin Southern Hemisphere§ were employed for the northern and southern hemispheres respectively. In the section on the northeast monsoon over South-East Asia, winds used in cross-sections and time-series were derived from plotted and manually analysed charts prepared by the Malaysian Meteorological Service (MMS) in the Kuala Lumpur Monsoon Activity Centre. Malaysian rainfall and upper air data were extracted from monthly abstracts published by the MMS.

This data base is considered generally adequate for the purpose of the present summary. The Atkinson and Sadler (1970) and Sadler (1975) upper wind averages were taken over a range of periods varying from under five years to over twenty. Reynolds’s (1983) SST means were computed from surface marine data up to 1976 and are widely referenced. MSLP anomalies over the oceans are based only on objective analyses, produced by the Bureau of Meteorology, Melbourne, Australia (southern hemisphere, period 1977–1986) and Japan Meteorological Agency, Tokyo (northern hemisphere, period not stated). No data were available for a large portion of the Indian Ocean. High cloud anomalies are based on only a seven-year record, which includes the strong ENSO event of 1982–83. This should be taken into account when interpreting the diagrams.

The tropical circulation, November 1987–April 1988

Southern Oscillation
The SOI is a measure of the state of the Southern Oscillation (see e.g. Troup 1965). The formula used in Darwin RMC can be found in Dixon et al. (1988) or Ropelewski and Jones (1987). Figure 1 shows monthly values of the SOI from January 1982 to April 1988, and Fig. 2 shows five-month running means of the SOI up to February 1988. Clearly seen are the major negative excursion of 1982–83 and the weaker event of 1986–87.

![Fig. 1 Monthly SOI, January 1982–April 1988.](image1)

![Fig. 2 Five-month running mean SOI, January 1982–February 1988.](image2)

The monthly SOI fluctuated with small negative values for the whole of the period November 1987 to April 1988, with the exception of March, when a small positive value occurred. The trend in SOI values suggests that the moderate to strong ENSO warm event of 1987 (see e.g. Garden et al. 1989; Wagner 1987) drew to a close during the austral spring. Garden et al. found that this event was at its peak by late autumn and was well into decline by October 1987.

Since the SOI remained small throughout the period it might be expected that seasonal anomaly patterns of SST, MSLP and tropospheric circulation would show characteristics close to long-term means. This was not the case. For example, the summer monsoon was generally poorly developed and the number of southern hemisphere tropical cyclones well below the climatological mean. The northeast monsoon over much of southern Asia was weaker than normal in mean intensity, though there were more northerly surges than normal over South-East Asia.

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*Darwin Tropical Diagnostic Statement, issued by the Northern Territory Regional Office, Bureau of Meteorology, PO Box 735, Darwin 0801, Australia.

†Monthly Report on Climate System, issued by Long-range Forecast Division, Forecast Department, Japan Meteorological Agency, 1–3–4 Ote-Machi, Chiyoda-ku, Tokyo, Japan.

§Climate Monitoring Bulletin, Southern Hemisphere, issued by National Climate Centre, Bureau of Meteorology, GPO Box 1289K, Melbourne 3001, Australia.
O'Lenic (1988) presented time-series of five-month running mean equatorial standardised 850 hPa wind anomaly. For the longitude belt 135°E–180° this parameter was still westerly until at least October 1987, almost one year after its peak westerly value, whereas during the much stronger 1982–83 ENSO event it remained westerly for only five months after reaching its peak. Figures 1 and 2 show a similar effect in the respective monthly and five-month running means of the SOI. These facts suggest that though the 1986–87 ENSO event was not strong it was very slow in decaying, in agreement with Janowiak (1988) who found that the warm event ended during the March-May 1988 season.

**Sea surface temperature and mean sea level pressure**

Figure 3 shows the mean SST distribution and the mean SST anomaly for the six months November 1987 to April 1988. Anomalously warm water covered most of the region. The notable exception was the cool region over the northwest Pacific. The warmest anomalies extended from the Bay of Bengal eastward over the Philippines and northward to Japan as well as affecting parts of the Australian coast.

**Fig. 3** Six-month mean SST (dashed lines) and mean SST anomaly (solid lines) (°C), November 1987–April 1988 (C = cold, W = warm).

Monthly anomaly charts are presented in Fig. 4. Perhaps the most telling feature was that warm anomalies, initially evident over the equatorial west Pacific, had weakened considerably by April 1988, in some parts being replaced by weak cool anomalies. This is consistent with the dissipation of the ENSO event by the end of the period. The seasonal anomaly pattern and the individual monthly patterns for November 1987 to February 1988 are similar to the mature phase composite of Rasmusson and Carpenter (1982).
Charts of MSLP and MSLP anomaly, at 0000 UTC, averaged over the six-month period, are at Figs 5 and 6 respectively. The monsoon trough was best developed over the southwest Pacific where it was a little more intense than normal. Over northwest Australia it was merged with the heat trough and positive anomalies in this area show that it was not as deep as normal. Positive anomalies persisted over Australia, though they weakened significantly from the 1987 winter (cf. Garden et al. 1989). Rasmusson and Carpenter (1982) stated that pressure changes in the central Pacific lead those at Darwin (of opposite sign) by several months. Prolonged positive anomalies in the Australian region are consistent with this observation, particularly in view of the slow decline of ENSO noted earlier. On a monthly basis it was observed that a significant negative anomaly had developed over the east Indian Ocean and Indonesia towards the end of the period, a sign that the monsoon was belatedly becoming better organised following the decline of the ENSO event.

Fig. 5 Six-month mean 0000 UTC MSL pressure (hPa), November 1987–April 1988.

A comparison of Fig. 6 with Fig. 3 corroborates the generally accepted inverse relationship between SST and surface pressure (e.g. Nicholls 1979) in the northern hemisphere, where the major features were persistent through the season. However in the south this relationship was not evident except in the western Pacific. Positive SST anomalies in the southern tropics were strongest west of 150°E. Pressure anomalies were also positive in this area. It appears that local SST anomalies were having little effect on the pressure distribution in the region, which was readjusting in response to larger-scale circulation changes associated with the demise of the ENSO event.

Lower tropospheric flow
Figure 7 shows the long-term mean flow at 950 hPa for the months November to April. Figure 8 shows the 950 hPa wind field for November 1987 to April 1988, and Fig. 9 the vector anomalies for the same period. These figures indicate an inhibited monsoon circulation in the southern hemisphere through the following features.

(a) Over maritime areas the summer monsoon trough axis was displaced north of its mean position and, as indicated by anticyclonic anomalies, was poorly developed.

(b) Weak monsoon westerlies north of the trough imply a weak inflowing branch of the Hadley cell.

(c) Over tropical Australia dominance of a continental heat trough effect, rather than interhemispheric monsoonal flow, is indicated by an enhanced trough near 140°E and the southward displacement over land of an inflow near 130°E.

Anomaly patterns in the northern hemisphere reflected variations in the strength of the subtropical ridge and the low-level branch of the Hadley cell. The Asian northeast monsoon was generally weaker than normal. Increased northerly components in the tropical northwest Pacific may show a stronger Hadley cell near the dateline.

Fig. 6 Six-month mean MSL pressure anomaly (hPa), November 1987–April 1988.

Fig. 7 Climatological six-month mean 950 hPa winds, November–April (after Atkinson and Sadler 1970). Isotachs in m s$^{-1}$.
The six-month vector anomaly pattern of Fig. 9 is broadly similar to the individual monthly patterns and also similar to that of the season twelve months earlier (see Dixon et al. 1988). The difference between the two seasons was that in November 1986 the ENSO event was developing, whereas one year later it was well beyond its peak. The broad westerly anomalies over the tropical west Pacific were similar to the mature phase composite of Rasmussen and Carpenter (1982) and implied that convergence still existed east of the dateline. This was consistent with the low number of southern hemisphere cyclone genesis events west of the dateline, a point examined more closely later.

Figure 10 shows the mean monthly positions of the monsoon trough during the season, compared to 1986–87 and also to climatology. In February 1988, the month when the trough was best developed, it was difficult to distinguish it from the north Australian heat trough. For comparison, Fig. 10 also shows the long-term mean and 1987
heat trough positions in February. As might be expected from the demise of the ENSO event, the monsoon trough was in most months south of the positions for the corresponding months of the 1986–87 season. In the east the trough oscillated about the monthly climatological positions, though the South Pacific convergence zone (SPCZ) (e.g. Trenberth 1976 or Rasmusson and Carpenter 1982) was displaced northeast of the long-term mean (see Figs 7 and 8), a characteristic of ENSO events.

Upper tropospheric flow
Figures 11, 12 and 13 respectively show the 200 hPa long-term mean flow for November to April, the flow for November 1987 to April 1988 and vector anomalies for the same period.

Fig. 11 Climatological six-month mean 200 hPa winds, November–April (After Atkinson and Sadler 1970). Isotachs at 5.0 m s$^{-1}$ intervals.

Fig. 12 Six-month mean 200 hPa winds, November 1987–April 1988. Isotachs in m s$^{-1}$.

Fig. 13 Six-month mean 200 hPa vector anomaly analysis, November 1987–April 1988.

The most obvious feature in the anomaly field in connection with the monsoon is the pattern of westerly to northwesterly anomalies west of 160°E, an area of cross-equatorial easterly to southeasterly mean flow. The meridional component of this flow constitutes the upper tropospheric return branch of the Hadley cell, which was evidently below normal strength. The strong anomalous divergence prominent in 1986–87 (Dixon et al. 1988) east of 160°E was no longer present, though the southeasterly anomalies north of the equator in this region suggest there was still some anomalous, though reduced, upper divergence east of the dateline. The anomalies in the remainder of the tropics were generally small, perhaps reflecting a return towards 'normal' conditions after the ENSO event.

Interactions between the hemispheres
Figure 14 shows a cross-section along the equator of meridional wind for November 1987 to April 1988. The southerly corridors at 94°E and 112°E were on the eastern sides of two equatorial anti-clockwise circulations (see Fig. 8) and extended through middle levels. The long-term mean flow at 950 hPa (Fig. 7) has a northerly component between 70°E and 180°E. This is further evidence that low-level cross-equatorial flow into the southern hemisphere monsoon was below average.

Analyses of velocity potential for the six months November 1987 to April 1988, at 950 hPa and 200 hPa, are at Figs 15 and 16 respectively. Monthly mean high cloud amount and high cloud anomaly for the period are at Figs 17 and 18. They are of cloud tops above 400 hPa, observed by the geostationary satellite GSM–3, based on a 1° × 1° grid. Climatology is 1978–1984, over the oceans only. High cloud amount is accepted as a good indicator of deep convection in the tropics.
Fig. 14 Equatorial cross-section of six-month mean meridional wind, November 1987–April 1988. Isotachs at 5.0 m s$^{-1}$ intervals.

Fig. 15 Six-month mean velocity potential at 950 hPa, November 1987–April 1988. Units 10$^5$ m$^2$s$^{-1}$; negative dashed.

Fig. 16 Six-month mean velocity potential at 200 hPa, November 1987–April 1988. Units 10$^5$ m$^2$s$^{-1}$; negative dashed.

Fig. 17 (a) to (f). Monthly mean high cloud amount from GMS-3, November 1987–April 1988. Contour interval 10%, above 30% stippled.
Figures 15 and 16 suggest that maximum ascent was occurring across Borneo and Sumatra, and into the eastern Indian Ocean, with another branch extending into the southwest Pacific from around Irian Jaya. The monthly high cloud amounts shown in Fig. 17 are in good agreement with areas of likely convection diagnosed by the velocity potential maps. The anomaly patterns in Fig. 18 clearly show the persistent above normal convection near the equatorial dateline. This is consistent with the northeastward displacement of the SPCZ and an eastward displacement of the ascending branch of the Walker circulation. The ENSO warm event was apparently still exerting some control over the circulation in spite of the smallness of the SOI. It seems that continuing warm SST anomalies in the central Pacific (see e.g. Wagner 1987) were still having a significant effect on convection near the dateline but not affecting the broadscale circulation over the eastern Pacific.

Figure 18 also shows reduced convection over much of the southern monsoonal region. The notable exception was March 1988, when a significant positive anomaly appeared between northwest Australia and southern Indonesia, an area affected by two monsoon depressions late in the month. By this time a cool SST anomaly had been replaced by a warm one (see Fig. 4).

Tropical cyclones

The number of genesis events in the southern hemisphere was well below the climatological average, particularly in the Australian region. In the northern hemisphere winter season cyclone activity was near normal.

Tracks of all tropical cyclones analysed in the RMC area from November 1987 to April 1988 are shown in Fig. 19. All northern hemisphere tracks to December 1987, and all southern hemisphere tracks east of 90°E, are based on official best tracks; the remainder represent operational best tracks and are therefore preliminary. Table 1 lists the systems in order of occurrence for each ocean basin, with notional lifetime (tropical cyclone warning duration) and maximum mean surface wind speed.

Northern hemisphere

Five tropical cyclones (Maury, Nina, Ogden, Phyllis, and Roy) developed in the northwest Pacific. Nina was classified as a super typhoon. Both Maury and Ogden made landfall over Vietnam, Ogden as a gale force system and Maury after weakening to a tropical depression. The remaining three followed long westward paths, successively battering the Philippines as typhoon-strength systems before dissipating in the South China Sea. None of these cyclones recurred into
Fig. 19  Tropical cyclone tracks, November 1987–April 1988. Calendar month number in brackets after name at the start of each track.

Tropical depression
Severe tropical cyclone/typhoon

--- Location of maximum intensity

--- Tropical cyclone/storm

Table 1. Tropical cyclones within the Darwin RMC area November 1987–April 1988.

<table>
<thead>
<tr>
<th>Tropical cyclone name</th>
<th>Duration</th>
<th>Maximum wind m s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Indian Ocean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'05B'</td>
<td>31 Oct–3 Nov</td>
<td>28</td>
</tr>
<tr>
<td>'06B'</td>
<td>11 Nov–13 Nov</td>
<td>26</td>
</tr>
<tr>
<td>'07A'</td>
<td>8 Dec–11 Dec</td>
<td>23</td>
</tr>
<tr>
<td>'08B'</td>
<td>20 Dec–21 Dec</td>
<td>18</td>
</tr>
<tr>
<td>Western north Pacific</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maury</td>
<td>16 Nov–19 Nov</td>
<td>23</td>
</tr>
<tr>
<td>Nina</td>
<td>19 Nov–29 Nov</td>
<td>75</td>
</tr>
<tr>
<td>Ogden</td>
<td>24 Nov–25 Nov</td>
<td>18</td>
</tr>
<tr>
<td>Phyllis</td>
<td>11 Dec–19 Dec</td>
<td>51</td>
</tr>
<tr>
<td>Roy</td>
<td>8 Jan–18 Jan</td>
<td>49</td>
</tr>
<tr>
<td>South Indian Ocean (west of 105°E)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>'01S'</td>
<td>2 Nov–5 Nov</td>
<td>23</td>
</tr>
<tr>
<td>Ariny</td>
<td>10 Dec–14 Dec</td>
<td>33</td>
</tr>
<tr>
<td>Frederic (Ezenina)</td>
<td>30 Jan–2 Feb</td>
<td>44</td>
</tr>
<tr>
<td>Gwenda</td>
<td>7 Feb–15 Feb</td>
<td>46</td>
</tr>
<tr>
<td>Gasitao</td>
<td>16 Mar–23 Mar</td>
<td>49</td>
</tr>
<tr>
<td>Australia (105°E–165°E)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agi</td>
<td>11 Jan–14 Jan</td>
<td>26</td>
</tr>
<tr>
<td>Charlie</td>
<td>23 Feb–1 Mar</td>
<td>31</td>
</tr>
<tr>
<td>South Pacific (165°E–180°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anne</td>
<td>8 Jan–14 Jan</td>
<td>51</td>
</tr>
<tr>
<td>Bola</td>
<td>26 Feb–4 Mar</td>
<td>46</td>
</tr>
<tr>
<td>Dovi</td>
<td>9 Apr–15 Apr</td>
<td>31</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Tropical storms and typhoons</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typhoons</td>
<td>3 (2.6)</td>
<td>1 (1.3)</td>
<td>1 (0.7)</td>
<td>0 (0.3)</td>
<td>0 (0.2)</td>
<td>0 (0.7)</td>
</tr>
<tr>
<td>Tropical storms</td>
<td>1 (1.7)</td>
<td>1 (0.7)</td>
<td>1 (0.2)</td>
<td>0 (0.1)</td>
<td>0 (0.2)</td>
<td>0 (0.5)</td>
</tr>
</tbody>
</table>
Southern hemisphere

Table 3 lists the monthly distribution of southern hemisphere tropical cyclones within the Darwin RMC area, and Table 4 the annual distribution by ocean basin. Note that the long-term averages in these tables also include cyclones westward from the RMC boundary to the east coast of Africa, an area for which November 1987 to April 1988 data were unavailable.

Table 3. Monthly frequency (November 87–April 88) of southern hemisphere tropical cyclones 70°E–180°. (Note: long-term averages after JTWC Guam 1987) also include cyclones between 70°E and the east coast of Africa.)

<table>
<thead>
<tr>
<th>Number of cyclones 1987/88</th>
<th>1959–87 average (Africa–180°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov</td>
<td>1</td>
</tr>
<tr>
<td>Dec</td>
<td>1</td>
</tr>
<tr>
<td>Jan</td>
<td>3</td>
</tr>
<tr>
<td>Feb</td>
<td>3</td>
</tr>
<tr>
<td>Mar</td>
<td>1</td>
</tr>
<tr>
<td>Apr</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4. Annual frequency of southern hemisphere tropical cyclones by ocean basin (after JTWC Guam 1987). (Note: south Indian average also includes cyclones between 70°E and the east coast of Africa.)

<table>
<thead>
<tr>
<th>Basin</th>
<th>Nov 87–Apr 88</th>
<th>Annual average (1959–87)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Indian (west of 105°E)</td>
<td>5</td>
<td>9.3</td>
</tr>
<tr>
<td>Australian (105°E–165°E)</td>
<td>2</td>
<td>10.5</td>
</tr>
<tr>
<td>South Pacific (165°E–180°)</td>
<td>3</td>
<td>5.8</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
<td>25.6</td>
</tr>
</tbody>
</table>

Only two cyclones, *Agi* and *Charlie*, formed in the Australian region, both in the Coral Sea. *Charlie* caused agricultural damage on landfall on the Queensland coast. Three cyclones, *Anne*, *Bola* and *Dovi*, occurred in the South Pacific region. Of these *Anne* and *Bola* were hurricane-force systems responsible for destruction and loss of life when they crossed New Caledonia and Vanuatu respectively. The south Indian Ocean was the most active of the three regions with cyclones in all months except April. Of the five tabulated systems there, four intensified to hurricane force.

Comparison with long-term statistics (Joint Typhoon Warning Center 1987) shows that ten tropical cyclone occurrences during the 1987–88 season was the lowest number on record for the reliably observed 30-year period 1959–1988.

Table 4 indicates that activity was particularly suppressed in the Australian region. (Note in Table 4 that the annual averages include cyclones in the months May to October, a total of 1.1 cyclones per year.) For comparison, there were 25 cyclones observed during November to April of the 1982–83 major El Niño year (7 in the south Indian Ocean, 6 in the Australian region, and 12 in the South Pacific), approximately equal to the annual mean.

Using the definition of Nicholls (1985), the total number of ‘cyclone days’ within 105°E–165°E during November 1987 to April 1988 was 14 (*Agi* 5 days, *Anne* 2 days, *Charlie* 7 days) compared with the 25-year annual average of 55 days. This was the lowest number since the 1940–41 season (Nicholls 1985) and is all the more significant when it is noted that detection of cyclones was poorer then (the seasonal mean number of recorded cyclone days was approximately 20 before 1950). This number may also be compared with the 1982–83 El Niño year when there were 6 tropical cyclones in the region for 33 cyclone days. These two seasons were the only occasions when no cyclones occurred in the northern region (125°E–142°E). The November 1987 to April 1988 season was the first during which no cyclones were observed in the western region (105°E–125°E) in 79 years of record (Lourensz 1981), although one cyclone (*Herbie*) occurred in May 1988.

Based on the mean 9 am July-August-September 1987 pressure at Darwin of 1016.2 hPa, a regression formula (Nicholls 1985) predicted a below average 37 cyclone days for the 1987–88 season. This was a substantial overestimate, though it fell within the range of prediction uncertainty of that equation.

Clearly, the dearth of cyclone occurrences in the southern hemisphere cannot be attributed solely to the influence of the declining moderate El Niño event of 1986–87. Different factors appear to have operated in different areas, and no single factor can be identified which would explain the extraordinarily low number of genesis events.

Over most of the Australian region and the east Indian Ocean the general weakness of the monsoon circulation appears to have been a major contributor. Love (1982) related the genesis of tropical cyclones to surges in the summer monsoon; it is reasonable to suppose in this case that surge activity was below normal during the 1987–88 season. Comparison of the monsoon trough position during the season (Figs 8 and 10) with maps of initial disturbance location (refer e.g. Gray 1967; Love 1982) shows the trough to have been generally well north of the preferred areas of genesis, which are related to the mean monsoon trough position. This suggests that the trough latitude itself may have been a significant factor: convective clusters which may have developed on
or near the trough were subject to a reduced coriolis parameter. Finally, examination of mean velocity potential charts (Fig. 15) reveals that low-level divergence was analysed over the Indian Ocean northwest of Australia, another preferred genesis area. Figures 6 and 9 display anomalous ridging in this region.

Despite the eastward shift of the Walker circulation and associated persistence of a favourable upper-level outflow, tropical cyclone occurrence in the summer hemisphere east of 160°E was also below average. Garden et al. (1989) noted that a cool SST anomaly migrated west to Vanuatu during the 1987 southern winter. Figure 4 shows that anomalously cool SST existed in favoured genesis areas of the southwest Pacific and off the northwest Australian coast for a large proportion of the 1987–88 cyclone season. It is likely that this was also a factor inhibiting cyclogenesis.

Northeast monsoon over South-East Asia

This section covers the months October 1987 to March 1988. These months may be considered as the normal northeast monsoon season in South-East Asia. The section focusses particularly on the season in Malaysia where the northeast monsoon has a major impact.

The northeast monsoon onset was later than usual in Malaysia and the monsoon trough fluctuated in intensity and latitude throughout the season. This led to dry conditions in eastern Peninsular Malaysia in some months though the rest of Malaysia received normal rainfall for the season. Northeasterly surges were active throughout the period and 10 to 20-day oscillations were prominent. The number of near-equatorial vortices was close to normal.

Onset of the northeast monsoon

An objective definition of northeast monsoon onset applicable to all of South-East Asia (north of the equator) is the time at which the 850 hPa and 700 hPa zonal wind components become easterly and remain so for at least 20 days during the month that follows. Based on this criterion it was found that onset occurred on 3 October 1987 over the northern Philippines and 6 October over central Thailand. It then advanced southward reaching the southern Philippines on 12 October, and northeastern Borneo and Peninsular Malaysia on 1 December before developing over northwestern Borneo on 10 January 1988. Onset normally occurs along the northeast coast of Peninsular Malaysia in mid-November, arriving at the southern peninsula around early December. On the northwestern coast of Borneo onset is normally not until late December (Cheang 1980). Figure 20
depicts the monsoon onset at seven South-East Asian centres during 1987–88.

Figure 21, which is a latitude/time cross-section of 850 hPa zonal wind along longitude 103°E, clearly depicts the onset over Indo-China. After onset, the monsoon trough moved southward but disappeared intermittently before re-forming near the equator early in November and retreating north for the rest of that month. After November the trough fluctuated nearer the equator. Figure 10 shows that the trough was well north of its mean position for November, suggesting the late monsoon onset in Malaysia. Cheang (1987) observed that the monsoon trough advanced steadily equatorward during October/November of strongly positive SOI (anti-El Niño) years whereas it disappeared frequently during the same months of strongly negative SOI (El Niño) years, when zonal easterlies prevail throughout South-East Asia for extended periods. The behaviour of the monsoon trough during the 1987 onset, when it began to prevail over South-East Asia only in November, zonal easterlies having dominated during October, is thus consistent with a near-zero SOI.

Chang et al. (1979) to play an important role in enhancing near-equatorial disturbances over the South China Sea.

Cheang (1980) defined a northerly surge over the South China Sea as an increase in the average northerly wind component of at least 2.5 m s⁻¹ to an average speed of not less than 7.5 m s⁻¹ within 24 to 48 hours. The increase must begin in the northern region of the South China Sea and be associated with a surface pressure increase over China. Table 5 depicts the frequency of occurrence of surges by latitudinal zone and month (November 1987 to March 1988) compared with the long-term mean frequency computed from a 20-year record. The incidence of northerly surges over the South China Sea was close to normal in November 1987 and generally above normal from December 1987 to March 1988. Northerly anomalies were evident at gradient level in this area (Fig. 9).

Table 5. Occurrence of northerly surges over the South China Sea during November 1987–March 1988. Figures in brackets denote long-term averages.

<table>
<thead>
<tr>
<th></th>
<th>20°–15°N</th>
<th>15°–10°N</th>
<th>10°–5°N</th>
</tr>
</thead>
<tbody>
<tr>
<td>November</td>
<td>5 (5.6)</td>
<td>4 (4.2)</td>
<td>3 (2.3)</td>
</tr>
<tr>
<td>December</td>
<td>7 (5.9)</td>
<td>6 (4.8)</td>
<td>6 (3.7)</td>
</tr>
<tr>
<td>January</td>
<td>6 (6.1)</td>
<td>6 (4.8)</td>
<td>6 (3.6)</td>
</tr>
<tr>
<td>February</td>
<td>5 (3.8)</td>
<td>4 (2.8)</td>
<td>2 (1.8)</td>
</tr>
<tr>
<td>March</td>
<td>5 (1.9)</td>
<td>2 (1.5)</td>
<td>2 (0.9)</td>
</tr>
<tr>
<td></td>
<td>28 (23.3)</td>
<td>22 (18.1)</td>
<td>19 (12.3)</td>
</tr>
</tbody>
</table>

Weather systems
The systems that bring wet spells to South-East Asia are the monsoon trough, near-equatorial cyclonic vortices and tropical easterly waves (Cheang 1987). Only the first two of these classes of system are discussed here.

Figure 10 shows the monthly positions of the monsoon trough from November 1987 onward while Fig. 21 depicts its behaviour during the onset period. Rainfall over Peninsular Malaysia, especially along the east coast, was below normal during November 1987 and January–February 1988. This was probably due mainly to the location of the monsoon trough away from the region during these months, when it retreated over northern Borneo, leaving cross-equatorial northeasterlies over the peninsula. Lim and Quah (1978) found that this feature was associated with dry conditions over Peninsular Malaysia.

Table 6 depicts the frequency of occurrence of near-equatorial cyclonic vortices which appeared at 850 hPa and 700 hPa over Malaysia and the South China Sea, from November 1987 to March
1988, compared with long-term averages. A near-equatorial vortex is counted as such from the day it first appears in the 850 hPa and 700 hPa wind fields over the Malaysia-South China Sea region, until it either dissipates or moves westward to the Bay of Bengal. Occurrences in 1987–88 were close to normal. Although January is normally the month of least occurrence of these systems, the number observed in January 1988 was equal to the lowest recorded. As already noted, January 1988 produced below normal rainfall in Peninsular Malaysia. Figure 18(c) shows an anomalously low amount of high cloud in this region for January 1988.

Table 6. Occurrence of near-equatorial vortices over the Malaysia-South China Sea region during November 1987–March 1988 compared with long-term averages.

<table>
<thead>
<tr>
<th>1987/1988 actual</th>
<th>Long-term Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>November</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>December</td>
<td>4</td>
<td>4.5</td>
</tr>
<tr>
<td>January</td>
<td>2</td>
<td>3.4</td>
</tr>
<tr>
<td>February</td>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>March</td>
<td>5</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>22.2</td>
</tr>
</tbody>
</table>

Most of the vortices developed in situ over the northern Borneo-South China Sea region. Only seven out of the total of 23 vortices originated over the west Pacific and six of these occurred in November 1987. Three of the disturbances which originated over the west Pacific developed from easterly waves.

Low frequency (10 to 20-day) oscillations
Yap et al. (1982) found that the 10 to 20-day wet and dry cycle over the South China Sea-Malaysia region during the 1978–1979 northern winter monsoon was strongly influenced by the major cold surges which occur on a 10 to 20-day time-scale; the weaker surges occur on a 4 to 5-day time-scale (Murakami 1979).

To examine oscillations of this mode, a recursive 10 to 20-day band-pass filter was applied to time-series of: (a) average surface pressure in China, (b) surface pressure in Hong Kong, (c) surface pressure in Kota Bharu (6°N, 102.5°E) and (d) daily total rainfall at four stations along the east coast of Peninsular Malaysia, where 50 to 60 per cent of annual rainfall is received during the northeast monsoon. These filtered series are graphed in Fig. 22. The raw series are also shown.

Ten to 20-day oscillations are very distinct in the filtered series of surface pressure and rainfall. The four filtered series are approximately in phase from November 1987 onward, though the rainfall series displays some phase variation. China surface pressure series lead Hong Kong surface pressure series by 2–3 days whereas the latter leads Kota Bharu surface pressure and rainfall series by one day. The peaks in China and Hong Kong surface pressure are associated with cold outbreaks over Siberia, the influence of which, spreading to the equatorial region, is clearly shown by the Kota Bharu surface pressure. During October and early November 1987 the major rain spells along the east coast of Peninsular Malaysia coincided with periods of lower pressure in Kota Bharu. The reverse is true after late November 1987. This different relationship can be explained by the fact that the major rain spells during October and early November 1987 were mainly associated
with the vortices in the nearby monsoon trough. On the other hand, after the onset of the northeast monsoon around the end of November, northerly surges associated with cold outbreaks over China were the main factors which enhanced equatorial convection.

Oscillations in the northwest monsoon and north Australian rainfall

A measure of the strength of monsoon surges through Indonesia and north Australia used in the Darwin RMC is the MSL pressure difference between Singapore and Darwin. A strong positive difference is associated with a well-developed monsoon trough lying near or south of Darwin. Figures 23 and 24 show 5-day running means of the Singapore-Darwin pressure difference, and Darwin 850 hPa zonal wind respectively.

Figure 23 clearly displays an oscillation with a period of 20–30 days, similar to that described by Murakami (1979) over the Bay of Bengal, Malaysia and the South China Sea, using geopotential data. The major peaks suggest oscillations in the 30 to 50-day mode. Such oscillations were found by Yasunari (1979), Cheang et al. (1981) and Krishnamurti and Subrahmanyan (1982) to be associated with the active and break cycles of the summer monsoon in southern Asia. The oscillations are less obvious in the 850 hPa series but still show phase agreement with the pressure difference series. A peak in the pressure series during February produced only weak westerly flow at Darwin. The monsoon trough remained rather inactive; it was linked to the heat trough which was broad and not well-defined, resulting in only a weak pressure gradient.

Comparison of the Singapore-Darwin pressure difference can also be made with time-series of rainfall at Darwin, and with area weighted weekly north Australian district average rainfall. The rainfall series are graphed at Figs 25 and 26 respectively. The districts used comprise all of mainland Australia lying north of latitude 20°S.

Fig. 25 Darwin daily rainfall, 1 November 1987–30 April 1988.

Fig. 26 Area weighted weekly district average rainfall for 14 north Australian rainfall districts, 29 October 1987–4 May 1988.

The district average rainfall time-series closely follows the three-peak pattern of the pressure difference series, suggesting that the monsoonal rainfall was strongly influenced by low frequency oscillations of the monsoon circulation.

Figure 27 shows a histogram of area weighted district average monthly rainfall, for November 1987 to April 1988, over the same districts as in
Fig. 26. Rainfall was below average for most of the season, particularly the peak monsoon months of January and February. The above average rainfall for December was related to the early onset of the monsoon, a transient feature.

Fig. 27. Area weighted monthly district average rainfall for 14 north Australian rainfall districts (solid) compared to climatology (hatched), November 1987-April 1988.

Finally, it is of interest to compare the Singapore-Darwin pressure difference behaviour with Figs 22(a) to (c). The Singapore-Darwin maxima in December, January and February occurred about two days, four days and one day respectively after actual maxima at Kota Bharu. There appeared little relationship between the raw Kota Bharu data and the 5-day mean differences for Singapore-Darwin after 11 February, though a peak in the latter occurred about two days after one in the filtered series at Kota Bharu on 25 March. The inference is that northerly surges of the northeast monsoon in the winter hemisphere did not exert a strong influence on the southern summer monsoon, consistent with earlier conclusions based on wind anomalies.

Summary
Though the SOI was small the mature phase of the 1986–87 ENSO event had some influence on the circulation in the Darwin RMC area during the period November 1987 to April 1988, particularly in the first half of the season. The Hadley circulation was below normal strength and the ascending branch of the Walker circulation was displaced east of its normal longitude. Warm SST anomalies in the central Pacific apparently still exerted some influence on convection near the dateline, despite the smallness of the SOI. The summer monsoon, although having an early onset in northern Australia, fluctuated in strength and was less developed than normal. This, together with the northerly displacement of the monsoon trough, affected southern hemisphere tropical cyclone activity which was very much below normal for the season. Low frequency oscillations were prominent in the intensity of the summer monsoon circulation and were strongly linked to the main weather events.

In the northern hemisphere the northeast monsoon was below normal strength west of 110°E. Further east it was near normal strength though its onset was delayed. Northerly surges of the monsoon were linked to a stronger than normal subtropical ridge over eastern China. Low frequency oscillations were linked to the main South-East Asian weather events. Fluctuations in the northeast monsoon through south Asia had little influence on the intensity of the northwest monsoon in the southern hemisphere.

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