The tropical circulation in the Australian/Asian region - May to October 1987: the declining influence of a moderate El Niño event

G.S. Garden, M.A. Bergin, I.J. Butterworth and G.J. Kingston
Regional Office, Bureau of Meteorology, Darwin, Australia
and
B.K. Cheang and H.V. Tan
Malaysian Meteorological Service, Kuala Lumpur, Malaysia

(Manuscript received June 1988; revised December 1988)

A synoptic overview of the tropical circulation between 70°E and the dateline is presented for the period May to October 1987, encompassing the northern summer monsoon and the southern hemisphere winter. Analyses of upper and lower tropospheric flow, sea surface temperature, cyclone tracks, circulation indices and rainfall data over South-East Asia, India and Australia are discussed.

A moderate El Niño warm event in its declining phase appeared to exert a broad influence over the area during the period. The ascending arm of the Walker cell was displaced eastward to the dateline. Summer monsoon onset over India and Asia was late and weaker than normal. Monsoon rainfall was well below normal. Winter rainfall over Indonesia, Papua New Guinea and parts of the southwest Pacific was suppressed. On the other hand, cyclone activity in the northwest Pacific was average, although the area of genesis was displaced eastward. Low-frequency oscillations in the 30 to 50-day mode were found to be distinct in the pressures and upper winds of South-East Asia and the west Pacific.

Introduction

This paper is the third in an ongoing series of seasonal climate summaries of the tropical circulation within Darwin Regional Meteorological Centre’s (RMC) area of responsibility (70°E-180°). Emphasis is focussed on the area between 20°S and 20°N. The time-period encompasses the boreal summer monsoon and the austral winter.

The aim of the review is to diagnose significant circulation anomalies from long-term mean climatology and identify their impact upon regional climate. Aspects of the mean lower and upper-level flow are first discussed and an overview of the 1986/87 El Niño-Southern Oscillation (ENSO) or warm event is presented. Large-scale anomalies of sea surface temperature (SST), pressure and wind during May-October 1987 are then described in the context of the moderate ENSO episode that prevailed. Finally, a number of regional features are discussed: tropical cyclone activity, the monsoon and rainfall over South-East Asia and India, and Australian rainfall.

Mean wind analyses and derived fields are from the non-operational but real-time automated tropical analysis scheme (Davidson and McAvaney 1981) run by Darwin RMC. Vector anomalies are from climatological mean winds presented in Atkinson and Sadler (1970) and Sadler (1975). SST analyses are based on manually drawn charts using ship and satellite data. Weekly analyses stored in 5°x5° grid-point form were used to generate monthly mean fields; anomalies are departures from the SST climatology of Reynolds (1983).
For the discussion of the southwest monsoon over South-East Asia, winds used in time-series and cross-sections were derived from plotted and manually analysed surface and upper air charts prepared by the Malaysian Meteorological Service. Rainfall data for Singapore and Thailand were supplied by the Meteorological Services of the two countries. Malaysian rainfall and upper air data were extracted from monthly abstracts published by the Malaysian Meteorological Service. Rainfall data for Indonesia and the Philippines were extracted from synoptic messages.

As background to the anomaly fields presented herein, broad features of the large-scale flow will be briefly noted. Figure 1 shows the long-term mean six-month May to October low-level (950 hPa) flow. Wintertime southeast trade winds flow equatorward from the southern hemisphere subtropical ridge located along 30°S. The mean South Pacific convergence zone (SPCZ), indicated by cross-hatching, stretches from the Solomon Islands to 10°S, 180° and beyond the dateline. This is an area of weak streamline confluence but significant downstream speed convergence. West of Papua New Guinea, southeast trades turn along the near-equatorial trough and form the southwest monsoon current flowing towards the summertime monsoon trough (from northern India to east of the Philippines). On a monthly basis, the monsoon trough does not extend into the northwest Pacific until July, although the trade wind intertropical convergence zone (ITCZ) to the east is well defined during the whole period. The Asian monsoon trough is furthest north (into central China) during July-August, and migrates rapidly equatorward to 10°-15°N during October. Easterly winds from the Pacific anticyclone decline in strength after May-June.

In the upper levels (200 hPa, refer Fig. 2), the northern hemisphere subtropical ridge overlays the Asian surface trough. The tropical upper tropospheric trough (TUTT) along approximately 20°N extends to 140°E during its most active months of June-September. The subequatorial ridge lies southwest of the TUTT and, on average, its axis lies north of the surface trough/ITCZ. Major centres of outflow are located over Bangladesh and the Solomon Islands. Strong northeast cross-equatorial flow streams from the northern to southern hemisphere. The winter subtropical jetstream is much stronger and more extensive than its summer hemisphere counterpart.

**Fig. 2** Climatological mean 200 hPa streamline analysis for May-October (after Atkinson and Sadler 1970). Isotachs in m s⁻¹.

### The Southern Oscillation

Many observational and modelling studies have shown that significant correlations exist between ENSO events and broadscale circulation anomalies, especially in the Pacific and eastern Indian Oceans (e.g. Selkirk 1984). In particular, ENSO warm events are well correlated with negative excursions of the SOI.

Values of the Troup SOI (Troup 1965) between May and October 1987 are listed in Table 1 (earlier values of SOI from January 1982 were graphed in Dixon et al. (1988)). The trend towards zero during the period (from a minimum of -22 in April 1987) suggests a corresponding decline in the life cycle of the ENSO event. This conclusion is confirmed by the behaviour of other circulation parameters during the period.

<table>
<thead>
<tr>
<th>Month</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOI</td>
<td>-20</td>
<td>-18</td>
<td>-18</td>
<td>-13</td>
<td>-11</td>
<td>-7</td>
</tr>
</tbody>
</table>
Figure 3, showing a graph of normalised Darwin pressure anomaly from May 1986 to March 1988, places the 1986/87 event in perspective. This index, calculated as a three-month running mean with each month normalised by the standard deviation, is highly correlated with Troup's SOI. Graphs of the same index for the extreme warming of 1982/83, and for the six-event composite from Rasmusson and Carpenter (1982) are provided for comparison. For the latter, note that all six events displayed the same phase with respect to the seasons, so compositing was done by simple averaging of corresponding months. Numbers on the composite curve denote the five successive phases of central and eastern Pacific SST anomalies (antecedent, onset, peak, transition and mature).

Fig. 3 Darwin normalised pressure anomaly (three-month running mean) during ENSO events. Heavy solid line (after Rasmusson and Carpenter 1982) is for the classical six-event composite; numbers 1-5 identify antecedent, onset, peak, transition and mature stages respectively. Thin solid line is for 1986/87 event, peaking in 1987. Dashed line is for 1982/83 event, peaking in early 1983.

The amplitude of the composite curve is smallest, being an average of three major and three minor events. The amplitude of the 1986/87 curve exceeds two standard deviations, which suggests this event should be described at least as moderate. Wagner (1987) referred to it as 'moderately strong'.

Another major feature of Fig. 3 is the six-month phase displacement of the 1986/87 curve. Here the index peaks during March/April cf. August/September in the composite. Therefore any comparison of anomalies with the Rasmusson and Carpenter (1982) composite involves a background flow in 1986/87 that is half a year out of step with the composite background. This effect is exacerbated west of the dateline where major seasonal flow reversals take place in association with onset of the Asian monsoon.

It is unclear whether or not comparing anomalies under these circumstances is valid. Selkirk (1984) calculated seasonally stratified correlations of zonal and meridional 200 hPa wind anomaly with SOI, revealing that while strong correlations existed over the Darwin RMC area during September-February, generally weaker correlations were evident during the months March-August. This suggests that the above comparison of anomalies may not be valid; certainly, some difficulty occurred in reconciling three-month means during May to October 1987 with the composite ENSO.

Trenberth and Shea (1987) have noted that in earlier 30-year periods of SOI the tendency for El Niño events to show the same relative phase does not always occur. The secular SOI time-series is therefore an aperiodic one. It is perhaps unfortunate that the influential Rasmusson and Carpenter composites coincided with a period when the phases tended to match. Subsequent events (1982/83 and 1986/87) both deviated noticeably from the composite model.

Tropical circulation — May to October 1987

MSL pressure and sea surface temperature
Mean sea level (MSL) 0000 UTC pressure averaged over the six-month period, and mean MSL pressure anomaly charts, are shown in Figs 4(a) and (b). The absence of a 0000 UTC MSL pressure climatology necessitated manual averaging of six charts of routinely prepared monthly mean pressure anomaly. Data for these individual analyses were based primarily on mean station data received in Darwin RMC. Over the sea, anomalies were based on deviations of objective numerical analyses from automated analysis climatologies (provided by the Melbourne World Meteorological Centre and Japan Meteorological Agency).

The MSL pressure anomaly field shows higher than normal pressure over almost all the Darwin RMC area. The southern hemisphere subtropical ridge was much stronger than average. Anomalies greater than +1 hPa dominated the tropics in the vicinity of the maritime continent (Indonesia/ Papua New Guinea), and over India and southern China at the location of the monsoon trough. The only areas of below normal pressure were at equatorial latitudes near the dateline, and in the data sparse Indian Ocean area west of 90°E.

Figure 5 shows the corresponding six-month mean SST and SST anomaly fields. Examination of monthly SST anomaly charts revealed that broadscale features in Fig. 5 displayed remarkable persistence during the entire period. Anomalously warm SSTs up to 1.5°C dominated the Indian Ocean, the South China Sea and the
Australian seaboard. Cool anomalies characterised the North Pacific and equatorial South Pacific. Temperatures near Fiji became progressively cooler during the period, and this cool anomaly migrated slowly west towards Vanuatu, SST around and eastward of the South China Sea and Philippines area maintained a consistent positive anomaly, which approached 2°C during the last two months of the period.

It may at first appear difficult to reconcile the pressure anomaly and SST anomaly fields, given the generally recognised inverse correlation between pressure and SST (e.g. Nicholls 1979). However, in the central and eastern Pacific beyond the range of Darwin RMC analyses, very substantial SST warming was occurring in association with a well-developed ENSO event (Climate Diagnostics Bulletins, May-October 1987*). One manifestation of such events is a weaker than normal Walker circulation. It would appear that pressure anomalies over the RMC area were being forced by displacement of the larger scale circulation associated with ENSO, effectively swamping any atmospheric response to local SST anomalies.

Earlier circulation summaries by Kingston et al. (1987) and Dixon et al. (1987) identified antecedent, onset and peak phases of the current ENSO event from June 1986 to April 1987. A comparison of Fig. 5 with the Rasmusson and Carpenter (1982) composite suggests that the pattern of cooling over the southwest Pacific and mid-latitude northwest Pacific with warming near the equatorial dateline is consistent with the peak phase. However, west of longitude 180°, SST anomalies in their composite charts are weakest and such pattern matching over a limited subset of the Pacific domain may be misleading. Indeed, based on analyses covering the entire Pacific, Wagner (1987) characterised the period March-May 1987 as the 'mature phase' of ENSO.

Low-level flow
Charts of 950 hPa vector wind anomaly for May-June-July (MJJ) and August-September-October (ASO) 1987 are presented in Figs 6(a) and (b) respectively. Evident are some clearly defined anomalous airflows. The most significant was a large area of westerly anomalies extending across the equatorial Pacific towards 180°, indicating anomalous convergence in the vicinity of the dateline. This reflected a northeastward displacement of the SPCZ from its mean position in the southern hemisphere, combined with the persistence of a well-developed ITCZ/monsoon trough along 5°N to beyond the dateline (cf. the long-term mean easterly wind regime depicted in

*Climate Diagnostics Bulletin, available from Climate Analysis Center, NOAA/NWS/NMC, Room 605, World Weather Building, Washington DC 20233, USA.
Fig. 1). For most of the period the SPCZ was linked with a near-equatorial trough at low levels.

These westerly anomalies, together with those over Papua New Guinea, northern Australia and south of Indonesia, cover areas where seasonal southeast or northeast winds prevail, so the trades were typically weaker than normal. The only area of enhanced southeast trades was south of the SPCZ, although this feature decreased significantly from MJJ to ASO 1987.

Comparison of Figs 6(a) and (b) with the wind anomaly composites of Rasmusson and Carpenter (1982) makes it difficult to categorize the ENSO event during May-October 1987 with the same phase as the SST anomaly pattern. Eastward contraction of both westerly anomalies north of the equator and easterly anomalies over the southwest Pacific from MJJ to ASO indicate a move from the transition to mature phase of the event. (Note that in contrast to SSTs, wind anomaly composites west of the dateline normally show very strong ENSO signals.)

Further west, easterly wind anomalies dominated South-East Asia and India, opposing the summer monsoon flow. A ridge of anticyclonic anomalies overlaid the mean monsoon trough in both MJJ and ASO, indicating a much weaker monsoon than normal. This is consistent with episodes of large positive Darwin pressure anomalies (Shukla and Paolino 1983).

Upper tropospheric flow
Charts of 200 hPa vector wind anomaly for MJJ and ASO are shown in Figs 7(a) and (b). The large area of anomalous westerly flow equatorward of latitude 20° from Indian longitudes to Papua New Guinea longitudes is striking. This pattern was associated with considerably reduced strength of the equatorial easterly jet (Fig. 2 shows that wind speeds are normally in excess of 15 m s⁻¹ within the outflow jet during the summer monsoon). Cross-equatorial upper return flow above the surface monsoon stream was well below average.

Fig. 7(a) Mean 200 hPa vector wind anomaly for May-July 1987.

Fig. 7(b) Mean 200 hPa vector wind anomaly for August-October 1987.

Over Asia, significant westerly anomalies north of 30°N were a result of the northern subtropical jet stream being both stronger than normal and displaced about 5 latitude degrees south of its
mean position. This suggests that baroclinic processes played a more important role in the 1987 Asian summer monsoon season than usual. Westerly anomalies over northern Australia were due to northward displacement of the southern hemisphere subtropical ridge.

Large cyclonic anomalies superimposed over the average position of the northwest Pacific TUTT during MJJ 1987 show a much more active trough than in the mean. Later in the season (ASO), the TUTT returned to near normal.

The anticyclonic anomaly pair near the dateline indicates an eastward displacement of enhanced upper outflow in both hemispheres into the central Pacific, characteristic of ENSO events (e.g. Arkin 1982). Associated with this was eastward translation of the upward branch of the Walker cell to the vicinity of the dateline. In Fig. 7(b) the northern hemisphere anomaly appears to weaken during ASO, consistent with a decline of the El Niño.

It is possible to identify those anomalies at 200 hPa which may be directly attributable to ENSO. Selkirk (1984) showed that during periods of negative SOI, significant easterly anomalies would be expected along the equator near the dateline, and over southwest Western Australia; significant westerly anomalies would be diagnosed over Japan, northern India and just southwest of Java/Sumatra. Comparison with our Figs 7(a) and (b) would therefore suggest that observed easterly anomalies in the southern Indian Ocean and equatorial Pacific were responses to El Niño forcing, while westerly anomalies over the equatorial Indian Ocean, northern Australia and within the northern hemisphere subtropical jet were only partially forced by the ENSO event.

**Interhemispheric interactions**

An equatorial cross-section of meridional wind is shown in Fig. 8, averaged over the six months May to October 1987. This chart is very similar to individual three-month means (MJJ and ASO). Comparison with the June-August long-term mean shown in Kingston et al. (1987) indicates that both low-level and upper-level cross-equatorial flows were weaker than normal, consistent with earlier deductions. The lower tropospheric southerly wind component was particularly weak, implying very little net effect of southeast trade surges from the southern to northern hemisphere.

Six-month mean (May-October 1987) velocity potential maps at 950 hPa and 200 hPa are shown in Figs 9(a) and (b). These charts are representative of the situation depicted by the three-month

---

**Fig. 9(a) Mean velocity potential at 950 hPa for May-October 1987. (Units 10^5 m^2 s^-1.)**

**Fig. 9(b) Mean velocity potential at 200 hPa for May-October 1987. (Units 10^5 m^2 s^-1.)**
subsets MJJ and ASO. Monthly analyses of mean high cloud amount and mean high cloud anomaly are given in Figs 10(a) and (b) reproduced from Japan Meteorological Agency’s Monthly Report on Climate System*. These charts are of cloud tops above the 400 hPa level, based on monthly mean black body temperatures measured by the geostationary meteorological satellite GMS-3. In the tropics, high cloud (so defined) is accepted as a good proxy for deep layer convection. Anomalies are from a seven-year climatology for ocean areas.

Figures 9(a) and (b) suggest that an ascending core of the Hadley circulation was centred in the South China Sea and immediately east of the Philippines, with another upward branch in the southern Bay of Bengal/Sumatra region. The major area of subsidence was in the Coral Sea/southwest Pacific. There were reports of significant drought in Fiji and areas of Papua New Guinea during the period. Elongation of the upper and lower patterns towards the equatorial Pacific was associated with an upper divergence/lower convergence maximum near the dateline, due to northeastward displacement of the SPCZ in conjunction with a more active ITCZ.

The widespread weakening of the low-level trades and southeast monsoon, and the below average equatorial easterly jet at upper levels was evidence of a weaker than normal (meridional) Hadley cell operating over Darwin RMC longitudes. This was reflected by below normal tropical convection over most of the region.

Figure 10(a) shows the distribution of convection for each month of the period; the overall pattern is in good agreement with that diagnosed in Figs 9(a) and (b). Of more relevance is the anomaly pattern shown in Fig. 10(b), clearly showing the enhancement of convection in the equatorial Pacific and near the dateline and reduction in convection in the area of the southwest monsoon. Above normal convection east of the dateline was noted on satellite imagery received in Darwin RMC during the period.

*Available from Long-range Forecast Division, Forecast Department, Japan Meteorological Agency, 1-3-4, Ote-machi, Chiyoda-ku, Tokyo, Japan.

Fig. 10(a) Monthly mean high-cloud amount measured by GMS-3 for May through October 1987 (courtesy of Japan Meteorological Agency). Contour interval is 10%; areas above 30% stippled.
Tropical cyclones

Post-analysed tracks of tropical cyclones and typhoons in the RMC area during May-June and August-October 1987 are shown in Figs 11(a) and (b) (Joint Typhoon Warning Center (JTWC) Guam 1987). Table 2 lists these systems in order of occurrence for each ocean basin, with notional lifetime (as measured by warning duration) and maximum surface wind speed.

**Tropical cyclones in the southern hemisphere**

There were two tropical cyclones in the southern hemisphere between May and October 1987. Tropical cyclone *Blanch* occurred in late May in the southwest Pacific. Cyclones in this area are not unknown in May; Joint Typhoon Warning Center Guam (1987) statistics show an average of 0.5 cyclones (from 1959-78) and 0.7 (in the period 1981-87).

In June, a short-lived cyclone (JTWC codename 28S) developed in the Indian Ocean near 8°S. This was the first June genesis event in the southern Indian Ocean since at least 1959, based on statistics which date only from that time (JTWC Guam 1987). This event was probably encouraged by consistently warmer SSTs in the area (+2°C anomaly in June 1987), and the much reduced vertical shear associated with the near overhead position of the mean 200 hPa subtropical ridge and weakened trades noted earlier.

**Tropical storms and typhoons in the northwest Pacific**

Occurrence of typhoons and tropical storms by month, compared with 1959-87 averages (JTWC Guam 1987) is given in Table 3. Cyclone activity was close to average throughout the six-month
period. September was the most active month with six tropical storm genesis events of which five reached typhoon intensity (mean maximum surface wind > 32 m s⁻¹). A large number (5 out of 15) of northwest Pacific typhoons reached super typhoon intensity (maximum wind speeds ≥ 65 m s⁻¹).

Table 2. Tropical cyclones within the Darwin RMC area for May-October 1987.

<table>
<thead>
<tr>
<th>Tropical Cyclone</th>
<th>Duration</th>
<th>Maximum wind (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western North Pacific</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruth</td>
<td>18 Jun - 19 Jun</td>
<td>17</td>
</tr>
<tr>
<td>Sperry</td>
<td>27 Jun - 01 Jul</td>
<td>37</td>
</tr>
<tr>
<td>Thelma</td>
<td>07 Jul - 16 Jul</td>
<td>65</td>
</tr>
<tr>
<td>Vernon</td>
<td>16 Jul - 21 Jul</td>
<td>33</td>
</tr>
<tr>
<td>Winnie</td>
<td>22 Jul - 01 Aug</td>
<td>63</td>
</tr>
<tr>
<td>Alex</td>
<td>23 Jul - 28 Jul</td>
<td>33</td>
</tr>
<tr>
<td>Betty</td>
<td>09 Aug - 16 Aug</td>
<td>70</td>
</tr>
<tr>
<td>Cary</td>
<td>13 Aug - 22 Aug</td>
<td>43</td>
</tr>
<tr>
<td>Dinah</td>
<td>21 Aug - 31 Aug</td>
<td>65</td>
</tr>
<tr>
<td>Ed</td>
<td>22 Aug - 28 Aug</td>
<td>17</td>
</tr>
<tr>
<td>Freda</td>
<td>04 Sep - 17 Sep</td>
<td>63</td>
</tr>
<tr>
<td>Gerald</td>
<td>04 Sep - 10 Sep</td>
<td>53</td>
</tr>
<tr>
<td>Holly</td>
<td>05 Sep - 15 Sep</td>
<td>70</td>
</tr>
<tr>
<td>Ian</td>
<td>23 Sep - 01 Oct</td>
<td>55</td>
</tr>
<tr>
<td>Peke</td>
<td>28 Sep - 03 Oct</td>
<td>50</td>
</tr>
<tr>
<td>June</td>
<td>29 Sep - 01 Oct</td>
<td>17</td>
</tr>
<tr>
<td>Kelly</td>
<td>10 Oct - 16 Oct</td>
<td>47</td>
</tr>
<tr>
<td>Lynn</td>
<td>16 Oct - 27 Oct</td>
<td>70</td>
</tr>
<tr>
<td>North Indian Ocean</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02B</td>
<td>02 Jun - 05 Jun</td>
<td>27</td>
</tr>
<tr>
<td>04B</td>
<td>15 Oct - 16 Oct</td>
<td>23</td>
</tr>
<tr>
<td>05B</td>
<td>31 Oct - 03 Nov</td>
<td>20</td>
</tr>
</tbody>
</table>

Southwest monsoon over South-East Asia

Orgill (1967) defined onset of the southwest monsoon over South-East Asia as that period during the months of May and June when lower tropospheric equatorial westerly winds move northward into southern China. Using upper-level wind charts from 1936-1964, he determined the mean calendar date of onset of the southwest monsoon in Indo-China as 17 May, with a range of 33 days. An objective form of this definition of southwest monsoon onset is the time at which the 850 hPa and 700 hPa zonal wind components become positive and stay positive for at least 20 days during the month that follows. Based on this criterion, it was found that onset of the 1987 southwest monsoon occurred on 28 May over Indo-China and 5 June over Peninsular Malaysia.

Figure 12 which is a latitude/time cross-section of 700 hPa zonal wind along longitude 103°E, clearly depicts the onset. After onset, southwestlies progressed eastwards to northwestern Borneo/northern Philippines on 7 June, to northeastern Borneo on 8 June, and to the central and southern Philippines/west Pacific on 12 June. Thus onset over Indo-China in 1987 was late, although within the range of onset dates determined by Orgill (1967).

During the period from early May (before onset), through 12 June 1987 (when the monsoon finally prevailed over all South-East Asia and the west Pacific), changes that took place in the upper air circulation were found to agree with those noted in earlier literature on onset of the northern summer (southwest) monsoon (e.g. Cheang 1987). Changes observed on daily 850 hPa and 200 hPa streamline analyses (between 2 May and 12 June but not shown) included: northwestward movement of the 200 hPa anticyclone from Peninsular Malaysia/South China Sea region to the Burma/Tibetan Highland region; appearance of the tropical upper-level easterly jet over South-East Asia; northeastward retreat of the low-level subtropical ridge from Indo-China to the northwest Pacific; development of tropical cyclone activity over the Bay of Bengal around the onset in Indo-China (refer Fig. 11(a)).

Table 3. Occurrence of tropical storms and typhoons in the northwest Pacific during May-October 1987. Figures in brackets are 1959-87 averages from JTWC, Guam (1987).

<table>
<thead>
<tr>
<th>Tropical storms and typhoons</th>
<th>Typhoons</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>0 (1.0)</td>
</tr>
<tr>
<td>Jun</td>
<td>2 (1.8)</td>
</tr>
<tr>
<td>Jul</td>
<td>4 (4.1)</td>
</tr>
<tr>
<td>Aug</td>
<td>4 (5.2)</td>
</tr>
<tr>
<td>Sep</td>
<td>6 (4.9)</td>
</tr>
<tr>
<td>Oct</td>
<td>2 (4.1)</td>
</tr>
<tr>
<td>Total</td>
<td>18 (21.1)</td>
</tr>
</tbody>
</table>

Of note is the location of tropical depression genesis in Figs 11(a) and (b), particularly during August-October. Seven systems developed near or east of 160°E. Typhoon Peke was the first during the past twenty years (since typhoon Sara, September 1967) to form in the central North Pacific and cross the dateline into the eastern hemisphere (JTWC 1987). This is consistent with eastward displacement of the upward branch of the Walker cell during ENSO events. In contrast to the weak TUTT situation in 1986 (Kingston et al. 1987), the well developed TUTT of the 1987 season appeared to play a positive role in enhancing cyclone genesis and intensification in the northwest Pacific (cf. Sadler 1976, 1978).
Fig. 11 Tracks of tropical cyclones during: (a) May to July 1987; (b) August to October 1987. Legend: . . . . tropical depression; -- -- tropical storm/cyclone; —— typhoon/severe tropical cyclone. Month number is given after the name of each track.
On the whole, most countries of South-East Asia experienced a deficiency of rainfall, especially during July 1987. In the Philippines the only significant rainfall was caused by the passage of typhoons Betty and Cary. Most of Indonesia suffered from low rainfall, except Sumatra and eastern Java. The generally low rainfall could be associated with the low-level easterly anomalies described earlier. The improvement in Malaysia and Thailand during August and September may be associated with southward movement of the centre of low-level convergence/upper-level divergence noted on three-monthly velocity potential maps.

Low-frequency oscillations of wind, pressure and rainfall

Low-frequency oscillations of period 30-40 days were found by Yasunari (1979), Cheang et al. (1981) and Krishnamurti and Subrahmanyan (1982) to be associated with active and break cycles of the summer monsoon, and also with the northward movement of monsoon convection. Upper winds in South-East Asia typically change direction over a two to three-week period in response to the active/break cycle of the monsoon in association with northward movement of the equatorial subsidiary ridge/monsoon trough system, as well as the westward intrusion of tropical disturbances from the west Pacific.

To examine oscillations of this mode, a Gaussian low-pass filter was applied to time-series of: (a) average surface pressure in Peninsular Malaysia, Sumatra/south Thailand, Indo-China, west Pacific, India, China and Australia; (b) 850 hPa and 200 hPa average zonal wind over Malaysia; and (c) total daily rainfall in Peninsular Malaysia, Sabah and Sarawak (northern Borneo). These filtered series are graphed in Figs 13(a) to (d). Westerly winds at 850 hPa are positive (following the usual convention), whereas easterly winds at 200 hPa are denoted as positive. This arrangement is made for easy reference to intensity of the monsoon.
Thirty to 50-day oscillations are very clear in the filtered series of surface pressure of Indo-China, northern Sumatra/southern Thailand, Peninsular Malaysia, west Pacific and India. They are not as distinct in the filtered series of rainfall and upper winds of Malaysia. In the filtered series of upper winds, the 30 to 50-day mode is not as clear because the breaks around 25 June and 22 August 1987 were very short. The filtered series of surface pressure of China and northwest Australia do not exhibit an oscillation of the 30 to 50-day mode, but rather a lower frequency mode.

There is a slight phase difference between the pressure series of Indo-China, Peninsular Malaysia, northern Sumatra/southern Thailand and those of India and the west Pacific. Of interest is that rainfall in Malaysia was at a minimum when the southwest monsoon was most intense (strongest 850 hPa westerly winds, strongest 200 hPa easterly winds and lowest pressure) and vice versa.

Indian summer monsoon

Climatologically, the Indian summer monsoon reaches the subcontinent first at the southern State of Kerala by the first week of June and covers the entire country by the middle of July. Figure 14(a) shows the advance of the southwest monsoon in 1987 along with normal dates in Fig. 14(b) (after Rao 1976) over the country. Although onset of the monsoon over south Kerala occurred almost on time (2 June), its further advance over different parts of the country was delayed substantially. Onset was delayed by more than four weeks in some parts of northwest and far western India.

Seasonal (June to September) rainfall departures analysed on the basis of individual station rainfall are shown in Fig. 15. Departures from normal were most negative over northwest India, where acute drought was suffered, and most positive in the northeast, with heavy flooding.

By the end of the monsoon season, most northwestern border States had very large rainfall deficiencies. Area weighted seasonal rainfall over India was below normal. This situation is well correlated with the ENSO event in the central Pacific. Shukla and Paolino (1983) showed that when antecedent normalised Darwin pressure anomaly was positive from December to May, and increasing during that period, then a deficit of monsoonal rains over India was highly likely. This sequence of events was observed in 1987 (Fig. 3).

Retreat of the 1987 southwest monsoon was around normal, commencing in far west-northwest India on 12 September. By 13 October withdrawal had occurred from all but the southern third of the country, and on 24 October it was complete.

Weather systems

At the start of the season, tropical storm 02B developed over the Bay of Bengal and crossed the Bangladesh coast (Fig. 11(a)), ushering in the monsoon over Assam and adjoining eastern States. No depressions developed over the head of the Bay of Bengal. Normally two to three such depressions form during each of the monsoon months (June-September). However during late August to mid-September, three westward-moving depressions formed over the land along about 24°N (east of 78°E). These depressions were short-lived (5 days in total).
Rainfall over northern Australia

A histogram of area weighted, monthly district average rainfall for the period May to October 1987 is presented in Fig. 16. Districts comprise all those north of 20°S within Australia (see Fig. 17 for locations). For comparison, normal district average rainfall (similarly processed) is also shown. It can be seen from Fig. 16 that only in June did rainfall exceed the average.

Six-month cumulative district rainfall and decile ranges are shown in Fig. 17 and clearly illustrate that easternmost districts 31 and 32 were the only two whose cumulative rainfall was

The usual monsoon trough near the foothills of the Himalayas was rarely well organised, and there was frequent penetration by mid-latitude systems which disturbed the normal monsoon flow pattern (southward displacement of the subtropical jet has previously been noted). Furthermore, the remnants of typhoons from the South China Sea which normally travel westwards to regenerate into monsoon depressions over the head of the Bay of Bengal mostly took a northward track, reducing the frequency of formation of such depressions.

Fig. 16 Area weighted monthly district average rainfall over continental Australia north of 20°S during May-October 1987.

Fig. 17 Location map of rainfall districts referred to in the text; six-month cumulative rainfall deciles for May-October 1987 are superimposed.
classified as higher than average — decile 8 and 9 respectively. Cumulative rainfall at Willis Island was also classified as above average (decile 8). A possible reason for this was enhanced low-level convergence along the north Queensland coast evident in the 950 hPa wind anomaly charts (Figs 6 (a) and (b)). Northwest wind anomalies meeting southeast wind anomalies implies increased downstream deceleration in the easterly trades; also this occurred over an area of warm SST anomaly.

During the winter months June to August, the number of northwest Australian cloudbands (NACs cf. Tapp and Barrell 1984) was comparable to that observed in 1986. Despite this, winter rainfall was not enhanced over tropical Australia as it was in 1986. Satellite imagery (3-hourly GMS infrared) showed that the dominant tendency for NAC location at maturity was near the coast of Western Australia, well west of that observed in the preceding year. As the bands translated eastward they tended to weaken — mean 200 hPa flow over Western Australia for 1987 was anticyclonic, with southwest upper wind anomalies, in contrast to the marked cyclonic anomalies over Australia in 1986 noted by Kingston et al. (1987).

Summary

A moderate to strong ENSO event exerted a major influence on the flow within the Darwin RMC area during May-October 1987. The main driving forces of the tropical atmosphere, the Hadley and Walker circulations, were both operating at below normal strength. The late-arriving summer monsoon over India and South-East Asia was very weak, resulting in widespread below average rainfall. Precipitation was also suppressed over Indonesia, Papua New Guinea and the southwest Pacific.

The ENSO event was some six months out of phase with the Rasmussen and Carpenter (1982) composite. This seems to have had a positive effect on cyclone genesis in the mid-North Pacific, as equatorial low-level westerly anomalies near the dateline reinforced the seasonal ITCZ, despite the large-scale suppression occurring further west.

Low-frequency oscillations with periods in the 30 to 50-day mode were observed in the pressures and upper winds of South-East Asia and the west Pacific.

Acknowledgments

Thanks to Mr R. Porteous for drafting many of the figures. Thanks to the Long-range Forecast Division of the Japan Meteorological Agency for permission to reproduce the high cloud amount and anomaly charts. Information supplied by the India Meteorological Department is gratefully acknowledged. Mr T. Casey provided the automated tropical analyses.

Two of the authors (BKC and HVT) wish to express their thanks to the Director General of the Malaysian Meteorological Service for permission to contribute to this report.

References


