The tropical circulation in the Australian/Asian sector – April to September 1986

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(Manuscript received February 1987; revised April 1987)

A synoptic analysis is presented of the tropical circulation between the longitudes 70°E and 180° for the southern hemisphere winter of 1986. From data analysed it is inferred that during this period the tropical Hadley Cells were weaker than normal with their foci of ascent and descent displaced eastwards from the climatologically normal positions. The changed large-scale circulation was associated with significant variations in regional climate: central Australia experienced record winter-time rains, a 28-year minimum in tropical cyclone numbers was observed in the northwest Pacific Ocean and the rainfall over the Indian subcontinent was below normal for the southwest monsoon season.

Introduction

This paper discusses the circulation anomalies that occurred in the tropical portion of the area of responsibility of the Darwin Regional Meteorological Centre (RMC). The emphasis of the paper has been to identify circulation features that are significantly different from the long-term mean flows and, where possible, to specify the implications of these anomalies as they relate to regional climate.

The analysis focuses on the area equatorward of latitude 20° between longitudes 70°E and 180°, and the time period covering the southern hemisphere 'winter' of April to September 1986 with a concentration on the months June, July and August (JJA). Initially the large-scale flow anomalies within the RMC area are examined and then three regional features: the southwest monsoon over India, the tropical storms and typhoons in the northwest Pacific Ocean, and the northwest Australian cloudbelt are analysed in some detail.

The data base used in the analyses was derived from three sources: plotted and manually-analysed surface and upper air charts prepared in the Darwin RMC, imagery from the Japanese Geostationary Meteorological Satellite (GMS), and the output (including derived fields and diagnostics) from an automated tropical analysis scheme (Davidson and McAvaney 1981).

The broad features of the large-scale flow over the tropical area of the Darwin RMC analysis domain during the southern hemisphere winter months may be briefly described by referring to the 950 hPa and 200 hPa level mean streamline charts for July 1986 (Figs 1 and 2). The analyses are typical of the period May to September.

At the 950 hPa level (Fig. 1) in the northern hemisphere the monsoon trough is located over the southeast Asian landmass and extends eastward at lower latitudes from Luzon in the Philippines into the equatorial west Pacific Ocean. In the southern hemisphere the subtropical ridge lies along the latitudes of continental Australia. Stable and 'dry' southeast trade winds flow equatorward, where they turn southwesterly and form the moist, unstable current that flows into the monsoon trough. To the north, easterly trade winds from the Pacific anticyclone converge into this trough.

At the 200 hPa level (Fig. 2), the northern hemisphere subtropical ridge approximately overlays the Asian monsoon trough, while over the Pacific the upper ridge is about 10° north of the Tropical Upper Tropospheric Trough (TUTT) (Sadler 1975), with the subequatorial ridge to its south. A strong northeasterly return flow streams across the equator and around the southern hemisphere upper ridge, where it merges with the winter-time jet stream westerlies.
The tropical circulation—winter 1986

Figure 3 shows the mean sea surface temperature (SST) anomaly chart for JJA 1986. The analysis is derived from weekly composite analyses of ship and satellite SST observations which are combined to yield a monthly analysis from which anomalies are computed using the means of Reynolds (1983). The JJA chart was then produced by averaging the 3 one-month anomaly charts. The dominant feature of the SST over the tropical region between 20°N and 20°S during the JJA period of 1986 was the extensive area of positive anomaly in the Indo-Australian area, with the very warm SST in the Coral Sea. The dipolar pattern, with a positive anomaly in the Coral Sea and a negative anomaly near the dateline, resembles the August-October antecedent SST condition (for an El Nino) anomaly map presented by Rasmussen and Carpenter (1982).

Figure 4 shows the JJA mean sea level (MSL) pressure anomaly chart. Perhaps the most notable feature is the broad area of lower than normal pressure throughout the tropical region which extends poleward to the weaker than usual subtropical ridge high pressure systems. Nicholls (1979) has shown that negative pressure anomalies over the Australian continent lead to a decrease in the strength of the prevailing easterly winds.
through the Indonesian and Papua New Guinea archipelagoes and, in the case of no other complicating effects, to positive SST anomalies in that area. The 1986 JJA anomalies appear to confirm Nicholls's observation.

Figure 5 shows the 950 hPa vector wind anomaly charts for the months April through to September (analysed wind fields from the automated analysis scheme, long-term means from Atkinson and Sadler 1970). These charts show large areas of westerly wind anomaly in the southern hemisphere where the southeast trades are the prevailing wind regime. These patterns are consistent with the inferences above which linked SST anomalies with the strength of the subtropical ridge, since the correspondingly weaker easterly wind regime is associated with warmer SST.

A consequence of the weakness of the southern hemisphere southeast trade winds was that the observed low-level winds over the Australian continent were of a more easterly (i.e. tropical) origin, rather than the long-term mean southerly, consistent with the observation by Darwin RMC forecasters (and noted in Darwin Tropical Diagnostic Statements*), that in 1986 the surges in the southern hemisphere trades did not penetrate as far north as they normally do in winter. By

*Darwin Tropical Diagnostic Statements issued monthly by Darwin RMC. (Published by NT Regional Office, Bureau of Meteorology, PO Box 735, Darwin, NT 0801.)
contrast, stronger than normal southerlies prevailed over the Indian Ocean between 80°E and 90°E, and over the southwest Pacific. Consistent westerly anomalies over the equatorial Pacific in the northern hemisphere imply a stronger than average current to the south of the monsoon trough, but weaker trades to the north. Easterly anomalies over India correspond to a weaker Indian monsoon flow than in the mean.

At 200 hPa (Fig. 6), significant cyclonic westerly anomalies over the Australian sector indicate the influence of vigorous baroclinic upper trough penetrations well into the southern hemisphere tropics. In conjunction with the tropical northeasterly wind anomalies east of 130°E, stronger than normal cross-equatorial upper flow was induced which provided a middle and high-level moisture channel over northern Australia. Also of note was the weak TUTT. For the 1986 season, the TUTT was poorly developed and much less extensive than in the long-term mean (where it extends westwards from the mid-Pacific to the Philippines—cf. Fig. 2). The role of the TUTT in initiating tropical cyclone genesis is well known (Sadler 1976), and its inactivity during 1986 may have contributed to the far below average number of northern hemisphere cyclones for the season. Furthermore, the associated absence of a pronounced subequatorial ridge probably contributed to the strength of the northeast wind anomalies across the equator.
Interhemispheric interactions

For the JJA period in 1986 a mean equatorial cross-section of meridional wind was prepared (Fig. 7(a)). For comparison with a long-term mean, Fig. 7(b) was adapted from Newell et al. (1972). When interpreting Fig. 7(a) it should be noted that the level of maximum wind near 200 hPa reflects the bias of satellite cloud winds which are nominally assigned to this fixed level. Comparison of GMS-derived cirrus winds with rawinsonde observations suggests that in the deep tropics a pressure level around 150 hPa would have been a more appropriate level assignment.

The most notable difference between Figs 7(a) and 7(b) is in the strength of the northerly component east of 120°E in the upper levels. There is also a corresponding increase in the underlying southerly wind at low levels, supported by the vector wind anomalies along the equator in Fig. 5. It is interesting that these stronger southerly winds cannot be attributed to the cumulative effect of southern hemisphere surges, but rather to the stronger southwesterly flow into the Pacific monsoon trough.
Fig. 5 950 hPa vector wind anomaly charts for April to September 1986.
Fig. 6 200 hPa vector wind anomaly charts for April to September 1986.
Velocity potential maps at 850 hPa and 200 hPa for July 1986 (Figs 8(a) and 9(a)) may be compared with the long-term means adapted from Van de Boogaard (1977) (Figs 8(b) and 9(b)). The 850 hPa chart is very similar to the 950 hPa pattern, and was selected because of the unavailability of a long-term mean at the latter level. There are considerable differences in the divergence patterns implied by these sets of charts. In July 1986 an area of low-level convergence/upper-level divergence over the Bay of Bengal, representing an upward branch of the tropical Hadley Cell, was not typical of the long-term mean. Usually the ascending branch is located over Indochina and extends towards the foothills of the Himalayas (Fig. 8(b)). In July 1986 the other major upward branch of the Hadley Cell was displaced eastwards to over the Philippines. The subsiding branch of the Hadley circulation was concentrated over the Coral Sea, whereas in the long-term mean it descends over a broad area beyond the analysis domain.

These charts (Figs 8 and 9) were for July only. In
Fig. 9 (a) Velocity potential at 200 hPa, July 1986. (Contour interval 10 x 10⁵ m²/s²)

Fig. 9 (b) Velocity potential at 200 hPa, long-term mean adapted from Van de Boogaard (1977). (Contour interval 10 x 10⁵ m²/s²)

Fig. 10 (a) The location of the velocity potential ridge axes at 950 hPa. The hatched area represents the envelope of positions occupied by these axes for the period May to September 1986. The crosses represent the centres of velocity potential maxima.

Fig. 10 (b) The location of the velocity potential trough axes at 200 hPa. The hatched area represents the envelope of positions occupied by the axes for the period May to September 1986. The crosses represent the centres of velocity potential minima.

In order to present a seasonal picture, the axes of the ridges and troughs of the velocity potential contours (associated with the areas of maximum convergence and divergence) were plotted for each month in Figs 10 (a) and (b). It can be seen that April was the transition month after which the principal areas of divergence migrated into the northern hemisphere. For the period May to September, the composite envelope formed by the velocity potential ridges and troughs at 950 hPa and 200 hPa were superimposed. Figure 11 (a) shows the intersection of these two envelopes. Qualitatively one would expect this region of maximum upper divergence/lower convergence to broadly coincide with the area of maximum cloudiness. The arm extending into the southwest Pacific is presumed to represent the South Pacific Convergence Zone (SPCZ), while the band in the northern hemisphere is the Inter-Tropical Convergence. Curiously, the Indian monsoon is manifested chiefly by cloudiness in the Bay of Bengal more than over the subcontinent.

In order to contrast this May-September 1986 pattern with the climatic mean, charts of cloudiness (Atkinson and Sadler 1970) were composited for the period. Figure 11 (b) is the composite of cloud cover greater than or equal to 5 octas. It would appear that the axis of major cloudiness in 1986 was somewhat further north than in the mean. The SPCZ was further east than in the mean. According to Rasmussen and Carpenter (1982) the SPCZ is southwest of its normal position in the months preceding an El Nino warm episode; this is at variance with the conclusion drawn from the SST pattern.
The southwest monsoon over India

The onset of the southwest monsoon generally occurs over a period of a month or so, commencing in late May over Sri Lanka and concludes as late as mid-July in the Punjab. One useful indicator of the likely nature of the time of monsoon onset is given by the difference between the mean zonal wind of the first and last fortnight of April. Figure 12 shows the vector difference between mean zonal winds over India at 250 hPa for these periods in 1986. For predominantly easterly winds (particularly north of 15°N) an early monsoon may be expected while a predominantly westerly pattern is characteristic of a late onset (Rao 1976). As can be seen from Fig. 12 the wind differences in 1986 were generally light westerly with a belt of easterlies between 15°N and 20°N. This pattern suggested a normal onset.

Figure 13 shows isopleths of the actual onset dates (solid lines) over the Indian subcontinent, as inferred from Darwin RMC analyses. Also shown are isochrones of the 'normal' date of onset as given by (and where necessary, interpolated from) Rao (1976) (dashed lines). By about 4 June the border between the dry continental and moist maritime air masses was around 12°N. On 12 June a low pressure system near Vishakhapatnam (approximately 18°N 83°E) bought the first rains to that part of India south of about 16°N. Finally a low pressure system near Calcutta (approximately 22°N 88°E) on 22 June moved northwest thus bringing the onset to northwest India.

The most important measure of the strength of the southwest monsoon is the total rainfall received on the Indian subcontinent. From those data available it would appear that rain totals were about 20 per cent below average over much of the Indian subcontinent except the western states south of 15°N where significantly above average rain totals were recorded.

Other 'proxy' data can be used to gauge the strength of the monsoon: monthly averages of low-level winds, MSL pressure anomalies, and 200 hPa winds. Figure 5 shows that there was a weak low-level easterly wind anomaly over southern India through April, May and June which intensified during the months July, August and September resulting in a 10 m/s easterly anomaly in an area where southwesterlies are the prevailing wind.
regime. Also associated with the weaker than normal monsoon westerlies were higher than normal MSL pressures over India during JJA (Fig. 4).

The 200 hPa wind anomaly chart for May 1986 (Fig. 6) does not show an anomalous wind circulation over India which is consistent from month to month. Perhaps the most marked feature is the anomalous northeasterly flow over India and the Bay of Bengal in June. Such a flow may be associated with a northward displacement of the upper subtropical ridge (and by inference, an ascending branch of the Hadley Cell).

**Bay of Bengal disturbances**

As noted in a previous section of this paper the Bay of Bengal appears to have been a centre for convective activity during the northern hemisphere summer. In order to examine this feature more closely a climatology of disturbances in this area was prepared. There were eight monsoon depressions and no tropical storms over the Bay of Bengal during the months June, July, August and September. Data presented by Rao (1976) show that over a 60-year period annual means of 7.3 depressions and 1.6 tropical storms were observed in these months. The tracks of the eight disturbances for 1976 are given in Fig. 14. The mean ‘over water’ lifetime for the depression occurring in the four months June to September was 4.6 days.

The distribution of over water lifetimes for depressions and cyclonic storms in the Bay of Bengal for the three months July, August and September is given in Fig. 15 along with the long-term distribution (Rao 1976). The data from Rao indicate an average (60 years) of 5.95 depressions annually for the three-month period compared with the observed 6.

While the comparison of the monsoon depression climatology for 1986 with the long-term mean suggests that this was a near normal year for the Bay of Bengal, the southwest monsoon over India was weaker than normal. This set of circumstances is consistent with the apparent shift of the ascending branch of the Hadley Cell to this area (as noted previously in the discussion on interhemispheric interactions).

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

The tracks of tropical storms and typhoons in the northwest Pacific basin between April and September 1986 are shown in Fig. 16. The occurrence of these systems by month is given in Table 1 and compared with the 1959-85 average as provided by the Joint Typhoon Warning Centre (1985). Although the genesis of five tropical storms and typhoons during the early season (April to June) was slightly above the long-term average of 3.5, the occurrence of the nine in the mid-season months (July to September) was well below the average of 14.6. In fact it was the lowest number of tropical storms and typhoons for at least the last 28 years.
Fig. 15 Histogram of depression lifetimes for 1986, and curve showing long-term (60 year) average of the monthly number of depressions of a given lifetime (1 to 9 days) (Rao 1976).

An analysis which attempts, at least qualitatively, to explain this minimum in tropical storm genesis events must interpret the parameters of Gray (1977) and McBride and Zehr (1981) in a synoptic fashion to assess the role of the environment on the climatology of genesis events. The synoptic features felt to be important are: the low-level vorticity around the monsoon trough (as determined by the easterlies poleward of the trough and the westerlies equatorward), the position and strength of the TUTT, the position of the upper anticyclone relative to the monsoon trough and finally the location of the monsoon trough relative to the warmest SST.

Anomalous flow patterns in the lower and upper troposphere during JJA appear not to have been conducive to cyclone genesis. The low-level westerly wind anomaly between the equator and 20°N (Fig. 5) in all months is consistent with stronger than normal monsoon westerlies and weaker trade easterlies, while it is difficult to infer unambiguously how the low-level background vorticity field was affected, there appears to have been an overall weakening of the low-level wind fields, and thus, the time averaged cyclonic vorticity

Fig. 16 Tracks of tropical storms and typhoons in the northwest Pacific April to September 1986.

Table 1. Occurrence of tropical storms and typhoons in the northwest Pacific, April to September 1986. Figures in brackets are the 1959-1985 average from the Joint Typhoon Warning Centre, Guam (1985).

<table>
<thead>
<tr>
<th>Typhoons</th>
<th>Typhoons and Tropical Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>APR</td>
<td>1 (0.6)</td>
</tr>
<tr>
<td>MAY</td>
<td>1 (0.8)</td>
</tr>
<tr>
<td>JUN</td>
<td>1 (0.9)</td>
</tr>
<tr>
<td>JUL</td>
<td>2 (2.7)</td>
</tr>
<tr>
<td>AUG</td>
<td>4 (3.3)</td>
</tr>
<tr>
<td>SEP</td>
<td>2 (3.1)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>11 (11.4)</td>
</tr>
<tr>
<td></td>
<td>14 (18.1)</td>
</tr>
</tbody>
</table>
about the monsoon trough. During July and September the upper ridge was displaced to the north of the monsoon trough, while in August the monsoon trough and upper ridge axes were coincident. It is noteworthy that July and September were the months with anomalously low cyclone activity. Also observed was a more northerly migration of the monsoon trough than is normal (particularly in August) thus placing the preferred cyclone genesis area over a cooler ocean surface and closer to the strong vertical shear of the mid-latitude upper westerlies. As noted earlier the TUTT was considerably weaker than usual, and, given that it contributes favourably to the conditions required for tropical cyclone genesis (Sadler 1976) its absence may be associated causally with the low number of cyclone genesis events.

During April and May 1986, SSTs were slightly above normal over most of the tropical northwest Pacific Ocean. This is seen in the anomaly chart of Fig. 17. During June and July negative anomalies began to intrude and by August (Fig. 17) a large area of below normal SST had become established east of the Philippines. While undoubtedly the SSTs exceeded 26.5°C in the vicinity of the monsoon trough (thus meeting a necessary condition for cyclone genesis (Gray 1977)) it is certainly the case that there was less energy available at the air-sea interface for tropical weather systems than normal.

The northwest Australian cloudband

During JJA 1986 a number of stations in central Australia received record rainfalls (Bureau of Meteorology 1986). Examination of GMS imagery for the period revealed the recurring presence of cloudbands crossing the northwest Australian coast and extending inland for thousands of kilometres. Figure 18 shows part of an unenhanced, full disk GMS image of a mature northwest Australian cloudband (NAC) extending from Broome (on the northwest coast of Australia) to the southeastern part of the continent.

Downey et al. (1981) have documented cases of the NAC and its association with enhanced rainfall over central and tropical northwest Australia. Tapp and Barrell (1984) have presented a climatology of the NAC, a phenomenon they describe as a large, primarily stratiform cloudband, that commences off the northwest Australian coast and on many occasions extends to the east coast.

Using unenhanced 3-hourly GMS IR imagery, and following 'commencement' and 'end of' NAC criteria set down by Tapp and Barrell (1984), comparisons for the 1986 winter with the Tapp and Barrell base climatology were prepared. The results of this comparison are given in Table 2. Clearly, the most marked departure from normal is the 250 per cent (approximately) increase in the number of days in June 1986 with cloudbands present.

Table 2. Comparison of some aspects of the northwest Australian cloudband base climatology (Tapp and Barrell 1984) with 1986 winter months June, July and August.

<table>
<thead>
<tr>
<th>Month</th>
<th>Number of cloudbands</th>
<th>Number of days with cloudband present</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>July</td>
<td>2.0</td>
<td>4</td>
</tr>
<tr>
<td>August</td>
<td>0.75</td>
<td>1</td>
</tr>
</tbody>
</table>

The source, area of subsequent coastal crossing and cloudband alignment is generally irregular, but during the 1986 winter months there was a tendency for NACs to cross the Western Australian coast near Broome, aligned towards the southeast through Giles or Alice Springs (see Fig. 18 for an example). Total rainfall over much of tropical Australia west of 140°E, was above to very much above average (decile 9 and 10) during the 1986 winter months (Bureau of Meteorology 1986). A detailed inspection of rainfall at Broome, Giles and

Fig. 17 SST anomalies for April to September 1986 from Darwin RMC analyses and the climatology of Reynolds (1983).
Alice Springs (see Fig. 18 for location) was made to determine the contribution associated with NACs. Table 3 lists total rainfall (with decile ranges in parentheses), for the 1986 winter months at the respective stations together with the total rainfall when the stations were affected by NACs. The percentage NAC contribution is also listed. The close relationship between the total winter rainfall and that associated with NACs, particularly at Alice Springs and Broome, is in good agreement with the findings of Downey et al. (1981).

The high frequency of cloudband events is presumably related to the interaction of the stronger than normal cross-equatorial upper flow over Australian longitudes with the tropical extensions of amplifying baroclinic troughs: this frequent superposition of a middle-and high-level moisture source from the summer hemisphere with synoptic scale ascent driven from the mid-latitudes, was a very favourable situation for rain over inland Australia.

Table 3. Comparison of total rainfall at Broome, Giles and Alice Springs during the 1986 winter months of June, July and August with the total rainfall associated with northwest Australian cloudbands at the respective stations during the same period. Figures in brackets are three-monthly total rainfall decile numbers.

<table>
<thead>
<tr>
<th>Rainfall (mm), Winter 1986</th>
<th>Station</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total rainfall</td>
<td>78 (10)</td>
<td>91 (9)</td>
<td>238 (10)</td>
</tr>
<tr>
<td>NAC associated</td>
<td>65 (9)</td>
<td>60 (8)</td>
<td>229 (10)</td>
</tr>
<tr>
<td>NAC percentage of total</td>
<td>83</td>
<td>66</td>
<td>96</td>
</tr>
</tbody>
</table>
Summary

A number of significant departures from the seasonal mean flow have been documented for tropical and subtropical areas between longitudes 70°E and 180° for the period April to September 1986. On the global scale of anomaly, the Hadley Cell ascent and descent branches were displaced from their mean positions. The ascending branch in the northern hemisphere exhibited two maxima over the season, one centred over the Bay of Bengal and the other over the Philippines. The descending branch of the Hadley Cell was concentrated over the Coral Sea, well westwards of its mean position. Also observed were lower than usual MSL pressures along the axes of the subtropical ridges in both hemispheres, suggesting that subsidence in the descending branches of the Hadley Cells was weaker than usual.

Another manifestation of the weaker than normal Hadley Cells was the below normal strength of the flow in the tropical low-level wind regimes (the southeast trades in the southern hemisphere and the southwest monsoon over India and the northeast monsoon over the northwest Pacific). The weakened trade wind regime in the southern hemisphere is considered to be an important factor in producing the widespread positive SST anomalies evident in the tropical waters. There is some evidence to suggest that these SST anomaly patterns were a part of the precursor conditions for an El Nino event.

The weaker than normal southwest Indian monsoon resulted in below average rain over most of the Indian subcontinent. Over the Australian continent, enhanced upper cyclonic flow appeared to be related to a significant increase in NAC and associated record rainfall over much of western and central tropical Australia in the period JJA.

In the northern hemisphere, the combination of a weaker than normal TUTT, the monsoon trough being north of its climatological position and the weakened low-level wind fields, reduced favourable tropical storm generation factors — resulting in a 28-year low in mid-season (July to September 1986) number of tropical storms in the northwest Pacific Ocean.

Acknowledgments

The authors would like to acknowledge the contribution of Mr R. Porteous in drafting the many figures presented, and Dr R. K. Datta of the India Meteorological Department in providing valuable rainfall data.

References


