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The tropical circulation in the Australian/Asian region — November 1990 to April 1991

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A summary of the tropical circulation from 70°E to the date-line, for November 1990 to April 1991, is presented. The Southern Oscillation did not exert any notable influence during this period. The Australian northwest summer monsoon was stronger than normal, resulting in above average rainfall over northern Australia. The Asian northeast winter monsoon was weaker than normal, resulting in below average rainfall across South-East Asia. In the western Pacific, tropical weather was more (less) active than normal north (south) of the equator. Associated with this, the Hadley circulation was anomalously weak in that region, and fewer cyclogenesis events than normal occurred in the southwest Pacific.

Introduction

This summary reviews the broadscale tropical circulation in the Australian/Asian region during the period November 1990 to April 1991. The area reviewed is the Darwin Regional/Specialised Meteorological Centre (RSMC) analysis domain; 40°S to 40°N, 70°E to 180°. The first section uses six-month average charts to describe the overall seasonal circulation and anomalies. The second section uses time series and monthly average charts to portray variations of the tropical circulation within the season. The final section briefly summarises the occurrence of tropical cyclones in this six-month period.

All data sources used are listed in the Appendix. Six-month mean charts were constructed using the Tropical Analysis Scheme (TAS) of Davidson and McAvaney (1981), and anomalies were calculated relative to the six-year climatology of Lavery et al. (1991). The exception to this is mean sea level pressure (MSLP) anomalies, for which the TAS chart was subjectively modified using monthly CLIMAT messages as discussed in Bate et al. (1993). Sea-surface temperature anomalies were calculated relative to the climatology of Reynolds (1983) and averaged over two three-month periods.

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Broadscale seasonal features

Southern Oscillation

Figure 1 shows the ten-year behaviour of Troup's Southern Oscillation Index (SOI) and its five-month running mean. Monthly SOI values were small (less than one standard deviation from the average of zero) in the preceding five months and through most of this season. This suggests a near normal Walker circulation during the season.

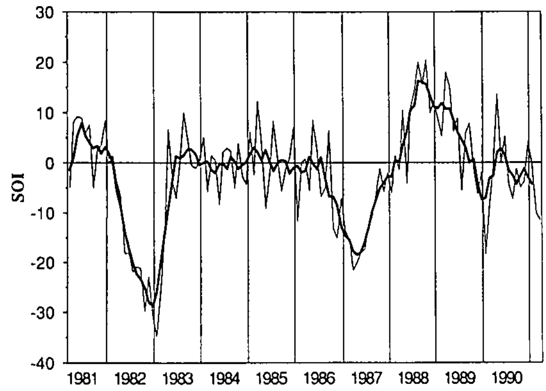
However, the five-month mean values became consistently negative, and monthly values fell to −10 and −12 during March and April 1991 respectively. This provided an early indication of a developing ENSO warm event (for example, Carello et al. (1994)).

Sea-surface temperature (SST)

Figure 2 shows SST anomalies for the two three-month halves of this season. Anomalies are very similar in the two charts. Warm SST anomalies occurred in the equatorial western Pacific, providing a further indication of a developing ENSO warm event.

Warm anomalies also occurred in the southwest Pacific. Hence the low number of cyclogenesis events in this region cannot be ascribed to cold SST. Other persistent regional anomalies included the warm SST anomalies in the equatorial Indian Ocean, the near-normal temperatures about tropical Australia, and the band of cold anomalies near 20°N.

Fig. 1 SOI time series for ten years to April 1991: monthly values (thin line); five-month running mean (thick line).



The tropospheric circulation

Figures 3, 4, 5 and 6 show the six-month mean and anomaly charts for mean sea level pressure (MSLP), gradient level (950 hPa) streamlines, 200 hPa streamlines and an equatorial cross-section of meridional wind. As discussed in Bate et al. (1993), the wind anomalies have been depicted using streamlines. All anomalies at 950 hPa are less than 5 m s^{-1} and at 200 hPa are less than 10 m s^{-1}.

The ridge of high pressure over eastern Asia was slightly weaker than normal, which was reflected in a weaker than normal low-level northeasterly flow (hence southwesterly anomalies) in this region. The exception to this was the stronger than normal extension of the ridge to the northeast of the Philippines, which produced an area of stronger than normal northeasterlies that enhanced the cross-equatorial flow to the Australian tropics at longitudes 120°E to 150°E.

Fig. 2 SST anomaly (°C) averaged over: (a) November 1990 to January 1991; (b) February to April 1991. Contour interval 1°C.

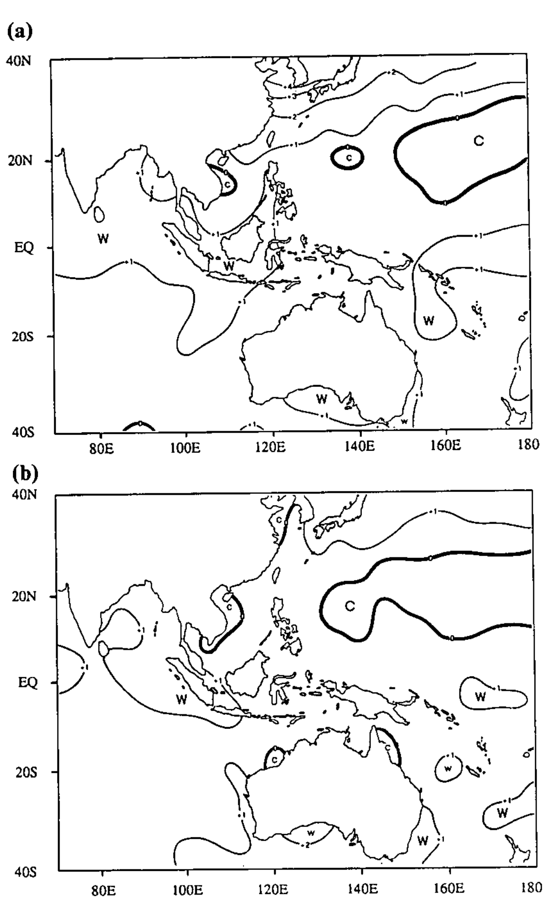
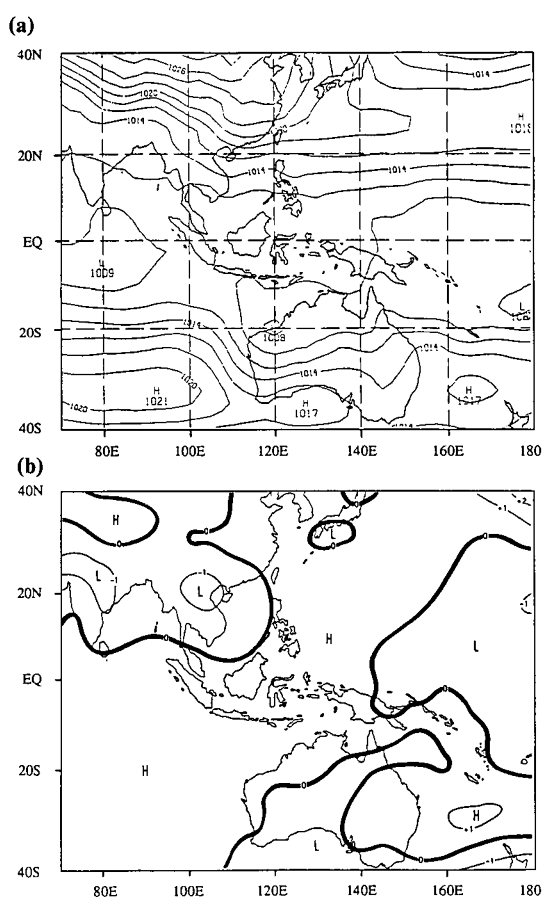


Fig. 3 Six-month MSL pressure (hPa) November 1990 to April 1991: (a) mean; (b) anomaly.



A notable feature of the Australian monsoon, which is apparent in long-term mean charts (for example, Lavery et al. (1991)), is the major contribution made by air of southern hemisphere origin. Southeast trade winds turn southwesterly around the Western Australian heat trough and contribute to the convergent westerly flow over the deep tropics. However, this season there were anomalously low pressures across the continent and high pressures about the north coast, hence a generally weakened trade flow and southwest inflow to the monsoon. The anomalously strong northwest monsoon about the north coast of Australia, then, was entirely a result of the enhanced cross-equatorial flow.

MSLP was marginally higher than normal over the equatorial and southern Indian Ocean. Associated with this, the equatorial westerly winds were generally weaker than normal, hence easterly anomalies are apparent.

The South Pacific convergence zone (SPCZ) was weaker than normal west of the date-line. Weak positive MSLP anomalies occurred through parts of the region, and convergence of low-level winds was reduced: both the southeasterly inflow from higher latitudes west of 170°E, and the northeasterly cross-equatorial inflow were weaker than normal. The latter was caused by a stronger than normal near-equatorial trough (NET) in the northwest Pacific and associated equatorial westerly wind anomalies.

At 200 hPa, anomalies were generally consistent with those in the lower troposphere. The east Asian jetstream and mid-latitude westerly trough were weaker than normal, as evidenced by the easterly anomalies which also appear at mid-tropospheric levels (not shown). This suggests fewer than normal cold outbreaks and surges of high pressure across China and the South China

Fig. 4 Six-month 950 hPa streamlines November 1990 to April 1991: (a) mean; (b) anomaly. Isotachs dashed; interval 5 m s^{-1}.

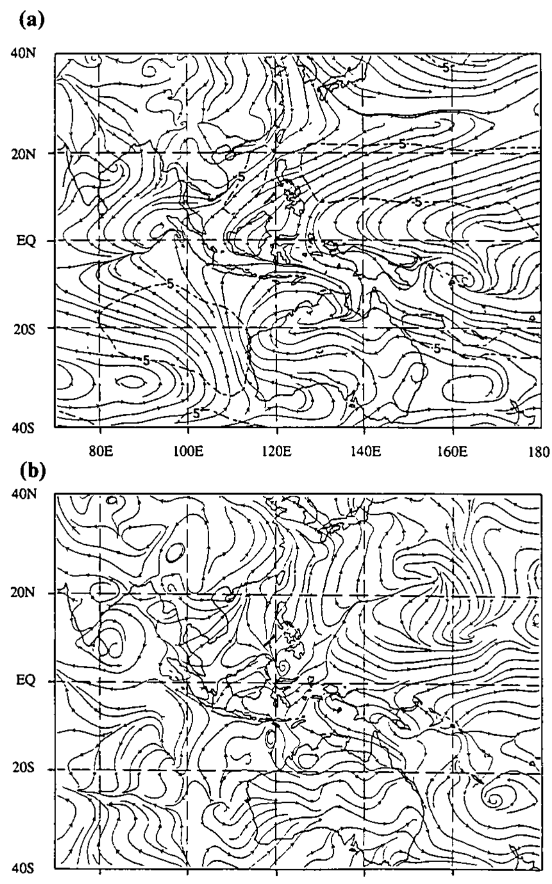


Fig. 5 Six-month 200 hPa streamlines November 1990 to April 1991: (a) mean; (b) anomaly. Isotachs dashed; interval 20 m s^{-1}, lowest 10 m s^{-1}.

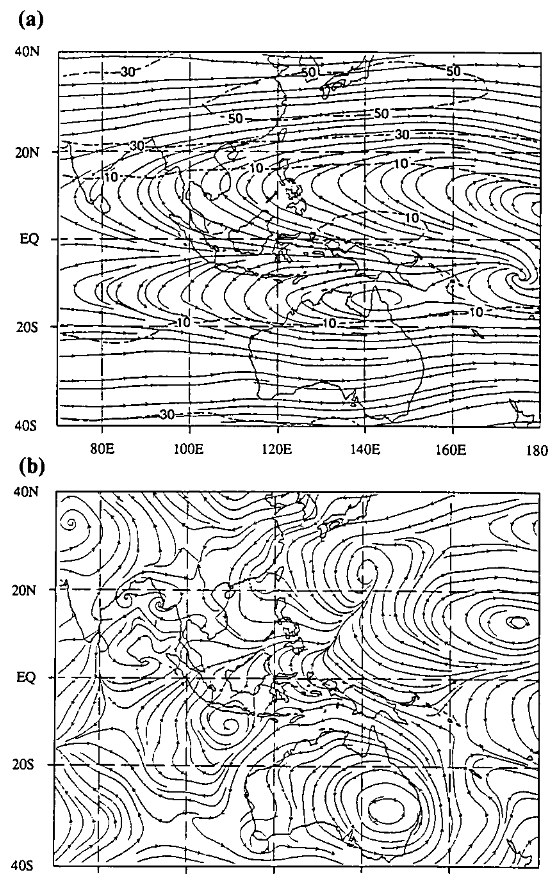
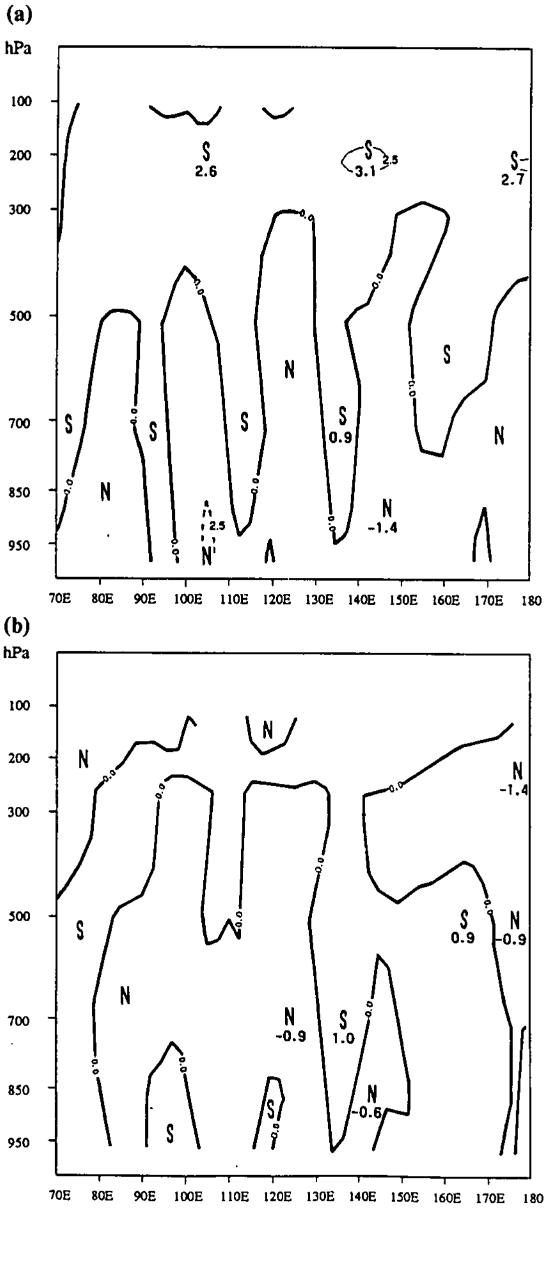


Fig. 6 Equatorial cross-section of six-month meridional wind November 1990 to April 1991: (a) mean; (b) anomaly. Isotach interval 2.5 m s^{-1}; negative (northerly) dashed.



Sea, which is consistent with the lower tropospheric anomalies previously noted.

A substantial wind anomaly confluence zone occurred to the east and northeast of the Philippines, and this had two major components. There was an anomalously strong cross-equatorial return flow from the Australian monsoon through longitudes 120°E to 150°E. The other component was the stronger than normal equatorial easterly wind outflow from the ridge overlying the northern NET. To the south, ridging was stronger than normal over eastern Australia while the trough in the westerlies was located further east over the southwest Pacific than normal.

The equatorial cross-sections of meridional wind and its anomaly further illustrate and summarise anomalies in the Hadley circulation. Across Australian longitudes there were generally stronger than normal low-level northerlies and upper-level southerlies, indicating an anomalously active Hadley circulation. The region from 150°E to the date-line also had a well developed Hadley circulation, however the upper-level northerly and low-level southerly anomalies indicate that it was weaker than normal.

Vertical motion and rainfall

Figures 7 and 8 show the six-month mean and anomaly charts for the divergent component of the wind in the lower troposphere (950 hPa) and the upper troposphere (200 hPa) respectively. The purpose of these charts is to identify significant regions of upper divergence (convergence) overlying low-level convergence (divergence), and hence infer deep tropospheric upmotion (downmotion). Note that the divergent wind is unreliable near the boundaries: it is calculated from velocity potential which has a zero boundary condition, constraining the divergent wind to flow perpendicular to the boundary.

The mean charts show typical broadscale features. These include general upmotion across the equatorial belt centred south of the equator, where upper divergence overlies low-level convergence, surrounded by general downmotion across the subtropics particularly in the northern (winter) hemisphere.

The anomaly charts show upper divergence and low-level convergence across northern Australia, implying greater than normal upmotion through the region. Conversely, the SPCZ had upper convergence and low-level divergence anomalies, indicating that upmotion through this region was weaker than normal. The area to the east and northeast of the Philippines was characterised by upper convergence and low-level divergence anomalies, providing the downward component of the enhanced Hadley circulation noted at these longitudes. To the east of 150°E, upper divergence and low-level convergence anomalies highlight enhanced upmotion in the northern hemisphere NET.

Low-level convergence anomalies over eastern China are consistent with the previously noted weakness of the high pressure system in this region. Upper divergence anomalies over southeast India and convergence anomalies over southern China were not complemented by significant anomalies at lower levels. Anomalies over the Indian Ocean were mixed and weak.

Fig. 7 **Six-month 950 hPa divergent wind component November 1990 to April 1991: (a) mean; (b) anomaly. Vector length indicates magnitude ($m\ s^{-1}$).**

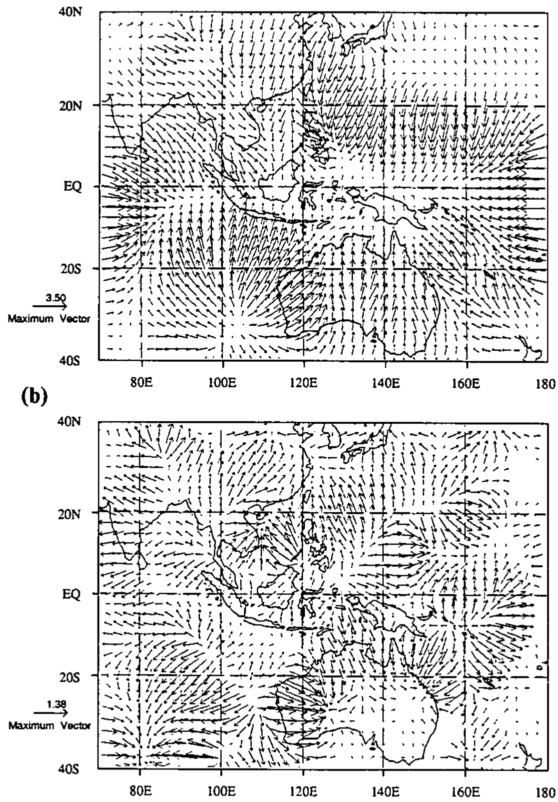


Fig. 8 **Six-month 200 hPa divergent wind component November 1990 to April 1991: (a) mean; (b) anomaly. Vector length indicates magnitude ($m\ s^{-1}$).**

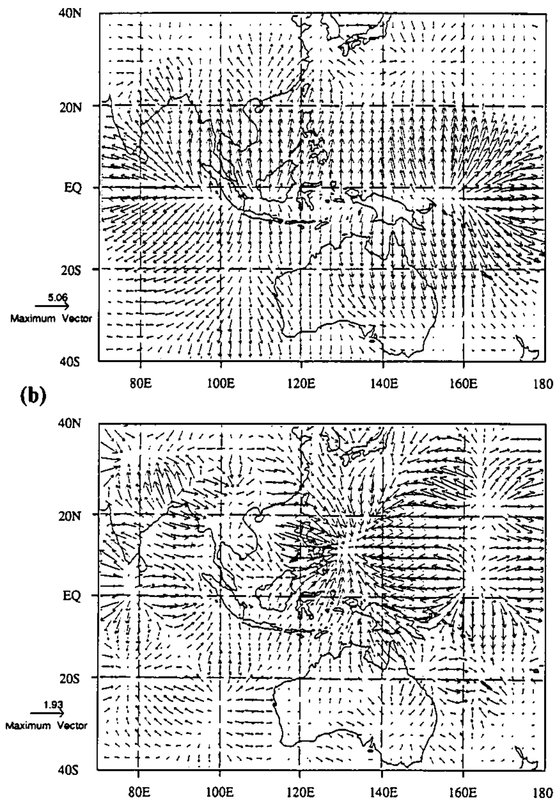
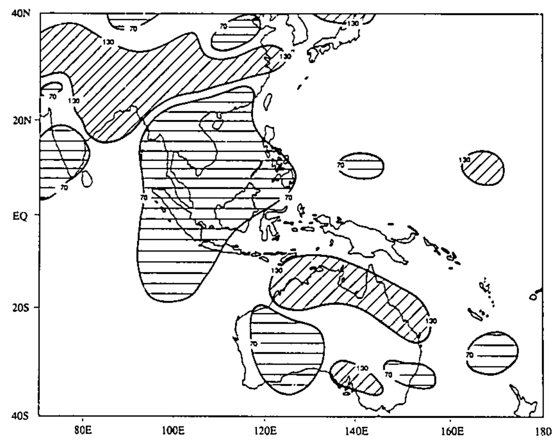


Figure 9 shows areas of anomalous rainfall during December 1990 to February 1991. Circulation anomalies suggest that the Australian northwest summer monsoon was more active than normal. This is confirmed by the broad region of high rainfall across northern Australia. The other major anomaly evident is the below average rainfall across South-East Asia including southern India. This reflects the weakness of the northeast monsoon.

Inspection of monthly rainfall quintile values in DTDS (see Appendix) shows that below average rainfall was also prevalent across South-East Asia during November 1990 and March to April 1991. Northern Australia experienced below average rainfall during November 1990 and March to April 1991, however wet season totals remained above average (SCO — see Appendix).

Fig. 9 **Anomalous rainfall areas December 1990 to February 1991. Areas shown had less than 70 per cent of normal rainfall (horizontal hatching), or above 130 per cent (diagonal hatching) (after *Monthly Report on Climate System*, February 1991).**



Intraseasonal variations

Broadscale variations

Figure 10 shows monthly anomalies of the percentage of area covered by high cloud. Large high-cloud amounts are assumed to indicate regions of deep tropical convection. The anomalously strong NET over the northwest Pacific, noted previously, comprised both a late decay during November and December, and an early redevelopment during March and April. This is reflected in the positive anomalies of high-cloud amount in this region during November and March to April.

High-cloud amount anomalies were generally weak or negative through South-East Asia, most notably south of the equator during November, and near and north of the equator during December. This reflects the weakness of the northeast monsoon. The anomalously strong northwest monsoon over northern Australia occurred predominantly in January (weak or positive anomalies) and February (strong positive anomalies). The southwest Pacific had weak or positive anomalies during November and December, and produced the first severe tropical cyclones (*Sina* and *Joy*) of the southern hemisphere summer. However, as the season progressed, negative anomalies

Fig. 10 Anomaly of monthly mean high-cloud amount (per cent area): (a) November 1990; (b) December 1990; (c) January 1991; (d) February 1991; (e) March 1991; (f) April 1991. Contour interval is 10 per cent (after *Monthly Report on Climate System*, November 1990 to April 1991).

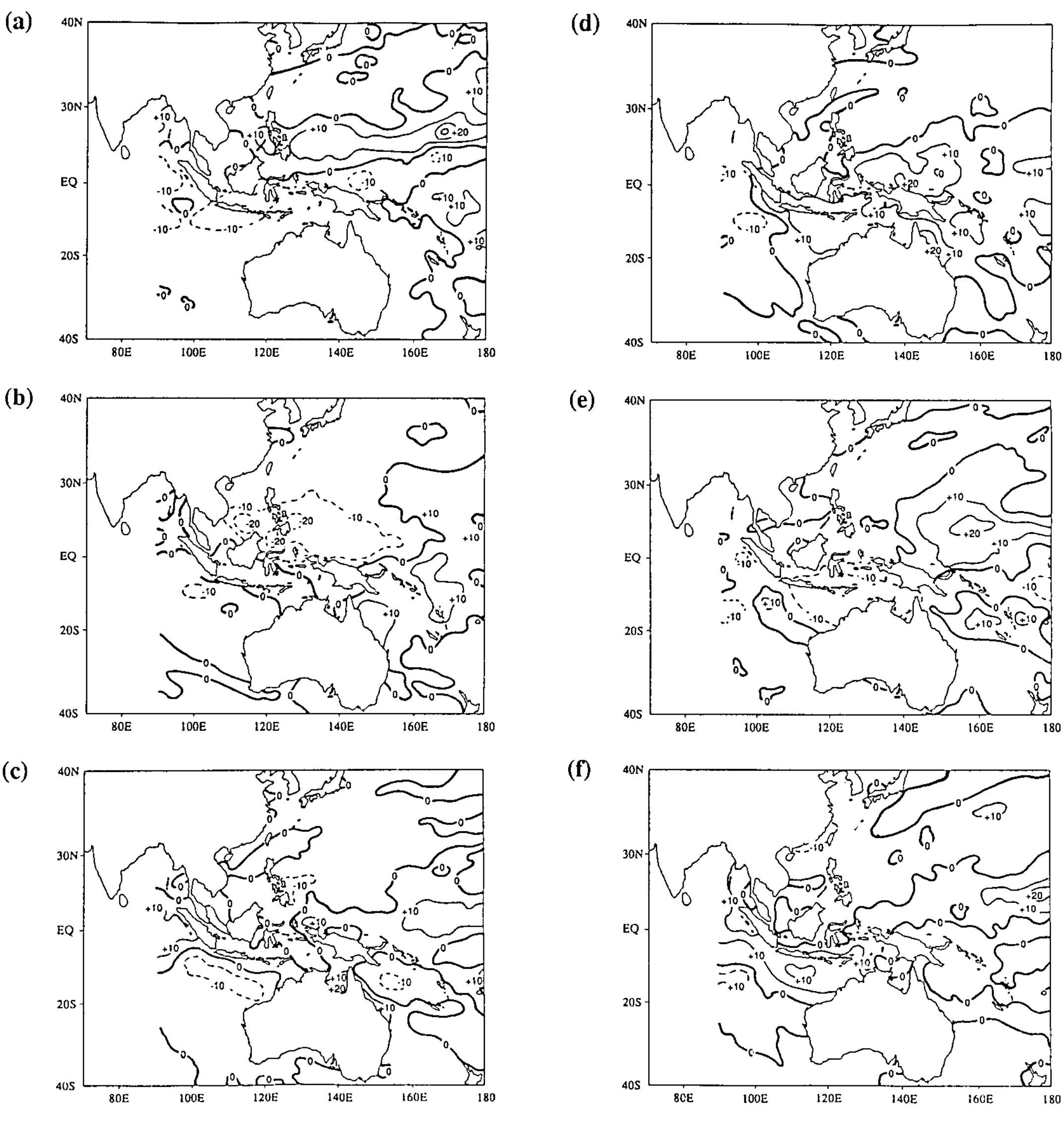
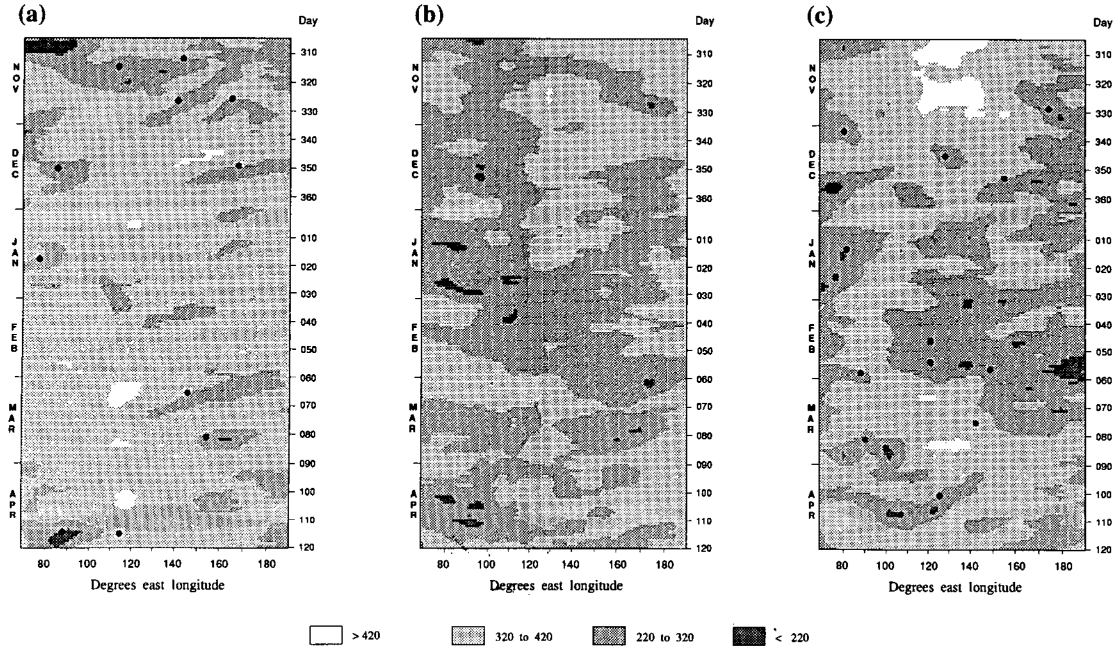


Fig. 11 **Time-longitude section of five-day running mean OLR (W m^{-2}), November 1990 to April 1991, averaged over the latitude band: (a) 5°N to 15°N; (b) 5°S to 5° N; (c) 15°S to 5°S. Black circles show cyclone genesis events.**



became more apparent: firstly during January when northern Australia was the more active region, then in parts of the region during March and April when the northern hemisphere NET became anomalously active.

The propagation characteristics of major regions of deep tropical convection are portrayed by the time-longitude plots of outgoing long wave radiation (OLR) in Fig. 11. Madden and Julian (1971, 1972) showed that a significant mode of variability in the tropical atmosphere consists of a broadscale zonal circulation which propagates slowly eastwards, and tends to revisit a given location each 40 to 50 days. The composite structure and close involvement of deep tropical convection in these 'Madden-Julian oscillations' (MJOs) has been displayed by Knutson and Weickmann (1987) and Rui and Wang (1990).

Prominent MJOs have been a feature of recent austral summer seasons (Butterworth et al. 1991; Keith et al. 1991; Bate et al. 1989). However, variations in tropical convection were less regular and well defined this season. Two clear MJO events occurred in the transition period September to November 1990: the first MJO propagated eastward from the Indian Ocean to the western Pacific during late September to mid-October (Bate et al. 1993); the second, during late October to late November, can be seen in the equatorial and northern bands in Fig. 11. Despite this early MJO activity, no clear events occurred from December to March. Several fragments of broadscale west to east propagation are evident during January and February, however there are other contributions to the overall pattern which make it impossible to identify an MJO event during this period. It wasn't until the transition period at the end of the season that the next MJO event occurred. The equatorial and southern bands in Fig. 11 show deep convection in the Indian Ocean during mid-April, which shifts eastwards to the western Pacific by the end of the month. Strong activity continued in the western Pacific during early May.

Australian northwest summer monsoon

The evolution of the Australian monsoon may be characterised with reference to Darwin (12°S 131°E) station data. Figure 12 shows the six-month time series of 850 hPa zonal and meridional wind, as well as daily rainfall. Westerly winds developed in the second half of December, and continued without easterly reversal until the end of February. The onset (21 December) and retreat (1 March) were each a few days earlier than the means determined by Holland (1986) of 24 December and 7 March respectively.

The period of northeast wind and rain during early December was a local response to tropical cyclone *Laurence*. The westerly winds that developed later in December were from the southwest

Fig. 12 **Darwin station data November 1990 to April 1991: (a) daily rainfall (bars), smoothed 850 hPa zonal wind (line) and its climatology (smooth line); (b) smoothed 850 hPa meridional wind (line) and its climatology (smooth line). Winds were smoothed by averaging four observations each day, then applying a three-day running average; climatology based on the 1950 to 1988 period.**

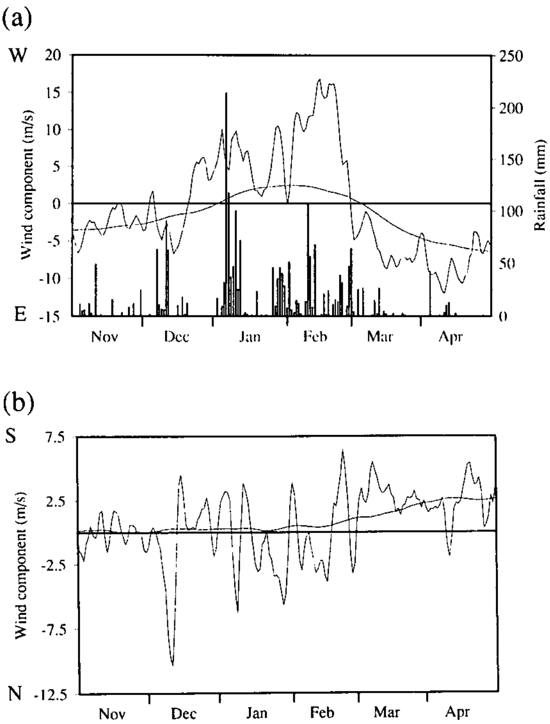


Fig. 13 **Onset dates of the northeast monsoon at six stations in South-East Asia in 1990.**

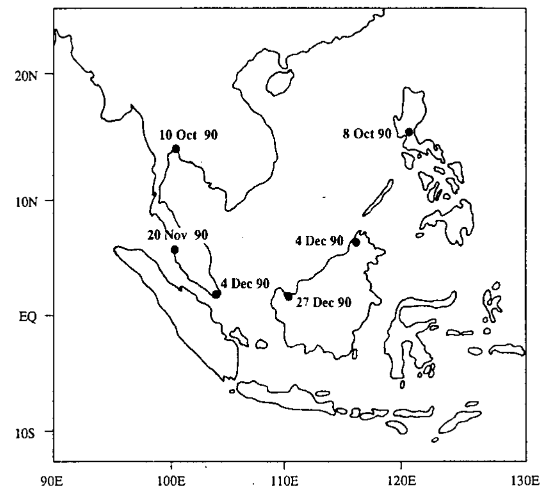
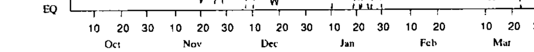


Fig. 14 **Latitude-time section of 850 hPa zonal winds in the longitudinal belt 100°E to 105°E across Indo-China and Peninsular Malaysia. E: easterly component winds; W: westerly component winds. Monsoon (near-equatorial) trough during October 1990 to March 1991, dashed line; long-term mean monsoon (near-equatorial) trough, solid line.**



and produced little rain, except over the northeast coast of Australia where severe tropical cyclone *Joy* exerted an influence. It wasn't until January and February that the northwest monsoon became very active, producing extensive rainfall across northern Australia. Despite the brief inactive period in mid-January when the westerly wind and rainfall eased, a record January rainfall total of 922 mm occurred at Darwin. The return of southeasterly winds was unusually rapid and strong, resulting in below average rainfall during March and April.

Asian northeast winter monsoon

Based on the definition used in Bate et al. (1989), dates for the onset of the monsoon are shown in Fig. 13. These dates were about normal. However, the southward progress of the monsoon (or near-equatorial) trough was interrupted rather than smooth, as can be seen in Fig. 14. Intrusion of low-latitude easterlies from the Pacific occurred around 10 and 25 October, washing out the monsoon trough. The trough also moved northward rather than southward during early October, mid-October and early November, due to embedded monsoon disturbances, whose tracks were from the South China Sea across Indo-China to the Bay of Bengal.

The monsoon trough disappeared to a position south of the equator for an unusually large proportion of the season, due to the prevalence of cross-equatorial flow. Associated with this was an unusually low number of near-equatorial cyclonic vortices, especially during January and February, as listed in Table 1. 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

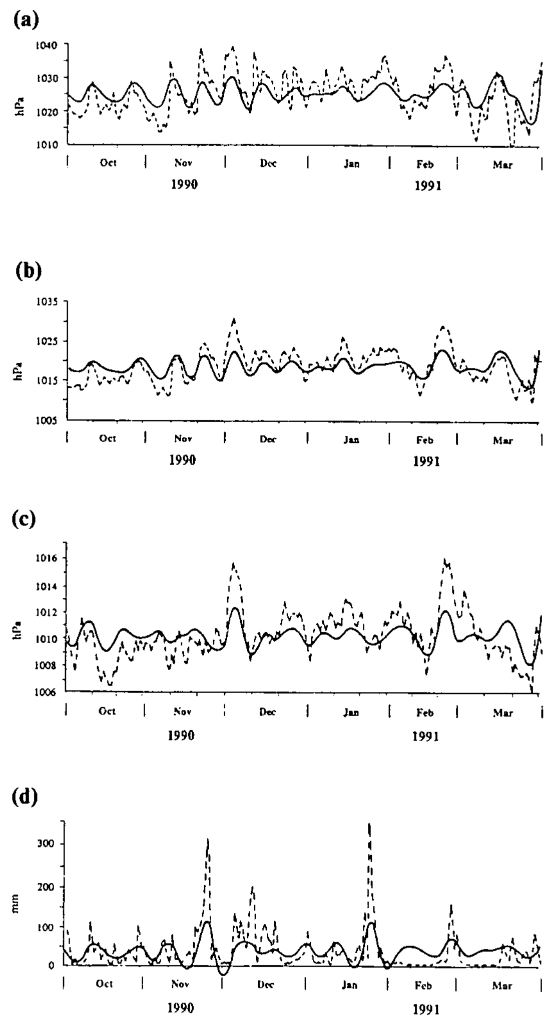
Table 1. **Occurrence of near-equatorial vortices over the Malaysia–South China Sea region during November 1990 to March 1991 compared with long-term averages.**

	Actual	*Long-term mean*
November	4	5.6
December	4	4.5
January	1	3.4
February	1	3.5
March	5	5.2

Table 2. **Occurrence of northerly surges over the South China Sea during November 1990 to March 1991 compared with long-term averages.**

	Actual	*Long-term mean*
November	1	2.3
December	2	3.7
January	4	3.6
February	2	1.8
March	0	0.9

Fig. 15 **Recursive 10 to 20-day band-pass filtered time series (solid line): (a) average China surface pressure; (b) Hong Kong surface pressure; (c) Kota Bharu surface pressure; (d) total daily rainfall at four stations along the east coast of Peninsular Malaysia. Raw data, dashed line.**



Malaysia–South China Sea region and continues to appear for at least two days until it either dissipates or moves westward to the Bay of Bengal.

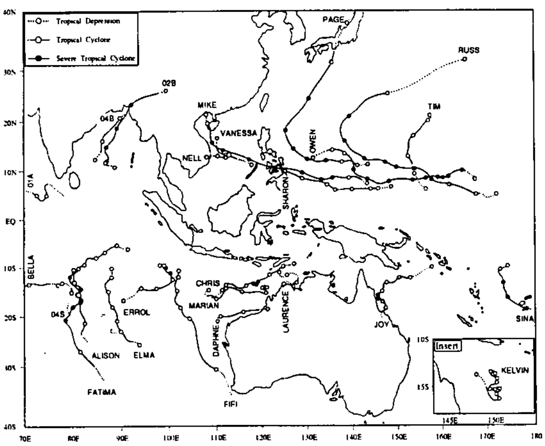
Northerly surges over the South China Sea which extended southwards of 10°N are listed in Table 2, using the definition of Cheang (1980). The number of surges was below normal overall, but returned to normal during January and February. Murakami (1979) and Yap et al. (1982) have shown the prominent contribution of the 10 to 20-day time-scale to cold northerly surges over the South China Sea. To examine oscillations in this low frequency mode, 10 to 20-day band-pass filtered time series are presented in Fig. 15. The four filtered series have reasonable coherence, with a time lag of about two to five days between the surge of high pressure over China and the Malaysian rainfall response. In the latter half of the season there appears to be a lengthening of the period of oscillation in all four series, and an increase in the time lag between high pressure surge and rainfall response.

The poor rainfall over the northeast monsoon region of South-East Asia, then, had two contributory factors. Most important was the low number of northerly surges over the South China Sea. Second, those surges that did occur tended to continue across the equator rather than converge into a near-equatorial vortex in this region.

Tropical cyclones

During November 1990 to April 1991, 25 tropical cyclones (TCs) (defined as having maximum ten-minute mean winds greater than 17 m s^{-1} or named systems) were analysed by Darwin RSMC. Operational tracks taken from the *Darwin Tropical Diagnostic Statement* are shown in Fig. 16. Table 3 lists the TCs in order of occurrence, within the various basins, showing duration and maximum intensity details. These details were obtained from Bannister and Smith (1993) for systems in the South Pacific and southeast Indian

Fig. 16 Tracks of tropical cyclones in Darwin RSMC area for November 1990 to April 1991. Circles show daily positions at 0000 UTC.



Ocean east of 90°E. The maximum intensity details for other TCs were obtained from Rudolph and Guard (1991, 1992), after applying a factor of 0.88 to convert maximum winds from the United States one-minute mean convention to the Australian ten-minute mean.

The southern hemisphere was marked by TC activity in the Australian region and southern Indian Ocean. Only one system occurred east of 165°E compared to an average of six (Bannister and Smith 1993), which is a reflection of the generally weakened SPCZ. Eight TCs occurred in the northwest Pacific, slightly above the average of 6.0 (Rudolph and Guard 1992). Cyclone activity reflected the active NET, which was stronger than normal during November and December and redeveloped early during March and April. In the northern Indian Ocean three TCs occurred, which is close to the average of 2.4 (Rudolph and Guard 1992). 02B was a particularly notable system, causing extensive death and destruction due to

Table 3. Tropical cyclones within the Darwin RSMC area November 1990 to April 1991.

TC name	*Dates (UTC) at TC intensity in Darwin RSMC area*	*Maximum 10-min mean wind ($m\ s^{-1}$)*	*Minimum MSLP (hPa)*
Northwest Pacific/South China Sea			
Mike	8 Nov–17 Nov	68	885
Nell	10 Nov–12 Nov	23	987
Owen	21 Nov–2 Dec	63	898
Page	22 Nov–30 Nov	63	898
Russ	14 Dec–24 Dec	56	916
Sharon	7 Mar–13 Mar	27	980
Tim	22 Mar–25 Mar	32	972
Vanessa	26 Apr–27 Apr	20	991
Northern Indian Ocean			
04B	16 Dec–18 Dec	20	991
01A	17 Jan–19 Jan	16	997
02B	25 Apr–30 Apr	63	898
Southern Indian Ocean (70°E–105°E)			
04S	3 Dec–4 Dec	25	984
Alison	14 Jan–17 Jan	29	976
**Bella*	24 Jan–25 Jan	—	—
Elma	26 Feb–3 Mar	31	965
Fatima	21 Mar–1 Apr	40	954
Errol	24 Mar–29 Mar	41	950
Australia (105°E–165°E)			
Laurence	10 Dec–12 Dec	18	996
Joy	19 Dec–26 Dec	46	940
Chris	16 Feb–21 Feb	31	976
Daphne	22 Feb–25 Feb	31	976
Kelvin	25 Feb–5 Mar	33	980
Marian	10 Apr–16 Apr	49	930
Fifi	16 Apr–19 Apr	28	975
South Pacific (105°E–180°)			
#Sina	24 Nov–28 Nov	39	960

* moved out of Darwin RSMC area before reaching peak intensity
\# moved out of Darwin RSMC area after reaching peak intensity

winds and storm surge as it approached and crossed the coast of Bangladesh.

Cyclone genesis positions have been marked on the Fig. 11 northern and southern bands as appropriate. A feature of interest is the fine structure within the MJOs of November (northern band) and April (southern band). East to west movement of TCs is evident within the broader envelope of the west to east moving active regions. This is similar to the structure described by Nakazawa (1988).

Summary

SOI values were small through most of the period November 1990 to April 1991, and the Walker circulation was not seen to exert any anomalous influence in the Darwin RSMC analysis region. Several regional anomalies did occur, though. The Australian northwest summer monsoon was very active during January and February, causing northwesterly wind anomalies and above average rainfall. This monsoonal activity was assisted by an anomalously strong Hadley cell operating to the east of the Philippines through longitudes 120°E to 150°E. The more typical source of lower tropospheric cross-equatorial surges to the Australian monsoon is eastern China and the South China Sea. However, the northeasterly flow through this region was weaker than normal, causing below average rainfall across South-East Asia.

In the northwest Pacific the NET was slow to weaken and early to reappear, causing generally more active tropical weather than normal. In the southwest Pacific, the SPCZ was noted to be weaker than normal with an anomalously low number of cyclogenesis events. In combination, these anomalies caused a weaker Hadley circulation than normal in the western Pacific.

Acknowledgments

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Appendix

Data sources used in this review were:

Darwin Tropical Diagnostic Statement (DTDS), November 1990 to April 1991, issued monthly by Bureau of Meteorology, GPO Box 735, Darwin, NT 0801, Australia.

Darwin RSMC grid-point analysis data from the Tropical Analysis Scheme and Australian region grid-point analysis data from the National Meteorological Centre, Melbourne.

Monthly CLIMAT messages received via the Global Telecommunications System.

Darwin RSMC weekly manual ship/buoy SST analyses, converted to grid-point format at 5°×5° resolution; six-month means calculated at each grid-point.

Monthly Report on Climate System, November 1990 to April 1991, issued monthly by Long-range Forecast Division, Japan Meteorological Agency, 1-3-4, Ote-Machi, Chiyoda-Ku, Tokyo 100, Japan.

Seasonal Climate Outlook (SCO), May 1991, issued monthly by National Climate Centre, Bureau of Meteorology, GPO Box 1289K, Melbourne 3001, Australia.

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