On the association between the Indian summer monsoon and the tropical cyclone activity over northwest Pacific

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An analysis of observed typhoon tracks and daily global wind data for 56 years (1948–2003) reveals that large-scale circulation anomalies associated with the interannual variability of the Indian monsoon play an important role in influencing the tropical Pacific cyclone activity. The cyclogenesis over northwest and tropical west-central Pacific is found to be about 1.33 times higher during weak monsoon years compared to strong monsoon years. Also, there is greater tendency for the Pacific cyclones to move northward and recurve (to the north of 20°N) during weak monsoon years. The enhanced cyclogenesis during weak monsoon years is found to be associated with enrichment of low-level cyclonic vorticity anomalies over a wide region of the subtropical Pacific extending from the China Sea, Taiwan and the Philippines region to the central Pacific; while the movement of the tropical cyclones is associated with anomalies of upper-tropospheric steering currents. Given that the interannual variability of the large-scale circulation over the Indo-Pacific sector is crucially determined by the El Nino/Southern Oscillation (ENSO) conditions, the present findings raise several questions pertaining to interactions among the large-scale circulation anomalies, tropical convection and the Pacific cyclonic disturbances, which are likely to provide better understanding of the dynamical linkages between monsoon variability and ENSO.

ONE of the interesting aspects of interannual variability in the tropics is the association between the Indian summer monsoon circulation and the convective activity over the west Pacific. The recent monsoon drought over India during 2002 is a good example that illustrates this point. The major decrease in the Indian monsoon rainfall during 2002 occurred in July, when the rainfall was deficient by nearly 50% of the long-term normal[1–4], which can be also noticed from Figure 1 *a*. The spatial distribution of observed rainfall[5] anomalies for July 2002 shows precipitation decrease over India, equatorial western Pacific and the Indonesian region (Figure 1 *b*). On the other hand, the equatorial eastern Indian Ocean and the west Pacific region north of the Philippines were associated with significant increase in precipitation during July 2002. Further, it can be seen that the belt of increased rainfall over the tropical Pacific in Figure 1 *b*, extended eastward from the Philippines and Taiwan regions far beyond the date line; along with a southeastward extension east of New Guinea. Tracks of observed typhoons for June to September of 2002 (Figure 2 *a*) indicate that as many as seven tropical storms formed over the west-central Pacific during July 2002 and most of them moved northward causing heavy rainfall over the Philippines–Taiwan region. Here, it must be mentioned that rather moderate El Nino conditions prevailed during 2002 in the tropical Pacific Ocean[4]. A similar case of enhanced activity of northward-moving tropical cyclones over the west Pacific was observed during August 1986 (Figure 2 *b*), which also turned out to be a year of monsoon drought over India[6]. Signatures of the strong and persistent cyclone activity during July 2002 and August 1986 can be readily inferred from the intensified cyclonic circulation anomalies and enhanced convection over northwest Pacific (Figure 3). On the other hand, it may be noted that suppressed convection and weak monsoonal circulation prevailed over the Indian subcontinent during these two years (Figure 3). Also seen in Figure 3 *a* and *b* is the pattern of above-normal convection over the equatorial eastern Indian Ocean and suppressed convection over the western Indian Ocean. Recent investigations have drawn attention to the role of equatorial Indian Ocean convective anomalies in affecting the Indian summer monsoon rainfall[4,7]. In this study, an attempt has been made to understand the dynamical teleconnections between the Indian summer monsoon and the large-scale circulation anomalies associated with tropical cyclone activity over northwest and west-central Pacific.

West Pacific cyclones and associated teleconnections over the Indian region

Meteorologists have since long examined the relationship between tropical cyclone activity over the west Pacific and associated changes in the monsoon circulation over India[8–12]. Documentation about the influence of westward-moving typhoons on the weather over India by Iyer[9], provides a comprehensive account of residual lows that travel from the China Seas across the hilly areas of Indo-China and enter the Indian region during the months of July–November. It is also known that remnants from the Pacific typhoons

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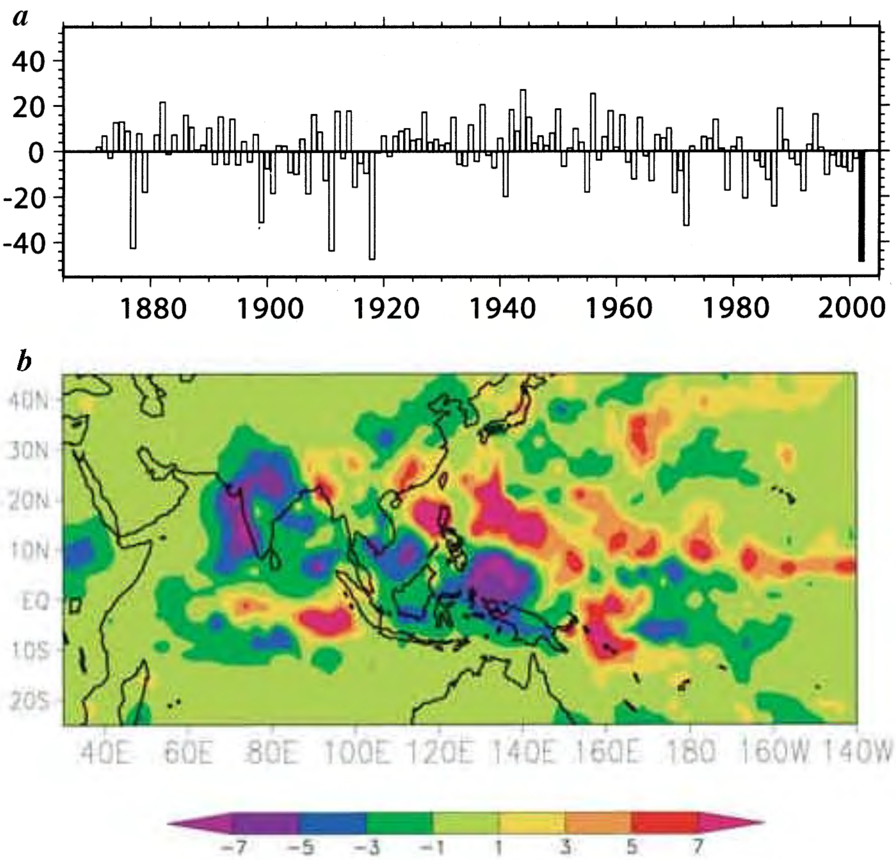

Figure 1. *a*, Variation of July rainfall over India (all-India rainfall) for the period (1871–2002) expressed as percentage departure from its long-term mean (273 mm). Note that the rainfall departure for July 2002 was nearly –50%. The all-India rainfall data are from http://www.tropmet.res.in. ***b***, Spatial distribution of rainfall anomaly (mm day^{-1}) during July 2002. The gridded rainfall data are from the Climate Prediction Center Merged Analysis of Precipitation, which is a product of merging rain gauge observations and precipitation estimates from satellites[5].

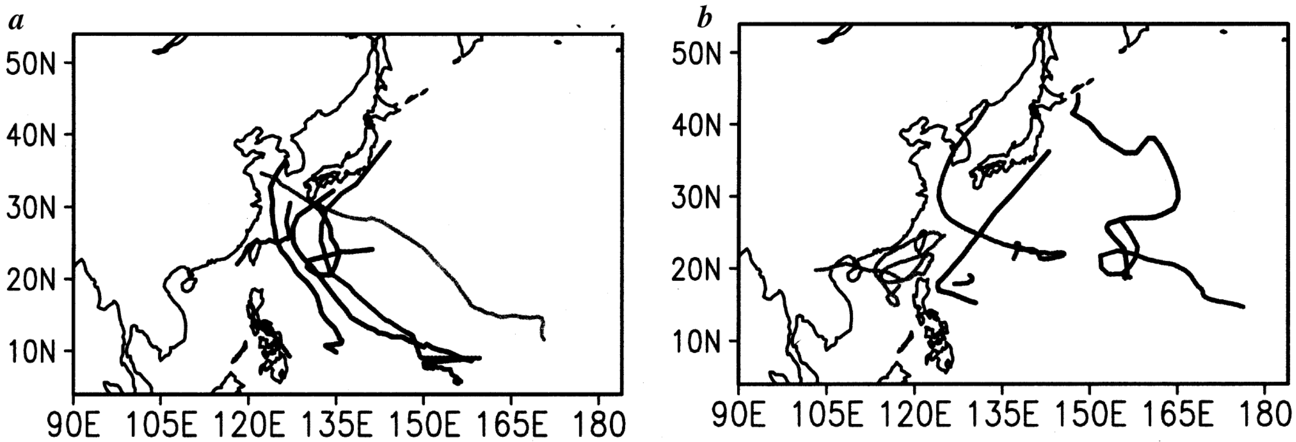

Figure 2. Observed cyclone tracks over tropical Pacific during (*a*) July 2002 and (*b*) August 1986. Each track is shown by a separate colour for easy identification.

originating in the far east can provide the nucleus for cyclonic systems over the Bay of Bengal[10]. Krishnamurti *et al.*[11] examined the dynamics of westward moving disturbances from the western Pacific and showed that a substantial number of monsoon disturbances (including depressions) over the northern part of Bay of Bengal form through a

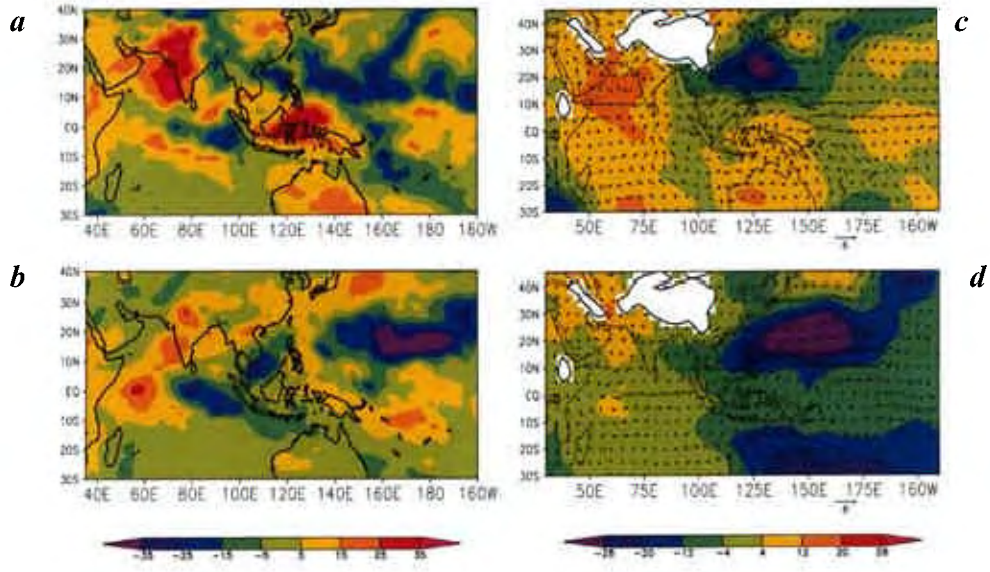

Figure 3. Anomalies of Outgoing Longwave Radiation (OLR) derived from NOAA satellite in Wm^{-2} from the Climate Diagnostic Center, USA (http://www.cdc.noaa.gov) during (***a***) July 2002 and (***b***), August 1986. OLR is a proxy for tropical convection. Deep convection in the tropics is characterized by low cloud-top temperatures and small OLR values. On the other hand, regions having high OLR values indicate scarcity or absence of cloud cover. ***c***, Anomalies of wind (ms^{-1}) and geopotential height (m) at 850 hPa during July 2002 from NCEP reanalysis. ***d***, Same as (***c***), except for August 1986.

downstream intensification mechanism. They proposed that superposition of quasi-stationary long waves and slow westward-travelling shorter waves can give rise to amplification of the propagating wave. Examination of maps of 24 h change of sea-level pressure (isallobaric maps) during July and August by Saha *et al.*[12] over a ten-year period (1969–78), revealed that a majority of lows and depressions that formed over the Bay of Bengal were associated with predecessor disturbances coming from the east. Their study suggested the existence of westward-moving wave disturbances with periods ranging up to 4 days, having westward phase speed around 6 m s^{-1} and wavelength of about 2300 km.

Another aspect of the relationship between the west Pacific cyclones and the Indian monsoon pertains to the occurrence of 'monsoon breaks'. The dynamical link between large-scale circulation changes during monsoon breaks and northward-moving typhoons over the west Pacific was pointed out in a study by Raman[13]. His results indicated that as the west Pacific typhoons, located between longitudes 110 and 140°E, crossed over to the north of 30°N, the axis of the monsoon trough over India moved to the foothills of Himalayas, resulting in a break-monsoon condition over the plains of India. In fact, the relationship between the summer monsoon rainfall over India and the number of typhoon days over the northwest Pacific shows a negative correlation[14]. Generally, the typhoon genesis over the northwest Pacific tends to be enhanced during weak phases of the monsoon intraseasonal variability; conversely the typhoon genesis is suppressed during periods of strong Indian summer monsoon[14]. The variability of the Indian monsoon rainfall in relation to convective activity of the equatorial trough over the Indian and west Pacific Oceans was examined by Joseph[15]. He noted that the cyclogenesis over the western Pacific was related to an out-of-phase variability in convection over the equatorial Indian Ocean and the west Pacific on the 30–50 day timescale.

Tropical storm tracks over the west Pacific exhibit pronounced sub-seasonal variations on the timescale of about 40 days, during May to November, which are determined by the position and strength of the subtropical high[16]. The variability of large-scale circulation features over the west Pacific is known to contribute to the genesis of tropical cyclones and track-type characteristics[17]. Studies have shown that when the genesis of Pacific typhoons occurs north of 20°N, or east of 150°E and north of 10°N, the probability of a recurving track is larger than that of a straight track[17,18]. For tropical disturbances that are generated equatorward of 20° latitude, the tropospheric vertical shear of the horizontal wind is a minimum; while tropical disturbances that intensify at latitudes poleward of 20°N in the northwest Pacific are observed to mostly result from disturbances which break away from their initial formation environment[18]. The large-scale circulation associated with these intensifications poleward of 20° latitude is considerably different from the climatological flow[18].

The issue of interannual variability of tropical cyclone activity over the west Pacific has also been explored by numerous investigators[19–24]. It is known that the frequency of formation of tropical storms over the Pacific Ocean, particularly in the southeastern quadrant (south of 15°N and east of 150°E), increases remarkably during El Nino years[19–21,24]. It can be noticed from these studies that the El Nino/Southern Oscillation (ENSO)-related circulation anomalies exert significant impact on the tropical cyclone activity over the Pacific basin. Accordingly, areas with anomalous cyclonic (anticyclonic) flow patterns tend to favour enhanced (suppressed) cyclogenesis respectively. Furthermore, the interannual variability in the frequency of monsoon depressions over the Bay of Bengal was examined by Chen and Weng[25]. They noted a reduction (increase) in the frequency of monsoon depressions during El Nino (La Nina) years, which they attributed to anomalous changes in the typhoon activity and westward propagating 12–24 mode over the western Pacific and south China Sea, in response to ENSO-induced large-scale circulation anomalies over the region. In this study, we analyse observed tracks of typhoons over the west Pacific from the Joint Typhoon Warning Center (JTWC), USA, over a 59-year period (1945–2003); along with daily winds from National Center for Environmental Prediction (NCEP) reanalysis[26] for the period 1948–2003, in order to gain insight into the teleconnection mechanisms that link the circulation variability over the west Pacific and the Indian monsoon region. The tracks of disturbances that are examined in this study, include low pressure systems ranging from depressions, tropical storms and typhoons (categories 1–5) based on the Saffir–Simpson scale.

A comparison of observed typhoon tracks for weak and strong Indian summer monsoons presented below, is helpful in understanding the variability of typhoon activity over the west Pacific. Note that the terminology 'weak monsoon'/'strong monsoon' used throughout the text refers to the Indian monsoon. The tropical cyclone tracks presented in Figure 4 *a* and *b* are based on nine weak monsoons and nine strong monsoons respectively. The nine weak monsoon cases correspond to the monsoon droughts during 1951, 1965, 1966, 1972, 1979, 1982, 1986, 1987, 2002; and the strong monsoons refer to nine cases of excess monsoon precipitation over India (1947, 1956, 1959, 1961, 1970, 1975, 1983, 1988, 1994). Table 1 provides year-wise information about the dates and time-periods of the cyclone tracks for the weak and strong monsoons respectively. Table 1 also shows a total of 163 cyclone tracks over the tropical Pacific during the nine weak monsoon years, and 148 tracks during the nine strong monsoon years. The weak (strong) monsoons are defined depending on whether the June–September All-India summer monsoon rainfall[27] is less (more) than 90% (110%) of the climatological normal. A comparison of Figure 4 *a* and *b* shows a greater ten-

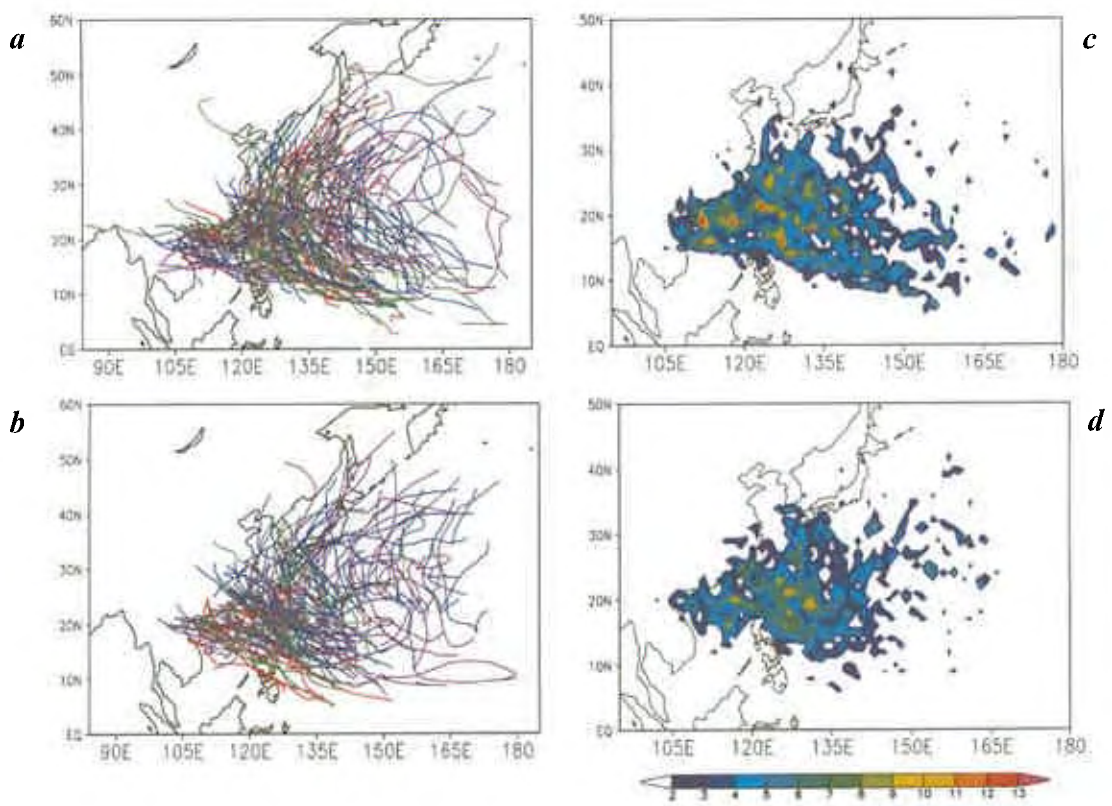

Figure 4. Typhoon tracks over tropical Pacific during (***a***) nine weak monsoon years (1951, 1965, 1966, 1972, 1979, 1982, 1986, 1987, 2002) and (***b***) nine strong monsoon years (1947, 1956, 1959, 1961, 1970, 1975, 1983, 1988, 1994). Tracks for June, July, August and September are shown in red, green, blue and purple respectively. (***c***), Cyclone density computed from nine weak monsoon years. (***d***), Same as (***c***), except for nine strong monsoon years. Cyclone density values are computed on 1° × 1° grid boxes, by counting the number of cyclones passing through any grid-box.

Dates of tropical cyclones over the Pacific during June to September for nine weak monsoon years and nine strong monsoon years. Dates are obtained from the Joint Typhoon Warning Center, USA. Typhoons that form during end of May and continue in June as well as those that form at the end of September and continue in October are considered in our analysis

nsoon	1951	1965	1966	1972	1979	1982	1986	1987	2002
	25 Jun–03 Jul	30 May–05 Jun	22 Jun–29 Jun	29 May–07 Jun	23 Jul–26 Jul	18 Jun–26 Jun	21 Jun–25 Jun	17 Jun–19 Jun	06 Jun–11 Jun
	26 Jul–02 Aug	01 Jun–03 Jun	11 Jul–14 Jul	31 May–07 Jun	28 Jun–07 Jul	28 Jun–02 Jul	28 Jun–02 Jul	24 Jun–02 Jul	28 Jun–28 Jun
	10 Aug–24 Aug	12 Jun–20 Jun	15 Jul–18 Jul	01 Jun–08 Jun	29 Jun–06 Jul	29 Jun–01 Jul	03 Jul–11 Jul	06 Jul–16 Jul	28 Jun–06 Jul
	30 Aug–04 Sep	18 Jun–26 Jun	17 Jul–20 Jul	22 Jun–30 Jun	24 Jul–08 Aug	02 Jul–04 Jul	13 Jul–17 Jul	15 Jul–22 Jul	29 Jun–11 Jul
	16 Sep–22 Sep	06 Jul–07 Jul	24 Jul–27 Jul	05 Jul–16 Jul	25 Jul–29 Jul	12 Jul–17 Jul	30 Jul–04 Aug	18 Jul–01 Aug	07 Jul–15 Jul
	24 Sep–26 Sep	07 Jul–16 Jul	31 Jul–02 Aug	05 Jul–22 Jul	02 Aug–06 Aug	21 Jul–30 Jul	09 Aug–16 Aug	21 Jul–30 Jul	08 Jul–13 Jul
		13 Jul–23 Jul	02 Aug–09 Aug	05 Jul–29 Jul	07 Aug–18 Aug	22 Jul–02 Aug	13 Aug–25 Aug	07 Aug–17 Aug	14 Jul–27 Jul
		21 Jul–27 Jul	12 Aug–16 Aug	07 Jul–25 Jul	15 Aug–26 Aug	04 Aug–14 Aug	15 Aug–17 Aug	07 Aug–24 Aug	18 Jul–21 Jul
		27 Jul–31 Jul	12 Aug–17 Aug	23 Jul–28 Jul	18 Aug–20 Aug	08 Aug–15 Aug	16 Aug–06 Sep	19 Aug–31 Aug	20 Jul–21 Jul
		31 Jul–07 Aug	17 Aug–18 Aug	30 Jul–04 Aug	30 Aug–04 Sep	17 Aug–27 Aug	17 Aug–29 Aug	20 Aug–28 Aug	20 Jul–27 Jul
		04 Aug–07 Aug	19 Aug–22 Aug	31 Jul–12 Aug	02 Sep–09 Sep	20 Aug–03 Sep	13 Sep–20 Sep	01 Sep–15 Sep	05 Aug–05 Aug
		15 Aug–20 Aug	20 Aug–24 Aug	08 Aug–19 Aug	12 Sep–17 Sep	27 Aug–05 Sep	19 Sep–30 Sep	03 Sep–17 Sep	02 Aug–05 Aug
		15 Aug–23 Aug	25 Aug–04 Sep	24 Aug–30 Aug	13 Sep–24 Sep	04 Sep–06 Sep		04 Sep–11 Sep	10 Aug–13 Aug
		16 Aug–19 Aug	29 Aug–30 Aug	24 Aug–31 Aug	17 Sep–22 Sep	04 Sep–16 Sep		21 Sep–03 Oct	11 Aug–20 Aug
		26 Aug–26 Aug	30 Aug–09 Sep	30 Aug–06 Sep	22 Sep–01 Oct	05 Sep–12 Sep		22 Sep–04 Oct	15 Aug–20 Aug
		26 Aug–28 Aug	01 Sep–01 Sep	09 Sep–18 Sep	23 Sep–26 Sep	15 Sep–19 Sep		24 Sep–26 Sep	10 Sep–10 Sep
		28 Aug–02 Sep	05 Sep–09 Sep	11 Sep–20 Sep		16 Sep–25 Sep		27 Sep–02 Oct	11 Sep–12 Sep
		30 Aug–02 Sep	06 Sep–10 Sep	12 Sep–21 Sep		21 Sep–22 Sep			22 Aug–01 Sep
		01 Sep–05 Sep	10 Sep–12 Sep	16 Sep–27 Sep					28 Aug–08 Sep
		04 Sep–12 Sep	11 Sep–18 Sep	30 Sep–04 Oct					30 Aug–10 Sep
		10 Sep–20 Sep	12 Sep–18 Sep						23 Sep–27 Sep
		13 Sep–14 Sep	14 Sep–17 Sep						26 Sep–02 Oct
		13 Sep–17 Sep	19 Sep–24 Sep						
		16 Sep–26 Sep	21 Sep–22 Sep						
		25 Sep–28 Sep	22 Sep–26 Sep						
		27 Sep–06 Oct	22 Sep–30 Sep						

Continued…

Table 1. (*Continued*)

Strong monsoon	1947	1956	1959	1961	1970	1975	1983	1988	1994
Tropical Pacific cyclone									
	17 Jun–23 Jun	18 Jun–20 Jun	04 Jul–06 Jul	02 Jun–05 Jun	29 Jun–30 Jun	26 Jul–30 Jul	19 Jun–26 Jun	29 May–03 Jun	02 Jun–09 Jun
	08 Jul–09 Jul	05 Jul–08 Jul	12 Jul–18 Jul	06 Jun–07 Jun	29 Jun–06 Jul	30 Jul–06 Aug	09 Jul–13 Jul	04 Jun–06 Jun	18 Jun–25 Jun
	17 Jul–19 Jul	27 Jul–03 Aug	02 Aug–12 Aug	06 Jun–07 Jun	12 Jul–16 Jul	05 Aug–07 Aug	09 Jul–18 Jul	18 Jun–24 Jun	29 Jun–05 Jul
	26 Jul–31 Jul	09 Aug–10 Aug	12 Aug–15 Aug	22 Jun–25 Jun	20 Jul–22 Jul	09 Aug–15 Aug	20 Jul–25 Jul	24 Jun–30 Jun	05 Jul–12 Jul
	04 Aug–09 Aug	03 Aug–05 Aug	19 Aug–23 Aug	23 Jun–02 Jul	28 Jul–31 Jul	11 Aug–18 Aug	05 Aug–17 Aug	11 Jul–19 Jul	08 Jul–11 Jul
	12 Aug–14 Aug	12 Aug–18 Aug	25 Aug–27 Aug	24 Jun–24 Jun	01 Aug–02 Aug	17 Aug–24 Aug	08 Aug–15 Aug	26 Jul–31 Jul	10 Jul–25 Jul
	26 Aug–31 Aug	25 Aug–02 Sep	25 Aug–31 Aug	26 Jun–27 Jun	03 Aug–04 Aug	25 Aug–03 Sep	12 Aug–15 Aug	05 Aug–08 Aug	11 Jul–28 Jul
	08 Sep–10 Sep	29 Aug–04 Sep	30 Aug–07 Sep	12 Jul–15 Jul	06 Aug–09 Aug	01 Sep–10 Sep	17 Aug–26 Aug	07 Aug–12 Aug	16 Jul–21 Jul
	10 Sep–15 Sep	01 Sep–11 Sep	05 Sep–06 Sep	16 Jul–19 Jul	09 Aug–15 Aug	04 Sep–08 Sep	25 Aug–27 Aug	13 Aug–21 Aug	23 Jul–26 Jul
	14 Sep–18 Sep	13 Sep–19 Sep	05 Sep–12 Sep	21 Jul–25 Jul	16 Aug–22 Aug	08 Sep–12 Sep	27 Aug–09 Sep	24 Aug–03 Sep	25 Jul–03 Aug
	22 Sep–25 Sep	18 Sep–24 Sep	11 Sep–19 Sep	27 Jul–03 Aug	23 Aug–31 Aug	15 Sep–21 Sep	20 Sep–28 Sep	24 Aug–29 Aug	27 Jul–31 Jul
	29 Sep–02 Oct	19 Sep–27 Sep	21 Sep–28 Sep	28 Jul–31 Jul	26 Aug–03 Sep	17 Sep–24 Sep	28 Sep–01 Oct	02 Sep–04 Sep	29 Jul–05 Aug
		23 Sep–27 Sep		01 Aug–08 Aug	04 Sep–04 Sep			05 Sep–17 Sep	30 Jul–13 Aug
				07 Aug–09 Aug	04 Sep–06 Sep			11 Sep–16 Sep	03 Aug–16 Aug
				14 Aug–15 Aug	04 Sep–08 Sep			12 Sep–16 Sep	12 Aug–22 Aug
				15 Aug–18 Aug	08 Sep–14 Sep			16 Sep–24 Sep	19 Aug–02 Sep
				20 Aug–26 Aug	20 Sep–29 Sep			18 Sep–22 Sep	20 Aug–29 Aug
				24 Aug–28 Aug				19 Sep–23 Sep	24 Aug–04 Sep
				29 Aug–03 Sep					30 Aug–08 Sep
				07 Sep–17 Sep					01 Sep–12 Sep
				08 Sep–10 Sep					06 Sep–14 Sep
				08 Sep–12 Sep					08 Sep–19 Sep
				21 Sep–24 Sep					14 Sep–23 Sep
				25 Sep–29 Sep					16 Sep–01 Oct
				27 Sep–05 Oct					19 Sep–29 Sep

dency for the tropical cyclones to move northward (north of 20°N) during weak monsoons compared to strong monsoons. In particular, it can be noticed that the re-curvature of the tropical cyclones north of 20°N is more pronounced during weak monsoons. From Figure 4 *a* and *b*, it can be observed that the concentration of cyclone tracks over the west-central Pacific (0–30°N; 110–160°E), is relatively higher during weak monsoon years compared to strong monsoons. Quantitative information based on the cyclone tracks can be deduced from the cyclone density values which are computed on $1° \times 1°$ grid-boxes by counting the number of cyclones passing through any grid-box. Maps of cyclone density for weak and strong Indian summer monsoons are shown in Figure 4 *c* and *d* respectively. It can be seen that the density of tropical cyclones over the tropical west-central Pacific is considerably higher during weak monsoons (Figure 4 *c*) compared to strong monsoons (Figure 4 *d*). In particular, the cyclone density values over the China Sea, the Philippines and Taiwan regions of northwest Pacific are relatively higher in Figure 4 *c* compared to Figure 4 *d*, which is consistent with the stronger recurvature of cyclones (north of 20°N) during weak monsoons. The overall increase in cyclone activity over northwest and tropical west-central Pacific (105–160°E; 5–28°N) during weak monsoon years relative to strong monsoon years, is also evident from the frequency distribution curves shown in Figure 5. The distribution curves correspond to the frequency/probability of occurrence of cyclones over northwest and tropical west-central Pacific for a range of cyclone density values. Clearly, it can be seen from Figure 5 that the probability of occurrence of cyclones is higher during weak monsoon years compared to strong monsoon years. By computing the area under the two distribution curves, it is found that the probability of the tropical Pacific cyclone activity is about 1.33 times higher during weak monsoon years compared to strong monsoon years. Here, it is realized that in addition to the frequency of tropical cyclones, the track characteristics of the cyclonic systems can also be quite different during strong and weak monsoon years. For example, the cyclone activity over west Pacific was substantially enhanced during 1994, which however turned out to be a case of strong summer monsoon over India. Examination of the west Pacific cyclones during 1994 revealed several westward-moving cyclones located to the south of 20°N.

Using the data of daily winds from NCEP reanalysis for the period 1948–2002, large-scale teleconnections between the west Pacific typhoons and the circulation anomalies over the Indo-Pacific region are examined. For this purpose, wind-anomaly composites are constructed for the typhoon dates selected based on the following criteria. The typhoon dates represent the period during which at least one tropical cyclone existed over the Pacific Ocean. In the case of multiple cyclones, the starting date corresponds to the date of formation of the first cyclone, and the ending date corresponds to the date of decay of the last cyclone. It must be mentioned that the composites of wind anomalies based on the typhoon dates have been constructed separately for weak and strong monsoon years. The anomaly composite of 850 hPa winds based on the typhoon dates during weak monsoon years is shown in Figure 6 *a*. The corresponding wind anomaly composite based on the typhoon dates during strong monsoon years is shown in Figure 6 *b*. The wind anomalies in Figure 6 *a* and *b* show several interesting features over the Pacific sector as well as the Indian monsoon region. A well-defined meridional pattern over the west-central Pacific, consisting of anomalous anticyclonic vorticity over the equatorial region, anomalous cyclonic vorticity over the subtropics and anomalous anticyclonic vorticity further northward to the east of Japan can be seen in Figure 6 *a*. Further, it can be noticed that the large-scale cyclonic circulation anomaly over the subtropical Pacific extends eastward from eastern China, Taiwan and the Philippines regions up to nearly 140°W. The southern flank of the cyclonic circulation anomaly in Figure 6 *a* shows anomalous westerlies, extending longitudinally across the Pacific basin, which clearly indicates weakening of the easterly trade winds; while the northern side of the cyclonic anomaly shows anomalous north-easterlies extending from the mid-latitude central-eastern Pacific to the subtropical west Pacific. The anomalous low-level cyclonic vorticity (positive shading) in Figure 6 *a* shows that the broad region over the subtropical west-central Pacific is conducive for genesis of tropical cyclones. On the other hand, the anticyclonic anomalies over the Indian subcontinent and easterly anomalies over the Arabian Sea correspond to weakening of the southwest monsoon circulation. The anticyclonic anomaly over India and the cyclonic shear zone over the equatorial Indian Ocean in Figure 6 *a*, are similar to those seen during monsoon breaks or weak monsoon conditions[28–30]. In contrast, the wind anomalies in Figure 6 *b*, computed for the typhoon dates during strong monsoon years, show stronger southwest

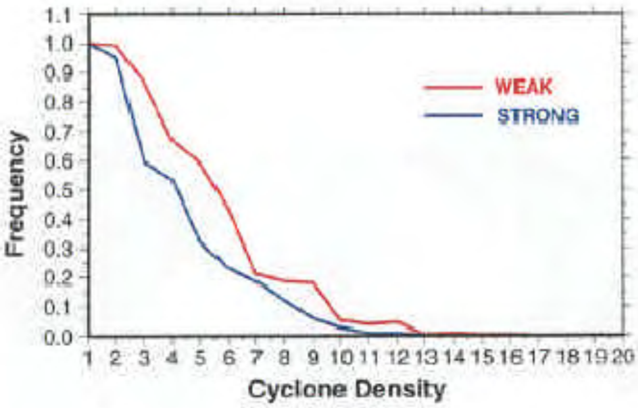

Figure 5. Frequency distribution of cyclones over northwest and tropical west-central Pacific (105–160°E; 5–28°N) for a range of cyclone density values. Distribution during weak (strong) monsoon years is shown by red (blue) line respectively. Distribution curves are normalized in the range [0–1].

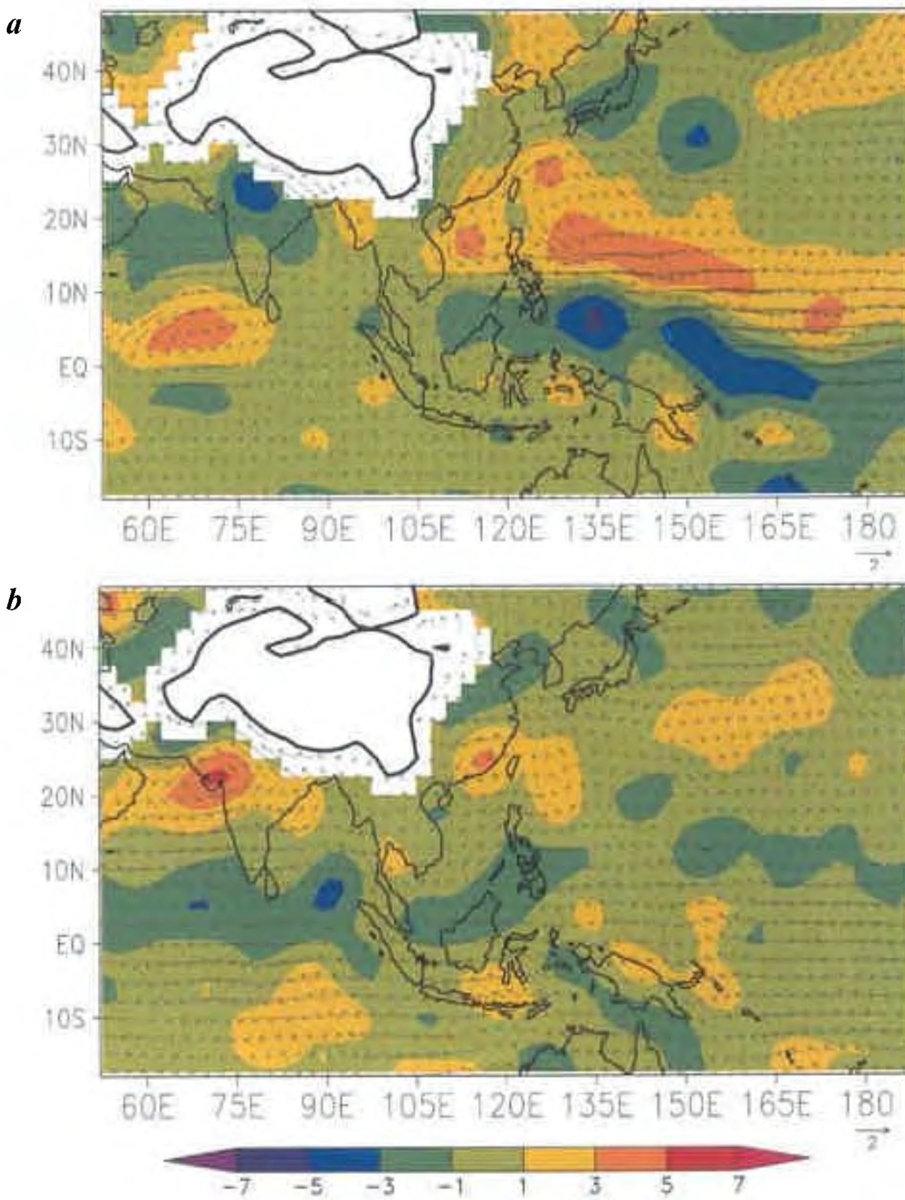

Figure 6. Composites of wind anomalies (ms^{-1}) at 850 hPa for (***a***) weak monsoon years and (***b***) strong monsoon years. Total number of typhoon days for the weak monsoon composite is 729 and for the strong monsoon composite is 600. Shading denotes relative vorticity (1×10^{-6} s^{-1}) anomalies.

monsoon circulation, intensified cross-equatorial wind anomalies and anomalous cyclonic circulation over India. Over the Pacific sector, the low-level wind anomalies in Figure 6 *b* show anomalous south-westerlies over south China Sea, cyclonic circulation anomaly over eastern China and Taiwan regions, and intensified easterly trade winds over the equatorial Pacific. Clearly, the region of anomalous cyclonic vorticity for the strong monsoon composite in Figure 6 *b* is confined over a much smaller region around eastern China and Taiwan compared to Figure 6 *a*.

The anomaly composite of 200 hPa winds based on the typhoon dates during weak monsoon years is shown in Figure 7 *a*. The anomalous westerlies over the Indian region indicate major weakening of the upper-level easterlies and the Tibetan high. It is important to note that the upper-level westerly anomalies in Figure 7 *a* are not just confined over the Indian region; instead they extend in both the hemispheres. It is known that during intensely weak phases of the Indian summer monsoon, the atmospheric general circulation in both the hemispheres is locked in a low-index Rossby regime[31]. Another conspicuous feature in Figure 7 *a* is the anomalous mid-latitude circulation pattern characterized by a cyclonic anomaly located over the Caspain Sea and Afghan–Pakistan region, an anticyclonic anomaly near 100°E around Mongolia, and an anomalous cyclone further eastward over northeast China, Korea and Japan. The anomalous low in the upper troposphere over west-central Asia and the Indo-Pak region is a feature

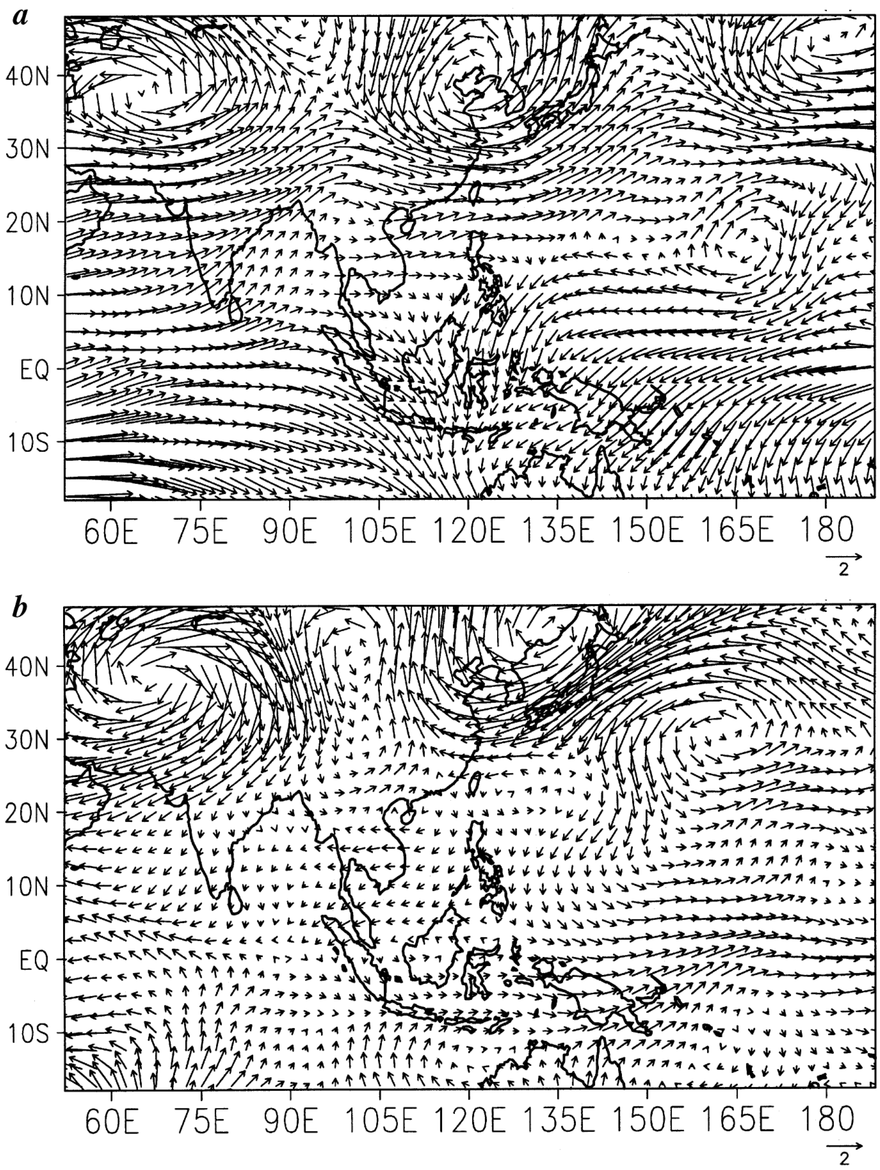

Figure 7. Same as in Figure 6, except for 200 hPa.

known to occur during weak episodes of the Indian monsoon[32–35]. Such anomalous lows embedded in the mid-latitude westerlies cause advection of cold and dry air, which intrudes from the extra-tropics into the Indian subcontinent and inhibits monsoon activity[28,32–35]. Furthermore, it is recognized that the mid-latitude pattern (Figure 7 *a*) extending from west-central Asia to the far-east, is a characteristic feature associated with out-of-phase variations in rainfall over the Indian monsoon region and the far-east[35,36]. Another large-scale feature in Figure 7 *a* is the anomalous anticyclone over the subtropical west-central Pacific, which is characterized by easterly anomalies over the equatorial region and westerly anomalies over the mid-latitudes and subtropics, which intrude as south as 15°N. While the anomalous upper level easterlies over the equatorial Pacific assist in westward movement of the tropical cyclones, the westerly anomalies which extend from the subtropics into the mid-latitudes (Figure 7 *a*) help steer the cyclones northward. This provides a possible explanation for the strong recurvature (north of 20°N) of northward-moving cyclones during weak monsoon years. However, the steering effect by the upper-level winds is considerably reduced over the Bay of Bengal and the Indian subcontinent because of the weakening of the Tropical Easterly Jet over the region (Figure 7 *a*). Nevertheless, the dynamics of the large-scale circulation anomalies in affecting the movement and track characteristics of west Pacific tropical cyclones during weak monsoon years, needs detailed investigation[37]. The anomaly composite of 200 hPa winds based on the typhoon dates during strong monsoon years (Figure 7 *b*), shows a strong anticyclonic anomaly over west-central Asia and easterly anomalies between 60 and 120°E. In the strong monsoon case (Figure 7 *b*), it can be noticed that the anomalous southerlies over the subtropical Pacific and westerlies over the equatorial Pacific are not conducive for northward movement of the tropical cyclones.

From the above discussions, it is clear that the formation and tracks of cyclonic disturbances over the tropical Pacific are significantly affected by anomalies in the large-scale circulation. Here, it must be pointed out that several cases of the weak (strong) Indian monsoons have coincided with El Nino (La Nina) conditions in the Pacific. In fact, the maps of SST anomalies (figures not shown) composited from the weak and strong monsoon cases, clearly indicate the ENSO signal. It is well-recognized that the ENSO influence in the tropics operates through anomalous changes in the east-west Walker circulation[38]. The weakening (strengthening) of the low-level wind anomalies over the equatorial Pacific in Figure 6 *a* (Figure 6 *b*) is a manifestation of the effect of ENSO on the trade winds. Likewise the anomalous easterlies (westerlies) in the upper troposphere over the equatorial Pacific in Figure 7 *a* (Figure 7 *b*) are consistent in indicating the ENSO influence on the east-west Walker circulation. The above discussions point to the role of ENSO in influencing the interannual variability of large-scale circulation over the Indo-Pacific sector (Figures 6 and 7). While the present findings mostly emphasize the significance of the large-scale circulation patterns in shaping the genesis and movement of tropical disturbances over the Pacific Ocean, they also raise a number of questions. For example, do the tropical cyclones in turn feed back onto the large-scale circulation anomalies over the Pacific and Indian region? If so, how does the large-scale circulation interact with the precipitation/convection anomalies associated with the Pacific typhoons? What is the role of ENSO-induced SST and convection anomalies in affecting the cyclone activity over the tropical Pacific? How do the convection and circulation anomalies over the Indian region dynamically interact with those over the Pacific? In the light of the present findings, it is suggested that the ENSO-monsoon dynamical connection involves changes not only in the east-west divergent circulations, but also interactive feedback among tropical convections, large-scale circulation patterns and cyclonic disturbances over the tropical Pacific. Further studies and model experiments will be required in order to unravel these dynamical linkages over the Indo-Pacific sector.

Summary

Dynamic teleconnections between the southwest monsoon circulation and the tropical cyclone activity over northwest and west-central Pacific are examined by performing an analysis of observed tracks of typhoons over the tropical Pacific for the period 1945–2003; along with supplementary diagnostics of daily global wind data from NCEP reanalysis during 1948–2003. The findings from the analysis suggest that large-scale circulation changes over the Indo-Pacific sector during strong and weak monsoons exert significant impact on the genesis and movement of cyclones over the tropical Pacific. First, it is seen that the number of tropical cyclones forming in the northwest and west-central Pacific is about 1.33 times higher during weak monsoon years compared to strong monsoon years. Secondly, there is a greater tendency for the tropical Pacific cyclones to recurve and move northward (north of 20°N) during weak monsoon years relative to strong monsoon years. The low-level wind anomalies show that the enhanced cyclogenesis during weak monsoon years is associated with enrichment of cyclonic vorticity anomalies over a wide-region of the subtropical Pacific extending from the China Sea, Taiwan and Philippines regions to the central Pacific. On the other hand, the low-level cyclonic anomaly during strong monsoon years is confined over a smaller region around Taiwan. Circulation anomalies in the upper troposphere reveal contrasting features during weak and strong monsoon years. It is found that the occurrence of anomalous upper-level easterlies over the equatorial Pacific and strong westerly anomalies over the subtropical and mid-latitude Pacific during weak monsoon years, help steer the cyclonic systems in a northward direction. On the contrary, the steering effect is substantially reduced during strong monsoon years. Given that the interannual variations of the trade winds and the east-west divergent circulations over the Pacific are crucially determined by the ENSO conditions, the findings raise a number of questions regarding the interactions among tropical convection, large-scale circulation anomalies and cyclonic disturbances over tropical Pacific, which constitute an integral part of the dynamical linkage between the monsoon and ENSO.

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