Seasonality of westward-propagating disturbances over Southeast and south Asia originated from typhoons

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[1] We investigate the seasonal changes in the westward-propagating disturbances (WDs) in Southeast and South Asia originated from typhoons over the western North Pacific. WDs tend to move over the northern part of the Indochina Peninsula and South Asia in summer, while over the southern part of the Indochina Peninsula and the Bay of Bengal in fall. Although the number of landfall on the Indochina Peninsula is the largest in fall, the active season for WD with a more west-oriented track is identified in late summer. The seasonality is related to large-scale atmospheric conditions. The easterly region throughout the latitude band 15°–25°N at 700 hPa during the active phases of intraseasonal variation in monsoon trough and the large-scale trough in lower troposphere over the Bay of Bengal are favorable conditions for taking the more west-oriented track of WD in late summer. Such conditions are found neither earlier summer nor fall.

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1. Introduction

[2] Some westward-propagating residual disturbances (WDs) over Southeast and South Asia were originated from the typhoons that formed in the western North Pacific and South China Sea (WNP-SCS) and made landfall on the Indochina Peninsula. Abundant rains accompanying typhoon-related WDs have caused several flooding resulting in heavy losses of life and widespread damages over Southeast and South Asia, Typhoons NIKI and USAGI being examples. The WD originated from Typhoon NIKI that made landfall on the Indochina Peninsula in mid-August 1996, and then passed through the Indochina Peninsula and South Asia (Figure 1b). Dartmouth Flood Observatory reported the extreme flood events in Bangladesh during the passage of the WD over South Asia (http://www.dartmouth.edu/~floods/index.html). In Southeast Asia, the abundant rain accompanied by the WD originated from Typhoon USAGI also caused the extreme flood events, devastated Northern Thailand and Central Vietnam in early August 2001. It is important to understand the frequency of WDs, because their associated rainfall strongly affects human activities in Southeast and South Asia.

[3] The previous studies [e.g., *Krishnamurti et al.*, 1977; *Saha et al.*, 1981] suggested that the WDs across the Indochina Peninsula were closely related to the some monsoon depressions over the Bay of Bengal. Statistical analysis by *Chen and Weng* [1999] indicated that about 60% of monsoon depressions in summer from June to August was related to the WDs that could be traced to typhoons in the WNP-SCS.

[4] The attention of previous studies relating to the WDs was primarily paid to the summer season, and did not focus on the WDs in fall. The frequency of typhoon that make landfall on the Indochina Peninsula, however, is greater in fall rather than in summer (Figure 2). In the present study, we investigate the seasonal changes in WDs originated from typhoons statistically, and how the seasonal changes are related to those in typhoons that make landfall on the Indochina Peninsula.

2. Data and Definition

[5] The best track data compiled by the Joint Typhoon Warning Center is used to identify the typhoons that make landfall on the Indochina Peninsula. In this study, typhoons refer to both tropical storms and typhoons, so the analyzed typhoons that make landfall on the Indochina Peninsula are defined as typhoons crossing the longitude of 110°E with maximum sustained wind speeds greater than 17 m s^{-1}. In order to search their subsequent movements over South Asia, we use relative vorticity derived from the European Center for Medium range Weather Forecast 40 year re-analysis (ERA-40) data with a resolution of 2.5°.

[6] Figure 1a shows the relative vorticity of WD originated from Typhoon NIKI with respect to longitude at 850, 700, 500, and 300 hPa levels. At 110°E, the WD has a larger relative vorticity in the lower level. During the passage of WD over the Indochina Peninsula (100°–110°E), the relative vorticity decays rapidly at 850 hPa level compared with those in upper levels, because a low-level disturbance is greatly influenced by mountainous terrain. Since the relative vorticity at 700 hPa is the largest than those at all levels in the west of the Indochina Peninsula, it would be an indicator of the movements of WD.

[7] It is noted that the higher relative vorticity at 700 hPa associated with the WD is accompanied by the active convection, according to the satellite data (not shown). Therefore, we define the WD as the relative vorticity at 700 hPa more than 5.0×10^{-5} s^{-1}. The disappearance location of WD is identified when the intensity of WD eventually reaches below the defined criterion. It is noted that the results using other criterions of 4.0×10^{-5} or 6.0×10^{-5} s^{-1} are essentially same as those using this definition.

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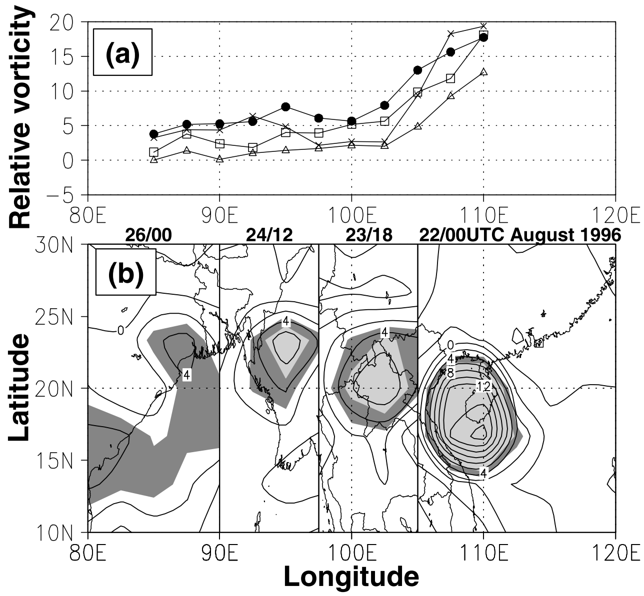

Figure 1. The case of Typhoon NIKI in 1996: (a) relative vorticity of WD with respect to longitude at 850 (cross), 700 (closed circle), 500 (square), and 300 (triangle) hPa levels, and (b) the relative vorticity at 700 hPa level. Contours interval is 2.0×10^{-5} s^{-1}. Dark and light shading indicate areas of anomalies greater than 3.0×10^{-5} s^{-1} and 5.0×10^{-5} s^{-1}, respectively.

[8] The analysis is confined to the period of 36 years from 1966 to 2001 when satellites have operated and the ERA-40 data completely covers. During the analysis period, a total of 170 typhoons are identified as typhoons that make landfall on the Indochina Peninsula. These typhoons form over the SCS (54%) and the east of the Philippines (46%). To examine the seasonal changes, the numbers of these typhoons are counted within a 10-day period (Figure 2). It is found that there are the seasonal changes with three peaks near early-July (190), late-August (240), and mid-November (320). As pointed out in the previous studies [*Harr and Elsberry*, 1991; *Chen and Weng*, 1996], the characteristics of typhoon tracks are influenced by the large-scale circulation relating to the Asia monsoon. By considering the short-term variation of typhoons that make landfall on the Indochina Peninsula, we here define three periods of 151–210 days (31 May–29 July), 211–270 days (30 July–27 September), and 271–330 days (28 September–26 November) as P1, P2, and P3, respectively.

3. Results

[9] Figure 3 shows the tracks of typhoons and WDs in each period. During P1 and P2, typhoons make landfall on the northern coast of the Indochina Peninsula. However, WDs in P1 rapidly disappear in the northern part of the Indochina Peninsula and the southern part of China, while a lot of WDs in P2 move westward over the northern part of the Indochina Peninsula, and even some WDs arrive at the northern part of the Bay of Bengal or South Asia. Furthermore, a few WDs in P2 reach the northern part of India. During P3, typhoons make landfall on the whole eastern coast of the Indochina Peninsula. Most of WDs move westward crossing over the southern part of the Indochina Peninsula, and then finally disappear in the western part of the Indochina Peninsula or the eastern part of the Bay of Bengal.

[10] In order to see the frequency of WDs in each period in a more quantitative way, the histogram of passage number of WDs with respect to longitude is shown in Figure 3. The number of WDs at 110°E, namely, the frequency of typhoons that make landfall on the Indochina Peninsula is the largest in P3 (Figure 2). The most active season for WD with a more west-oriented track is, however, identified in P2. The disappearance rate of WD during the passage over the Indochina Peninsula (110°–100°E), which is defined as the ratio of the number of disappearing WD to that of passage, is about 40% in both P2 and P3, while the largest rate more than 60% is in P1. Between the western part of the Indochina Peninsula and the central Bay of Bengal (100°–90°E), however, the rate in P3 increases by 90%. By contrast, the rate in P2 is about 40% even over the western region of the Indochina Peninsula, which means that the WDs can move more westward in P2 than in P3. Thus, the seasonal change in the frequency of WDs with a more west-oriented track is inconsistent with that of typhoons that make landfall on the Indochina Peninsula.

[11] The seasonal change in tracks of WDs is not related to the characteristics of typhoons: their intensities and genesis locations. It is greatly influenced by large-scale atmospheric circulation patterns in the lower-middle troposphere, consisting of the Asia monsoon, mid-latitude westerly, and trade easterly. Figure 4 shows the time series of 3-day mean zonal winds at 700 hPa averaged the area between 90°–110°E from June through November 1996, with the tracks of WDs in 1996. In P1 corresponding to the active monsoon season, the westerly region appears from south of 10°N up to 30°N. It extends far to the SCS from the Indian Ocean, which is favorable for disturbing the westward moving typhoons over the Indochina Peninsula. Even after a few typhoons make landfall, the WDs move somewhat northwestward and eventually disappear around the northern part of the Indochina Peninsula and the southern part of China, the WD related Typhoon FRANKIE being one example.

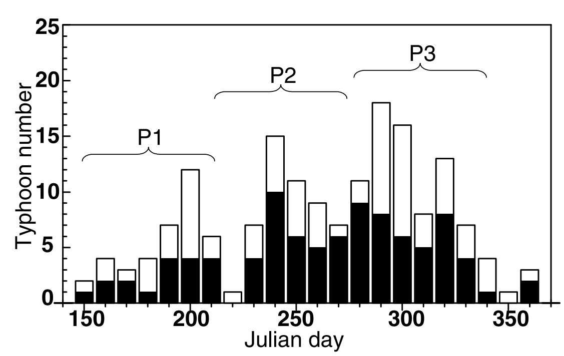

Figure 2. Number of typhoons that made landfall on the Indochina Peninsula during 1966–2001 counted in 10-day periods. Typhoons generated in the Philippine Sea are represented by black histograms, while the South China Sea represented by open histograms on the top of black histograms.

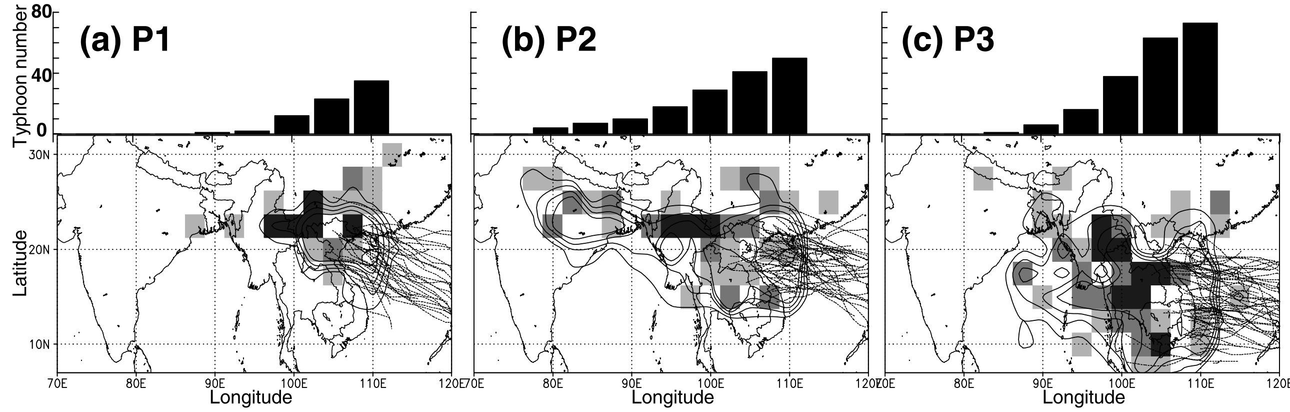

Figure 3. The typhoon tracks (dashed line), distribution of WD tracks (contour), disappearance location of WD (shading), and histogram of passage number of WD with respect to longitude in each season. Contour interval is 10. Black, dark, and light shading indicates areas of number greater than three, two, and one, respectively.

[12] On the other hand, during P3 corresponding to the withdrawal season of the Asian monsoon, the easterly region spreads between 5°–20°N relating to the trade easterlies. The trade easterlies over the WNP intrude westward over the Bay of Bengal through the Indochina Peninsula. The condition facilitates the westward movement of WD related to typhoons that make landfall on the whole east coast of the Indochina Peninsula. However, the mid-latitude westerly region simultaneously shifts to the lower latitude and spreads to South Asia and the northern part of the Indochina Peninsula, accompanied by the weakening of the Tibetan High, and therefore WDs in P3 take the way only in the southern part of the Indochina Peninsula and the Bay of Bengal, the tracks of WDs related Typhoons BETH and ERNIE being examples.

[13] It is of interesting that, only in P2, some WDs moves more westward through the northern part of the Bay of Bengal and South Asia. Although the climatological zonal winds over the Indochina Peninsula averaged during the period shows the westerly, the zonal wind often weakens or becomes easterly associated with the intraseasonal variation in the monsoon trough with a period of 30–60 days [e.g., *Nakazawa*, 1992], facilitating the westward movement of disturbances across the Indochina Peninsula. As the intense westerlies are dominant in the lower latitude corresponding to the active phases of monsoon trough near 20 August and 20 September 1996, easterly region simultaneously appear between 15°–25°N. The easterly region extends far to India from the WNP-SCS during the active phases, while monsoon westerly region extends eastward arriving at the east of the Philippines in the lower latitude. These easterlies seem to act as a steering flow of typhoon and WD moving to the west. The WDs related Typhoons NIKI, SALLY, and WILLIE move westward arriving at South Asia just during the active phases of intraseasonal variation in the monsoon trough. In contrast, during the inactive phases of intraseasonal variation, the westerly regions spread around the latitude of 20°N near 10 August 1996, which would disturb the westward movement of WD through the path over the Indochina Peninsula, Typhoon MARTY being examples. The similar relations between the frequency of WDs and the intraseasonal variation of monsoon trough in P2 are found in the other years as suggested by *Chen and Weng* [1999].

[14] Furthermore, the large-scale environment over the Bay of Bengal in P2 seems to sustain the intensity of WD reaching South Asia. Lower troposphere over the northern part of the Bay of Bengal is characterized by the existence of large-scale trough extending southward (not shown). The large-scale trough gives rise to large positive relative vorticity over South Asia and the northern part of Bay of Bengal. Additionally the southwesterlies around the large-scale trough over the Bay of Bengal bring the warm moist air to South Asia from the equatorial Indian Ocean (Figure 5). Since the condensation heating associated with cumulus convection is the most significant energy source for the tropical disturbances [*Lau and Lau*, 1992], the large-scale environment over the Bay of Bengal in P2 causes the slowdown of the decay of WDs in this region, resulting in that WDs tend to have a longer lifetime and be able to reach South Asia. Some WDs during the passage over South Asia

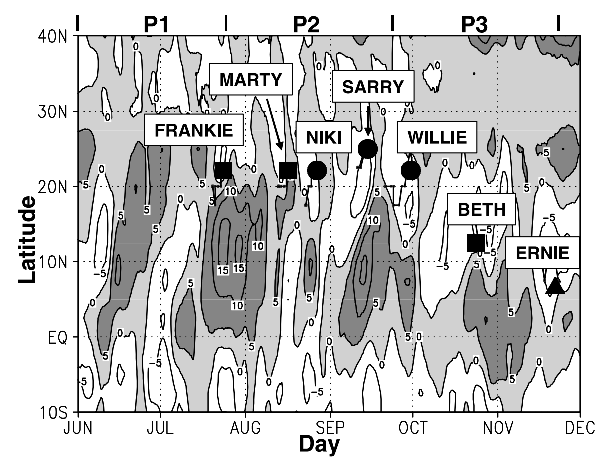

Figure 4. Time series of 3-day mean zonal winds at 700 hPa averaged the area between 90°–110°E from June through November 1996 and the tracks of WDs (line). Contour interval is 5 m s^{-1}. Light and dark shading indicate areas of greater than 0.0 m s^{-1} and 5.0 m s^{-1}, respectively. The disappearance locations depending on the longitude at 105°E (square), 100°E (triangle), and 95°E and 85°E (circle) of WDs are indicated.

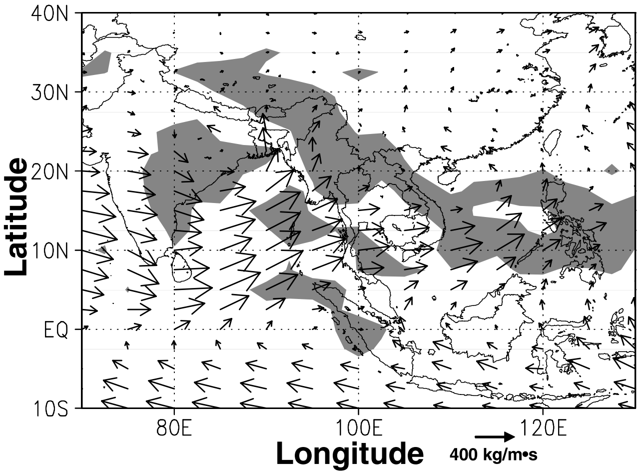

Figure 5. Vertical integrated water-vapor flux (kg m^{-1} s^{-1} arrows, scale at bottom) and its divergence from 925 to 300 hPa level in P2. The regions smaller than -3.0×10^{-5} kg m^{-2} s^{-1} are shaded.

during P2 are redeveloped, as shown in the WD relating to Typhoon NIKI (Figure 1). During P3, on the other hand, such conditions are not realized over the Bay of Bengal because of retreat of the Asian monsoon (not shown).

4. Summary

[15] We investigated the seasonal changes in the typhoon-related residual disturbances (WD). WDs tend to move over the northern part of the Indochina Peninsula and South Asia during P1 (June–July) and P2 (August–September), while over the southern part of the Indochina Peninsula and Bay of Bengal during P3 (October–November). Although the number of typhoons that make landfall on the Indochina Peninsula is the largest during P3, the most active season for WD with a more west-oriented track is identified during P2.

[16] The seasonality of WD seems to be related to large-scale atmospheric condition. During the active phases of intraseasonal variation in the monsoon trough in P2, the easterly region at 700 hPa level appears throughout the latitude band 15°–25°N extending far to India from the WNP-SCS. These easterlies seem to act as a steering flow of typhoon and WD moving to the west. Furthermore, the large-scale environment in the lower troposphere over the Bay of Bengal in P2, which is characterized by the existence of large-scale trough, large positive relative vorticity, and environmental inflow of warm moist air from warm oceans, cause the slowdown of the decay of WDs during the passage over South Asia and the Bay of Bengal. It facilitates the more west-oriented track of WDs over the northern part of the Indochina Peninsula and South Asia. Such conditions are found neither in P1 nor P3.

[17] Since the typhoon-related WDs affect the amount of rainfall around the countries of Southeast and South Asia, it is important to understand rainfall accompanied with typhoon-related WDs as well as the Asia monsoon. Observation of rainfall with better spatial and temporal resolutions will allow us a more quantitative understanding of this phenomenon as well as predicting water resources over Southeast and South Asia.

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