Interdecadal Changes in Summertime Typhoon Tracks

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ABSTRACT

The present work examines interdecadal variations of typhoon tracks in the western North Pacific (WNP) during the boreal summer (June–September) for the period 1951–2001. Typhoon tracks are expressed as percentage values of the total number of typhoon passages into a 5° × 5° latitude–longitude grid box with respect to the total number of typhoons formed in the WNP. The analysis period is divided into two interdecadal periods: ID1 (1951–79) and ID2 (1980–2001). From ID1 to ID2, typhoon passage frequency decreased significantly in the East China Sea and Philippine Sea, but increased slightly in the South China Sea. The time series of typhoon passage frequency over the East China Sea and South China Sea further reveal a regime shift in the late 1970s, while those over the Philippine Sea indicate a continuous downward trend of −9% decade^{-1}.

The interdecadal changes in typhoon tracks are associated with the westward expansion of the subtropical northwestern Pacific high (SNPH) in the late 1970s. The expansion of the SNPH to the southeast coast of Asia may result in a larger elliptic pathway of typhoon migration. This is consistent with the westward shift of the typhoon tracks from ID1 to ID2, resulting in an increase of typhoon passage frequency in the South China Sea and a decrease in the East China Sea. The change of typhoon tracks is partly due to the westward shift of major typhoon formation regions associated with a warmer sea surface temperature in the South China Sea. The decreasing typhoon passage frequency over the Philippine Sea is due to less typhoon formation in recent decades. This is consistent with the decreasing cyclonic relative vorticity in the lower troposphere.

1. Introduction

Most tropical cyclones form over tropical warm oceans where sea surface temperature (SST) is higher than 26.5°C, except in the South Atlantic and eastern South Pacific basins. Many factors influence tropical cyclone activity, including SST, vertical wind shear, thermodynamic instability/stability, upper-tropospheric momentum flux convergence, midtropospheric moisture, and so on (e.g., Gray 1968; Molinari and Vollaro 1989; Pfeffer and Challa 1992; DeMaria et al. 2001; Goldenberg et al. 2001; Baik and Paek 2001). Among these factors, high SST is favorable for tropical cyclone genesis and intensification, while strong vertical wind shear is unfavorable for genesis and tends to weaken storm intensity. Goldenberg et al. (2001) suggested that the recent increase in the activity of tropical cyclones over the North Atlantic is associated with the simultaneous increase in SST and decrease in vertical wind shear. DeMaria et al. (2001) showed that tropical cyclone formation in the early season over the tropical Atlantic is limited by vertical thermodynamic instability and midtropospheric moisture and that tropical cyclone formation at the end of the season is limited by vertical wind shear.

There are more frequent and intense tropical cyclones in the western North Pacific (WNP) than in any other ocean basins. The annual number of tropical cyclones formed in the WNP, locally known as typhoons, is about 27 (Yumoto and Matsuura 2001). More than half of the WNP typhoons are formed during June–October (i.e., typhoon season). The preferred regions of typhoon formation change seasonally with the annual migrations of the maximum SSTs and the intertropical convergence zone (McBride 1995).

Many previous studies demonstrated that the variation of tropical cyclone activity over the WNP is to some extent associated with the El Niño–Southern Oscillation (ENSO; Chan 1985; Wu and Lau 1992; Lander 1994; Chen et al. 1998; Chan 2000; Wang and Chan 2002) and quasi-biennial oscillation (Chan 1995). There is a

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frequency reduction in tropical cyclone formation in the WNP in the following summer of the El Niño year corresponding to a longitudinal shift of the Walker circulation (Chan 1985; Wu and Lau 1992; Chan 2000). Chan (1985) found that typhoons tend to form farther eastward in the summer after the El Niño year and are more likely to curve backward to the east of Japan. Changes in these large-scale circulations can shift the location of tropical cyclone formation and influence tropical cyclone activity (Lander 1994; Chan 2000; Wang and Chan 2002; Chia and Ropelewski 2002).

Although there have been extensive studies on the variability of tropical cyclone activity, including formation frequency and storm intensity, relatively less research effort has been expended on the long-term variability of tropical cyclone tracks. Obviously, tropical cyclone movement is greatly influenced by environmental circulation patterns such as the location and strength of the subtropical northwestern Pacific high (SNPH). Recently, Gong and Ho (2002) demonstrated that the summertime SNPH has strengthened and expanded to the southeast coast of Asia since the late 1970s. Because the SNPH is a part of the east Asian summer monsoon system, its modification might have brought about changes in monsoon circulation over east Asia over the last two decades, particularly in rainfall over central China (Gong and Ho 2002). Another plausible result of changes in the SNPH would be changes in tropical cyclone tracks in the WNP basin. This has motivated the present study.

In this study, we present evidence of interdecadal changes in summertime typhoon tracks, based on analyses of SST, geopotential height, horizontal wind, and typhoon data. Relevant links of the interdecadal changes to SST and large-scale circulation are discussed.

2. Data and statistical method

We used tropical cyclone data for 1951–2001 archived by the Regional Specialized Meteorological Centers–Tokyo Typhoon Center. The data include names, positions (in latitude and longitude), minimum surface pressures, and maximum wind speeds of tropical cyclones in every 6-h interval. A tropical cyclone can be divided into three stages depending on its maximum sustained wind speed: tropical depression ($v_{max} < 17$ m s^{-1}), tropical storm ($17 \leq v_{max} < 34$ m s^{-1}), and typhoon or hurricane ($v_{max} \geq 34$ m s^{-1}). In the present study, ''typhoons'' refer to both tropical storms and typhoons, so analyzed typhoons have maximum sustained wind speeds greater than 17 m s^{-1} during their lifetime.

To characterize the variability of typhoon tracks, we used the horizontal wind and geopotential height data reanalyzed by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996; Kistler et al. 2001). The NCEP–NCAR reanalysis data have a horizontal resolution of 2.5° × 2.5° latitude–longitude and are available from 1949 to the present. The monthly optimum interpolation SST data (Reynolds and Smith 1994) from the NCEP–NCAR reanalysis are used to investigate interdecadal changes in SST over the Tropics. The SST data are available on a T62 Gaussian grid resolution (≈1.87° × 1.87° latitude–longitude).

The present study demonstrates interdecadal changes in typhoon tracks. Thus, using an objective statistical method is critical to decide whether change signals are significant among any selected periods. The Student's *t* test is utilized in this study. This method is one of the widely used statistical tools and is documented in many textbooks (e.g., Wilks 1995). Here, its methodology is summarized briefly. Suppose that two independent time series that follow a *t* distribution. Their time means are denoted as $\overline{x}_1$ and $\overline{x}_2$, respectively. The null hypothesis is that $\overline{x}_1$ and $\overline{x}_2$ are the same and the alternative hypothesis is that they are different. The test statistic is given by

$$t = \frac{\overline{x}_1 - \overline{x}_2}{(s_1^2/n_1 + s_2^2/n_2)^{1/2}},$$

where s_1 and s_2 are standard deviations, and n_1 and n_2 are numbers of the two sample time series, respectively. From the above definition, if the absolute value of t is greater than critical values with α level of significance, the null hypothesis would be rejected at the $\alpha(\times 100)\%$ significance level. It implies that the two time series have different statistical characteristics.

3. Interdecadal changes in typhoon activity

Tropical cyclone activities vary at a wide variety of time scales, ranging from diurnal to interdecadal. Because this study is mainly concerned with interdecadal time scales, data analysis is performed with this time scale in mind. We first examine the climatology of the geographical distribution of typhoon formation location and its track during summer (here June–September) in the WNP basin. Then, we analyze long-term changes in typhoon tracks associated with those in the SNPH.

a. Climatology

Figure 1 shows the numbers of tropical cyclones formed over the tropical WNP (5°–20°N, 110°E–180°) for each summer and year within the second half of the twentieth century (1951–2001). The average number of annual and summertime typhoons formed is 22.5 and 13, respectively. The annual typhoon number is a little smaller than that in the entire WNP basin (27) because typhoons formed north of 20°N and east of the data line are not included in this study. In the subtropics, SSTs are cooler and vertical wind shear is relatively strong, so tropical cyclone formation there is less favorable than that over the Tropics. A large variability in annual and summertime typhoon formation is observed in Fig. 1. The standard deviation of annual and summertime ty-

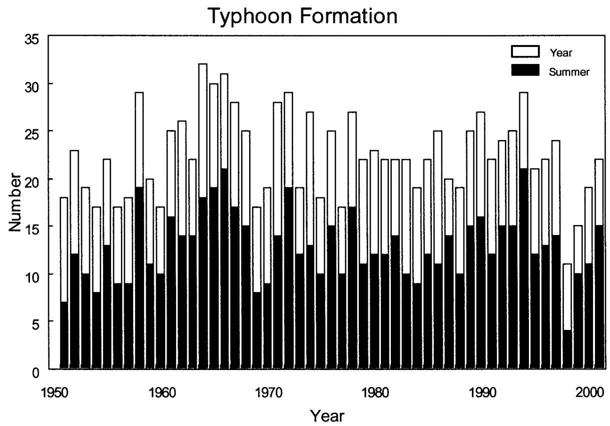

FIG. 1. Annual and summertime numbers of typhoons formed over the tropical western North Pacific (5°–20°N and 110°E–180°) from 1951 to 2001.

phoon numbers is 4.5 (20% of the mean value) and 3.6 (28% of the mean value), respectively. Since more than half of all typhoons occur during summer, the number of summertime typhoons formed is well correlated with that of annual typhoon formation. The correlation coefficient is 0.91 for the entire period, which is significant at the 99% confidence level.

It is noted in Fig. 1 that there are two peaks in the annual number of typhoons: one in the mid-1960s and the other in the late 1980s–early 1990s. Chan and Shi (1996) fitted the long-term record of tropical cyclone number to a second-order polynomial equation and examined its interdecadal variability. Yumoto and Matsuura (2001) suggested that the interdecadal variability is accounted for by changes in SST and convective activity in the WNP basin. A similar interdecadal variability is found in the summertime typhoon number, but the variability is smaller than that in the annual typhoon number.

The energy source for tropical cyclones is water vapor supplied from warm oceans. Warmer SSTs also reduce atmospheric stability and thus lead to deep tropical convection. Figure 2 presents the formation frequency (Fig. 2a) and passage frequency (Fig. 2b) of summertime typhoons within each 5° × 5° latitude–longitude grid box for the period 1971–2000. As shown in Fig. 2a, many typhoons form over the Philippines Sea (warm pool) between 10° and 20°N. The region of the Philippine Sea is marked by the monsoon trough, which is the birthplace for many tropical cyclones. In the region defined by 10°–20°N and 125°–150°E, at least one typhoon forms every two summers within each 5° × 5° grid box. Fewer typhoons originate over the equatorial region south of 10°N.

To obtain the geographical probability distribution of typhoon passage frequency (Fig. 2b), each 6-hourly typhoon position is binned into the corresponding 5° × 5° latitude–longitude grid box. The same typhoon migrating in the same grid box is counted only once. In the present study, the typhoon passage frequency is defined as the percentage value obtained by dividing the observed frequency by the total number of typhoon formation in the defined tropical WNP. The typhoon passage frequency is calculated every summer. This percentage implies a probability for a typhoon to appear in each 5° × 5° grid box as it moves. Because most typhoons move poleward in a curved pathway around the periphery of the SNPH, typhoon passage frequency is higher over the South China Sea, Philippine Sea (north or west of major typhoon formation regions), and the coast of southeast China (the frequency is as large as 30% in the first two regions). The typhoon passage frequency also reflects an elongated typhoon track areas of up to 20% frequency extending to the north of Philippine Sea and then toward Korea and Japan. This is a major pathway of typhoons that influence Korea and Japan during summer and early fall.

In general terms, a tropical cyclone in the WNP basin forms in the Philippine Sea and moves westward to terminate over southern China or south Asia, or moves poleward, dying out over land or cold ocean. When typhoons move farther northward, they encounter strong

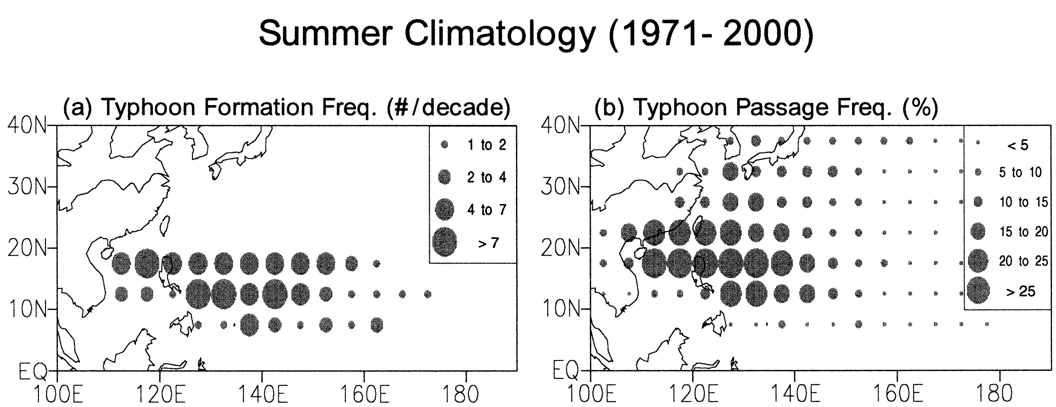

FIG. 2. Geographical distribution of summertime (a) typhoon formation frequency (number per decade) and (b) typhoon passage frequency (%) in each 5° × 5° grid area for the period 1971–2001.

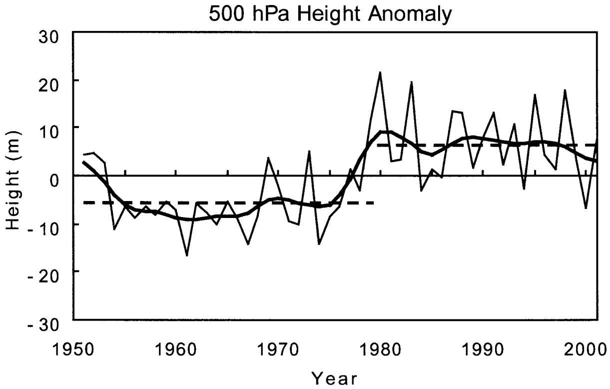

FIG. 3. Time series of SNPH anomaly in the region of 20°–25°N and 125°–140°E. Heavy solid line denotes 9-point Gaussian filtered values and heavy dotted lines denote the means for the periods 1951–79 and 1980–2001.

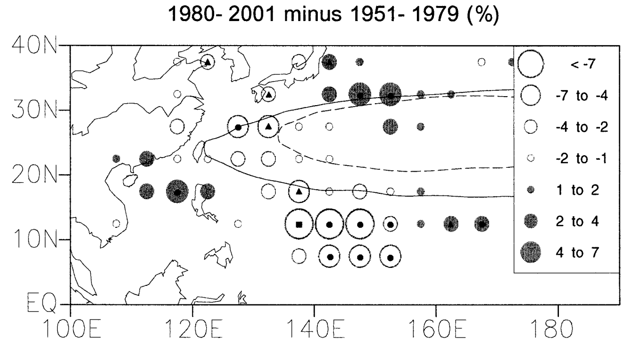

FIG. 4. Geographical distribution of the difference in typhoon passage frequency between the periods 1980–2001 and 1951–79. Dotted and solid lines indicate the mean position of 5780 gpm for 1951–79 and 1980–2001, respectively. Symbol ▲ represents the 90% confidence level, ● the 95% confidence level, and ■ the 99% confidence level.

midlatitude westerlies and shift to the northeast. At this stage, many typhoons transform into midlatitude cyclones.

b. *Interdecadal changes*

To examine interdecadal changes in typhoon tracks associated with changes in the SNPH, the whole analysis period is divided into earlier (1951–79) and later (1980–2001) periods. The two periods are referred to as ID1 and ID2, respectively. The reference year of 1979/80 is selected because the SNPH experienced a regime shift in the late 1970s characterized by an increase of geopotential height at 500 hPa in the WNP (Gong and Ho 2002). To see the variation of the strength of the SNPH with time, the domain-mean 500-hPa geopotential height anomaly over the region of 20°–25°N and 125°–140°E is shown in Fig. 3. The anomaly is simply a deviation from the long-term mean for 1951–2001. While the 500-hPa geopotential height anomaly shows a strong year-to-year variation, a sudden jump is found in the late 1970s. This height change is significant at the 99% confidence level. When the time series is divided into ID1 and ID2, the time-mean difference between the two periods is 12 units in term of geopotential height in meter (gpm), that is, -5.2 in ID1 versus 6.8 gpm in ID2. The number of years with positive anomalies greater than 5 gpm in ID1 and ID2 is 2 and 10, respectively. On the other hand, the number of years with negative anomalies less than -5 gpm in ID1 and ID2 is 20 and 1, respectively. In addition to the above evidence, the selection of 1979 as the reference year for the interdecadal regime shift can be justified from the changepoint analysis (see Table 1).

The expansion of the SNPH is also seen in the summer-mean position of 5780 gpm for each period in Fig. 4 (ID1 by dotted line, ID2 by solid line). The western edge of the 5780-gpm contour has reached Taiwan in ID2. The SNPH has been enlarged southward as well. The corresponding difference in typhoon passage frequency between the two periods is also displayed in the figure. The difference is represented by the percentage value as in Fig. 2b. The most significant differences in typhoon passage frequency appear in regions surrounding SNPH where significance of the difference is higher than the 90% confidence level (see the three marks in the figure). The most prominent change is observed over the Philippine Sea. The change is as large as about -7%, which is significant at the 99% confidence level. This value corresponds to a 50% decrease from the climatology. The typhoon passage frequency also decreases near east China and the surrounding oceans. On the whole, the region of decreased frequency covers areas extending northwestward from the Philippine Sea to northeast China. The typhoon passage frequency, however, increases slightly west and east of the locations of decreased frequency, that is, in the South China Sea, the east coast of Japan, and from the eastern Philippine Sea to the date line.

Because the region of decreased frequency dominates the analysis domain, ID2 experienced less typhoon passage frequency in the WNP basin, although the frequency of summer-mean typhoon formation remains about the same. The reduced passage frequency in the analysis domain is partly compensated by an increased number of landfall typhoons in south China and south Asian countries. Once typhoons strike land, they will quickly disappear. The number of landfall typhoons in the regions is 164 (138) compared to the total number 380 (278) of typhoons formed in the earlier 29 yr (later 22 yr). The ratio of landfall to the total number of typhoons is, respectively, 43% and 50% in ID1 and ID2.

For a further examination of the interdecadal changes in typhoon tracks, the time series of typhoon passage frequency averaged over three major regions are shown in Fig. 5. The three regions are the East China Sea (20°–30°N and 125°–135°E), the South China Sea (15°–20°N and 110°–125°E), and the Philippine Sea (5°–15°N and

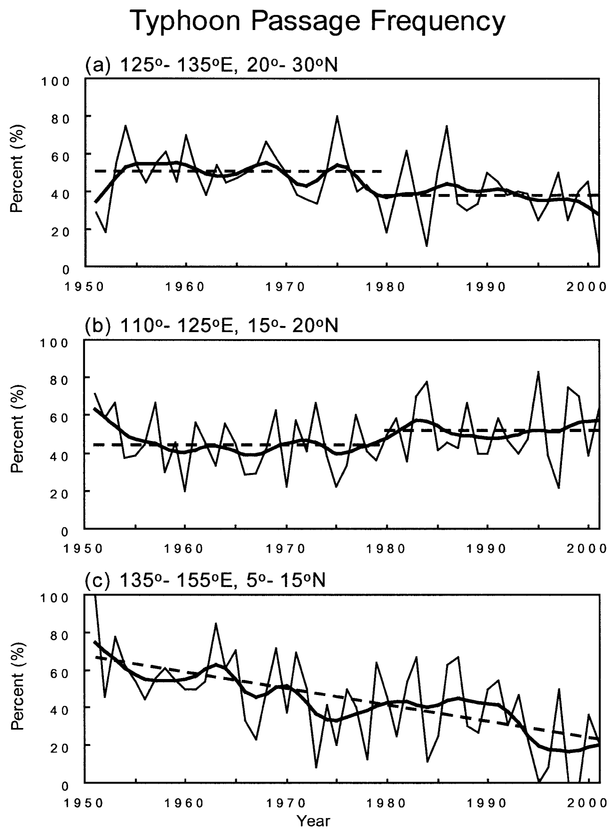

FIG. 5. Time series of typhoon passage frequency in the regions of (a) 20°–30°N and 125°–135°E, (b) 15°–20°N and 110°–125°E, and (c) 5°–15°N and 135°–155°E. Heavy solid line denotes 9-point Gaussian filtered values. Heavy dotted lines in (a) and (b) denote the means for the periods 1951–79 and 1980–2001, respectively, and heavy dotted line in (c) denotes the linear slope for the entire period.

135°–155°E). Note that the mean values of typhoon passage frequency in Fig. 5 are much higher than those in Fig. 2b. These differences are explained by different domain size in the two figures. There must be a higher typhoon passage frequency in a larger domain. It is found that the typhoon passage frequency over the East China Sea experienced a sudden decrease in the late 1970s, that is, the mean typhoon passage frequency is 50% in ID1, but decreases to 38% in ID2 (Fig. 5a). This 12% difference is equivalent to 27% of the climatology. It is significant at the 99% confidence level. The opposite change is found over the South China Sea, where the typhoon passage frequency is slightly increased from ID1 to ID2 (44% versus 52%), which is significant at the 95% confidence level (Fig. 5b). Over the Philippine Sea, a downward trend is evident (Fig. 5c). The rate of change is -9% decade^{-1}. It is significant at the 99% confidence level. In fact, there were no typhoon passages in the following recent three years: 1995, 1998, and 1999. Such a sharp decrease in typhoon passage frequency may be due to less typhoon formation in the region.

The significant changes of typhoon passage frequency in late 1970s in the East China Sea and South China Sea coincide with the interdecadal changes of the western boundary of the SNPH. This may be regarded as evidence that the tropical cyclone activity over the WNP basin is influenced by the expansion of the SNPH in recent decades. However, the lack of an abrupt change of typhoon passage frequency in late 1970s over the Philippine Sea requires explanations beyond the direct influence by the change of the SNPH.

TABLE 1. Significant change points of typhoon tracks over the East China Sea (20°–30°N, 125°–135°E), South China Sea (15°–20°N, 110°–125°E), and Philippine Sea (5°–15°N, 135°–155°E).

Regions	Year	t value	Confidence level (%)
East China Sea	1953	−4.116	99
	1954	−1.864	95
	1977	4.176	99
South China Sea	1954	4.836	99
	1980	−2.309	95
Philippine Sea	1966	5.490	99
	1994	3.932	99
	2000	−3.045	99

Although the current study and several previous studies have shown consistent interdecadal changes in WNP typhoon tracks and the SNPH, the selection of the reference year 1979/80 in the current study is a priori. To justify our selection of the reference year, we conduct a changepoint analysis. This statistical analysis can identify significant regime shifts in the time series of typhoon passage frequency with an objective manner. The details of the analysis are well described in Elsner et al. (2000) and Chu (2002). The changepoint analysis is applied to the three major changing regions. Years representing a significant changepoint are shown in Table 1. Over the East China Sea, years for the significant changepoint are found in the early 1950s and late 1970s. Over the South China Sea, the years are 1954 and 1980. These years of significant changes are clearly identifiable through a visual inspection of the time series of typhoon passage frequency (Figs. 5a and 5b). In the Philippine Sea, the three years for the significant changepoint (1966, 1994, and 2000) can also be detected easily in Fig. 5c.

In addition to the typhoon passage frequency, the corresponding changes in typhoon intensity are another concern of this study. To discover these, the interdecadal changes in typhoon passage frequency for major typhoons only are examined in Fig. 6. Here, a major typhoon is defined as a typhoon whose maximum sustained wind speed is greater than 50 m s^{-1} (category 3–5 on the Saffir–Simpson hurricane scale). The average number of summertime major typhoons is 5.4 in the WNP basin. The number of major typhoons has been increased for the entire period (0.2 decade^{-1}). However, it is not significant at the 90% confidence level.

Considering the climatological typhoon passage frequency, major typhoons (Fig. 6a) and all typhoons (Fig.

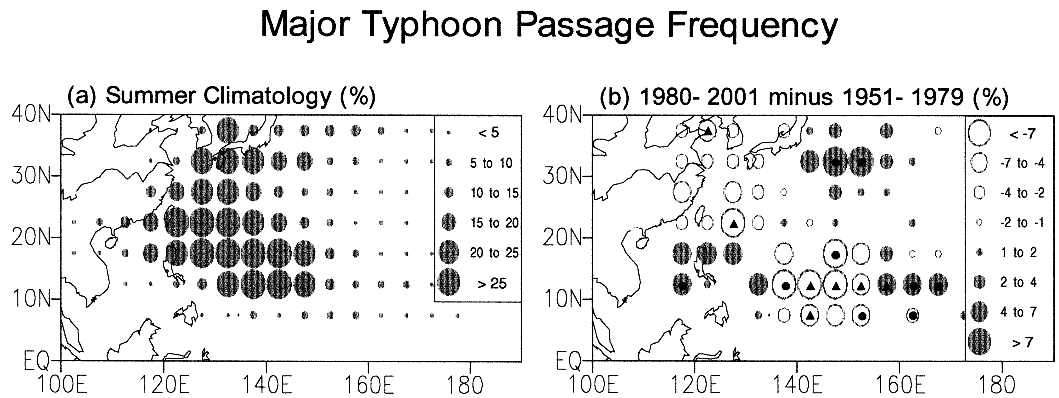

FIG. 6. Geographical distribution of major typhoon passage frequency for the period (a) 1971–2000 and (b) its difference between the periods 1980–2001 and 1951–79. Symbol ▲ represents the 90% confidence level, ● the 95% confidence level, and ■ the 99% confidence level.

2b) show quite analogous geographical distributions except over the midlatitudes: Korea to Japan. More frequent major typhoons are found east of Korea (130°–160°E). This can be easily understood because stronger typhoons tend to have a longer lifetime and many of them are able to reach the midlatitudes. The difference map (Fig. 6b) shows that the major typhoon passage frequency has decreased along the east coast of China, Korea, and Japan in the later period. Averaged over these regions, the climatological typhoon passage frequency is 20% and the difference between the two periods is 4%. Overall, the track changes for major typhoons and all typhoons between the two periods are quite similar. Thus, the pattern of interdecadal change in typhoon intensity is similar to that in typhoon passage frequency; that is, the typhoon intensity has decreased in the east coast of China and Philippine Sea and has increased in the South China Sea and east of Japan.

4. Effects of sea surface temperatures and large-scale flows

The interdecadal changes in typhoon tracks identified above may be due to the alteration of prevailing large-scale flow associated with the westward expansion of the SNPH. Besides, the shift in the locations of preferred tropical cyclone formation also affects typhoon activity and thus typhoon pathways. SST is an important controlling factor for tropical cyclone formation. In the following, we examine the possible effects of SST and large-scale flow on typhoons.

a. Sea surface temperatures

We examine the distribution of difference fields in SST and typhoon formation frequency between ID1 and ID2 (Fig. 7). SST increased from ID1 to ID2 in tropical regions where major changes in typhoon formation and passage are also identified (Fig. 7a). Beyond the Tropics, increased SST is found in most of the WNP basin, including regions with both increasing and decreasing changes in typhoon passage frequency. This implies that the changes in SST are not directly related to those in typhoon tracks. It is noted that SST decreases in the East Sea located between Korea and Japan and to the east of Japan over the midlatitude Pacific.

Chu and Clark (1999) examined interdecadal varia-

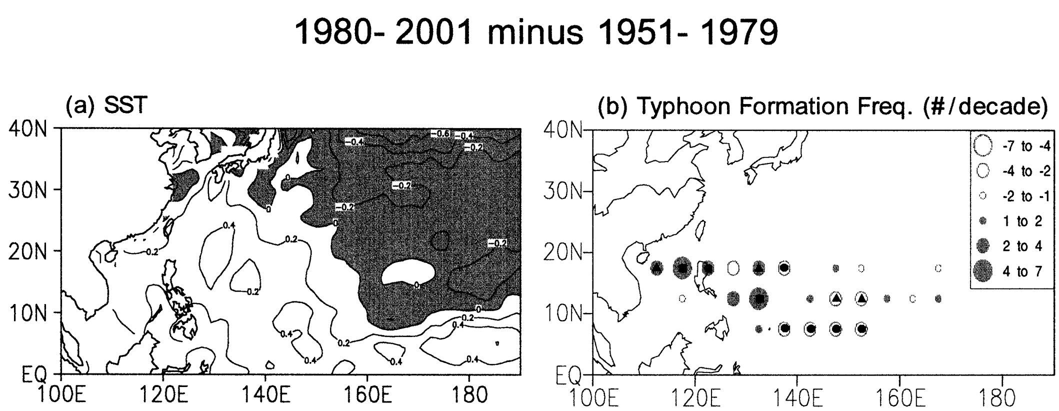

FIG. 7. Geographical distribution of difference in (a) SST and (b) typhoon formation location between the periods 1980–2001 and 1951–79. Contour intervals are 0.2°C for (a). Symbol ▲ represents the 90% confidence level, ● the 95% confidence level, and ■ the 99% confidence level.

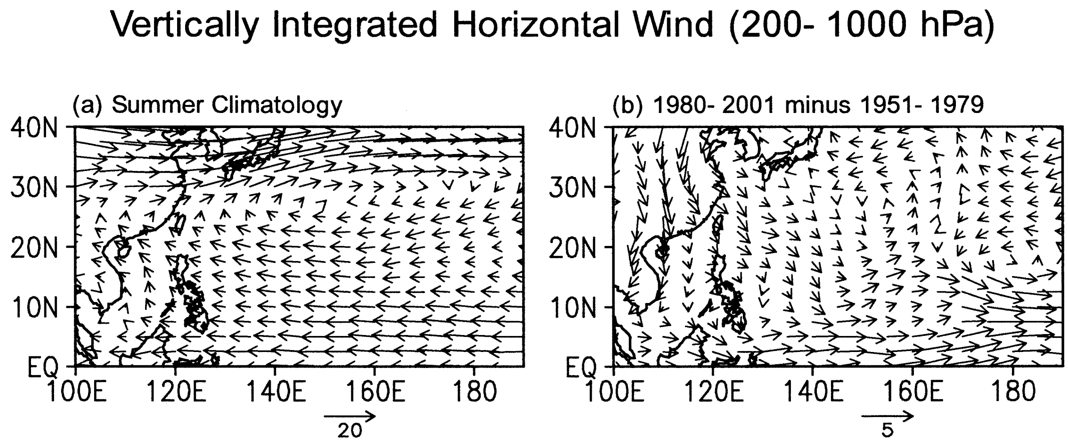

FIG. 8. Geographical distribution of vertically averaged horizontal wind in the troposphere (200–1000 hPa) for the period (a) 1971–2000 and (b) its difference between the periods 1980–2001 and 1951–79.

tions of tropical cyclone activity over the central North Pacific. They also divided the analysis period into earlier (1966–81) and later (1982–97) periods and compared SSTs between the two periods. In Chu (2002), the breaking of data into the two periods is supported by an independent statistical changepoint analysis. Their reference year is 1981/82, indicating that our selection of 1979 is a reasonbale choice. They found that the SST increase is evident in the central to eastern Pacific over the Tropics and suggested that it may lead to more cyclones in the central North Pacific in recent decades. Note that the increased SST over the Philippine Sea shown in Fig. 7a is extended to the whole tropical western Pacific south of 10°N.

Figure 7b shows changes in typhoon formation between ID1 and ID2. In the three regions, 15°–20°N and 115°–120°E, 10°–15°N and 125°–135°E, and 10°–15°N and 140°–145°E, where the mean typhoon formation frequency exceeds 7 decade^{-1} (Fig. 2a), typhoon formation frequency increases by 2–5 decade^{-1}. The change is about 50% above the climatology in the first two regions. In the tropical WNP as a whole, the typhoon formation frequency increased west of 135° and decreased east of 135°E. In particular, the change in the region of 5°–10°N and 135°–155°E is -3, about 60% below the climatology. The westward shifts of typhoon formation region in ID2 may be responsible for the interdecadal change in typhoon tracks.

It is known that tropical cyclone formation is favorable over regions with high SST. A positive correlation between SST and typhoon formation is observed over the South China Sea where both SST and typhoon formation have increased in the later period. When comparing the differences in SST and typhoon formation location over the entire WNP on a interdecadal time scale (Figs. 7a and 7b), there is, however, no clear coherent relationship between them. For example, while SST increases over most of the western tropical Pacific, the typhoon formation frequency increases west of 135° but decreases east of 135°E. High SST is one of the key factors for typhoon formation but other environmental factors such as vertical wind shear should also be considered (e.g., Gray 1968).

b. Large-scale flows

Tropical cyclone tracks are predominantly controlled by surrounding environmental flows. The direct cause of typhoon pathway exhibiting an elliptically curved shape in the WNP is the presence of the SNPH. Thus, if the SNPH expands (shrinks), the tropical cyclone track can show a more (less) elongated elliptic shape. Also, strong anticyclonic flow can hasten the march of tropical cyclones.

Figure 8 shows the distribution of the vertically averaged horizontal wind in the troposphere for the period 1971–2000 and its difference between ID1 and ID2. The vertically averaged wind through the whole troposphere is considered because tropical cyclones are to a good approximation steered by deep-layer-mean environmental flows. The climatological layer-mean flow (Fig. 8a) is characterized by an easterly flow in the Tropics and westerly flow in the midlatitudes. Between these flows, the SNPH is located in the WNP. The difference field (Fig. 8b) shows northerly flow in the Asian continent (e.g., Ho et al. 2003) and northwesterly flow in the subtropical western Pacific, particularly in the China Sea and Philippines Sea. Note that the regions of anomalous northwesterly flow in the subtropics match well with those of the reduced typhoon passage frequency (Fig. 4). This collocation clearly implies that the anomalous flow hinders the poleward migration of typhoons. In the equatorial region (0°–10°N), easterly flow is significantly reduced in ID2.

A large cyclonic flow in the vertically averaged horizontal wind in the WNP (Fig. 8b) mainly results from the lower-tropospheric flows below 500 hPa. During summer, in the upper troposphere, the horizontal flow over Asia and adjacent oceans is characterized by a huge anticyclone centered in the Tibetan Plateau. On the other hand, the SNPH dominates in the lower troposphere. Thus, splitting the wind fields into the upper and lower troposphere might be more meaningful to gain insight into changes in large-scale flows associated with tropical cyclones. However, the difference of horizontal wind in the upper and lower troposphere between the two periods indicates quite consistent features with the layer-mean winds (figure not shown).

There is a remarkable difference in the position and extent of the SNPH between ID1 and ID2 (Gong and Ho 2002). Since the late 1970s, the SNPH has enlarged, strengthened, and extended southwestward. This change gives rise to an anticyclonic circulation anomaly over the region from the South China Sea to the Philippine Sea. The difference field in 500-hPa horizontal wind between the two periods shows a prevailing westerly over the region from central China to the western Pacific in the subtropics and a northerly in the Philippine Sea (figure not shown). This regime shift in the SNPH is likewise found in typhoon passage frequency in the East China Sea with an opposite changing pattern (Fig. 5a). The typhoon passage frequency has increased slightly in the South China Sea (Fig. 5b). Thus, we suggest that the expansion of the SNPH affects the typhoon passage frequency and results in a larger elliptic pathway.

5. Conclusions and discussion

In this study, we have investigated interdecadal changes in summertime typhoon tracks in the WNP basin, with an emphasis on the relationship between the westward expansion of the SNPH and summertime typhoon passage frequency during the second half of the twentieth century. The results show that typhoon tracks underwent dramatic interdecadal changes in the East China Sea (20°–30°N and 125°–135°E). About 50% of all typhoons originated in the WNP passed through the region during 1951–79 (ID1) and 38% during 1980–2001 (ID2). This reduced typhoon passage frequency in the late 1970s is well correlated with the sudden increase in the SNPH index. Thus, it is concluded that the expansion of the SNPH to the southeast coast of Asia may lead to a larger elliptic pathway of tropical cyclones.

Another major change in typhoon passage frequency is found over the Philippine Sea (5°–15°N and 135°–155°E) where a continuous downward trend is found. A linear regression line fitted to the time series indicates a rate of change of $-0.6\%\ \mathrm{yr}^{-1}$. This downward trend is compatible with a 45% decrease of typhoon passage frequency over the past 50 years. Typhoons were even absent in 1995, 1998, and 1999 over the Philippine Sea. In the same region, however, SST exhibits an increasing trend opposite to that of typhoon passage frequency. In the broad WNP basin, no clear correlation exists between the difference fields (ID2 minus ID1) of SST and typhoon formation frequency.

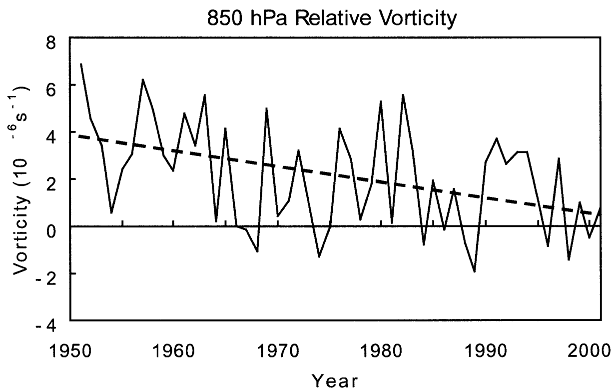

FIG. 9. Time series of 850-hPa relative vorticity averaged over the region of 5°–15°N and 135°–155°E.

There is a robust reduction in easterly flow within 0°–10°N over the Philippine Sea in ID2 compared to ID1. In order to depict changes in vorticity associated with the zonal wind reduction, the time series of relative vorticity at 850 hPa averaged over the region of 5°–15°N and 135°–155°E is shown in Fig. 9. The summer-mean relative vorticity shows a decreased trend. Its rate of change is $-0.6 \times 10^{-6}\ \mathrm{s}^{-1}\ \mathrm{decade}^{-1}$ and is significant at the 99% confidence level. The decreasing vorticity in the lower troposphere provides an unfavorable condition for tropical cyclone genesis and is connected with the pronounced decrease in typhoon activity over the Philippine Sea in the recent two decades. The vertical wind shear between 200- and 850-hPa zonal winds has increased over the region in ID2, as well (figure not shown). The increasing trend of vertical wind shear results from the reduced easterly wind in the lower troposphere.

The present study examined the differences in typhoon formation frequency between ID1 and ID2. The typhoon formation frequency increased west of 135° and decreased east of 135°E from ID1 to ID2. This westward shift of location for typhoon formation is consistent with the increase of typhoon activity in the South China Sea and the decrease in the East China Sea. This suggests that the changes of regions for typhoon formation partially affect the typhoon passage frequency.

From the findings of the relationship between the SNPH and typhoon passage frequency, a variable that includes the information of the SNPH could be used as a predictor for the long-range behavior of typhoon tracks (typhoon passage frequency). To investigate this possibility, we constructed composites of typhoon passage frequency for stronger SNPH years (1980, 1983, 1995, and 1998) and weaker SNPH years (1984, 1986, 1994, and 2000) since 1980 (Fig. 10). The starting year 1980 is chosen to exclude the effect of interdecadal differences between ID1 and ID2. While the difference map includes a large portion of interannual variability due to the limited sample, there is a clear separation in typhoon tracks to the west of 140°E. Overall, the de-

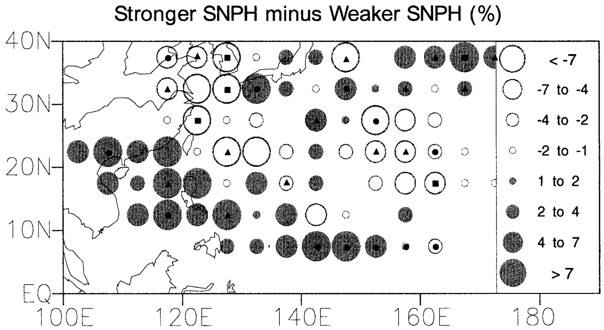

FIG. 10. Geographical distribution of difference in typhoon passage frequency composite between stronger SNPH years (1980, 1983, 1995, and 1998) and weaker SNPH years (1984, 1986, 1994, and 2000) since 1980. See Fig. 3 for the SNPH strength. Symbol ▲ represents the 90% confidence level, ● the 95% confidence level, and ■ the 99% confidence level.

creased (increased) typhoon passage frequency is found north (south) of 20°N in the WNP. The large decrease of typhoon passage frequency of below −7% is observed in eastern China, Korea, and the surrounding oceans. On the other hand, the large increase exceeding 7% is observed in the Philippine Islands and surrounding oceans.

Many studies documented the interdecadal changes of SST in the Pacific around the mid-1970s. Graham et al. (1994) indicated that the transition occurred in 1976; Trenberth and Hurrell (1994) indicated the interdecadal change in the mid-1970s; Wang (1995) selected 1977 as a transition year. These slightly different results may arise due to the following two reasons. First, the results are sensitive to the record length used for analysis. Second, surface and atmospheric variables may show different aspects of the climate system. Thus, their changes are not necessary to be exactly the same. In particular, the effect of tropical SST on atmospheric variables in the subtropics may not be understood simply.

Our analysis raises a further question concerning the SNPH–typhoon track relation: What are the factors responsible for the sudden increase of the SNPH in the late 1970s? This sudden increase seems to be correlated with the interdecadal shift of SSTs in magnitude and interannual variability over the eastern equatorial Tropics (Chang et al. 2000; Gong and Ho 2002). This can be a feasible factor because there have been more frequent and stronger El Niño episodes in recent decades. However, the detailed dynamical and physical mechanisms responsible for the relation between the SNPH and equatorial SST are still an open question.

There have been concerns about the reliability of tropical cyclone data in the 1950s and early 1960s prior to the weather satellite era. For example, Chu (2002) used tropical cyclone data since 1966. However, we decide to include the earlier data before 1966 in the present study. An obvious reason is that we need the longest possible data for studying interdecadal changes in the typhoon track and formation. The time series of typhoon passage frequency in the three major regions do not show any peculiar behavior in 1950–early 1960s (see Fig. 5).

The NCEP–NCAR reanalysis data are influenced by two major changes in the observing system as documented by Kistler et al. (2001). First, the upper-air networks were established in the International Geophysical Year, 1957. Second, the global operational use of satellite soundings was introduced in 1979. It is found that the usage of satellite observations affected the upper-atmospheric variables mostly over the Southern Hemisphere, not the Northern Hemisphere. The present study shows a fairly good correspondence between changes in typhoon passage and southwestward expansion of 500-hPa geopotential height over the subtropical western North Pacific in the late 1970s. This indicates that the NCEP–NCAR reanalysis data can be used for climate change studies, although they contain some problems.

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