P1.20 **DECADAL CHANGES IN SUMMERTIME TYPHOON TRACK**

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1. INTRODUCTION

Many previous studies demonstrated that the variation of tropical cyclone activity over the WNP is, to some extent, associated with the El Nino Southern Oscillation (ENSO) (Wu and Lau 1992, Lander 1994, Chen *et al*. 1998, Chan 1985, 2000, Wang and Chan 2002) and quasi-biennial oscillation (Chan 1995). There is a reduced frequency of tropical cyclone formation during the El Nino episode corresponding to a longitudinal shift of the Walker circulation (Chan 1985, Wu and Lau 1992). Chan (1985) found that typhoons tend to form farther eastward during El Nino summers 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 alter tropical cyclone activity (Lander 1994, Chan 2000, Wang and Chan 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. Since 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 cause of changes in the SNPH would be changes in the tropical cyclone tracks in the WNP basin. This has motivated the present study.

In this study, we present evidence of interdecadal changes of summertime typhoon tracks in the late 1970s, based on analyses of SST, geopotential height, horizontal wind, and typhoon data. Relevant links to surface boundary conditions and large-scale dynamics are discussed.

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2. DATA

We used tropical cyclone data for 1951-2001 archived by the Regional Specialized Meteorological Centers - Tokyo Typhoon Center. The data include names, positions (in longitude and latitude), minimum surface pressures, and maximum wind speeds of tropical cyclones in every 6-hour interval.

To characterize the variability of the typhoon tracks, we used the horizontal wind, temperature, and geopotential height data reanalyzed by the National Centers for Environmental Prediction /National Center for Atmospheric Research (NCEP/NCAR) (Kalnay *et al*. 1996). 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.

3. DECADAL CHANGES IN TYPHOON ACTIVITY

Tropical cyclone activity can vary on a wide variety of time scales, ranging from diurnal to decadal. These different time scales are apparently attributed to environmental influences with different time scales on tropical cyclone activity (Gray 1988). Since this study is mainly concerned with decadal 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 their tracks during summer (here June through September) in the WNP basin. Then, we analyze long-term changes in typhoon tracks in association with those in the SNPH.

3.1 Climatology

Figure 1 shows the time series of the annual and summertime numbers of tropical cyclones that formed over the tropical WNP (110°E-180° and 5°-20°N) for the latter half of the 20th century (1951-2001). The average number of annual and summertime typhoon 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 date line are not included in this study. Over 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. The time series shows a large variability in annual and summertime typhoon formation. The standard deviation of annual and summertime typhoon numbers is 4.5 (20% of the mean value) and 3.6 (28% of the mean value), respectively

It is noted in Fig. 1 that the annual number of typhoons formed has two peaks: 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 numbers 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 numbers, but the variability is smaller than that for the annual typhoon numbers.

Figure 2 presents the formation frequency (2a) and passage frequency (2b) of summertime typhoons within each 5°×5° longitude-latitude grid box for the period 1971-2000. 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. As shown in Fig. 2a, many typhoons form over the Philippines Sea (warm pool) between 5°N and 20°N where atmospheric easterly waves propagate northwestward from the date line to the South China Sea. Over the region defined by 125°-150°E and 10°-20°N, 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 the typhoon passage frequency (Fig. 2b), each six-hourly typhoon position is binned into the corresponding 5°×5° longitude-latitude 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 typhoons. This percentage implies the probability for a typhoon to appear in each 5°×5° grid box as it moves. Since most typhoons encounter the boundary of the SNPH and move in a curved pathway around it, typhoon passage frequency is higher over the South China Sea, Philippine Sea (north or west of major typhoon formation regions), and the east coast of South China. In particular, over the South China Sea and Philippine Sea, the frequency is as large as 30%. The passage frequency also shows 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.

3.2 Decadal changes

To examine decadal changes in typhoon tracks associated with changes in the SNPH, the whole analysis period is divided into earlier (1951-1979) and later (1980-2001) periods. The reference year of 1979/1980 is selected because the SNPH experienced a regime shift in the late 1970s (Gong and Ho 2002) (see their Fig. 5). The expansion of the SNPH is clearly seen in the summer-mean position of 5780 gpm (gpm: geopotential height in meter) for each two-decade period (dotted line denotes the earlier period and solid line denotes the later period) (Fig. 3). The western edge of the 5780 gpm contour has reached Taiwan in the later period. The SNPH has been enlarged southward, as well. The corresponding difference (1980-2001 minus 1951-1979) of 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 prominent change is observed over the Philippine Sea. The change is as large as about −7%. This value corresponds to a 50% decrease from the climatology. The typhoon passage frequency also decreases over east China and 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 a little along the west and east of the areas of decreased frequency, i.e., the South China Sea, the east coast of Japan, and eastern Philippine Sea to the date line.

For a further examination of the decadal changes in typhoon tracks, the time series of the typhoon passage frequency averaged over three major regions are shown in Fig. 4. The three regions are the East China Sea (125°-135°E and 20°-30°N), the South China Sea (110°-120°E and 15°-20°N), and Philippine Sea (135°-155°E and 5°-15°N). It is noted that the typhoon passage frequency over East China Sea experienced a sudden decrease in the late 1970s (Fig. 4a). The mean typhoon passage frequency is 50% for the earlier period, but decreases to 38% for the later period. This 12% difference is equivalent to 27% of the climatology. Similar characteristics are found over South China Sea except for the opposite sign and weaker signal (Fig. 4b). The typhoon passage percentage over the region is 35% in the earlier period and 41% in the later period. A downward trend is found over the Philippine Sea (Fig. 4c). The rate of change is –9% per decade. In particular, there was no typhoon passage in the recent three years, 1995, 1998, and 1999. This rapid decrease in the typhoon passage frequency may be due to less typhoon formation in the region.

As seen in Figs. 4a and 4b, the typhoon passage frequency over the East China Sea and South China Sea where the eastern boundary of the SNPH is located indicates a regime shift in the late 1970s. Although the two regions show opposite change patterns, more profound change is found in the East China Sea. This implies that the tropical cyclone activity over the WNP basin is influenced by the expansion of the SNPH in recent decades. Also, a stronger effect is observed in regions near to the SNPH interior. Note that the typhoon passage frequency over the Philippine Sea exhibits a gradual decrease with time instead of showing a sudden evolution. It may indicate that the decrease of typhoon activity in the Philippine Sea may not be directly linked to the SNPH.

4. EFFECTS OF SEA SURFACE TEMPERATURES AND LARGE-SCALE FLOWS

We found that the summertime typhoon tracks have experienced decadal changes in the WNP in the late 1970s (see Figs. 3-4). This may be due to the alteration of prevailing large-scale flow associated with the westward expansion of the SNPH. However, the shift in the region of preferred tropical cyclone formation also affects typhoon activities and modifies typhoon pathways. Moreover, the region of tropical cyclone formation can be influenced by surface boundary conditions such as SST and lower-level moisture.

4.1 Sea surface temperatures

We examined the geographical distribution of the difference in SST and typhoon formation location between the two periods (Fig. 5). As compared to the earlier period, the SST is increased over the regions of major formation and frequent typhoon passage in the later period (Fig. 5a). A statistical test denotes that this increasing SST trend above 0.3°C in the tropical WNP is statistically significant at the 95% confidence level because of its small inter-annual variability. It is noted that the increasing trend in SST is found in most of the WNP basin, including regions with both increasing and decreasing trends in typhoon passage frequency. This implies that the changes in SST are not directly related to those in typhoon tracks. It is also noted that SST decreases in the East Sea and to the east of Japan over the mid-latitude Pacific.

Chu and Clark (1999) examined decadal variations of tropical cyclone activity over the central North Pacific. They also divided the analysis period into earlier (1966-1981) and later (1982-1997) periods and compared SSTs between the two periods. Interestingly, their reference year (1981/1982) is similar to ours. They found that the SST increasing trend 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. This indicates that the warming trend of SST over the Philippine Sea shown in Fig. 5a is extended to the whole tropical Pacific.

Figure 5b shows changes in typhoon formation location between the two periods. As shown in Fig. 2a, there are three regions where the typhoon formation frequency exceeds 7 per decade (115º-120ºE and 15º-20ºN, 125º-135ºE and 10º-15ºN, and 140º-145ºE and 10º-15ºN). Note that the typhoon formation frequency increases by 3-4, about 40% above the climatology, in the first two regions for the later period. In the tropical WNP as a whole, typhoon formation increased west of 135ºE and decreased east of 135ºE. In particular, the change in the region of 135º-155ºE and 5º-10ºN is –3, about 60% below the climatology. These westward shifts of the typhoon formation region in the later period may be responsible for the decadal changes in typhoon tracks. While tropical cyclones migrate north or northeast describing an elliptical curve, the corresponding typhoon track could be shifted westward from its climatological position in recent decades. These features can be seen in Fig. 3.

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 trends have increased in the later period. When comparing the differences in SST and typhoon formation location over the entire WNP on a decadal time scale (Figs. 5a and 5b), however, there is 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 135ºE and decreases east of 135ºE. 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). This is somewhat reflected in Fig. 5.

4.2 Large-scale flows

Tropical cyclone tracks are predominantly controlled by surrounding environmental flows. The direct cause of the 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 6 shows the distribution of the vertically-averaged horizontal wind in the troposphere for the period 1971-2000 and its difference between the earlier and later periods. In climatology (Fig. 6a), there is an easterly flow in the tropics and westerly flow in the mid-latitudes. Between these flows, the SNPH is located in the WNP. The difference (Fig. 6b) shows northerly flow in the Asian continent and northwesterly flow in the subtropical western Pacific, particularly the China Sea and Philippines Sea. Note that the regions of anomalous northwesterly flow in the subtropics matches well with that of the reduced typhoon passage frequency (Fig. 3). This co-location clearly implies that the anomalous flow hinders the pole-ward migration of typhoons. In the equatorial region (0^{o}-10^{o}N), there is significant reduced easterly flow during the later period. Tropical cyclones can form as easterly waves propagate into the warm pool. Thus, less frequent and/or weaker easterly waves can result in decreased tropical cyclone formation in the region of 5^{o}-10^{o}N and 135^{o}-155^{o}E (see Fig. 5b).

There is a remarkable difference in the position and extent of the SNPH between the two periods (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 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). These changes are extensively observed in the western tropics showing a barotropic structure.

The expansion of the SNPH corresponds to an increase of geopotential height at 500 hPa in the WNP. 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^{o}-25^{o}N and 125^{o}-140^{o}E is shown in Fig. 7. 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. When the time series is divided into two periods at 1979/80, the number of years with positive anomaly greater than 5 gpm is 0 before 1979 and 11 after 1979. On the other hand, the number of years with negative anomaly less than –5 gpm is 20 before 1979 and 1 after that year. The time-mean difference between the two periods is 12 gpm (–5.2 gpm versus 6.8 gpm). This regime shift in the SNPH is likewise found in the typhoon passage frequency in the East China Sea with an opposite trend (Fig. 4a). The typhoon passage frequency has increased slightly in the South China Sea. Thus, it is suggested that the expansion of the SNPH is associated with the typhoon passage frequency and results in a larger elliptic pathway.

5. CONCLUSION AND DISCUSSION

In this study, we have investigated decadal changes in summertime typhoon tracks in the WNP basin, with a particular emphasis on the relationship between the westward expansion of the SNPH and summertime typhoon passage frequency during the latter half of the 20th century. The analysis results show that the typhoon tracks underwent dramatic decadal changes in the East China sea (125º-135ºE and 20º-30ºN). For example, 50% of typhoons originating in the domain might pass through the region during the earlier period (1951-1979) and 38% during the later period (1980-2001). 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 decrease in typhoon passage frequency is found over the Philippine Sea (135º-155ºE and 5º-15ºN). However, over that region, a continuous downward trend is found instead of an abrupt jump. A linear regression line fitted to the time series indicates a rate of change of –0.9% per year. This downward trend is compatible with a decrease of typhoon passage frequency of 45% over the last 50 years. No typhoon years are found in the region since 1995 to 1999. The typhoon activity variation with underlying SST changes can be naturally explained by tropical cyclones developing over warm oceans. Over the region, however, the present study revealed that SST indicates an increasing trend opposite to the typhoon passage frequency on a decadal time scale. There is a lack of correlation between the differences in SST and typhoon formation location when those changes are compared between the earlier and later periods as a whole in the WNP basin.

There is a robust enhanced (reduced) westerly (easterly) flow within 0º-10ºN over the Philippine Sea in the later period compared to the earlier period. Climatologically the equatorial easterly flow extends to the Indian Ocean where deep tropical convection can generate over the warm pool due to an abundant supply of latent and sensible heat fluxes. Furthermore, this equatorial easterly flow yields a negative meridional gradient of zonal wind and produces a positive relative vorticity in the tropics. In order to depict changes in vorticity associated with those in equatorial easterlies, the time series of relative vorticity at 850 hPa averaged over the region of 135º-155ºE and 5º-10ºN is calculated(figure not shown). The summer-mean relative vorticity has decreased due to the enhanced westerly anomaly. Its rate of change is -0.9×10^{-6} s^{-1} per decade and is significant at the 95% confidence level. The decreasing vorticity in the lower troposphere provides unfavorable conditions for tropical cyclone genesis and certainly explains the profound decrease in typhoon activity over the Philippine Sea in the recent two decades. The vertical wind shear between 200 hPa and 850 hPa zonal wind has increased over the region in the later period, as well (figure not shown). The increasing trend of vertical wind shear is evidently related to the enhanced westerly wind in the lower troposphere.

The present study examined the differences in the typhoon formation frequency between the two periods. The typhoon formation frequency has increased west of 135ºE and has decreased east of 135ºE in the later period compared to the earlier period. This westward shift of the region of typhoon formation is consistent with the increase of typhoon activity in the South China Sea and the decrease in the East China Sea. So it is suggested that the changes in typhoon formation region partially affect the typhoon passage frequency.

A further question has arisen in association with 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 decadal shift of SSTs in magnitude and inter-annual 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 Nino 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.

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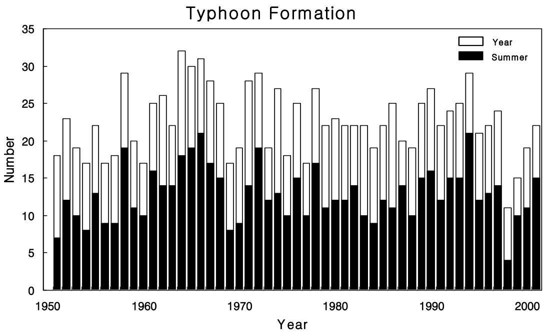


Fig. 1. Annual and summertime numbers of typhoons formed over the tropical western North Pacific (110°-180°E and 5°-20°N) from 1951 to 2001.

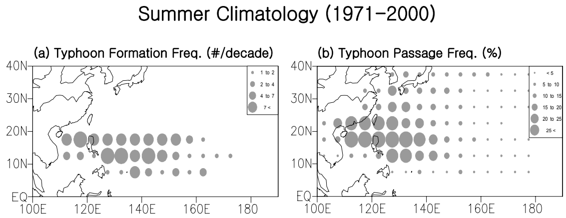


Fig. 2. Geographical distribution of summertime typhoon formation locations (number per decade) (a) and typhoon passage frequency (%) (b) in each 5°×5° grid area for the period 1971-2001.

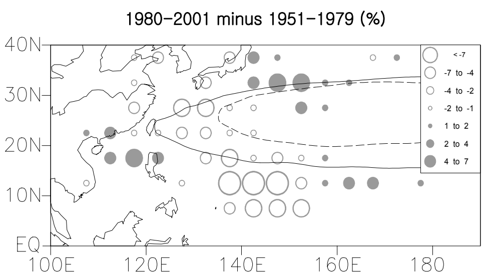
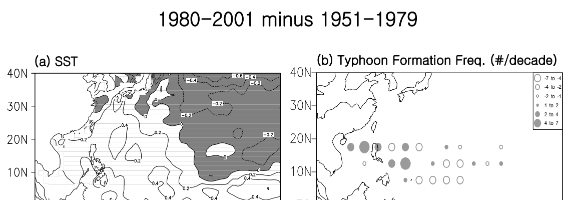


Fig. 3. Geographical distribution of difference in typhoon passage frequency between the periods 1980-2001 and 1951-1979. Dotted and solid lines indicate the mean position of 5780 gpm for 1951-1979 and 1980-2001,



respectively.

Fig. 5. Geographical distribution of difference in sea surface temperature (a) and typhoon formation location between the periods 1980-2001 and 1951-1979. Contour intervals are 0.2°C for (a).

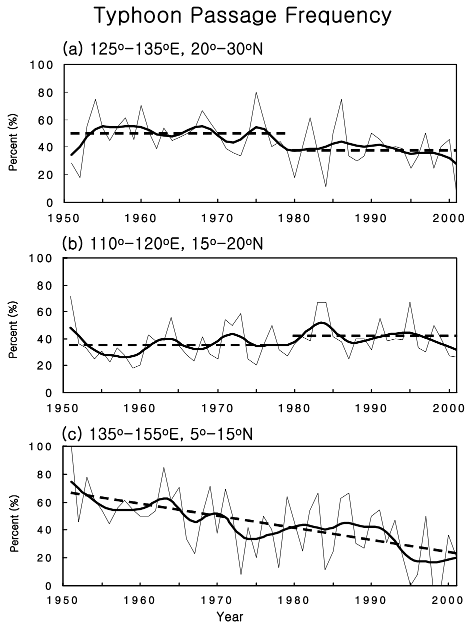


Fig. 4. Time series of typhoon passage frequency in the regions of 125°-135°E and 20°-30°N (a), 110°-120°E and 15°-20°N (b), and 135°-155°E and 5°-15°N (c). Heavy solid line denotes 9-point Gaussian filtered value. Heavy dotted lines denote the means for the periods 1951-1979 and 1980-2001 in (a) and (b) and denote the linear slope for the entire period in (c).

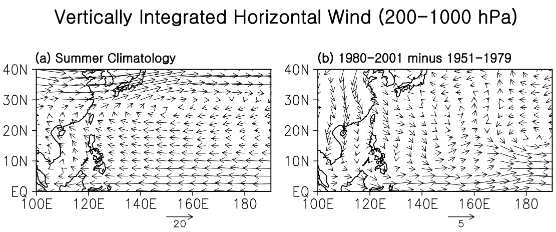


Fig. 6. Geographical distribution of vertically-aveaged horizontal wind in the troposphere (200-1000 hPa) for the period 1971-2000 (a) and its difference between the periods 1980-2001 and 1958-1979 (b).

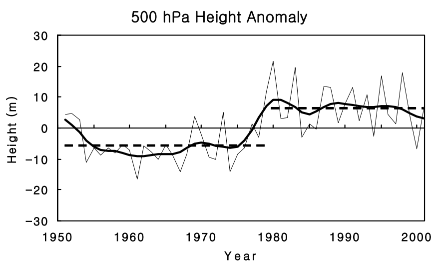


Fig. 7.. Time series of subtropical northwestern Pacific high (SNPH) anomaly in the region of 125°-140°E and 20°-25°N. Heavy solid line denotes 9-point Gaussian filtered value and heavy dotted lines denote the means for the periods 1951-1979 and 1980-2001.