Interdecadal Variability of Western North Pacific Tropical Cyclone Tracks

KIN SIK LIU AND JOHNNY C. L. CHAN

Laboratory for Atmospheric Research, Department of Physics and Materials Science, City University of Hong Kong, Hong Kong, China

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ABSTRACT

This study examines the interdecadal variability of the tropical cyclone (TC) tracks over the western North Pacific (WNP) during the 1960–2005 period. An empirical orthogonal function analysis of the 10-yr Gaussian-filtered annual frequency of TC occurrence shows three leading modes of TC occurrence patterns. The first mode is related to the variation of TC activity in the areas near Japan and its east. The second mode is characterized by a northeast–southwest dipole of TC occurrence anomalies along the southeast coast of China and an east–west dipole near Japan and its east. The third mode is similar to the second mode, except for the absence of the east–west dipole. These patterns are shown to be related to the decadal changes in the prevailing TC tracks.

Two characteristic flow patterns related to the first and third modes of TC occurrence pattern are identified. The first pattern is characterized by a north–south dipole of 500-hPa geopotential anomalies over the WNP. Such a pattern may affect the strength and westward extension of the subtropical high and the midlevel steering flow and hence the TC occurrence pattern. The Pacific decadal oscillation (PDO) is found to display a similar dipole-like structure. The decadal variability of TC tracks may therefore be partly attributed to the PDO signal. The second characteristic pattern shows a series of anomalous midlevel atmospheric circulations extending from the sea east of Japan to the south coast of China, which may explain the other part of the decadal variations.

1. Introduction

The variability of the tropical cyclone (TC) activity over the western North Pacific (WNP) has received much attention during the last decade. Many studies have been performed on the variations in TC number (e.g., Chan 1985; Dong 1988; Chen et al. 1998; Matsuura et al. 2003). Some more recent studies also examine the variations of TC intensity (Chan and Liu 2004; Camargo and Sobel 2005; Chan 2007, 2008). However, not many studies have been done on the variability of TC tracks, which has a significant impact on the TC landfalling activity along the coastal areas of East Asia. For example, a record-high number of 10 TCs made landfall in Japan in 2004. Does this represent an increasing trend on the TC landfalling activity in Japan? It is therefore very important to study the interdecadal variability of the TC track patterns over the WNP, which may be helpful in reducing economic and human damage through proper planning and preparation before the typhoon season.

The El Niño–Southern Oscillation (ENSO) phenomenon has been considered to be one of the important factors affecting the TC tracks over the WNP (Wang and Chan 2002; Elsner and Liu 2003), and it has a significant impact on the TC landfalling activity in the coastal areas rimming East Asia (Saunders et al. 2000; Wu et al. 2004). During El Niño years, the TC formation locations shift southeastward and the TCs tend to take the recurving path toward Japan and the areas to its east; therefore, the TC activity in these regions is likely enhanced. In contrast, fewer TCs follow the westward or west-northwestward track across the Philippines and the South China Sea (SCS), resulting in a significant decrease in TC activity over the SCS. The situation is almost reversed for La Niña years.

Ho et al. (2004) examined the interdecadal variability of summertime (June–September) typhoon tracks over the WNP. They divided the 1951–2001 period into two subperiods of 1951–79 and 1980–2001 and found that the typhoon passage frequency decreased significantly.

Corresponding author address: Prof. Johnny Chan, Dept. of Physics and Materials Science, City University of Hong Kong, Tat Chee Ave., Kowloon, Hong Kong, China.
E-mail: Johnny.Chan@cityu.edu.hk

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over the East China Sea and the Philippine Sea, but increased slightly over the SCS in the latter period. Such changes are related to the westward expansion of the subtropical high in the northwestern Pacific. Based on observational study and trajectory model simulation, Wu et al. (2005) showed that two prevailing typhoon tracks in the western North Pacific have shifted westward significantly during the past four decades. They then concluded that the typhoon influence on subtropical East Asia has been increasing. They further proposed that these changes are related to the change in large-scale steering flow associated with the westward expansion and strengthening of the subtropical high. Kim et al. (2005) examined the summertime TC activity over the WNP and identified the East Asian dipole pattern (EADP), which has a significant impact on the TC activity near east China, Korea, and Japan. This mode is associated with the anomalous atmospheric circulation centering near Japan. More recently, Nakazawa and Rajendran (2007) examined the relationship between large-scale atmospheric circulation and TC approach–landfall on Japan, and they identified the tropical cyclone landfall mode of the tropospheric circulation to be related to the TC landfalling activity in Japan based on a combined empirical orthogonal function (EOF) analysis. This mode is related to the variability of the subtropical high and is featured with a circulation center near 20°N, 140°E. TC activity in Japan tends to be below normal (above normal) in a year with an anomalous anticyclonic (cyclonic) circulation. Xie and Yan (2007) investigated the typhoon track patterns in the months of June–December over the WNP based on the EOF analysis of the daily typhoon track density function and obtained three principal EOF modes. The first mode represents the overall typhoon frequency and life span, the second mode shows a north–south dipole between northeast Asia and Southeast Asia, and the third mode shows an east–west dipole over the WNP. These patterns are found to be related to the snow cover over the Tibetan Plateau.

Most of these previous studies focused either on the interannual variation of TC tracks or decadal variations during a particular period of the year. Very few studies have tried to examine annual TC track variability on a decadal time scale and relate it to other climatic signals other than ENSO. The present study therefore represents an attempt to examine the interdecadal variation of the TC track pattern over the WNP and its possible relationship with other climatic signals, such as the Pacific decadal oscillation (PDO). The data and methodology employed in this study are shown in section 2. Section 3 presents the interdecadal variations of the TC track patterns over the WNP. The large-scale flow patterns related to these track patterns are shown in section 4. The possible relationship between these flow patterns and the PDO is examined in section 5. The summary and discussion are then given in section 6.

2. Data and methodology

a. Data

1) Best-track data

The 6-h best-track positions of TCs over the western North Pacific occurring between 1960 and 2005 obtained from the Joint Typhoon Warning Center (available online at https://metocph.nmci.navy.mil/jtwc/best-tracks/) are used to define the pattern of frequency of TC occurrence. Only the positions at which a TC has at least tropical storm intensity are considered to reduce the uncertainty in defining the tropical depression. The data quality prior to 1970 is considered to be poorer because of the lack of satellite coverage. Some of the weaker storms may be missing especially for the storms over the open ocean. We repeated the analysis using the data in the 1970–2005 period and similar results are obtained. Therefore, the data quality problem should not affect the results and conclusions obtained from the present study.

2) PDO index

The PDO index is obtained from the Joint Institute for the Study of the Atmosphere and Ocean of the University of Washington (Mantua et al. 1997), which is defined as the leading principal component (PC) of monthly sea surface temperature (SST) anomalies in the North Pacific Ocean poleward of 20°N. The PDO index for the months of July–October is averaged to represent the status of the PDO during the peak TC season.

3) Atmospheric data

Monthly 500-hPa geopotential heights and 500-hPa zonal and meridional winds are obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis dataset. The former shows the strength and extension of the subtropical high while the latter represents the large-scale midtropospheric steering flow. The horizontal resolution of the dataset is 2.5° latitude × 2.5° longitude.

b. Frequency of TC occurrence

The TC track pattern in a year is represented by the annual frequency of TC occurrence. The 6-hourly po-
3. Patterns of TC occurrence

An EOF analysis of the filtered frequency of TC occurrence\(^1\) suggests that TC tracks over the WNP can be represented by three characteristic track patterns. The loading patterns reflect the prevailing tracks that can be roughly classified into four types (see, e.g., Fig. 1a). The first type represents a west-northwestward straight track across the Philippines and the SCS (labeled as track A). Track B represents a northwestward straight track toward the east coast of China. Tracks C and D denote the recurving tracks toward the areas near Japan and the sea east of Japan, respectively. Temporal changes in the TC occurrence patterns are believed to be associated with those in the frequency of occurrence of these prevailing tracks. In the following, each loading pattern and the time series of the coefficients are examined in detail.

\(1\) See section 2 on the filtering method; hereafter all discussions will be referred to the filtered data unless otherwise stated.

a. Pattern 1 (EOF1)

The first EOF of the TC occurrence pattern (hereafter pattern 1) explains \(\sim 25.8\%\) of the total variance and shows positive loadings over the tropical WNP, extending to the middle part of the SCS and the east coast of China. This suggests an above-normal frequency of occurrence of both west-northwestward straight tracks across the Philippines and the SCS (track A) and northwestward tracks toward the east coast of China (track B) during the positive phase of this mode (Fig. 1a). Negative loadings are found over the areas north of \(30^\circ\)N, representing a below-normal frequency of occurrence of recurving TCs (tracks C and D). Note that this pattern is similar to the first mode of the interannual summertime (July–September) TC passage frequency obtained by Kim et al. (2005).

The time series of PC1 shows a significant interdecadal variation, with negative values during the periods of 1964–77 and 1992–2001 and positive values during the period of 1978–91 (Fig. 1d). In other words, this mode suggests a higher frequency of TC occurrence in Korea and Japan during the first two periods and in SCS and the Philippines during the latter period.

b. Pattern 2 (EOF2)

The second EOF (hereafter pattern 2) explains \(\sim 18.0\%\) of the total variance. Its main feature is the positive loadings extending from the western part of the tropical WNP to the SCS, suggesting a higher frequency of occurrence of west-northwestward straight tracks across the Philippines and the SCS (track A) during its positive phase (Fig. 1b). The eastern part of the tropical WNP shows negative loadings that extend to the areas near the east coast of China and Japan, indicating a lower frequency of occurrence of the northwestward straight tracks toward the east coast of China (track B) and the recurving tracks toward the areas near Japan (track C).

The time series of PC2 shows a significant decreasing trend (Fig. 1e). This mode is in its positive phase during 1964–76, but becomes insignificant after 1977 and then switches to the negative phase gradually after 1997. This mode appears to suggest a possible decreasing trend in the TC activity over the SCS and the rimming coastal areas and an increasing trend in the TC activity along the east coast of China during the last 45 yr.

c. Pattern 3 (EOF3)

The third EOF (hereafter pattern 3) explains \(\sim 15.2\%\) of the total variance. Positive loadings are found over the tropical WNP and extend to three areas, including the SCS, Japan, and the water east of Japan, suggesting an increase in the frequency of occurrence of tracks A, C, and D (Fig. 1c). Negative loadings are found near the east coast of China and form a northeast–southwest dipole along the southeast coast of China, which is similar to the pattern in the second EOF (see Fig. 1b). However, this mode shows prominent positive loadings over the tropical WNP east of \(135^\circ\)E, which extend to the areas near Japan and the waters east of Japan. A test of the possible degeneracy of these two modes (North et al. 1982) suggests that they are not well separated from each other, and therefore a similar feature is found in both modes. Note also
that pattern 3 is quite similar to the EADP defined by Kim et al. (2005); however, the loadings over the areas near Japan are different. Our results suggest that the EADP may also have a significant interdecadal variation.

The time series of PC3 suggests that this mode is not significant before 1987 (Fig. 1f). Then, it is in its positive phase during 1989–97 but switches to the negative phase in 1998.

d. TC occurrence pattern in different periods

The pattern of frequency of occurrence of tropical storms over the WNP has been shown to exhibit a significant interdecadal variation. According to the variation of the PC coefficients of the three modes, the sample can be divided into the following four periods: 1964–76, 1977–88, 1989–97, and 1998–2005. Although there is an uncertainty of 1 or 2 yr in the choice of the changepoint years, the mean TC occurrence patterns for each period are similar for the different choices of the changepoint years. Note that the period of 1998–2005 is considered, instead of 1998–2001, to extend the data length of this period. Because the TC occurrence patterns in 2002, 2004, and 2005 are similar to the mean TC occurrence pattern during 1998–2001, it is likely that the same TC occurrence pattern should persist into the period of 2002–05.
1) 1964–76

The TC occurrence pattern during 1964–76 is dominated by the positive phase of pattern 2, as suggested by the time series of PC2 (cf. Figs. 1d–f) and the mean TC occurrence pattern in this period (cf. Figs. 1b and 2a). The TC activity over the SCS and the tropical WNP west of 140°E is enhanced, which suggests that more TCs formed in these areas and took the west-northwestward path across the Philippines and the SCS. On the other hand, fewer TCs formed over the tropical WNP east of 140°E and followed the northwestward track toward the east coast of China and the recurving tracks toward the areas near Japan, resulting in reduced TC activity in these areas.

2) 1977–88

The mean TC occurrence pattern during 1977–88 is very similar to the positive phase of pattern 1 (cf. Figs. 1a and 2b), which suggests the domination of this mode in this period. Enhanced TC activity is found over the western part of the tropical WNP and extends to the Philippines and the SCS, as well as the east coast of China. In contrast, a large area of negative anomalies is found over the WNP north of 20°N, suggesting a reduced frequency of occurrence of recurring TCs.

3) 1989–97

The positive phase of pattern 3 appears to dominate the period of 1989–97 (cf. Figs. 1c and 2c). The mean TC occurrence pattern in this period shows positive anomalies over the tropical WNP east of 140°E, which extend to the SCS, and the areas near Japan and its east, which suggests the higher frequency of occurrence of the prevailing tracks along these areas. On the other hand, negative anomalies are found along the east coast of China, forming a northeast–southwest dipole along the southeast coast of China, which is much similar to the one found during the period of 1964–76.

4) 1998–2005

The mean TC occurrence pattern during 1998–2005 is dominated by the negative phase of patterns 2 and 3 (see Figs. 1e,f). A northeast–southwest dipole can clearly be seen near the southeast coast of China, with a positive center near Taiwan and a negative center over the South China Sea (Fig. 2d), which is similar to the one found in the period of 1989–97 but with opposite signs. This pattern indicates a shift in TC activity from the SCS to the southeast coast of China. A west–east dipole is also found near Japan, with a positive center near Japan and a negative center over the sea.
east of Japan. It is worth noting that this pattern is almost the opposite of that during 1964–76 (cf. Figs. 2a,d).

e. Summary

The pattern of the TC tracks over the WNP has been shown to exhibit a significant interdecadal variation and can be represented by three major characteristic track patterns, namely, patterns 1, 2, and 3. The main feature of pattern 1 is lower TC activity in the areas near Japan and the sea east of Japan resulting from the lower frequency of occurrence of recurving TCs. Pattern 2 is characterized by a northeast–southwest dipole of TC activity anomalies along the southeast coast of China, indicating the opposite change in the frequency of occurrence of the west-northwestward straight track across the Philippines and the SCS, and the northwest–eastward straight track toward the east coast of China. An east–west dipole is also found in the areas near Japan and the sea east of Japan. Pattern 3 is similar to pattern 2 except that positive loadings are found in both the areas near Japan and the sea east of Japan.

The track pattern over the last 42 yr can be divided into the following four subperiods: 1964–76, 1977–88, 1989–97, and 1998–2005. The first three periods are dominated by the positive phases of patterns 2, 1, and 3, respectively, while the last period is dominated the negative phase of patterns 2 and 3.

4. Large-scale atmospheric circulation

As discussed before, the preferred TC occurrence pattern in a year is largely affected by the genesis locations and the subsequent tracks of the TCs. The former is partly related to the position and extension of the monsoon trough and the latter is influenced by the steering flow, both of which are controlled by the large-scale flow. To understand the interdecadal variations of TC occurrence therefore requires an investigation of the interdecadal variations of the large-scale flow patterns. Because the subtropical high and the midtropical high are important to TC movement (e.g., Chan and Gray 1982), the 500-hPa geopotential heights and zonal and meridional winds are examined. These fields are first filtered using a 10-yr Gaussian filter, and a singular value decomposition (SVD) analysis is performed on these anomalous fields. The time series of the expansion coefficients of each SVD mode is then compared with those of the TC occurrence patterns 1, 2, and 3. The physical connection between these flow patterns and TC occurrence pattern is then examined. The results suggest two characteristic flow patterns closely related to patterns 1 and 3. However, no prominent flow pattern related to pattern 2 is found, which may be due to the degeneracy between EOFs 2 and 3 of the TC occurrence pattern. The major difference between these two patterns is on the region represented by the recurving tracks toward the areas near Japan (track C). The flow patterns related to these patterns may be similar and cannot be separated by the current analysis.

a. Pattern 1

1) Flow pattern

The 500-hPa flow pattern related to pattern 1 can be represented by the second SVD mode, which explains 13.8% of the total squared covariance. The homogeneous correlation map of 500-hPa geopotential height shows a north–south dipole with negative correlations over the extratropical WNP centered at about 40°N, 160°E and positive correlations over the subtropical WNP (Fig. 3a). Negative correlations are also found over the tropical WNP east of 130°E. The corresponding zonal wind pattern shows positive correlations over the areas along 35°N and near the equatorial WNP, and negative correlations in between (Fig. 3b). The correlation coefficients between their expansion coefficients is very high (r = 0.93), suggesting a strong coupling between the geopotential high and the zonal wind.

The time series of the expansion coefficients of geopotential height, zonal wind, and the PC of pattern 1 shows similar interdecadal variations (Fig. 3c). The TC occurrence pattern is in its positive phase during the period of 1978–91, which coincides with the positive phase of this characteristic flow pattern. Indeed, the expansion coefficients of zonal wind and geopotential height are highly correlated with the PC coefficient of pattern 1, with correlation coefficients of 0.77 and 0.57, respectively, both of which results suggest a possible relation between them.

2) Impact on TC occurrence pattern

If a characteristic flow pattern dominates in a particular year, the associated steering flow may affect the TC movements; the TCs tend to follow some preferred prevailing tracks, resulting in a particular TC occurrence pattern. Because a high correlation exists between the flow pattern and pattern 1, the changes in geopotential height and zonal wind associated with this flow pattern may have an effect on the TC occurrence pattern.

During the positive phase of this flow pattern, an anomalous low is found over the extratropical WNP and an anomalous high is observed over the subtropical WNP (see Fig. 3a). The latter suggests that the subtropical high is stronger than normal and extends more
westward, which tends to prohibit TCs from recurving, resulting in a significant decrease in the number of TCs with recurvature tracks toward the sea east of Japan. This partly explains the decrease in TC activity over these areas, which is the key feature of pattern 1. The easterly anomalies over the subtropical WNP tend to steer the TCs toward the SCS and southeast China (see Fig. 3b).

b. Pattern 3

1) Flow Pattern

The anomalous 500-hPa flow pattern related to pattern 3 is characterized by the third SVD mode of 500-hPa geopotential height and meridional wind, which explains 3.3% of the total squared covariance. The spatial pattern of the former shows an east–west dipole over the region north of 20°N, with a negative center near Japan and a positive center over the North Pacific Ocean centered at about 30°N, 170°E (Fig. 3d). Geostrophy would suggest an anomalous southerly flow over the region between 140° and 165°E, and an anomalous northerly flow over the region between 115° and 130°E (Fig. 3e). The negative center near Japan forms another northeast–southwest dipole with the positive center near the south coast of China, which has a significant effect on the zonal flow near the east coast of China.
The expansion coefficients of geopotential height and meridional wind for the third SVD mode is highly correlated with the PC of pattern 3 ($r = 0.53$ and $r = 0.60$, respectively) and their time series shows similar interdecadal variation (Fig. 3f), suggesting a possible connection to this TC occurrence pattern. The time series of the expansion coefficient of geopotential height shows a similar variation, but its correlation with the TC occurrence pattern is lower. Note that the positive phase of this flow pattern dominates the period of 1986–96, which roughly coincides with the positive phase of pattern 3.

2) Impact on TC occurrence pattern

The anomalous flow pattern is closely related to the track changes associated with pattern 3. The two dipoles of anomalous circulations play an important role in the changes of the meridional steering flow near the east coast of China and the region between 140° and 165°E. During the positive phase of this flow pattern, the anomalous cyclonic circulation near Japan and the anomalous anticyclonic circulation near the south coast of China give rise to strong northerly anomalies extending from east China to the Philippines. As a result, TCs approaching the Philippines tend to move toward the SCS and the south coast of China. On the other hand, the southerly flow associated with the east–west dipole of anomalous circulations over the ocean east of Japan tends to steer the TCs toward the areas east of 150°E, resulting in the increase of TC activity in these areas. These track changes partly explain the decrease of TC activity near the east coast of China and the increase of TC activity in the areas near Japan (see Fig. 1c).

c. Discussion

Some previous studies have examined the relation between TC track type and large-scale atmospheric circulation (Harr and Elsberry 1991; Camargo et al. 2007a,b). It is useful to compare the characteristic flow patterns identified in the present study with the results of these studies.

Harr and Elsberry (1991) examined the 700-hPa large-scale atmospheric circulation anomalies associated with straight-moving and recurving storms occurring in the months of May–October during the period of 1947–89. They found that the atmospheric circulation associated with straight-moving storms is featured with an anomalous anticyclonic circulation near Japan and an anomalous cyclonic circulation over the SCS. The anomalous easterlies between 20° and 30°N tend to steer the storms formed east of the Philippine Sea toward the northern part of the SCS or east China, a track similar to track B in Fig. 1. Indeed, this pattern is similar to the negative phase of pattern 3 in the present study, which suggests an increased frequency of occurrence of track B (straight-moving track) but a decreased frequency of occurrence of tracks C and D (recurving tracks), a TC occurrence pattern consistent with the results of Harr and Elsberry (1991).

In their study, recurving storms are further divided into recurving south and recurving north storms, with the former defined as the storms that formed south of 20°N and west of 150°E that then recurved (track C in Fig. 1) and the latter defined as the storms that formed either north of 20°N or east of 150°E and north of 10°N that then recurved (tracks C and D in Fig. 1). The atmospheric circulation associated with recurving south storms is different from that with straight-moving storms. The anomalous anticyclonic circulation is located more eastward and appears as the north–south-oriented anticyclonic anomalies between 20° and 40°N along 155°E, together with an anomalous cyclonic circulation over the Yellow Sea. This pattern is similar to the positive phase of pattern 3, which suggests an increased frequency of occurrence of track C (recurring track) but decreased frequency of occurrence of track B (straight-moving track), again consistent with the results of Harr and Elsberry (1991). The anomalous atmospheric circulation associated with recurving north storms is very similar to the negative phase of pattern 1. Both patterns show an anomalous cyclonic circulation along 25°N, representing the weaker subtropical high, and both studies consistently suggest the increased frequency of occurrence of recurring tracks.

A more recent study by Camargo et al. (2007a,b) also examined the relationship between TC track type and large-scale atmospheric circulation. Based on cluster analysis, they classified the TC tracks as seven types, labeled as clusters A–G. Clusters A and E represent the storms that form east of the Philippines and then recurve toward the areas near Japan, with the genesis location of cluster E being more eastward. Note that these clusters are similar to our track C (see Fig. 1). Cluster C also represents the recurving track, except that the genesis location is more eastward and the storms tend to recurve toward the open ocean east of Japan, like our track D in Fig. 1. Clusters B, D, and F generally show a straight trajectory extending from the Philippine Sea to the SCS, but their mean genesis locations are different, which are similar to track A in this study. The composite of daily 500-hPa anomalous wind field associated with cluster A shows a broad anticyclonic circulation north of 25°N centered at about 35°N, 155°E, and a cyclonic circulation south of 25°N and west of 150°E. A similar pattern is found for cluster C,
except that the circulation dipole is more eastward. It is worth noting that these two patterns can be generally represented by the negative phase of pattern 1, which is also associated with an increased frequency of recurving tracks C and D. The atmospheric circulation associated with clusters B, D, and F (straight tracks) is featured with anomalous anticyclonic circulation between 20° and 40°N, with different positioning and strength for the different clusters. This pattern is similar to the positive phase of pattern 1, which also suggests the increased frequency of straight tracks. Therefore, pattern 1 in the present study represents the decadal change in the large-scale atmospheric circulation, which is favorable for straight-moving (recurving) tracks in its positive (negative) phase, consistent with the results of Camargo et al. (2007a,b).

5. Relationship with Pacific decadal oscillation

It is well known that the PDO has an effect on the climate of East Asia and the Pacific Ocean (Zhu and Yang 2003; Chan and Zhou 2005; Zhou et al. 2007). However, very few studies have been done on its effect on TC activity. Therefore, the relation between PDO and TC occurrence pattern is examined. The PDO index for the months July–October is filtered using the same 10-yr Gaussian filter. The filtered values are then compared with the PC coefficients of the three TC occurrence patterns. The PDO is generally in its negative phase between 1964 and 1976 and switches to positive phase after 1977 (Fig. 4). However, it switches back to negative phase after 1998.

Time series of the PDO index is positively correlated with the PC coefficients of patterns 1 and 3, with correlation coefficients of 0.54 and 0.51, respectively, which are significant at the 95% confidence level. While these correlations appear to be not very high, the phase changes of PDO are associated with the shifts of the TC occurrence patterns, suggesting a possible connection to these patterns. For example, the phase change of PDO in 1976/77 is associated with the shift of pattern 1 from negative to positive phase (Fig. 4). The time series also suggests that their relation appears to be higher before 1989. Indeed, the correlation coefficient rises to 0.86 if only the period of 1964–88 is considered. On the other hand, both the PDO and pattern 3 show a phase shift in 1997/98 (Fig. 4). Pattern 3 is dominant only after 1987, and its variation is almost in phase with the PDO index. Indeed, a very high correlation coefficient of 0.90 exists for the period of 1987–2002. These results suggest that the PDO appears to have a higher correlation with pattern 1 before 1988 and with pattern 3 after 1989.

The PDO may not be the sole factor affecting the TC occurrence pattern. For example, Matsuura et al. (2003) showed that the long-term variation of SST in the tropical central Pacific is related to the interdecadal variation of TC activity over the WNP. The westerly wind anomalies and the eastward extension of the monsoon trough associated with the higher SST favor the TC formation over the eastern part of the WNP, which may have an influence on the TC occurrence pattern, especially for pattern 3. Indeed, the filtered SST anomalies in the area of 10°–20°N, 180°E–150°W is highly correlated with the PC coefficient of pattern 3 ($r = 0.77$). The time series of the SST anomalies (not shown) shows positive values during the period of 1986–97, and correspondingly the positive phase of pattern 3 become dominant in this period. This could partly explain why the PDO influence on pattern 1 is less significant after 1988.

To examine the relationship between PDO and TC occurrence patterns further, the influence of PDO on the large-scale flow pattern is examined. The correlation map between the PDO index and the 500-hPa geopotential height for the months of July–October shows a distinct north–south dipole (Fig. 5a). Negative correlations are found over the extratropical WNP, with the maximum amplitude in Japan and the region near 45°N, 170°E. Positive correlations are observed over the subtropical WNP, with the maximum amplitude in Japan and the region near 45°N, 170°E. Positive correlations are observed over the subtropical WNP, with the maximum amplitude in Japan and the region near 45°N, 170°E. Positive correlations are observed over the subtropical WNP, with the maximum amplitude in Japan and the region near 45°N, 170°E. Actually, this pattern can be considered to consist of two dipoles, a north–south dipole over the eastern part of the WNP and a northeast–southwest dipole over the region extending from Japan to the SCS. This pattern is also quite similar to the characteristic 500-hPa flow pattern related to pattern 1 (see Fig. 3a). Indeed, the PC2 of the 500-hPa geopotential height is highly correlated with
the PDO index \((r = 0.71)\), which suggests a possible connection of PDO to this large-scale circulation, and hence pattern 1. The PDO also has a significant influence on the 500-hPa zonal wind. The correlation map between the PDO index and the zonal wind shows positive correlations between 25° and 35°N, extending from the east coast of China to the sea east of Japan, a pattern similar to the EOF1 of zonal wind. Indeed, the PC1 of zonal wind is highly correlated with the PDO index \((r = 0.79)\).

The PDO is generally in its positive phase between 1977 and 1997 and is featured with a north–south dipole of 500-hPa geopotential height anomalies, with an anomalous low on the north side and an anomalous high on the south side. However, the features of this pattern are quite different in the periods of 1977–88 and 1989–97. For the period of 1977–88, the two dipoles are quite obvious, especially the one over the eastern part of the WNP (Fig. 6a). As a result, the subtropical high is stronger than normal and extends more westward. Such a pattern is quite similar to the positive phase of the characteristic flow pattern related to pattern 1 (see Fig. 3a). For the period of 1989–97, the north–south dipole over the eastern part of the WNP weakens sig-

Fig. 5. Correlation maps between the July–October PDO index and 500-hPa (a) geopotential height and (b) zonal wind. Shaded areas indicate the correlations are significant at the 95% confidence level. Plus-shaped boxes (rectangular shaped) indicate the positive (negative) centers.
nificantly and the northeast–southwest dipole near the east coast of China becomes dominant, resulting in strong westerly anomalies extending from the east coast of China to Japan (Fig. 6b). Note that this pattern is quite similar to the positive phase of the characteristic flow pattern related to pattern 3 (see Fig. 3d). The PDO shifts to its negative phase after 1998 and the pattern of 500-hPa geopotential height appears to be reversed. An anomalous high is located east of Japan, and areas with relatively lower geopotential height are found over the subtropical WNP centered at about 20°N, 170°E and over the SCS (Fig. 6c). As a result, strong easterly anomalies are found over the region between 20° and 40°N. Therefore, TCs tend to be steered toward the areas near the east coast of China and Japan in this period (see Fig. 2d); this pattern is similar to the negative phase of pattern 3, consistent with the phase shift of this TC occurrence pattern in 1998 (see Fig. 1f).

6. Summary and discussion

a. Summary

This study examines the tropical cyclone (TC) occurrence pattern over the western North Pacific (WNP), which is found to exhibit a significant interdecadal variation and can be represented by three major modes. The first mode is featured with a variation of TC activity in the areas near Japan and the sea east of Japan as a result of the change in frequency of occurrence of recurving TCs. The second mode is characterized by a northeast–southwest dipole of TC activity anomalies along the southeast coast of China, indicating the opposite change in the frequency of occurrence of the west-northwestward track across the Philippines and the South China Sea and the northwestward track toward the east coast of China. An east–west dipole is also found in the areas near Japan and its east. The third mode is similar to the second mode except that positive loadings are found in both the areas near Japan and its east.

Based on the principle component coefficients of the three modes, the track patterns in the last four decades can be divided into the following four subperiods: 1964–76, 1977–88, 1989–97, and 1998–2005. The first three periods are dominated by the positive phase of the second, first, and third modes, respectively, while the last period is dominated the negative phase of the second and third modes.

Two characteristic 500-hPa flow patterns related to the first and third modes are identified. The former is featured with a north–south dipole of 500-hPa geopotential height anomaly. The southern center over the subtropical WNP has a significant effect on the strength and extension of the subtropical high and hence the number of recurving TCs. The latter is characterized by a northeast–southwest dipole of 500-hPa geopotential height anomaly near the southeast coast of China.
which affects the zonal winds over the areas extending from the east coast of China to Japan.

The Pacific decadal oscillation (PDO) is shown to have a significant influence on the subtropical high and the midlevel steering flow during the peak TC season. The PDO induces a north–south dipole of geopotential height anomaly over the WNP, which affects the intensity and extension of the subtropical high as well as the zonal winds. Indeed, the PDO index is related to both of the two characteristic flow patterns and the first and third modes of the TC occurrence pattern.

**b. Discussion**

Some previous studies have examined the variations of TC tracks over the WNP (e.g., Ho et al. 2004; Xie and Yan 2007). It is therefore useful to compare their results with those of the present study. Ho et al. (2004) examined the interdecadal variability of summertime (June–September) typhoon tracks over the WNP. They divided the 1951–2001 period into two subperiods of 1951–79 and 1980–2001 and found that the typhoon passage frequency decreased significantly over the East China Sea and the Philippine Sea, but increased slightly over the SCS in the latter period. Such changes are related to the westward expansion of the subtropical northwestern Pacific high. Note that the typhoon season, domain, and study method in the study of Ho et al. (2004) are different from the present study. Their study examined the tracks of typhoons formed in the months of June–September and over the tropical WNP (south of 20°N), while the present study considers the entire typhoon season (January–December) and the entire WNP. Therefore, the results of this study cannot be compared directly with that of Ho et al. (2004). Nevertheless, the TC occurrence pattern during 1980–2001 (not shown) also shows negative anomalies over the Philippine Sea and near east China and positive anomalies over the SCS, which is consistent with the results of Ho et al. (2004). However, the present study shows that the track patterns have exhibited several decadal changes within the two epochs identified by Ho et al. (2004).

Another study by Xie and Yan (2007) investigated the typhoon track patterns in the months of June–December over the WNP based on the empirical orthogonal function (EOF) analysis of the daily typhoon track density function (TDF) and obtained three principal EOF modes. The first mode represents the overall typhoon frequency and life span, the second mode shows a north–south dipole between northeast Asia and Southeast Asia, and the third mode shows an east–west dipole over the WNP. These patterns are found to be related to the snow cover over the Tibetan Plateau.

The method employed by the study of Xie and Yan (2007) is different from the present study. They studied the variability of the track pattern of typhoons (tropical storms not included) in the months of June–December based on the EOF analysis of daily TDF. Nevertheless, some similarities can be found between these two studies. First, the second mode of their TDF (a north–south dipole) is similar to the first mode of the TC occurrence pattern of the present study. Both patterns show a north–south dipole although the locations of the dipole centers are different. A similarity also exists between the third mode of their TDF (an east–west dipole) and the second mode of the TC occurrence pattern of the present study. Both show an east–west dipole over the WNP north of 15°N, with positive (negative) values east (west) of 145°E, although the patterns are different over the tropical WNP and the SCS. Therefore, both studies consistently show the shifts of typhoon tracks in the north–south and east–west directions on an interannual (Xie and Yan 2007) and interdecadal (this study) scale.

This study has identified the interdecadal variation of the TC occurrence pattern over the WNP, which has a significant impact on the TC landfalling activity along the coastal areas of East Asia. For example, the recent period (1998–2005) is dominated by the TC occurrence pattern that suggests higher TC activity along the east coast of China and the areas near Japan; this pattern is likely to persist before a significant shift in the TC occurrence pattern. Therefore, it is expected that the risk of TC landfall in these areas may become higher in the coming few years. Wu et al. (2005) also show the growing typhoon influence on East Asia, which is probably related to the prevalent TC occurrence pattern identified in this study. Further work on the interdecadal variations in landfall frequency would provide additional information on the dominant modes of variability, which could also be related to the PDO or other atmospheric or oceanographic oscillations. Such results will obviously be useful for planning purposes.

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**REFERENCES**


