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STATISTICAL CLASSIFICATION AND CHARACTERISTICS ANALYSIS OF BINARY TROPICAL CYCLONES OVER THE WESTERN NORTH PACIFIC OCEAN

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Abstract: Using the 1949-2007 western North Pacific tropical cyclones (TCs) best-track data archived at the Shanghai Typhoon Institute of China Meteorological Administration for the western North Pacific from 1949 to 2007, both the characteristics of binary and multiple TCs and samples of interactions among TCs and multi-TCs are identified and statistically analyzed. According to the various features of individual TC tracks and interacting tracks, seven distinct types are proposed to describe the binary system of TCs and their interaction samples. The mean trajectories of the west and east component of binary TCs in each type are obtained using a new cluster analysis technique. These types are then analyzed in terms of landfall process, occurrence seasonality, coexistent lifetime, especially the large-scale patterns of atmospheric circulation. Finally, typical steering flows and conceptual models of the binary TCs at different phases are established based on six-hourly flow maps of the binary system and the averages are determined of the mean steering flow of ten representative binary TCs. Then, typical steering flows and conceptual models at the beginning, middle and final phase in each type are established to describe the large-scale circulation patterns of the binary system interaction types.

Key words: binary tropical cyclones; landfall; statistical classification; steering flow

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1 INTRODUCTION

Tropical cyclone (TC) track is usually influenced by large-scale atmospheric circulation, surrounding synoptic-scale systems, mid-latitude systems (Chen and Luo[1]), mesoscale or micro-scale vortices (Lei and Chen[2]) and another TC nearby. These systems may cause anomalous TC tracks and bring great difficulties to track prediction. Through a series of laboratory experiments, Fujiwhara demonstrated that the relative movement of two counterclockwise vortices close to each other is a counterclockwise mutual rotation, and there exists a tendency of attraction to each other (Fujiwhara[3, 4]). This phenomenon is commonly referred to as the Fujiwhara effect, or the so-called binary TCs effect. Besides the laboratory experiments of Fujiwhara, the binary TCs interaction has been studied from three aspects by far, namely, statistical analysis of observations (Brand[5], Dong and Neumann[6], Lander and Holland[7], Wang and Fu[8], Carr et al.[9], Carr and Elsberry[10]), synoptic analysis of typical samples and numerical modeling studies (Chang[11], Wang and Zhu[12,13], Wang and Holland[14], Tian and Shou[15], Lou and Ma[16], Wu et al.[17]). Statistical analysis suggested that anomalous tracks are often observed when the binary TCs interact with each other, and the track forecasting errors for these cases are greater than those of non-binary TC cases over the western North Pacific (Brand[5]). In addition, Dong and Neumann[6] showed that the binary TCs are considerably common in the western North Pacific.

Chen and Ding[18] introduced the concept of direct and indirect interaction between two interacting TCs. Lander and Holland[7] pointed out a modified mode of the classical Fujiwhara effect. In this mode, “the smaller TC being captured by the larger TC” tends to occur rapidly for the binary TCs within the first few

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hours, followed by a period of relatively stable cyclonic rotation, and finally by merging or separation. Carr et al.[9] proposed three conceptual modes of binary TCs interaction, including direct, semi-direct and indirect interaction, based on seven years of observations over the western North Pacific starting from 1997. The direct interaction, the so-called Fujiwhara effect, is categorized into one-way influence, mutual interaction, or merger of two TCs. After that, the separation distances and rotation rates—criteria for distinguishing among the three conceptual modes, were defined by Carr and Elsberry[10] but still subjectively applied. To avoid the subjectivity of classification in the aforementioned studies, in this paper, the binary TCs and multi-TCs interaction samples are selected from the TCs in the western North Pacific Ocean from 1949 to 2007. The basic statistical features of the selected samples are summarized in section 2, in which seven distinct types are proposed to describe the interaction samples of the binary system. The characteristics of individual types are discussed in detail in section 3. These interaction types are analyzed in terms of landfall process, seasonality, coexistent lifetime and the characteristics of large-scale steering flows in sections 4 and 5, and the typical steering flows for each type at the beginning, middle and final phase are also given.

2 DATA AND SAMPLES SELECTION AND BASIC STATISTICAL FEATURES

2.1 *Data*

The TC best track data over the western North Pacific Ocean (including the South China Sea) utilized in this study are collected from the data archive issued by Shanghai Typhoon Institute (STI) of the China Meteorological Administration (CMA) for the years 1949–2007. This dataset consists of 6-hourly information which includes the date, time, position, central pressure and speed of the TC. In addition, the average large-scale steering flow field is studied with the NCEP reanalysis wind data.

2.2 *Approach for samples selection*

From the TC best-track datasets, two named TCs which occur simultaneously were first selected as binary TCs. The trajectory and intensity information of each pair of TCs during their coexisting phase will be used in this study. The binary TC cases were further determined from the coexistent TCs according to the following criteria:

1) Only two named TCs which attain at least tropical-strorm intensity during their coexisting period are considered.

2) During the coexisting period, the distance between the two named TCs sometimes has to be less than 1600 km.

3) The two named TCs have to coexist for at least 48 hours.

4) If there are three or more TCs coexisting over the ocean and the distance among them is less than 1600 km, it will be regarded as a multi-TCs interaction.

According to the standards, 211 cases containing 163 pairs of binary TCs and 48 groups of multi-TCs systems were observed over the western North Pacific Ocean from 1949 to 2007.

2.3 *Basic statistical features*

Figure 1 shows the frequency of TCs interaction cases per year during the period 1949–2007 over the western North Pacific Ocean. Clearly, the mean value is 3.6 times per year. There are two peaks of TC binary interaction activity, one in the mid-1960s and the other in the early 1990s. However, the interaction cases happen with a relatively low frequency in the 1950s and from the late 1990s to 2007, during which the occurrence times per year is below the multi-year mean value. During the 1970s and 1980s, the interaction is more active.

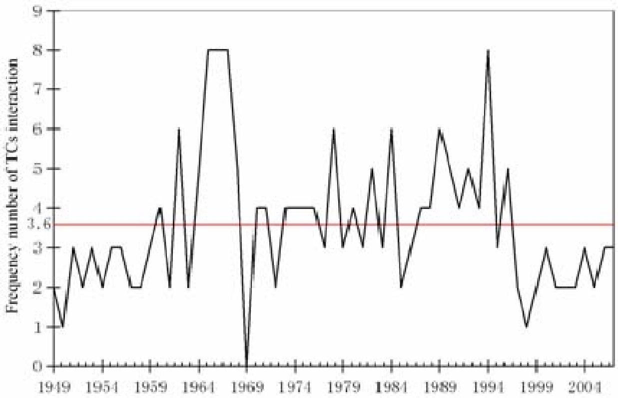


Fig. 1. Numbers of TCs interaction cases per year from 1949 to 2007 over the western North Pacific. (The middle line is the mean value for years.)

Figure 2 shows the number of binary TCs and multi-TCs interaction cases per month observed in the western North Pacific Ocean from 1949 to 2007. The TCs interaction activity is distributed quite regularly throughout much of the year. Interaction cases occur almost throughout the period from May to December, with observed maxima at 65 and 55 times in August and September, respectively. Furthermore, TCs interaction occur 34 and 31 times in July and October, respectively. Nearly 87.7% of all TCs interaction cases occur from July to October, consistent with the high frequency of TC genesis. During the 59 years, just one binary interaction case was observed in January, and there was no case identified in February, March and April by far. Besides, the multi-TCs interaction, only about one fifth of all TCs interction cases, occurs mainly from July to October, with maxima in August and September. Although the multi-TCs interaction is quite rare, it does become a much more complex type of mutual interaction for the binary pairs and much harder to forecast the track.

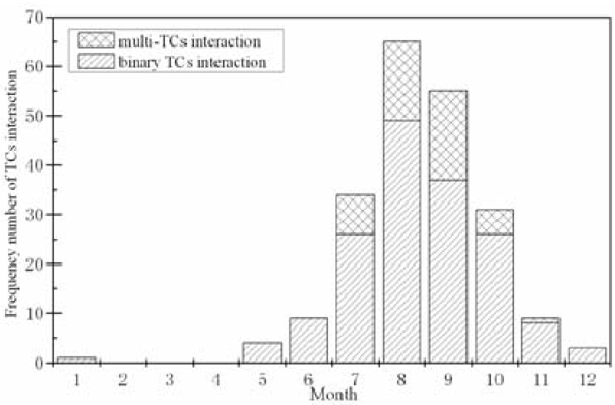


Fig. 2. Numbers of TC interaction cases per month during the period 1949–2007 over the western North Pacific.

3 CLASSIFICATION OF BINARY TROPICAL CYCLONES INTERACTION

There are four main TC track types over the western Pacific Ocean, including westward, northwestward, recurvature and abnormal moving trajectory (Zhu[19]). According to the trajectory features of each TC track and the relative track between two interacting TCs during their coexisting phase, seven distinct types are proposed, based on empirical analysis, to describe the binary system interaction samples. For each binary system, both TCs can be regarded as an eastern TC and a western TC according to their relative geographic position. Besides, there appear to be four binary TCs interaction cases whose paths are too complex and difficult to categorize. Therefore, a new cluster analysis technique, based on a regression mixture model, is put forward to obtain the mean regression trajectories of all the western and eastern TCs in each interaction type. The mean regression trajectories for types A through F are shown in Fig. 3 and the density of the dots changes with TC movement speed. Type G is typically the Fujiwhara-type mutual effect. TCs tracks in this type are too abnormal to obtain the mean regression trajectory, thus Fig. 3 does not give the mean trajectory of type G. The characteristics of the mean trajectory in types A through G will be discussed in detail later.

As shown in Fig. 3a, the typical tracks of eastern and western TCs in type A move straightly toward the northwest. The two TCs in type A move in a long, narrow region between 10° N and 20 °N, with a relatively steady separation distance between them. The straight-moving western TC usually extends from east of the Philippines to South China coast or Vietnam. The mean track of eastern TCs is typically located about 13° longitude to the east of the western TCs.

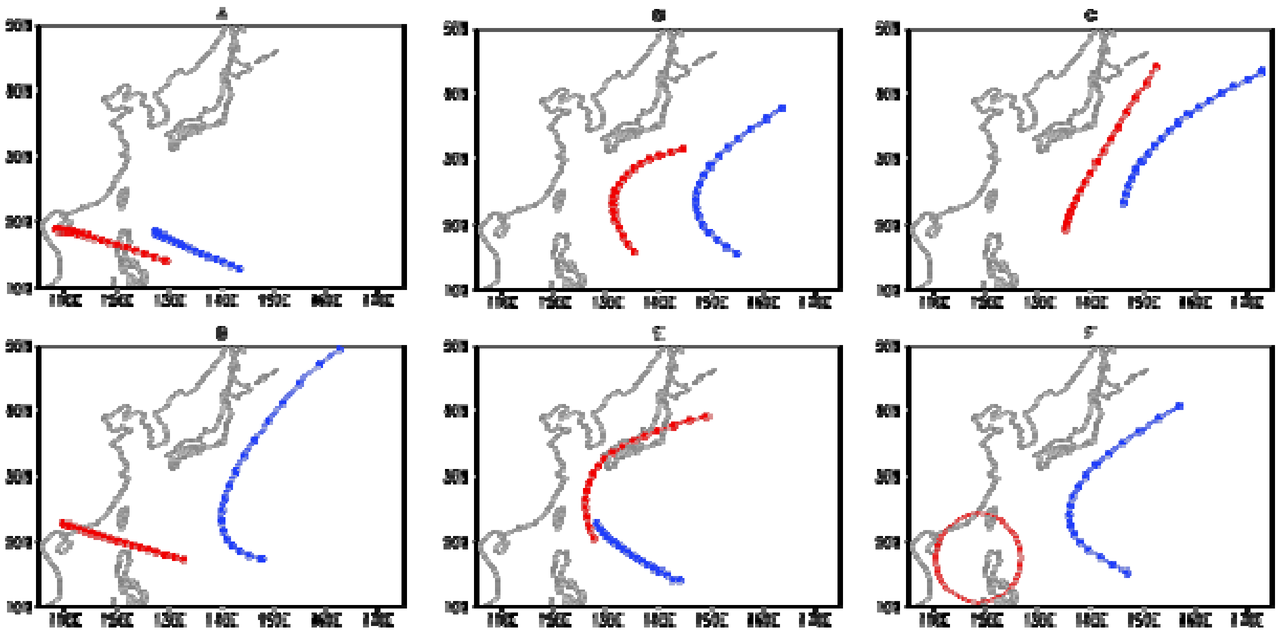


Fig. 3. The mean regression tracks in A–F binary interaction types. (In each of the figures, the left curve shows the track of the western TC and the right curve shows the track of the eastern TC.)

In type B, the tracks of eastern and western TCs are both recurving trajectories, as shown by the mean regression curves in Fig. 3b. The western TCs usually move from east of the Philippines toward the northwest, and then turn to the northeast as they reach the East China Sea. Most of the western TCs occur between Japan and the Philippines. The typical track patterns of the eastern and western TCs are somewhat similar, with the turning point of the latter about 14° longitude further east. So the eastern TCs always stay over the ocean. Although both the TC tracks are recurving, the eastern one turns faster and has a larger turning angle than that of the western one. And the eastern TC accelerates eastward away from the western TC as it enters the middle-latitude westerlies after turning northward.

Although the mean tracks in type C are also straight, they generally move toward the east or northeast (see Fig. 3c). During the binary TCs interaction period, the genesis of eastern and western TCs in type C are at higher latitudes than those of types A and C, especially for the eastern TCs whose typical original latitude is about 23° N. Because of the existence of the Fujiwhara effect between two TCs, the western TC generally slows down before turning around. However, it becomes faster along with the increase in distance between the two TCs and the influence of the westerlies.

It is clear from Fig. 3d that the western TCs in type D typically follow a straight, northwestward track, while the eastern TCs a recurving track. The mean track of the western TCs in type D is very similar to that in type A, but the former typically stays far away from the equator in angle as well as position. They usually move across the Philippines and the South China Sea, and finally make landfall on the South China coast. Reversely, the recurving eastern TCs first move toward northwest, and then turn northeastward rapidly in the region of 140° E under the influence of western TCs and the subtropical high.

In contrast to the case in type D, the mean track of eastern TCs in type E is straight toward the northwest, whereas that of the western TCs is a recurving trajectory (see Fig. 3e). Western TCs happen mostly between the Philippines and Japan. Due to the existence of binary interaction between the two TCs, eastern TCs always move toward northwest at low speeds. The eastern TCs with weak intensity usually decay in the basin of eastern Philippines and Taiwan islands while the strong ones keep moving northwestward.

The western TCs in type F always follow anomalous tracks, such as looping or stagnation. In general, the western TCs occur irregularly in the South China Sea, as shown by the circular region in Fig. 3f. And the eastern TCs typically follow a recurving track with the mean turning point at about 135° E. According to the Fujiwhara effect, the minimum distance between the interacting TCs is within 1000 km before the western TC turns around, and there also exists obvious cyclonic mutual rotation between them. The existence of the eastern TC thus can separate the western TC from the subtropical high and cause the western TC to slow down. Therefore, the looping motion of the western TC ends with the eastern TC turning around and moving away from it.

Besides the six types mentioned before (as shown in Fig. 3), the seventh interaction type is type G which belongs to the so-called Fujiwhara effect. In this type, the two interacting TCs both move with quite complex trajectories. Therefore, in this paper, we define as type G the cases in which the separation distance is steadily within 700 km during the binary interaction period. Also in this case, strong mutual rotation occurs with a 6-hourly rotation rate of at least 20°. Accordingly, it is too difficult to attain the mean regression tracks in type G. These binary interaction cases usually take place between 15° N and 30° N and stay west of 145° E.

4 GENERAL PROPERTIES OF EACH INTERACTION TYPE

4.1 *Basic statistical data*

Table 1 shows the basic statistical date in each binary interaction type. It is clear that the interaction cases in type A (18.2%) and B (17.6%) occur more frequently as compared with those in other types. In the cases of types C, D, E and F, interaction cases take up 13% to 14% of all binary systems and the TCs are very close to each other, while for the type G the percentage (10.7%) is relatively small. The landfall percentages of western or eastern TCs in each type are also given in Table 1. Obviously, the landfall percentages of western TCs are much higher than that of eastern TCs in each type except type G. Moreover, the eastern TCs in types B, C and D have almost no impact on the Chinese Mainland by far. More than 80% of the western TCs in types A, D and E make landfall, and more than a half of them affect China. The western TCs in types B, C and G have relatively low frequencies of landfall, especially for type B, which has the lowest landfall rate over China.

4.2 *Seasonality*

In order to understand the seasonal characteristics of binary interaction cases, Fig. 4 gives the number of binary system cases by the month for each interaction type in 59 years, based on the genesis data of two coexisting TCs. According to the discussion in section 2 of this paper, there exists almost no interaction case from January to February. Therefore, the number of binary TCs interaction cases that happened from May to December is shown in Fig. 4, type by type.

Table 1. Basic statistical dates in each binary interaction types.

Types	Frequecy	Percentage in all Types (%)	Landfall frequency for western TCs	Percentage for western TCs(%)	Landfall frequency for eastern TCs	Percentage for eastern TCs (%)
A	29	18.2	26/16	89.7/55.2	6/1	20.7/3.4
B	28	17.6	13/2	46.4/7.1	1/0	3.6/0
C	23	14.5	5/3	21.7/13.0	3/0	13.0/0
D	20	12.6	17/12	85/60	5/0	25/0
E	20	12.6	16/7	80/35	7/4	35/20
F	22	13.8	12/6	54.5/27.3	6/3	27.3/13.6
G	17	10.7	3/2	17.6/11.8	7/6	41.2/35.3
All	159	100	93/49	58.5/30.8	36/15	22.6/9.4

As can be seen from Fig. 4, all the interaction types occur from July to September. The anomalous tracks of western TCs in type F have less dependence on the season. However, the seasonal evolutions of binary interaction activity are remarkably different among types A, B and E, and type A peaks in July and August, type B in September and October, and type E in September. And the cases in type D occur mainly from July to October, with maxima in September. For the cases in type C, there exists an obvious peak season, with more than a half occurring in the midsummer August. Cases in Type G which belongs to the type of the Fujiwhara effect appear just in July, August and September.

Figure 5 shows the distribution of coexisting lifetime for individual binary TCs in each type and for all cases in the period 1949–2007. The mean coexisting lifetime of the binary systems in types B, D, and F is 7.30 days, 6.36 days, and 7.48 days, respectively. And the values are all above the average coexisting time for all cases. Moreover, it is the western TCs in these three types that all follow recurving tracks and display an even longer coexisting time between the eastern and western TC after they separate from each other. For the other four types, whose typical lifetimes are below the total mean value, type G has the smallest value in the average lifetime (3.82 days). The coexisting lifetime in type G is about 2.5 to 4 days. If the separation distance is short enough, one of the two TCs tends to decay or merge into the circulation of the other. We can also see from Fig. 5 that the life of type F (3 to 11.25 days) is the longest.

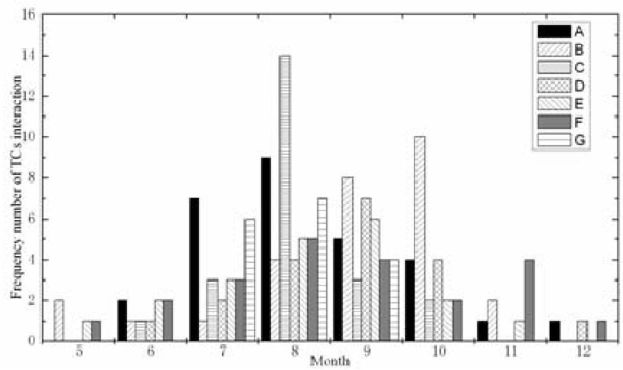


Fig. 4. Month-to-month numbers for each type of binary TCs interaction during the period 1949–2007.

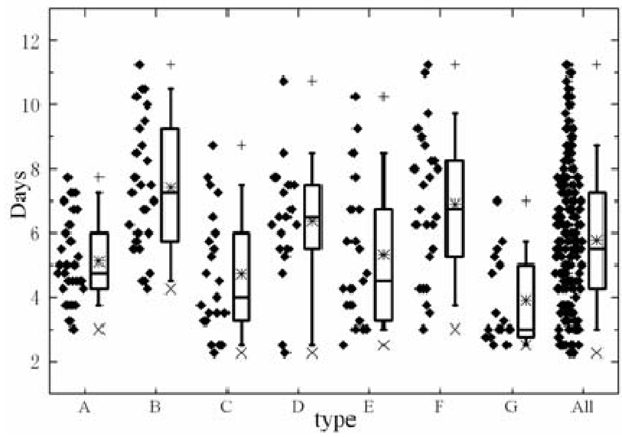


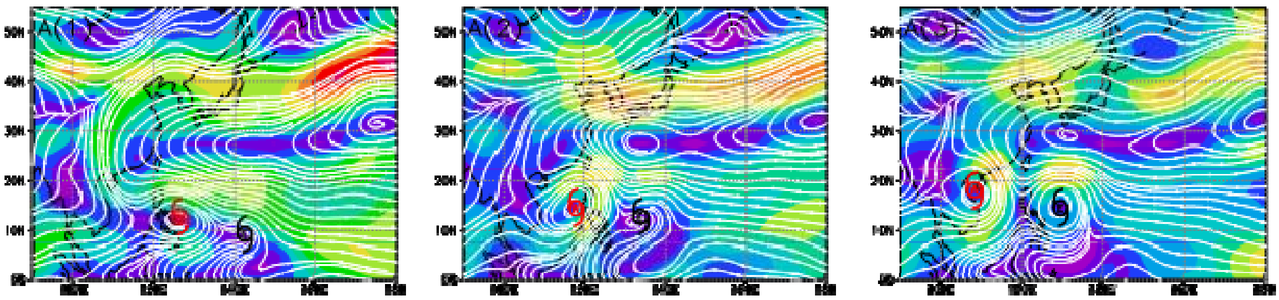
Fig. 5. Distribution of coexistence lifetime of each type of binary TCs interaction for all cases in the period 1949–2007.

5 ANALYSIS OF LARGE-SCALE STEERING FLOW PATTERNS FOR EACH TYPE

The movement of TCs is largely determined by the ambient flow, or the so-called large-scale steering flow. It is well known that different tropospheric levels have different correlation with TC intensity and direction. Consequently, in this paper, the steering flow is determined by the vertical averages of several pressure levels, or layer-means, which depend upon the TC intensity. And the central pressure of the weaker one in two interacting TCs is selected as the standard. If the pressure is higher than 990 hPa, just use the 500-850 hPa mean, and the pressure within 970-989 hPa corresponds to the 400-850 hPa mean, 950-969 hPa to the 300-850 hPa mean, 940-949 hPa to the 250-850 hPa mean, and pressure below 940 hPa to the 200-700 hPa mean. According to the above criteria, 6-hourly large-scale mean steering flow charts are drawn with NCEP reanalysis wind field data. In order to analyze the steering flow evolution during the binary interaction period, the mean steering flows at the beginning, middle and final phase of ten representative interaction cases selected from each type are temporally averaged as the typical steering flows. Finally, the typical steering flows in three distinct stages (labeled 1, 2 and 3) are plotted in Fig. 6 to Fig. 11 for interaction types A to F.

5.1 *Type A*

As shown in Fig. 6, the strength of the subtropical high is powerful in type A, with the subtropical ridge extending to the middle and lower reaches of Yangtze River. At the beginning of binary interaction stage (see Fig. 6A(1)), eastern and western TCs are embedded in the steady and smooth eastern winds in the south of the subtropical high. The vertical distance between the TC and subtropical ridge is usually greater than 10° longitude. In Fig. 6B(2), two TCs move toward the west or northwest under the force of stable subtropical circulation, with the distance between the TC and the subtropical ridge reduced to 10° longitude gradually. Finally, western TCs make landfall or decay around Hainan Province of China, and then eastern TCs may decay in the basin east off the Philippines or continue westwards or turn northwards.



A(1) A(2) A(3)

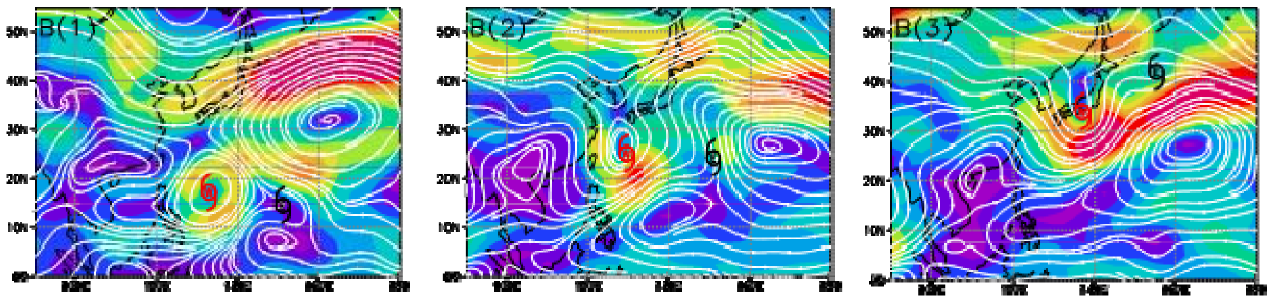
Fig. 6. The typical steering flows at the beginning (A(1)), middle (A(2)) and final (A(3)) phase in type A. The shadow shows the wind speed.

Evidently, the subtropical high ridge line is always located between 25° N and 30° N during the whole interaction process. Though separation distance between the two interacting TCs is in the range of 12° to 15° longitude, the mutual rotation caused by the binary system interaction is slow due to the existence of a stable and powerful subtropical high. In addition, the statistical data in Table 1 shows that the landfall rate of western TCs in type A reaches to 89.7%, with more than a half (55.2%) of them making landfall over the southern China coast and Hainan Island.

5.2 *Type B*

For type B with two recurving TCs, at the beginning stage, the subtropical high circulation center is located over the ocean and there is a long-wave trough between the subtropical high and the continental high (see Fig. 7A(1)). Under this large-scale situation, if the western TC is alone over the basin, it is much easier for it to move around the subtropical anticyclone and recurve into the westerlies. However, in the case that there exists another TC near it, namely the eastern TC, in the east or southeast of the western TC, the eastern TC is acting to inhibit the recurvature of the western TC because of the mutual interaction between the two TCs as they are getting closer to each other. Simultaneously, the western TC may act to encourage the recurvature of the eastern TC. Then the eastern TC will first turn around the subtropical high when it reaches the southwestern edge of the subtropical anticyclone, with noticeable cyclonic mutual rotation between the two TCs (see Fig. 7B(2)). With the eastern TC moving away, the western TC begins to turn northeastward with the zonal circulation instead.

It is clearly shown from Fig. 7B that a trailing anticyclone is generated behind the eastern TC via Rossby wave dispersion, in consistency with the conceptual model of Carr et al[9]. Based on the numerical method, Luo and Ma[16] demonstrated that the dispersion-induced anticyclone increases the density of the isolines between the eastern TC and the subtropical high and then accelerates the eastern TC. After the two TCs turn around, such a dispersed anticyclone merges into the subtropical high, which helps to extend the high pressure system to the southwest (see Fig. 7C). According to the statistical data for the 59 years, no landfall of this type is identified for the eastern TCs (see Table 1).



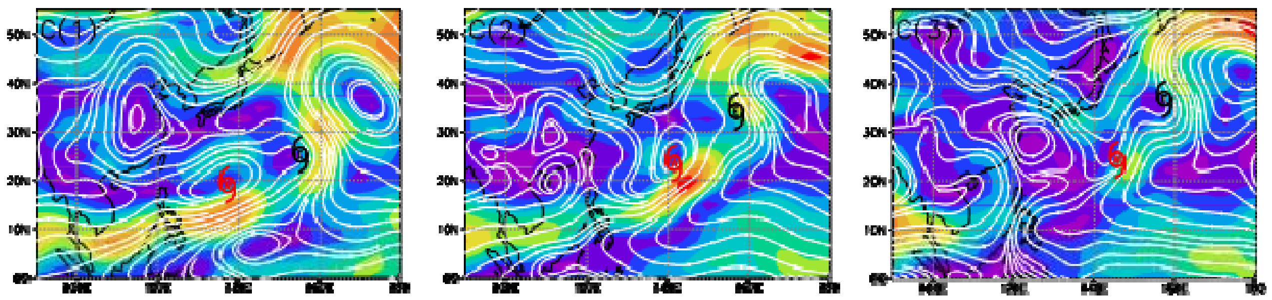
B(1) B(2) B(3)

Fig. 7. The typical steering flows at the beginning (B(1)), middle (B(2)) and final (B(3)) phase in type B. The shadow shows the wind speed.

5.3 *Type C*

As can be seen from Fig. 8, the large-scale circulation of type C is characterized by the high pressure ridge extended from the subtropical high to the southwest. And the orientation of the subtropical ridge is north-south or southwest-northeast. At the beginning phase, both eastern and western TCs are involved in the southwestern flows of the subtropical high, with the eastern TC rapidly moving north-northeastwards under the influence of the southwestern flows and western TC. The western TC moves eastward as affected by the weak southwestern flows and the interaction between the two TCs. As shown in Fig. 8c, the subtropical ridge further extends westward during the binary interaction processes, with the orientation of the two TCs changing to northeast-southwest. Then the western TC turns northward or northeastward. Finally, the binary TCs gradually move away from each other and turn around the subtropical high or decay one by one.

Type C mainly generates at the west side of the South China Sea. On this occasion, western TCs are likely to affect China or the Philippine Islands, but rarely have any impact on China. And eastern TCs even have no influence on China (see Table 1). According to Fig. 4, more than half of the binary interaction cases in type C occur in August, being fairly consistent with the large-scale situation of meridional circulation in this type.

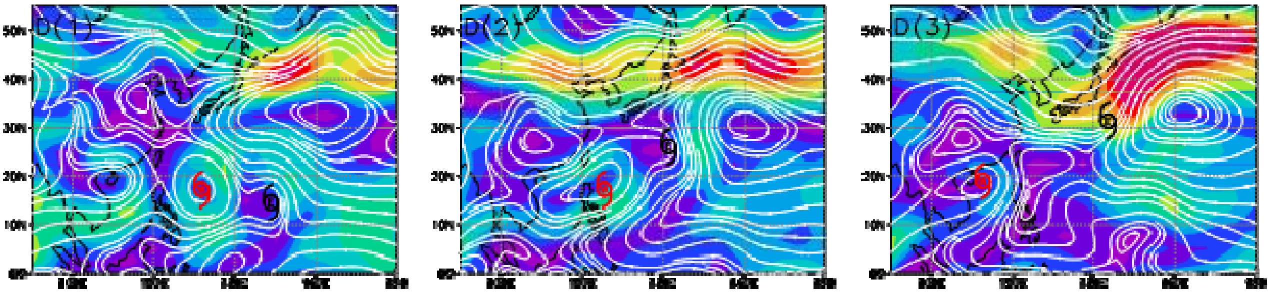


C(1) C(2) C(3)

Fig. 8. The typical steering flows at the beginning (C(1)), middle (C(2)) and final (C(3)) phase in type C. The shadow shows the wind speed.

5.4 *Type D*

It is known from Fig. 3 that the typical tracks of western TCs in type D are straight toward the northwest and eastern TCs follow recurving tracks. In Fig. 9a, it can be seen that the subtropical high circulation in type D is similar to that of type A at the beginning stage of the interaction process, with the subtropical ridge stretching to the east coast of China, whereas the vertical distance between the TC and subtropical high ridge in type D is smaller than that in type A. In this phase, eastern TCs usually move toward the northwest under the effect of the subtropical high system and the poleward steering flow of the western TC, while western TCs move westwards or northwestwards. As shown in Fig. 9b, the subtropical high retreats eastwards and breaks at the longitude of the eastern TC, with the continental high developing during the middle phase of mutual interaction between two westward TCs. Under this condition, eastern TCs will recurve to the north, then to the northeast due to the influence of the subtropical high, while western TCs follow straight tracks toward the west because of the influence of continental high steering flows. Finally, after the two TCs move far away from each other, eastern TCs turn into the westerlies and western TCs keep moving westwards or northwestwards with a landfall rate 60% over the Hainan, Taiwan, Fujian and Zhejiang Provinces of China.

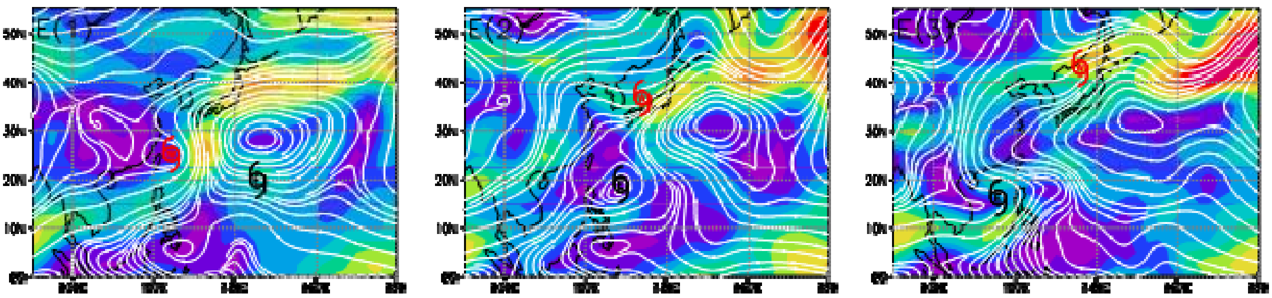


D(1) D(2) D(3)

Fig. 9. The typical steering flows at the beginning (D(1)), middle (D(2)) and final (D(3)) phase in type D. The shadow shows the wind speed.

5.5 *Type E*

Figure 10 illustrates the large-scale steering flow patterns of type E. At the initial interaction stage, western TCs commonly appear at the southwest or west edge of the subtropical high. Eastern TCs are located at the southeast of the western TCs and embedded in the eastern air flow to the south of the subtropical high. And then western TCs rapidly turn around with the guidance of the subtropical high. It is clear from Fig. 10b that, in the southwest side of the subtropical high, a trailing anticyclone behind the western TC generates via the dispersion of Rossby waves along with the recurvature of the western TC. In the process of the western TC recurving and the eastern TC moving westward, this anticyclone is just located between the two TCs. So eastern TCs cannot turn around but continue moving westwards. Eventually, after western TCs turn away from eastern TCs, the dispersed anticyclone merges into the subtropical high circulation which continues to strengthen and extend to the west.



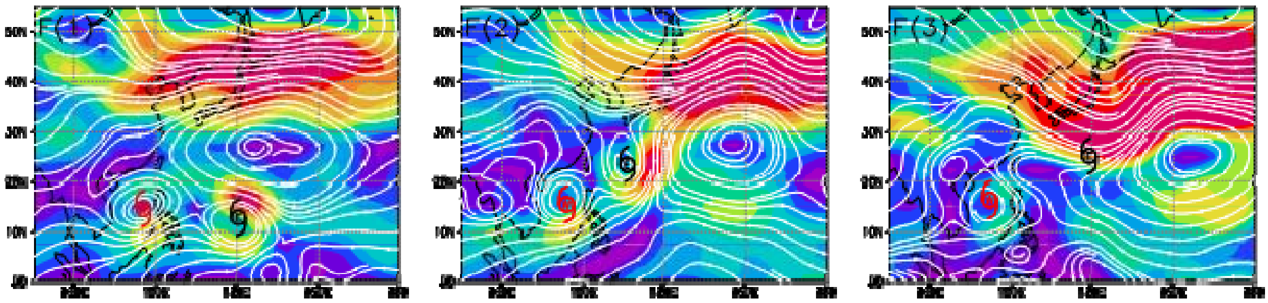
E(1) E(2) E(3)

Fig. 10. The typical steering flows at the beginning (E(1)), middle (E(2)) and final (E(3)) phase in type E. The shadow shows the wind speed.

Western TCs in type E may have an impact on the east coast of China, Korean Peninsula or Japan with the landfall rate at 80% (see Table 1) as they turn around. For eastern TCs, some will turn northward after western TCs move away and others will still keep moving westward, with the weaker ones decaying in the basin and the stronger ones making landfall (at a rate of 35%) on the southeastern China or even Hainan Province and the Philippines.

5.6 *Type F*

The western TCs activities in type F often occur in the South China Sea with anomalous tracks. As shown in Fig. 11a, at the beginning phase of the mutual interaction, western TCs are usually present in the South China Sea or over the ocean near the Philippines. Located in the eastern air flow of the subtropical high, eastern TCs move westwards with a trailing anticyclone behind it via the Rossby wave dispersion. The subtropical high system retreats eastwards and separates from the continental high with the westward movement of the eastern TC. When the two TCs approach each other gradually and the eastern TC moves to the east of the western TC, it will obstruct the connection between the western TC and the subtropical high circulation (see Fig. 11b). At the same time, the dispersed anticyclone behind the eastern TC extends further to the west and produces a poleward steering flow to the western TC. When the forces of two steering flows become equal to each other, the western TC will act to slow down or loop locally. Finally, the anomalous behavior of the western TC ends with the turning away of the eastern TC. At the same time, the subtropical high ridge line stretches westwards rapidly. Thus the stagnant duration of the western TC depends on the turning speed of the eastern TC.



F(1) F(2) F(3)

Fig. 11. The typical steering flows at the beginning (F(1)), middle (F(2)) and final (F(3)) phase in type F. The shadow shows the wind speed.

Xie[21] specially discussed the influence of the western Pacific TC on the TC over the South China Sea. He pointed out that the movement of the western TC is determined by the latitude difference between the subtropical high ridge and the western TC after the eastern TC turns away. If the latitude difference is greater than 8 latitudes, the anticyclone ridge behind the eastern TC will extend westwards to the northeast side of the western TC which will move toward the west. If the latitude difference is less than 5 latitudes, the anticyclone ridge usually extends to the southeast side of the western TC which tends to turn northwards or accelerate moving to the northeast. The statistics shows that some of the western TCs in this type move across the Philippine Islands and then loop over the South China Sea. They will bring continuous precipitation to the coast and will have an impact the coastal areas in Fujian and Guangdong Provinces after the looping is over.

5.7 *Type G*

Type G is defined as the typical Fujiwhara type with the minimum distance between the two TCs steadily within 700 km. Besides, the interaction between the two TCs in this type is stronger than the large-scale steering flow. The two interacting TCs appear to rotate cyclonically relative to the system centroid which still follows the large-scale steering flow. The mutual interaction between the two TCs can be separated into two cases. One case is that the larger TC dominates the motion of the smaller TC, which slightly affects the larger one or is even absorbed into the larger cyclonic circulation. Another case is that binary TCs with equal size will experience significant mutual rotation relative to the system centroid. The coexisting lifetime of binary TCs in type G is the shortest relatively (see Fig. 5), indicating that the binary interaction is in an unstable state. When the two TCs in type G occur near the coastal area of China, the eastern TC is prone to make landfall over China easily with a higher landfall rate than the western TC (see Table1).

6 SUMMARIES

In this study, we first make a detailed statistical analysis on the cases of binary and multiple TCs interaction for a period of 59 years over the western North Pacific. Seven distinct interaction types are then proposed to describe the binary system interaction samples according to the track features of the western and eastern TCs. Moreover, the mean regression tracks of the western and eastern TCs in types A to F are obtained using a new cluster analysis technique. The TCs interaction in type G belongs to the so-called Fujiwhara effect. Finally, large-scale steering flow patterns in each of the interaction types are analyzed. Then the typical steering flows at the beginning, middle and final phase in each type are established for which the main characteristics are summarized as follows:

When two interacting TCs are present in the south of the subtropical high with a long vertical distance between TCs and the subtropical ridge line, they will follow the rules of type A. If the vertical distance is short enough, the subtropical high system will retreat eastwards and separate from the continental high.

Thus, in this case, binary TCs interaction of type D occurs. In addition, western TCs in the above two types have a high tendency percentage of landfalls, more than half of them over China.

When the subtropical high circulation center is located over the ocean with a meridional circulation, the eastern TCs positioned at the east or northeast of western TCs tend to recurve rapidly across the western TCs. These cases belong to type B. If the eastern TCs are located to the southeast of the western TCs, southwest of the subtropical high system, they will act as the interaction cases in type E. And if the subtropical high circulation extends southwestwards, then the binary TCs embedded in the southwestern flows will move following the cases in type C. In these three types, the two TCs in type E usually make landfall but do not in the other two types.

When western TCs are present in South China Sea with another TC generated in the easterly flow, they tend to follow complex tracks. These interaction cases belong to type F, in which the stagnant or looping time of western TCs depends on the turning speed of eastern TCs. For type G, the two interacting TCs are so close that they will appear to rotate cyclonically and follow complex tracks with a high tendency of landfall. Thus it is greatly difficult to forecast the TC tracks in these two interaction types.

It is clear from the analysis of the features of TC interaction types that the track patterns are mutually consistent with the lager-scale steering flow modes, implying the reasonability of the classification method. However, the results of this study are merely drawn from a statistical point of view, on which we will make further check by numerical modeling methods in a follow-up study.

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