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A METHOD OF RAPID CLASSIFICATION OF TROPICAL CYCLONE TRACKS OVER CHINA AND ITS APPLICATION

LIU Yin (刘 寅)[1, 2], CHEN Xiao-yu (陈小宇)[3], ZHAO Hong (赵 虹)[4], ZHAO Quan-qin (赵泉钦)[1],
ZHANG Dao-yuan (张道远)[1], FEI Song (费 松)[1]
(1. Jiangsu Meteorological Observation Center, Nanjing 210009 China; 2. Jiangsu Institute of Meteorological Sciences,
Nanjing 210009 China; 3. Jiangsu Meteorological Observatory, Nanjing 210008 China;
4. Luhe Meteorological Bureau, Nanjing 211599 China)

Abstract: Using data of tropical cyclones making landfall in China between May and October each year during the 1951-2015 period from the Shanghai Typhoon Institute, China Meteorological Administration (CMA-STI) Tropical Cyclone (TC) Best Track Dataset, we developed a method of rapid classification of TC tracks based on their average movement velocities and noted three types of tracks: a westward type, a northwestward type, and a northward type. We compared the climate characteristics of the westward and northward types and discuss their corresponding causes. The results show that the westward and northward types account for more than 80% of all TCs making landfall in China. Their climate characteristics, such as the frequency, landfall intensity, duration over land, velocity over land, movement distance over land, and other changes, show both similarities and differences. Both TC types show significant increases in their over-land durations, indicating that the effects of these landfalling TCs are increasing. However, the causes of these two TC types are similar and different in certain respects. The changes in large-scale steering flows have significantly affected the frequencies and over-land velocities of the landfalling TCs of the westward and northward types. In addition, differences between the changes in formation locations of the westward and northward types may lead to significant difference in their landfall intensities.

Key words: tropical cyclone; track classification; climate characteristics; cause analysis
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1 INTRODUCTION

Tropical cyclones (TCs) are warm-core cyclonic vortexes that originate over tropical oceans, and they rank among the top 10 types of natural disasters worldwide. China is located in the East Asian monsoon region, where tropical system activity is vigorous every summer. On average, China experiences 7 TC landfalls annually, leading to tremendous losses of lives and property in the southeast coastal provinces of China (Chen and Ding[1]; Zhao and Wu[2]; Chen and Wang[3]). Against a background of global warming, the frequency and impacts of strong TCs over the northwest Pacific have gradually increased, with significant changes in their prevailing tracks (Emanuel[4]; Webster et al.[5]; Wu et al.[6]; Zhao et al.[7]; Zhao et al.[8]). These changes are bringing greater attention to TC landfalls in China and the effects of disasters that they cause.

TC tracks are an important basis for assessing the geographic extent and disaster risk posed by TCs, and these tracks can generally be classified according to their characteristics, including their shape, length, and trajectory. The main goal of TC track classification is to obtain multiple types of tracks with varying life cycles, active seasons, impacts, and regions for the purpose of classifying and summarizing their characteristics and impacts and providing a theoretical foundation for TC track analysis and prediction (Huang et al.[9]).

Researchers have generally classified TC tracks using certain subjective recognition methods (Liang[10]; Chen [11]; Meng et al.[12]). Recently, cluster analysis has been favored by scholars in China and elsewhere. This method generally excludes the use of subjective factors and thus maintains a maximum degree of objectivity. Based on the coordinates of TCs at their maximum and final intensities, Elsner obtained an ideal TC track classification using K-means cluster analysis and showed that this method was suitable for classifying TC and hurricane tracks [13]. However, because K-means cluster analysis requires vector data with the same length, its utilization ratio of TC tracks is relatively low, and it is easy to miss important information regarding

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Biography: LIU Yin, Ph. D., primarily undertaking research on tropical cyclones.
Corresponding author: CHEN Xiao-yu, e-mail: kristophchan@gmail.com

TC tracks. To address this issue, Camargo et al. developed a hybrid regression model and reported that this new method of cluster analysis was useful for effectively classifying TCs with different characteristics and could be used to analyze the relationship between different types of TC tracks and large-scale environmental changes [14]. To solve the problem of clustering vector data with different lengths, Nakamura et al. added a mass matrix to their K-means cluster analysis and considered the track characteristics of TCs at their powerful stages [15]. They achieved good results when applying this method to the classification of TC tracks over the Pacific. Currently, scholars in China have mainly used the method of Nakamura et al.[15] to classify landfall TC tracks, with the only differences being the index coefficients and classification numbers (Zheng et al.[16]; Ma et al.[17]). For example, Zhang et al. used cluster analysis to classify TCs making landfall in China during the periods of 1951—2009 and 2000—2009[18]. They mainly divided these TCs into three types: type 1 TCs that moved westward after making landfall in southern China, type 2 TCs that moved inland after making landfall in southeast coastal China, and type 3 TCs that moved toward high latitudes and turned after making landfall in coastal provinces such as Fujian and Zhejiang. Based on their results, Zhang et al. conducted statistical and composite analysis of the characteristics, including the durations and intensities, of these three types of TC and found that they display different climate characteristics [18]. Nonetheless, their classifications were based mainly on landfall locations, and the different types still lacked clear definitions, resulting in certain errors in classification.

These studies of TC track classification are based mainly on cluster analysis theory, which requires very precise selection of index coefficients and generates a relatively large number of track types, which creates disadvantages for later statistical analysis (Zheng et al.[16]). The existing studies are often problematic in terms of partial overlaps between types and even classification errors, and the classification results warrant improvement. In addition, landfalling TCs account for the majority of TCs that cause losses of lives and property in coastal China (Chen and Ding[1]). Therefore, we selected TCs making landfall in China during the 1951—2015 period and attempted to find a simple, effective, and reasonable method of rapid classification to identify the main types of TCs affecting China with significantly different climate characteristics and aid in analyzing TCs passing over China and climate prediction in a context of global warming.

2 DATA

The data we used were taken from the Shanghai Typhoon Institute, China Meteorological Administration (CMA-STI) Tropical Cyclone (TC) Best Track Dataset, which is compiled from meteorological data obtained during the TC season each year by the Shanghai Typhoon Institute with the trust of the China Meteorological Administration. The dataset includes information such as the TC international numbers of the northwest Pacific, 6-hour locations (longitude and latitude), intensity marks, near-core maximum wind velocities, and near-core minimum atmospheric pressures. Compared with the TC best track datasets released by the Japan Meteorological Agency (JMA) and Joint Typhoon Warning Center (JTWC), the CMA-STI dataset includes more abundant over-land track information of TCs that make landfall in China. This study focused mainly on the tracks of TCs making landfall in China and their relevant characteristics, and the formation and development of typhoons over the northwest Pacific and the South China Sea are relatively independent of each other and show significant differences in seasonal changes (Li et al.[19]). Thus, we selected TCs that formed and reached tropical storm intensity (near-core maximum wind velocity >17.2 m/s; we define TC formation as the time when a TC reaches tropical storm intensity for the first time during its life cycle) over the northwest Pacific (excluding the South China Sea, i.e., located east of 122° E) and maintains intensities exceeding that of a tropical storm after making landfall in China (the mainland, Hainan and Taiwan) between May and October during the period of 1951—2015 (Fig.1). We thus selected 246 TCs that meet these criteria. We mainly investigated the rapid classification and climate characteristics of TCs with over-land intensities greater than those of subtropical low pressure systems (near-core maximum wind velocity >10.8 m/sec) after making landfall in China.

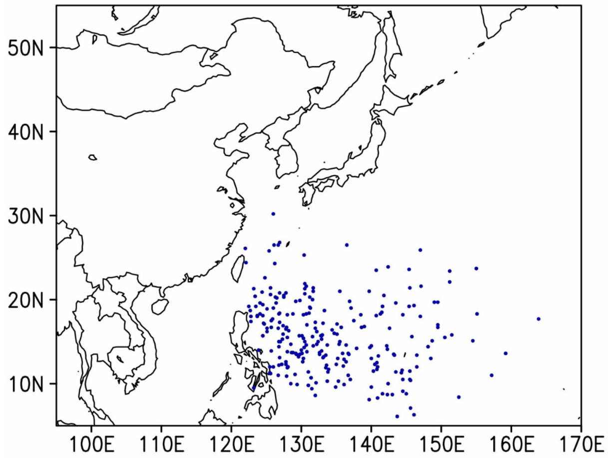

Figure 1. Formation locations of TCs selected in this study (i.e., locations where the TCs reached tropical storm intensity for the first time during their life cycles).

We also used global reanalysis data of monthly mean wind developed by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) spanning the period of 1965—2015 and the geographic range of 90°S–90°N and 0°E–360°E; the spatial resolution is 2.5°×2.5°. The data are gridded globally into 10,512 (144×73) cells with 17 wind levels.

3 METHOD OF RAPID CLASSIFICATION OF TRACKS

The classification of TC tracks in this study was based mainly on the average TC movement velocities and consisted of the following two steps: (1) calculate the average movement velocities over land, mainly consisting of the zonal velocity Vx and meridional velocity Vy, and (2) then, classify the TC tracks based on the arctangent of (Vy/Vx). Since most of the TCs over the northwest Pacific Ocean move northwestward, we assigned the movement angles to three ranges: 0–30°, 30–60°, and 60–90°. Compared with various methods of TC track classification proposed previously, the method developed in this study is simpler and faster to implement.

Figure 2 shows the classification results obtained using the proposed rapid TC track classification method. Figs.2a, 2b, and 2c show the tracks of the three ranges during their life cycles (intensity greater than that of a

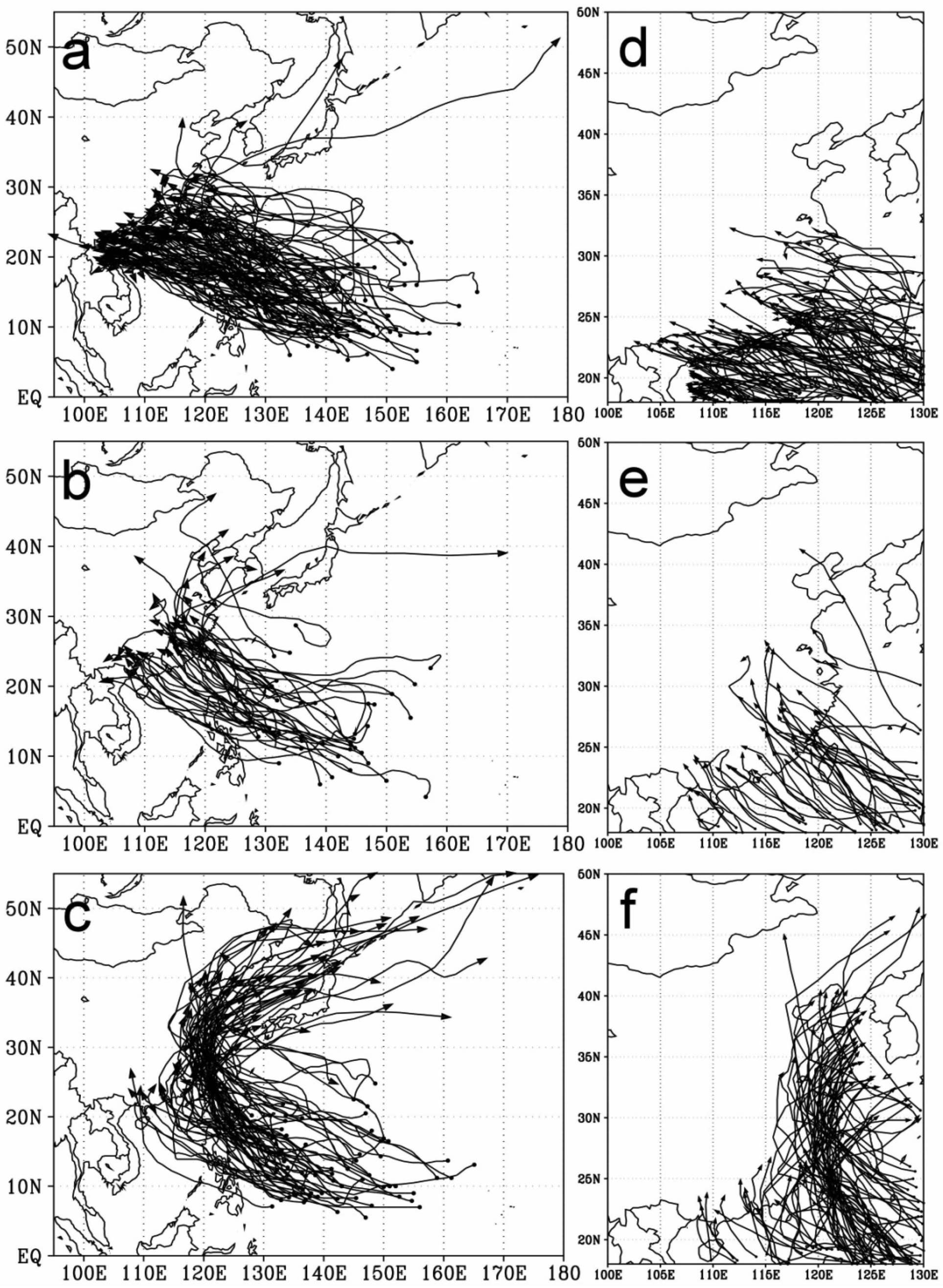

Figure 2. Results of using the rapid TC track classification method proposed in this study. Tracks of life cycles (intensity exceeding that of a tropical low pressure system) of (a) Westward Type, (b) Northwestward Type, and (c) Northward Type landfalling TCs. (d), (e), and (f) are the same but over the landfall regions.

tropical low pressure system). TCs with the three movement-angle ranges (0–30°, 30–60°, and 60–90°) are designated Westward Type, Northwestward Type, and Northward Type TCs, respectively. Our findings indicate that these three type designations are able to capture the main characteristics of each type of TC track, resulting in ideal effects. To better understand the effects of the classification and serve the main purpose of focusing on the TCs making landfall in China, Figs. 2d, 2e, and 2f show the effects over land, respectively, of the Westward Type, Northwestward Type, and Northward Type (intensity exceeding that of a tropical low pressure system). These results also show that the classification based on these three types of TCs is useful.

To quantify the TC track classifications, Table 1 lists statistics, including the number of TCs of each type, its fraction of the total number of TCs, and its mean annual frequency. The Westward Type TCs account for almost half of the total TCs, with an average of 1.9 per year. The Northward Type TCs rank second in number, with an average of 1.2 per year. These two types account for over 80% of the total TCs, indicating their relative abundance. In contrast, the Northwestward Type TCs accounts for less than 20%, with an average of fewer than one per year.

Table 1. Number of each TC type, its fraction of the TC total number, and its mean annual TC number.

Type	Number of TCs	Fraction of total TCs	Mean annual frequency
Westward	122	49.6%	1.9
Northwestward	46	18.7%	0.7
Northward	78	31.7%	1.2

4 COMPARISON AND CAUSAL ANALYSIS OF THE CLIMATE CHARACTERISTICS OF TYPICAL TRACK CLASSIFICATIONS

4.1 *Comparison of the climate characteristics of the Westward and Northward landfalling TCs*

As shown in Table 1, the majority of TCs making landfall in China are of the Westward and Northward Types, which account for over 80% of the total. Statistics indicate that the Northwestward Type was absent during the 34 years of 1951—2015. Therefore, to reasonably assess the classification effects from the perspective of climate characteristics, we chose to compare the two typical tracks of the Westward Type and Northward Type. In addition, Webster et al. showed that against a background of global warming, sea surface temperatures (SSTs) increased during the 1970—2004 period, leading to significant changes in TC frequency and intensity and a significant increase in the frequency of Category 4 and 5 TCs[5]. Emanuel et al. noted that the TC power dissipation index (PDI) increased significantly since the mid-1970s, and the longer life cycles and stronger intensities of TCs accompanied by the effects of changing global SSTs played important roles in this PDI increase [4]. Based on previous analysis methods, we also attempted to analyze the climate characteristics of various TC types from the perspective of frequency, over-land duration, and landfall intensity. Satellite observation technology has been applied to TC observation since the mid-1960s, and the accuracies of TC frequency, core location, and moving tracks have greatly improved, based on the previous analysis time periods (Zhao and Wu[20]; Wu and Zhao [21]). We therefore focused mainly on analyzing the trends in the climate characteristics of TCs making landfall in China during the 1965—2015 period.

Figure 3 shows the frequency, over-land duration, and landfall intensity of the Westward Type landfalling TCs during the 1951—2015 period. During these 65 years, the Westward Type TCs making landfall in China showed significant interannual oscillations; their annual frequency peaked at 5 in 1990 and showed a slightly decreasing trend after 1965. Meanwhile, the annual frequency of the Northward TCs showed a slightly increasing trend (see Fig.4). In addition, the over-land durations of the Westward and Northward Type TCs both showed significant increasing trends during the 1965—2015 period: these durations increased from 11.5 hours and 14.2 hours to 28.0 hours and 38.5 hours, respectively, i.e., increases of 143.5% and 171.1%, respectively.

Moreover, these changes both pass the 95% significance test (Kundzewicz and Robsona[22]; Yue and Wang [23]) (all significance tests in this study are the Mann-Kendall test), which is consistent with the results of Chen et al. [24]. In addition, the increase in the over-land duration of the Northward landfalling TCs is significantly greater than that of the Westward landfalling TCs. The significant changes in the landfall intensities of these two types of TCs are very different. The landfall intensity of the Westward TCs decreased from 34.7 m/s to 28.6 m/s, whereas that of the Northward TCs increased from 27.2 m/s to 33.9 m/s. Both changes pass the 95% significance test. The changes in the frequency and over-land duration of these two types of landfalling TCs are consistent with the results of Wu et al. regarding the prevailing TC tracks over the northwest Pacific Ocean during the 1965—2003 period [5]. Against the backdrop of global warming, due to changes in large-scale environmental

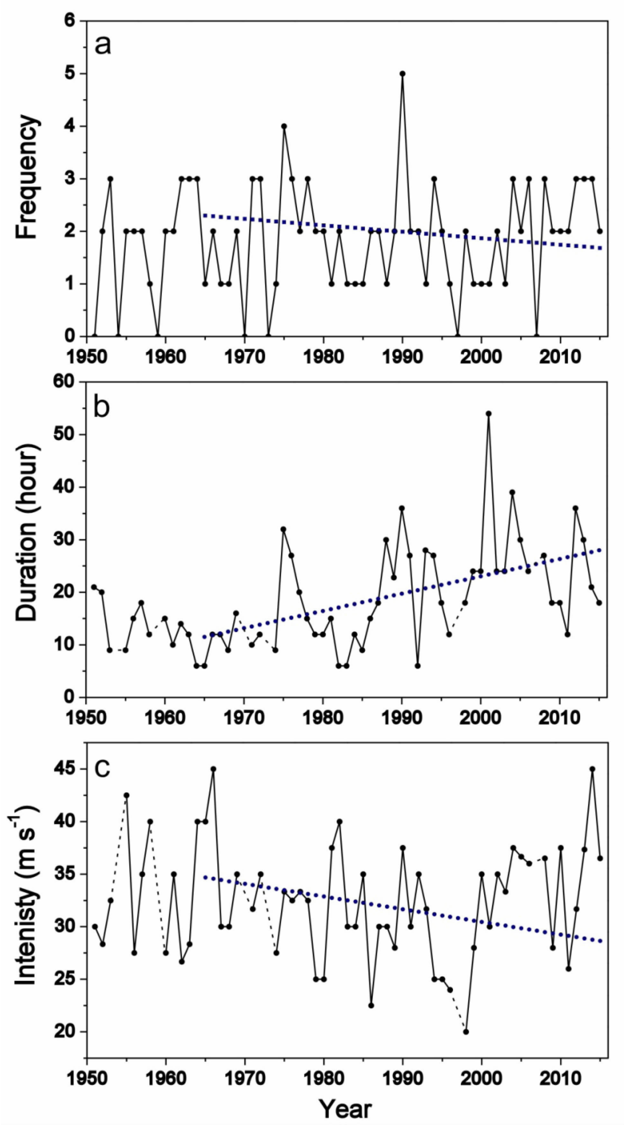

Figure 3. (a) Frequency (black solid line), (b) over-land duration (black solid line), and (c) landing intensity (black solid line) of 1951–2015 Westward Type landfalling TCs. The blue dotted lines denote trends during the 1965–2015 period, and the black dashed lines span missing years.

circulations, the prevailing TC tracks changed significantly: there was a gradual decrease in TCs entering the South China Sea and moving westward and an increase in TCs that moved northward or turned adjacent to Taiwan. This indirectly confirms that the proposed rapid classification method is useful for identifying the distribution of prevailing TC tracks and their changes, discovered by Wu et al., and is useful for distinguishing the two typical types of landfalling TC tracks[6].

To further analyze the differences in climate characteristics between the Westward and Northward landfalling TCs, Fig.5 and Fig.6 were prepared to show the over-land movement velocities, movement distances, zonal movement velocities, and meridional movement velocities of the two TC types. A comparison of Figs. 5a and 6a shows that the over-land movement velocities of these two TC types both decreased between 1951 and 2015. That of the Westward landfalling TCs decreased from 6.86 m/s to 5.93 m/s, a decrease of 13.6%, whereas that of the Northward landfalling TCs decreased from 6.41 m/s to 5.49 m/s, i.e., 14.2%. Figs. 5b and 6b show that the over-land movement distances of the Westward and Northward landfalling TCs increased significantly during the 1965—2015 period. That of the Westward landfalling TCs increased from 221.6 km to 448.1 km, an increase of 102.2%, whereas that of the Northward landfalling TCs increased from 311.8 km to 593.4 km, or 90.3%. These increasing trends of the two landfalling TC types both pass the 95% significance test. Similar to the over-land durations, the over-land movement distance of the Northward TCs was significantly greater than that of the Westward TCs, indicating that the activity of these two TC types differed significantly after making landfall. These TCs have slowed and have moved greater distances, leading to significant increases in their

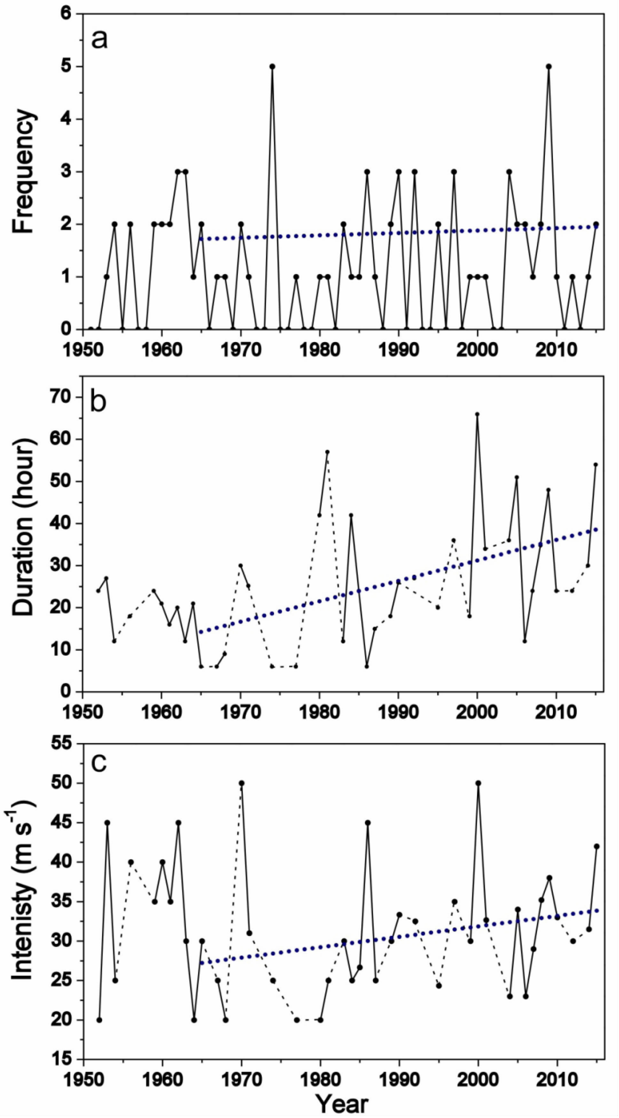

Figure 4. Same as Fig.3, but for the Northward Type.

over-land duration, which is highly consistent with the results of Chen et al.[24]. To analyze the changes in over-land movement velocities of these two landfalling TC types in detail, we decomposed their over-land velocities in the zonal and meridional directions and analyzed them separately (Figs.5c and 6c and Figs.5d and 6d). The results show that the annual variations in the over-land meridional velocity of the Westward landfall TCs and the zonal velocity of the Northward TCs were very small. Therefore, the decrease in over-land velocity of the Westward TCs was due mainly to a decrease in the zonal component, and that of the Northward TCs was due to a decrease in the meridional component. The combination of the changes in these factors suggests that the changes in over-land duration are due not only to changes in the over-land velocity and distance but also to other factors. For example, the increased landfall intensity may be one cause of the longer duration of the Northward TCs.

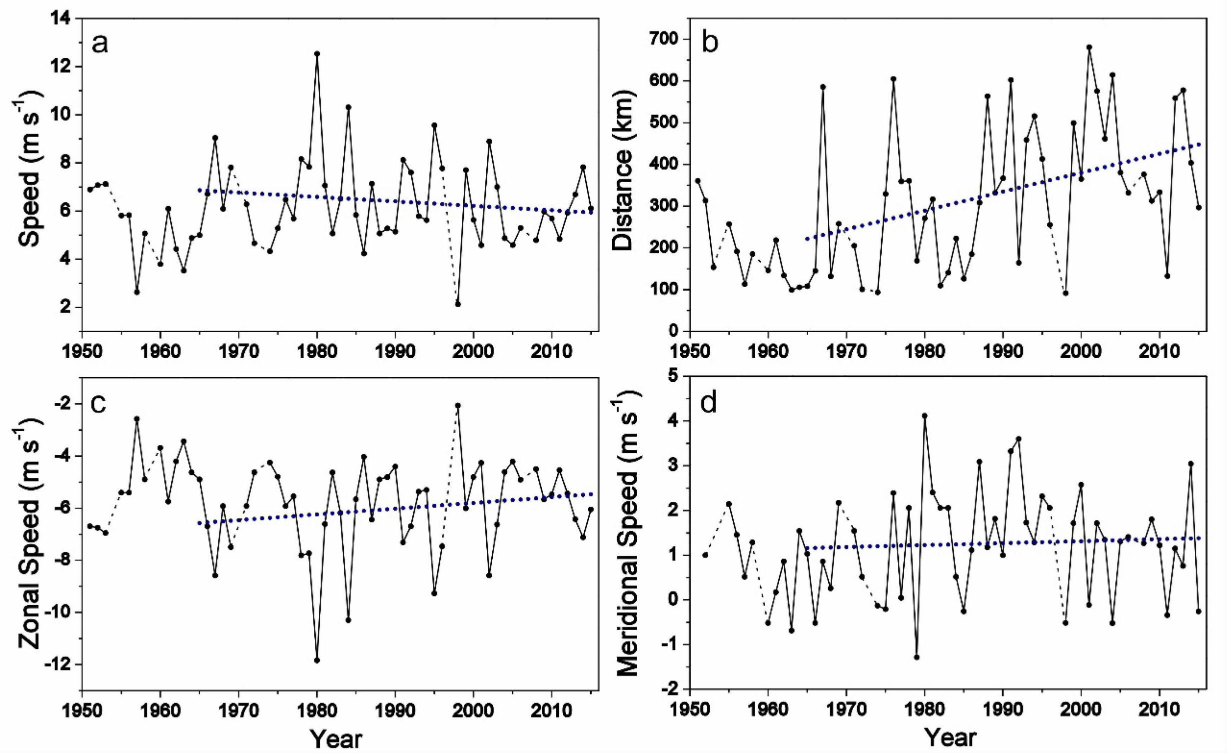

Figure 5. (a) Over-land movement velocity (black solid line), (b) over-land movement distance (black solid line), (c) over-land zonal movement velocity (black solid line), and (d) over-land meridional movement distance (black solid line) of the Westward landfalling TCs during the 1951–2015 period. Blue dotted lines denote trends during the 1965–2015 period, and black dashed lines span missing years.

4.2 *Causal analysis*

Early studies (Adem and Lezama[25]; Franklin et al.[26]; Chan[27]; Dong and Neumann[28]; Wang[29]; Zhao et al.[30]) showed that TC movement is controlled mainly by large-scale environmental steering flows, whereas studies of recent years showed that TC movement is controlled by both large-scale environmental steering flows and small-scale propagation (beta drift). This small-scale propagation is closely related to factors including tropical cyclonic circulations, environmental flows, planetary vorticity gradients, and adiabatic heating (Holland[31]; CARR III and Elsberry[32]; Wu and Wang[33]). Therefore, using NCEP/NCAR monthly mean wind velocities measured during the 1965—2015 period (spatial resolution of 2.5°×2.5°) and the method of Wu et al.[34] and Wu et al.[6], we calculated the large-scale steering flow (i.e., the average steering flow between 850 hPa and 300 hPa within 500 km of the TC core during the May-September period) and obtained the average difference in the large-scale wind field between 850 hPa and 300 hPa over the northwest Pacific Ocean during the 1965—2015 period (the average of 1990—2015 minus the average of 1965—1989). As shown in Fig.7, the changes in the large-scale steering flow during this period were mainly manifested as a cyclonic circulation with its core located over eastern China. The westerly anomaly over coastal southern China tended to block TCs originating from the northwest Pacific Ocean, leading to fewer Westward landfalling TCs (Fig.3a). In addition, some TCs may have been affected by the large-scale wind anomaly and turned northward, thereby increasing the frequency of Northward TCs to some degree (Fig.4a). Furthermore, the westerly anomaly over coastal southern China could also have caused the decrease in over-land movement velocities of the Westward landfalling TCs. The foregoing analysis indicates that this decrease was due mainly to the decrease in its zonal component, and thus, the westerly anomaly may be an important reason for the decrease in the zonal velocity of the Westward landfalling TCs (Fig. 5c). Similarly, the northeasterly anomaly north of 30°N may have caused the decrease in meridional velocities of the Northward landfalling TCs passing over this region (Fig.6d).

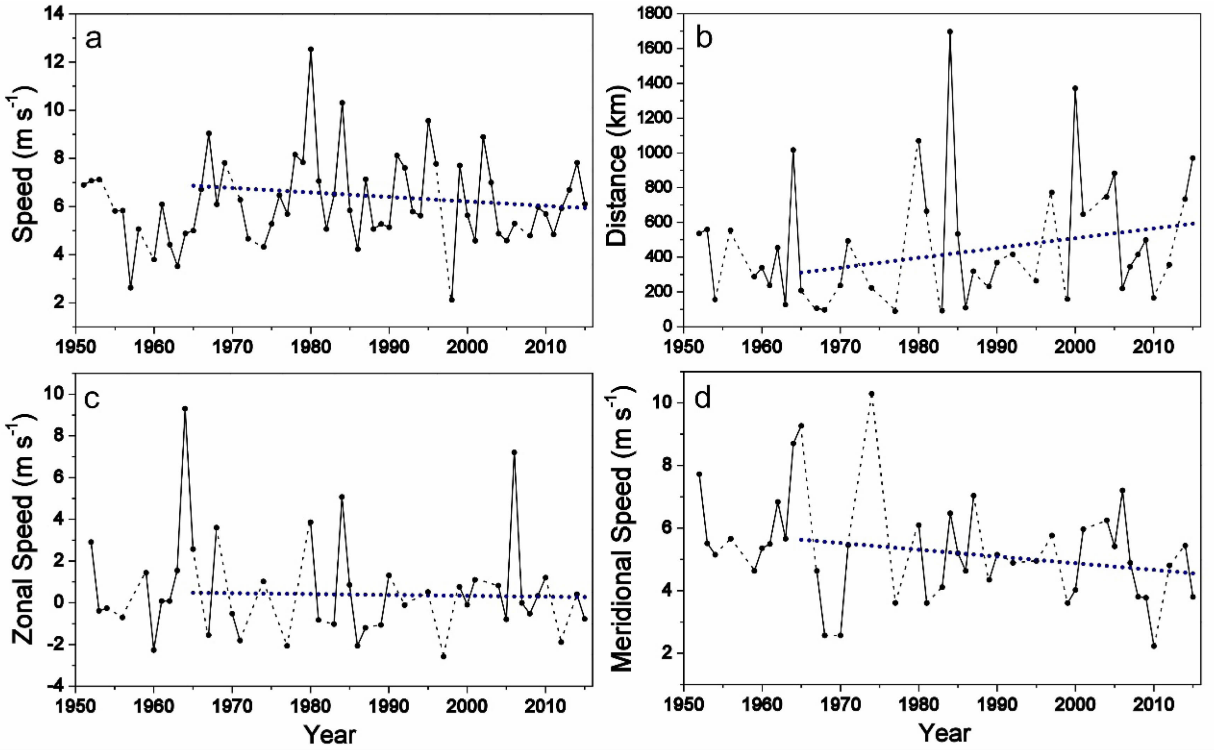

Figure 6. Same as Fig.5, but for the Northward Type.

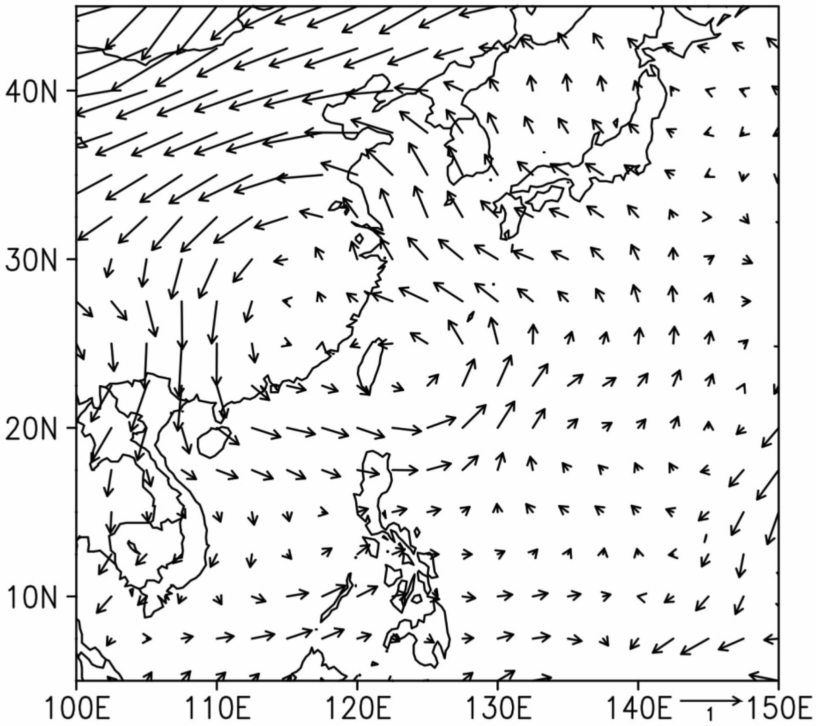

Figure 7. Difference in average large-scale wind velocities between 850 hPa and 300 hPa over the northwest Pacific Ocean during the 1965–2015 period (the average of 1985–2015 minus the average of 1965–1984), units of m/s.

Vertical wind shear is another important factor affecting TC life cycles (Xin et al.[35]; Yin et al.[36]; Li and Xu[37]). Previous studies indicated that weak vertical wind shear is one of the prerequisites for generating TCs, whereas strong vertical wind shear can weaken TCs or slow their development. Thus, weak vertical wind shear is important for TC formation and development and for maintaining its structure (Gray[38]; Frank and Ritchie[39]; Corbosiero and Molinari[40]). Based on the NCEP/NCAR monthly mean wind velocities spanning the 1965—2015 period (spatial resolution of 2.5° ×2.5°), Fig.8 was developed to show the changes in vertical shear of the horizontal winds (200–850 hPa) over the northwest Pacific Ocean during this period. Combined with Fig.1, these results show that the examples selected in this study were located mainly over the negative zone before making landfall (i.e., decrease in vertical shear of horizontal wind), which was beneficial to the maintenance of their TC structures over the ocean. In addition, the vertical shear of the horizontal wind over coastal eastern China also decreased, which was also beneficial for maintaining the TC structure over the ocean and thus enhanced the increase in the over-land duration for part of the Northward TCs. Similarly, the vertical shear of the horizontal wind over coastal eastern China increased, thereby reducing the over-land duration for part of the Northward TCs. However, the above analysis indicates that the over-land durations of both the Westward and Northward Types increased, and thus, other factors need to be considered when analyzing the TC over-land durations.

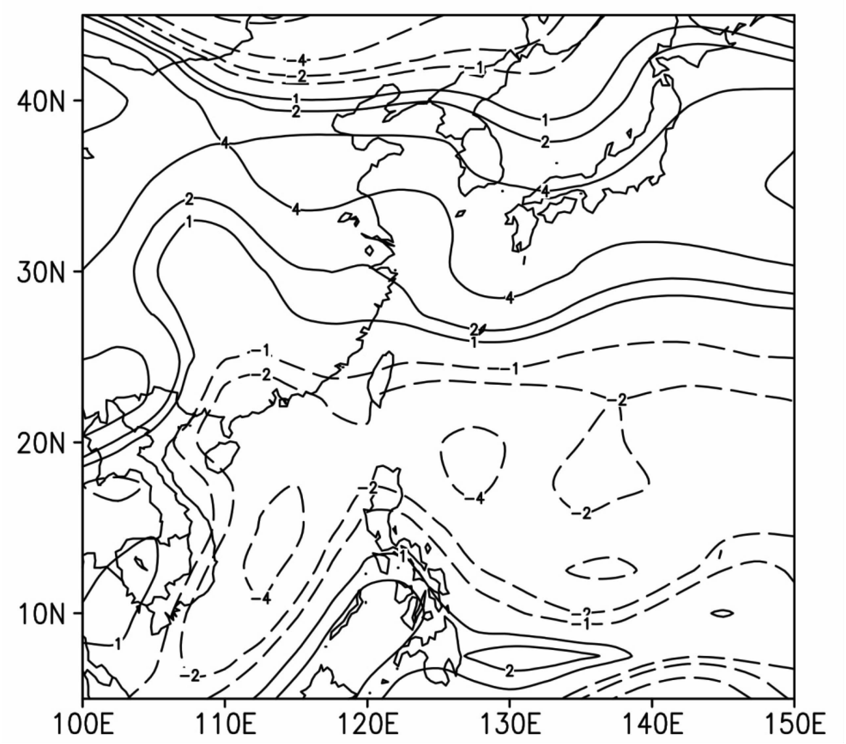

Figure 8. Changes in vertical shear of horizontal winds (200–850 hPa) over the northwest Pacific Ocean during the 1965–2015 period, units of 0.01 m/s·year.

Figure 9 shows the annual mean formation longitudes of the Westward and Northward landfalling TCs during the 1951—2015 period. The formation longitude of the Westward landfalling TCs decreased with time after 1965, indicating that these formations have tended to occur farther west and closer to Asia. Therefore, the time between formation and landfall of these TCs has shortened, hindering their absorption of water vapor and energy from the sea and leading to weaker intensity upon landfall. In contrast, the formation longitude of the Northward landfalling TCs has increased with time, resulting in longer times for them to absorb water vapor and energy and stronger landfall intensities. In addition, the northwest Pacific SSTs at low latitudes has increased significantly (Vecchi and Soden[41]), which has enhanced the maintenance and intensity of these two types of TCs while over the sea. However, the impacts of SSTs on the landfall intensities of these two TC types need to be investigated based on a variety of data in a follow-up study. While stronger TC landfall intensity tends to increase over-land TC duration, the landfall intensities of the Westward and Northward TCs show completely different trends. The over-land durations of both TC types increased, indicating that an analysis of TC over-land durations must take into account the combined effects of many factors.

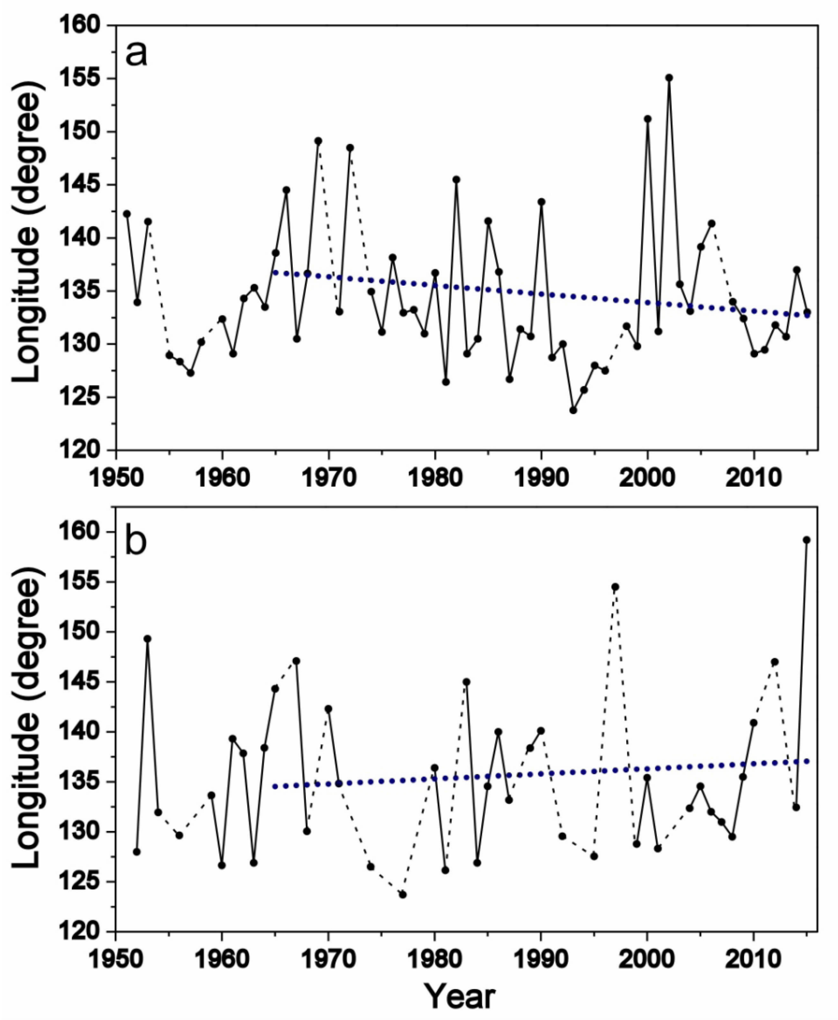

Figure 9. Mean formation longitude (black solid line) of (a) the Westward Type and (b) Northward Type of TCs during the 1951-2015 period. The blue dotted lines denote the trends between 1965 and 2015, and the black dashed lines span missing years.

5 CONCLUSIONS

To accurately determine the geographic extent and disaster risk of TC impacts and to minimize their economic losses, it is necessary to perform TC classifications and statistical analyses. Based on the TCs making landfall in China during the 1951—2015 period, we developed a simple, practical, and rapid classification method for classifying TCs making landfall in China. Based on the results, we also compared the climate characteristics of the typical tracks of three classes and discussed their possible causes. The following conclusions were obtained:

(1) The rapid classification method developed in this study yields a division of the tracks of TCs making landfall in China into three types: Westward Type, Northwestward Type, and Northward Type. The Westward and Northward Types account for over 80% of the total landfalling TCs.

(2) The climate characteristics of the Westward and Northward landfalling TCs are similar and different in certain respects. Both the frequency and landfall intensity of the Westward (Northward) TCs show decreasing (increasing) trends, whereas the over-land durations, movement velocities, and movement distances of both TC types show increasing, decreasing and increasing trends, respectively. The similarities and differences between the climate characteristics of these two landfalling TC types show that the rapid classification method is useful for distinguishing the two typical track types noted by Wu et al. and indirectly confirm the feasibility and practicality of the rapid classification method developed in this study[6].

(3) The significant increases in the over-land durations of the Westward and Northward landfalling TCs indicate that the effects of TCs passing over China are increasing. The post-landfall decrease in movement velocity and increase in movement distance are two of the reasons for the increase in over-land duration. In addition, the contributions of other factors to these two TC types are different. The decrease (increase) in landfall intensity of the Westward (Northward) TCs is beneficial (adverse) to the maintenance of post-landfall TC structure and intensity, and the corresponding

changes in the regional vertical wind shear are adverse (beneficial) to the increase in the over-land duration of the Westward (Northward) TCs.

(4) Changes in the large-scale steering flow are the main reason for the changes in the frequencies and over-land movement velocities of the Westward and Northward landfalling TCs. The differences between the changes of the formation locations of the Westward and Northward landfalling TCs may be the main reason for the significant difference between the landfall intensities of these two TC types.

The rapid method of classifying TC tracks developed in this study shows good results. It distinguishes between TC types with different climate characteristics, providing useful information for analyzing TCs that make landfall in China and for climate prediction. However, the discussion of TC over-land durations presented here may be too simplistic. In addition to the several factors mentioned in this study, TC over-land durations are also related to the TC structure, underlying surface condition, and other weather systems. The effects of each factor merit further investigation. Application of the rapid TC track classification method to climate zoning and disaster assessment is a focus of a follow-up study.

REFERENCES:

[1] CHEN Lian-shou, DING Yi-hui. An introduction to the West Pacific Typhoons [M]. Beijing, Science Press, 1979: 227-229 (in Chinese).

[2] ZHAO Hai-kun, WU Li-guang. Review on climate change of tropical cyclones in the Northwest Pacific [J]. J Meteor Sci, 2015, 35(1):108-118 (in Chinese).

[3] CHEN Hua, WANG Kai. The impacts of the interaction of typhoons with the midlatitude trough on its track after recurvature [J]. J Trop Meteor, 2015, 31(2): 145-152 (in Chinese).

[4] EMANUEL K. Increasing destructiveness of tropical cyclones over the past 30 years [J]. Nature, 2005, 436 (7051): 686-688.

[5] WEBSTER P J, HOLLAND G J, CURRY J A, et al. Changes in tropical cyclone number, duration, and intensity in a warming environment [J]. Science, 2005, 309 (5742): 1844-1846.

[6] WU L G, WANG B, GENG S Q. Growing typhoon influence on east Asia [J]. Geophys Res Lett, 2005, 32(4), L18703, doi:10.1029/2005GL022937.

[7] ZHAO H, JIANG X, WU L. Modulation of northwest Pacific tropical cyclone genesis by the intraseasonal variability [J]. J Meteor Soc Japan, 2015, 93, 1, doi: 10.2151/ jmsj.2015-006.

[8] ZHAO H, WU L, ZHOU W. Assessing the influence of the ENSO on tropical cyclone prevailing tracks in the western North Pacific [J]. Adv Atmos Sci, 2010, 27(6): 1361-1371.

[9] HUANG Yong, LI Chong-yin, WANG Ying. Further study of the characteristics of frequency variation of tropical cyclones activity over western North Pacific and the relationship with sea surface temperature [J]. J Trop Meteor , 2009, 25(3): 273-280 (in Chinese).

[10] LIANG Bi-qi. Tropical Meteorology [M]. Guangzhou: Sun Yat-sen University Press, 1990: 190-191 (in Chinese).

[11] CHEN Rui-shan. Typhoon [M]. Fujian: Fujian Science and Technology Press, 2002: 92-94 (in Chinese).

[12] MENG Ying, LU Juan, LIAO Qi-long. Analysis of the characteristics of the West-Pacific Typhoon affecting the sea area around the Island of Taiwan [J]. J Trop Meteor, 2005, 21(3): 315-322 (in Chinese).

[13] ELSNER J B. Tracking hurricanes [J]. Bull Amer Meteor Soc, 2003, 84(2): 353-356.

[14] CAMARGO S J, ROBERTSON A W, GAFFNEY S J, et al. Cluster analysis of typhoon tracks. Part I: General properties [J]. J Climate, 2007, 20(3): 3635-3653.

[15] NAKAMURA J, LALL U, KUSHNIR Y, et al. Classifying North Atlantic tropical cyclone tracks by mass moments [J]. J Climate, 2009, 22(4): 5481-5494.

[16] ZHENG Ying-qing, YU Jin-hua, WU Qi-shu, et al. K-means clustering for classification of the northwestern Pacific Tropical Cyclone tracks [J]. J Trop Meteor, 2013, 29(4): 607-615 (in Chinese).

[17] MA Chao, LIU Qing-qing, XU Hong-shi. Spatio-temporal characteristics analysis of landfall tropical cyclones over China based on tracks clustering analysis [J]. Marine Forecasts, 2016, 33(3): 65-70 (in Chinese).

[18] ZHANG W, LEUNG Y, WANG Y. Cluster analysis of post-landfall tracks of landfalling tropical cyclones over China [J]. Clim Dyn, 2013, 40(5-6): 1237-1255.

[19] LI Xue, REN Fu-min, YANG Xiu-qun, et al. A study of the regional differences of the tropical cyclone activities over the South China Sea and the Western North Pacific [J]. Clim Environ Res, 2010, 15 (4): 504-510 (in Chinese).

[20] ZHAO H, WU L. Inter-decadal shift of the prevailing tropical cyclone tracks over the western North Pacific and its mechanism study [J]. Meteor Atmos Phys, 2014, 125(1-2): 89-101.

[21] WU L, ZHAO H. Dynamically derived tropical cyclone intensity changes over the western North Pacific [J]. J Climate, 2012, 25(1): 89-98.

[22] KUNDZEWICZ Z W, ROBSONA (Eds.). Detecting trend and other changes in hydrological data [M]. World Meteor Org, Geneva, Switzerland, Rep. WCDMP-45, 2000, Rep. WMO-TD 1013, 157 pp.

[23] YUE S, WANG C. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series [J]. Water Resour Manage, 2004, 18 (3): 201-218.

[24] CHEN X, WU L, ZHANG J. Increasing duration of tropical cyclones over China [J]. Geophys Res Lett, 2011, 38 (2): 195-201 (in Chinese).

[25] ADEM J, LEZAMA P. On the motion of a cyclone embedded in a uniform flow1 [J]. Tellus, 1960, 12(3): 255-258.

[26] FRANKLIN J L, FEUER S E, KAPLAN J, et al. Tropical cyclone motion and surrounding flow relationships: searching for beta gyres in Omega dropwindsonde datasets [J]. Mon Wea Rev, 1996, 124(1): 64-84.

[27] CHAN J C L. An observational study of the physical processes responsible for tropical cyclone motion [J]. J Atmos Sci, 1984, 41(6): 1036-1048.

[28] DONG K, NEUMANN C J. The relationship between tropical cyclone motion and environmental geostrophic

flows [J]. Mon Wea Rev, 1986, 114(1): 115-122.

[29] WANG Y. On the bogusing of tropical cyclones in numerical models: The influence of vertical structure [J]. Meteor Atmos Phys, 1998, 65(3-4): 153-170.

[30] ZHAO H, WU L, ZHOU W. Observational relationship of climatologic beta drift with large-scale environmental flows [J]. Geophys Res Lett, 2009, 36 (18): 120-131 (in Chinese).

[31] HOLLAND G J. Tropical cyclone motion: Environmental interaction plus a beta effect [J]. J Atmos Sci, 1983, 40 (2): 328-342.

[32] CARR III L E, ELSBERRY R L. Observational evidence for predictions of tropical cyclone propagation relative to environmental steering [J]. J Atmos Sci, 1990, 47(4): 542-546.

[33] WU L, WANG B. Effects of convective heating on movement and vertical coupling of tropical cyclones: A numerical study [J]. J Atmos Sci, 2001, 58 (23): 3639-3649.

[34] WU L G, WANG B. Assessing impacts of global warming on tropical cyclone tracks [J]. J Climate, 2004, 17(8): 1686-1698.

[35] XIN Chen, WANG Yong-qing, ZHONG Wei. The effects of convective cells on hurricane's intensity in highly sheared wind environments [J]. J Trop Meteor, 2015, 31 (2): 202-212 (in Chinese).

[36] YIN Hao, WANG Yong-qing, ZHONG Wei. Characteristics and influence factors of the rapid intensification of tropical cyclones with different tracks in the Northwest Pacific [J]. J Meteor Sci, 2016, 36(2): 194-202.

[37] LI Kan, XU Hai-ming. A comparative analysis of the intensifying and weakening landfall tropical cyclones during extratropical transition over China [J]. J Trop Meteor, 2013, 29(3): 411-420 (in Chinese).

[38] GRAY W M. Global view of the origin of tropical disturbances and storms [J]. Mon Wea Rev, 1968, 96 (10): 669-700.

[39] FRANK W M, RITCHIE E A. Effects of vertical wind shear on the intensity and structure of numerically simulated hurricanes [J]. Mon Wea Rev, 2001, 129(9): 2249-2269.

[40] CORBOSIERO K L, MOLINARI J. The effects of vertical wind shear on the distribution of convection in tropical cyclones [J]. Mon Wea Rev, 2002, 130(8): 2110-2123.

[41] VECCHI G A, SODEN B J. Global warming and the weakening of the tropical circulation [J]. J Climate, 2007, 20(17): 4316-4340.

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