Vol.23 No.3 **JOURNAL OF TROPICAL METEOROLOGY** September 2017

Article ID: 1006-8775(2017) 03-0323-11

THE ABRUPT CHANGE OF TROPICAL CYCLONE NUMBER OVER THE WESTERN NORTH PACIFIC IN THE MID–1990s

LI De-lin (**李德琳**)[1, 2], XIAO Zi-niu (**肖子牛**)[1], XIN Fei (**信 飞**)[3], ZHOU Xiu-hua (**周秀华**)[4]

(1. State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029 China; 2. University of Chinese Academy of Sciences, Beijing 100049 China; 3. Shanghai Climate Center, Shanghai 200030 China; 4. Guangxi Climate Center, Nanning 530022 China)

Abstract: Based on the CMA tropical cyclone (TC) best track data as well as the reanalysis datasets from the NCEP/NCAR and NOAA, the variation characteristics of TC number from 1949 to 2013 over the western North Pacific (including the South China Sea) are examined. Notably, the time series of TC number exhibits a significant abrupt change from more to less around 1995. Comparative analysis indicates that the environmental factors necessary to TC formation also change significantly around the mid-1990s. After 1995, accompanying with anomalous warm sea surface temperature (SST) in western equatorial Pacific, a La Niña-like pattern in tropical Pacific appears obviously. However, compared with the period before 1995, the vertical upward movement decreases, vertical shear of tropospheric zonal wind increases, and sea level pressure (SLP) rises, all of which are unfavorable to TC formation and work together to make TC number reduce markedly after 1995. Furthermore, when the typical interannual more and less TCs years are selected in the two separate stages before and after 1995, the relative importance of oceanic and atmospheric environments in interannual TC generation is also investigated respectively. The results imply that the SST over the tropical Pacific exerts relatively important influence on TC formation before 1995 whereas the atmospheric circulation plays a more prominent role in the generation of TC after 1995.

Key words: tropical cyclone; abrupt change; sea surface temperature; atmospheric circulation
CLC number: P444 **Document code:** A
doi: 10.16555/j.1006-8775.2017.03.009

1 INTRODUCTION

Tropical cyclone (TC), which generates on tropical oceans, is the strong cyclonic vortex with a warm-cored structure. The strong wind, rainstorm, storm surge, and other disastrous weathers along with the occurrence of TC often bring serious economic losses and casualties to the affected areas. The western North Pacific including the South China Sea is the main original region with the most frequent TC activities. Therefore, the variation features of generation, activity, and intensity of TCs over the western North Pacific have been the key issues on which the domestic and foreign meteorologists always focus. Due to the restriction and influence of large scale air-sea climate background, the TC number over the western North Pacific are characterized by pronounced seasonal, interannual, and interdecadal variations[1-3].

Early studies of Pan[4] and Li[5] suggested that less TCs generated over the western North Pacific when sea surface temperature (SST) of eastern equatorial Pacific rose continuously. Chen et al.[6] indicated that the association between regional SST and TC number was not obvious. They also pointed out that, although the regional SST reached the thermal condition, the interannual differences of TC activities were mainly caused by the atmospheric circulation response to SST. The work of Chen et al.[7] showed that the different anomalous circulation patterns induced by the different heating sources of two types of El Niño events could affect the generation and position of TCs over the western North Pacific. Under the state of global warming, both the intensity and potential damage of TCs presented a strengthening tendency[8, 9]. However, Chan[10] argued that this strengthening tendency should be attributed to the interdecadal variation of TCs. In addition, many domestic researches revealed that the interannual and interdecadal variations of some important large-scale circulation systems, such as the South Asian high, western Pacific subtropical high, East Asian monsoon, intertropical convergence zone, could significantly impact the TC generating conditions, intensity changes, and moving tracks[11-18]. The atmospheric circulation in the Southern Hemisphere also played an

---

Received 2015-09-21; **Revised** 2017-06-21; **Accepted** 2017-08-15

Foundation item: Key Project of Natural Science Foundation of Yunnan (2016FA041); National Natural Science Foundation of China (41375105); External Cooperation Program of BIC, CAS (GJHZ1729)

Biography: XIAO Zi-niu, Research Fellow, primarily undertaking research on air-sea interaction, climate change, and weather and climate prediction.

Corresponding author: XIAO Zi-niu, e-mail: xiaozn@lasg.iap.ac.cn

important role in the formation and development of TCs over the western North Pacific. Specifically, the strengthened cross-equatorial flow response to the cold air outbreak in Australia could incorporate into the intertropical convergence zone, resulting in the intensified disturbance and advection that avail the formation of TCs [19-21].

Numerous studies confirmed that there existed a global interdecadal abrupt climate change in the mid-to-late 1970s, and from then on, the air-sea background of the North Pacific region changed remarkably[22]. With the abrupt warming appearing in the central and eastern tropical Pacific and abnormal cooling showing up in the central North Pacific, the Pacific Decadal Oscillation (PDO) altered its phase, the sea level pressure (SLP) over North Pacific decreased significantly, and the Aleutian Low deepened and moved southward[23]. Meanwhile, the intensity of atmospheric circulation systems such as the East Asian summer monsoon and the western Pacific subtropical high also exhibited pronounced changes [24]. A series of interdecadal variations of environmental factors pushed the TC number over the western North Pacific into a relatively small period. Recent research demonstrated that the unprecedented powerful tropical Pacific easterly trade winds decreased the global warming trend[25]. Moreover, the East Asian summer monsoon recovered and began to strengthen around the early 1990s, along with which, the western Pacific subtropical high displayed a characteristic of interdecadal transition[26]. Also, the PDO phase altered suddenly around 1997 [27]. In a word, the previous studies above imply that the 1990s might be a new period of interdecadal climate background over the North Pacific.

Previous studies on TC climatology always focus on the seasonal, interannual, and interdecadal characteristics of TCs. However, less attention has been paid to the abrupt change of TC number. In particular, there must be some differences in TC generation and activity under different interdecadal climate backgrounds. Therefore, by examining the abrupt change in the time series of TC number, we first compare the characteristics of interdecadal variations in the environmental factors closely related to TC formation in the separate periods before and after the abrupt change of TC number; then, as we know, the interannual variation would be modulated by the interdecadal variation of climate background, so we further detect the main environmental factors that contribute to the interannual variations of TC number before and after the abrupt change respectively. In consideration of the different generation characteristics of TCs in different climate backgrounds, the analyses in this paper might have practical significance for improving the TC prediction level and reducing the accompanying disasters.

2 DATA AND METHODS

The best-track data of TCs over the western North Pacific including the South China Sea for the period of 1949–2013 are obtained online at China Meteorological Administration Tropical Cyclone Data Center website (http://tcdata.typhoon.gov.cn/). The monthly gridded data with 2.5°×2.5° horizontal resolution of wind, SLP, and omega are taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset from June 1949 to October 2013. For the same period, the monthly gridded SST analysis is based on the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST V3b with 2.5°× 2.5° horizontal resolution. All of the gridded data above are averaged into the typhoon season (from June to October) mean. The linear trend of gridded data in typhoon season is removed before analysis.

To examine the interdecadal stages for the generation of TCs over the western North Pacific and identify the abrupt change year reaching high confidence level, we go directly to the observations and apply the method of Mann-Kendall [28-29]. The composite mean difference method is applied to compare the characteristics of environmental factors during the two separate periods before and after the abrupt change of TC number. In order to remove the interference of interdecadal variation, we use the running correlation method [30] (the running window length is 11 years) when analyzing the interannual characteristics of TCs in different interdecadal climate background.

3 VARIATION CHARACTERISTICS OF WESTERN NORTH PACIFIC TC NUMBER

As schematically illustrated in Fig.1, the time series of yearly numbered TCs from 1949 to 2013 is characterized by pronounced interannual and interdecadal variations. We can see the interdecadal variation tendency of TC number from the thick solid line (11-year smoothing) in Fig.1. The TC number is above the mean value before 1975, and then it reduces gradually. During the 1980s, the number of TC maintains a steady state with slight growth. It is noteworthy that the TC number has reduced markedly since the early 1990s and entered a relatively less-than-normal period after 1990.

The climate abrupt change refers to the discontinuous jump in a relatively steady state [28, 31]. To confirm whether there exists any catastrophe point in the time series of TC number, we employ the Mann-Kendall method, and the result is plotted in Fig.2. The positive sequence UF line decreases from positive to negative gradually, and its first intersection with the inverted sequence UB line is steadily in 1995. And the intersection point with 0.05 significant level in Fig.2 denotes the abrupt change year from more to less in the time series of TC number. Generally accepted, 85% of TCs generate in the typhoon season, so we concentrate our work on the relationship between the variation of TC number and the environmental factors in typhoon season. The abrupt change point of TC number averaged in typhoon season also appears around 1995 by the Mann-Kendall test (figure not shown).

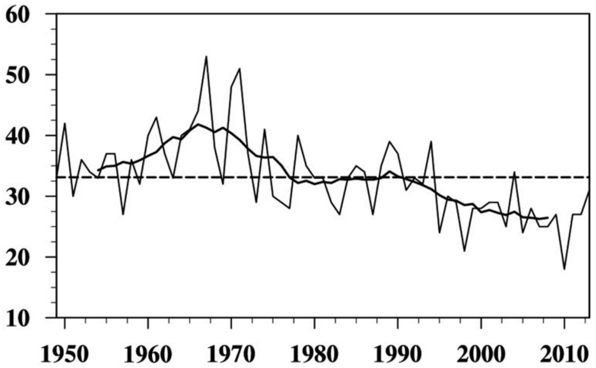

Figure 1. Time series of yearly numbered TCs for the period of 1949–2013. The thin and thick solid lines represent the TC number and its 11-year smoothing, respectively. The dashed line indicates the mean value of TC number for the whole period.

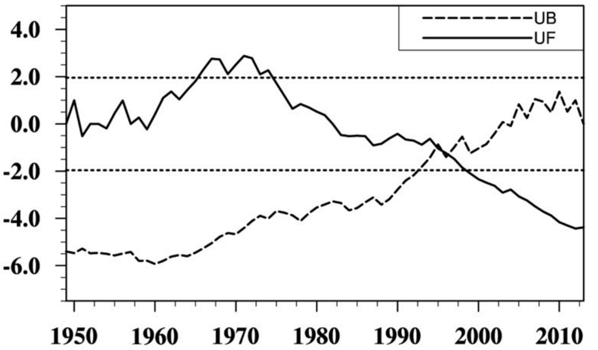

Figure 2. The Mann-Kendall abrupt change test of the time series of TC number from 1949 to 2013. The solid and dashed lines indicate the positive sequence UF and inverted sequence UB of TC number, respectively. Dotted lines represent the α=0.05 significance level.

4 CHARACTERISTICS OF AIR–SEA BACKGROUND BEFORE AND AFTER THE ABRUPT CHANGE OF TC NUMBER

Previous studies have demonstrated that there were significant differences in the air-sea environmental fields in different periods when more and less TCs generated [15, 18, 32-36], and these large scale environmental factors mainly included the SST, SLP, omega, wind field at high and low levels, vertical shear of tropospheric wind and so on. Were these environmental fields closely tied to TC formation undergoing evident change after 1995? In this section, we employ the composite mean difference approach to answer this question and reveal the different characteristics of air-sea background before and after the abrupt change of TC number.

4.1 *Sea surface temperature, low–level wind and vertical movement*

The SST is an important environmental factor which is crucial to the generation and development of TC. On one hand, SST is the indispensable thermal condition for the formation of warm-cored structure; on the other hand, SST is the major forcing for atmospheric circulation in the tropics. Fig.3 displays the composite mean difference between typhoon season SST and 850hPa wind after 1995 and those before 1995. After the abrupt change of TC number in 1995, SSTs in the northwest and southwest Pacific increase markedly with the 0.05 significance level, with a maximum anomaly exceeding 0.5℃. Together with the decrease in SSTs over the central and eastern tropical Pacific and the Southern Indian Ocean, the cold phase of PDO-like pattern occupies the Pacific. Xiao et al. [27] have proved that PDO undergoes an abrupt phase change from warm to cold in 1997 by the moving t-test technique. In general, with positive SST anomalies in the western tropical Pacific and negative SST anomalies in the central and eastern tropical Pacific, a La Niña-like pattern as exhibited in Fig.3 should correspond to more TCs. However, the TC number reduces after 1995, which means the relationship between this La Niña-like pattern and TC number has altered in the mid-1990s. Actually, we find the ranges of typhoon season SST reaching the basic thermal condition (SST$\geqslant$26.5°C) are almost the same in the separate periods before and after 1995 (figure not shown). In other words, the threshold value of the thermal condition for TC generation does not change during the whole period, so the anomalous warming of western North Pacific SST cannot contribute to the abrupt change of TC number in 1995. The following analysis will demonstrate the impacts of the different SST anomalous patterns on the interdecadal variation in TC generating locations.

By taking 15°N and 150°E as dividing lines of TC generating region, we get four source regions, i.e., Northwest (NW), Northeast (NE), Southwest (SW), and Southeast (SE). Then, we count the percentages of TC number in each region before and after 1995. As listed in Table 1, compared to the period before 1995, the average generating location of TCs is a bit northwestward after 1995. Moreover, more TCs favor the NW and NE source regions after 1995. Combined with the SST anomalies field in Fig.3, after the abrupt change of TC number in 1995, when the SST over the central and eastern tropical Pacific is anomalously cold, the average generating location moves northwestward, which is in agreement with the statistical results in the work of Yang et al.[35]. Additionally, Wang et al.[36] have noted that the location of TC generation shifts northward and westward when the PDO and ENSO are

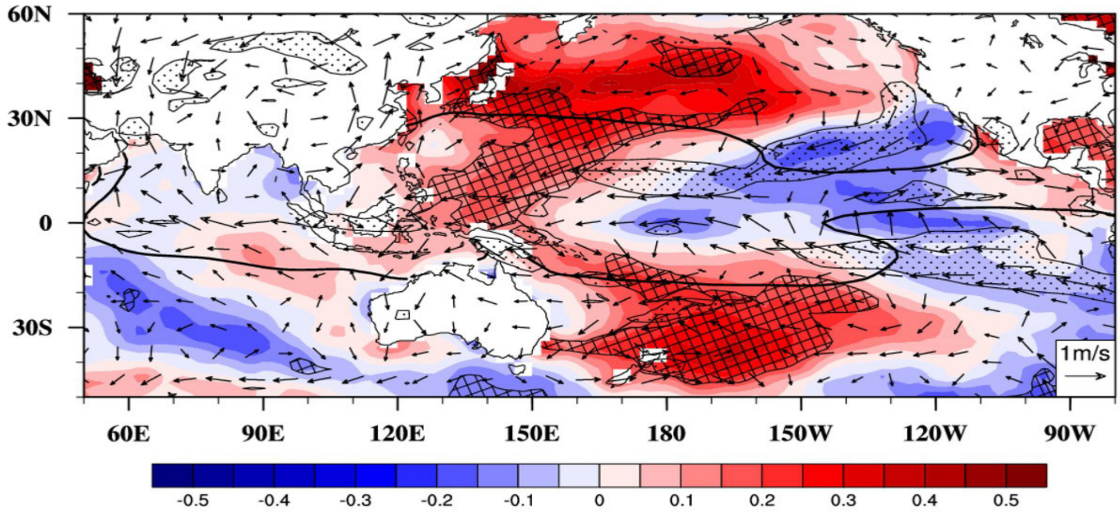

Figure 3. The composite mean difference between the typhoon season SST (shaded contours, units: ℃) and 850 hPa wind (vectors, units: m/s) in the period after 1995 and those before 1995. The gridded (dotted) areas indicate the anomalies of SST (850 hPa wind) reaching the α=0.05 significance level. The thick black lines represent the 26.5℃ contour of the averaged SST after 1995.

both in cold phase. The composite mean difference in the 850hPa wind field of typhoon season is plotted in Fig.3. There is a weak anomalous anticyclonic circulation at the center of (145°E, 20°N) which is not conducive to the formation and development of TCs after 1995.

Table 1. The average generating locations and percentages of typhoon season TC number in the four generating locations during the separate periods before and after 1995.

	Before 1995	After 1995
Average	139.1 °E, 15.5 °N	137.3 °E, 16.1 °N
NW	40.6%	48.3% ↑
NE	11.6%	12.3% ↑
SW	35.8%	29.7% ↓
SE	12.0%	9.7% ↓

Note: The symbol ↑ (↓) indicates increasing (decreasing).

The majority of TCs over the western North Pacific generate within the areas of (110°E–180°, 5–25°N), thus we further detect the vertical movement features in the TC generating region by calculating the composite difference of 5–25°N meridional-mean omega in typhoon season after and before 1995 (Fig.4). Combining Fig.3 with Fig.4, we can see that the positive SST anomalies over the Western Pacific Warm Pool and its vicinity do not stimulate strong vertical upward movement in 110–160° E. On the contrary, the pronounced weakened vertical upward movement appearing in 120–150° E (Fig.4) is associated with the anomalous anticyclone on 850hPa (Fig.3). Hence, the weak vertical upward movement goes against the development of low-pressure disturbance, which could be one of the main reasons that cause less TC generations after 1995.

4.2 *Vertical shear of tropospheric zonal wind*

The vertical shear of tropospheric zonal wind, also known as convection ventilation, is an important impact factor for the formation and development of TCs. Here the tropospheric vertical zonal wind shear is represented by the difference between weighted average zonal wind of tropospheric upper part (600–200 hPa) and that of lower part (1,000–600 hPa) [11]. When the vertical wind shear is very small, the potential heat could concentrate in a limited space, which not only prompts the formation of warm-cored structure but also ensures that the pressure of the initial disturbance continues to decrease [37]. Thus, we calculate the composite mean difference of the typhoon season vertical zonal wind shear after and before 1995. As presented in Fig.5, the amplitude of vertical zonal wind shear increases on the whole, especially in the south of TC generating region. Meanwhile, in the central and north of TC source region, the decreasing and increasing areas of vertical zonal wind shear show a staggered distribution.

The mean values of the anomalies of vertical zonal wind shear averaged in the whole and four separate source regions are displayed in Table 2. Taking Table 1 as reference, we can notice the effects of vertical zonal wind shear variations on TC numbers in the four generating locations. After the abrupt change of TC number in 1995, the amplitude of vertical zonal wind shear in the north of the generating location reduces slightly (Table 2), corresponding to enlarged percentages of TC number in the NW and NE source regions (Table 1). In the meantime, the increased amplitude of vertical zonal wind shear in the south of generating region coincides with the reduced percentages of TC number in the SW and SE locations. Consequently, the slight increase of the vertical zonal wind averaged in the whole TC source region (110°E–180°, 0–30°N)

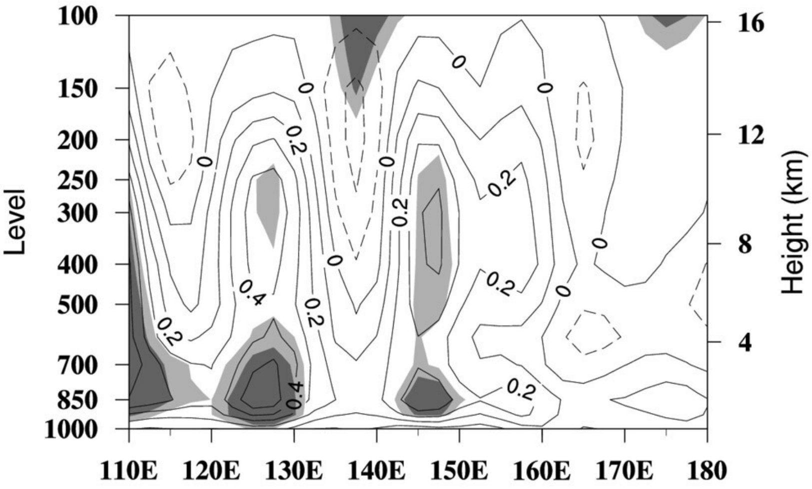

Figure 4. The zonal (110°E−180°) vertical section of composite mean difference between typhoon season 5−25°N meridional-mean omega (units: 10^{-2} Pa/s) in the period after 1995 and that before 1995. The omega data is magnified one hundred times. The deep (shallow) areas indicate the α=0.05 (0.10) significance level.

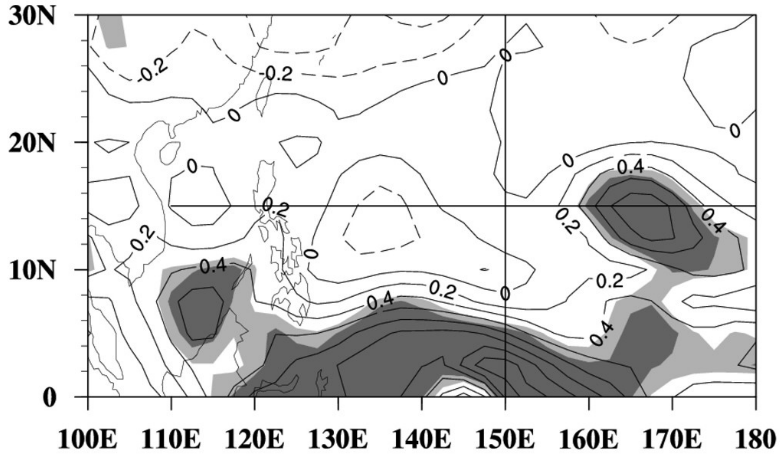

Figure 5. The composite mean difference between the typhoon season vertical zonal wind shear (units: m/s) after 1995 and that before 1995. Cross lines (15°N and 150°E) indicate the regional division of TC generating location. The deep (shallow) areas indicate the α=0.05 (0.10) significance level.

after 1995 could make fewer TCs generate. So the interdecadal increase in tropospheric vertical zonal wind shear is one of the main factors that lead the TC number to decrease after 1995.

Table 2. The difference of vertical zonal wind shear averaged in the whole region and separate four generating locations in the period after and before 1995.

Generating location	Vertical zonal wind shear (m/s)
The whole region	0.20
NW	−0.10
NE	−0.03
SW	0.40
SE	0.47

4.3 *Sea level pressure*

It is generally accepted that the high pressure zone over the North Pacific can influence the generation and development of TCs. Fig.6 is the composite mean difference between typhoon season SLP in the period after 1995 and that before 1995. The SLP in the western North Pacific generally rises, and a small area in the east of the Hawaiian Islands passes the 0.05 significance level with a positive anomalous center reaching 0.5hPa, whereas the SLP close to the East Asian continent in the western Pacific decreases. Higher SLP contributes to suppressing the formation of initial low pressure disturbance, which is one of the main reasons that cause less TCs generate after 1995. It is without doubt that the relationship between SLP and SST is very close, and previous studies have pointed out that the interdecadal variation of SLP over the North Pacific is correlated with the phase transition of with uncertain mechanism[38].

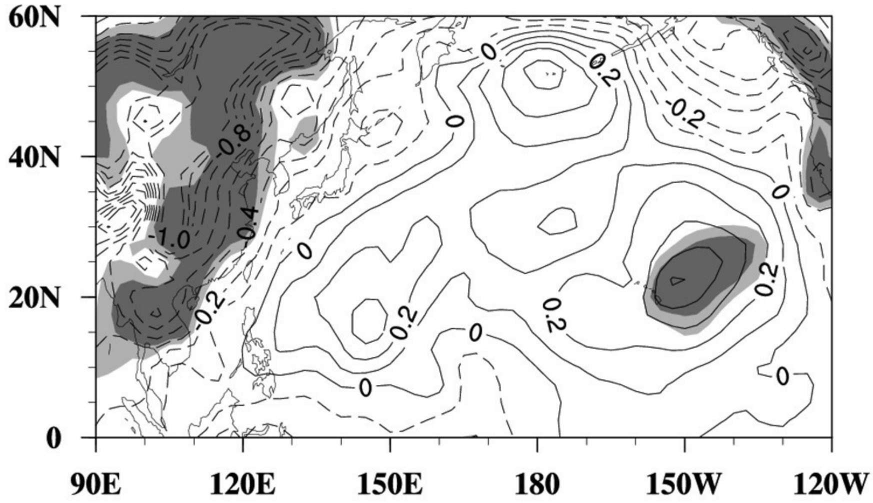

Figure 6. Same as Fig.5, but for the SLP (units: hPa).

5 INTERANNUAL VARIATION CHARACTERISTICS OF MAIN IMPACT FACTORS FOR TC GENERATION BEFORE AND AFTER TC NUMBER ABRUPT CHANGE

The analyses above have revealed that the different impact factors for the abrupt change of TC number have inconsistent changing directions, in other words, different factors make different contributions to the TC number abrupt change in the mid-1990s. In this section, we focus on the weighted effects of different environmental factors on the interannual variation of TC number during the individual periods before and after 1995. Then, by comparing the associations between environmental factors and TC numbers before and after 1995, we are hoping to measure the contributions of different factors to the abrupt change of TC number in 1995.

Using 1995 as the abrupt change point of TC number, the whole period is divided into two stages: 1949–1994 and 1995–2013. We get the typical years with interannual more and less TCs shown in Table 3 by standardizing the time series of TC numbers and taking ±1.0 and ±0.6 as the division standards in these two stages respectively (Fig.7). And the composite mean difference method is applied to characterize the features of environmental factors of these typical years during the separate periods before and after 1995.

Table 3. The typical years with more and less TCs in the separate stages before and after 1995.

	Before 1995	After 1995
Typical more years	1950, 1960, 1961, 1966, 1967, 1970, 1971, 1978, 1994	1999, 2000, 2001, 2004, 2006, 2009, 2013
Typical less years	1951, 1957, 1976, 1977, 1983, 1986, 1987, 1991	1998, 2003, 2005, 2008, 2010

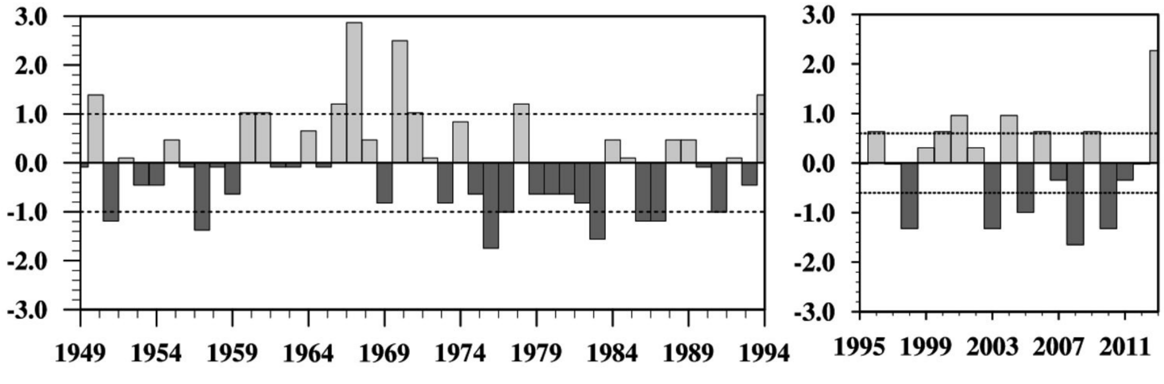

Figure 7. Standardized time series of TC numbers in the separate stages: (a) 1949-1994 and (b) 1995-2013. Dotted lines represent the standards to select the interannual typical years.

5.1 *Differences of SST, low-level wind, and vertical movement in typical years*

Figure 8 displays the composite mean difference between the typhoon season SST and 850hPa wind in typical more TCs years and those in typical less TCs years during the individual stages before and after 1995. As illustrated in Fig.8a, the La Niña-like SST anomalies pattern which is beneficial to more TCs occurs on the tropical Pacific with the 0.05 significance level, and the anomalous easterlies on 850hPa occupies the central and western equatorial Pacific. Thus the interannual variation in the generation of TC is largely modulated by the phases of ENSO before 1995. While, in the case of 1995–2013, the difference of the central and eastern equatorial Pacific SST in typical more and less TCs years is small. Strikingly, the pronounced positive SST anomalies pattern which has some resemblance to the El Niño Modoki dominates in the central equatorial Pacific, and this anomalous SST pattern corresponds to more TC formations after 1995 (Fig.8b). Therefore, during the period after 1995, the effect of tropical SST on TC generation weakens and the modulation mechanism changes. In addition, as shown in Fig. 8b, the 850hPa anomalous equatorial westerlies from the anomalous cyclonical circulation centered at (180°, 30°N) on the North Pacific, together with the cross-equatorial flow generated from the strengthened anomalous southerlies near Australia, form into the anomalous westerlies occupying most of the tropical Pacific. Notably, the anomalous meridional wind from the high latitudes of Southern Hemisphere might be a key mechanism for the interannual variation in the formation and development of TCs after 1995. With the help of a numerical model, Xu et al.[39] demonstrated that the cold surges from Southern Hemisphere could benefit the formation of warm-cored disturbance by reducing the stability in mid- and low- levels and reinforcing the low-level convergence.

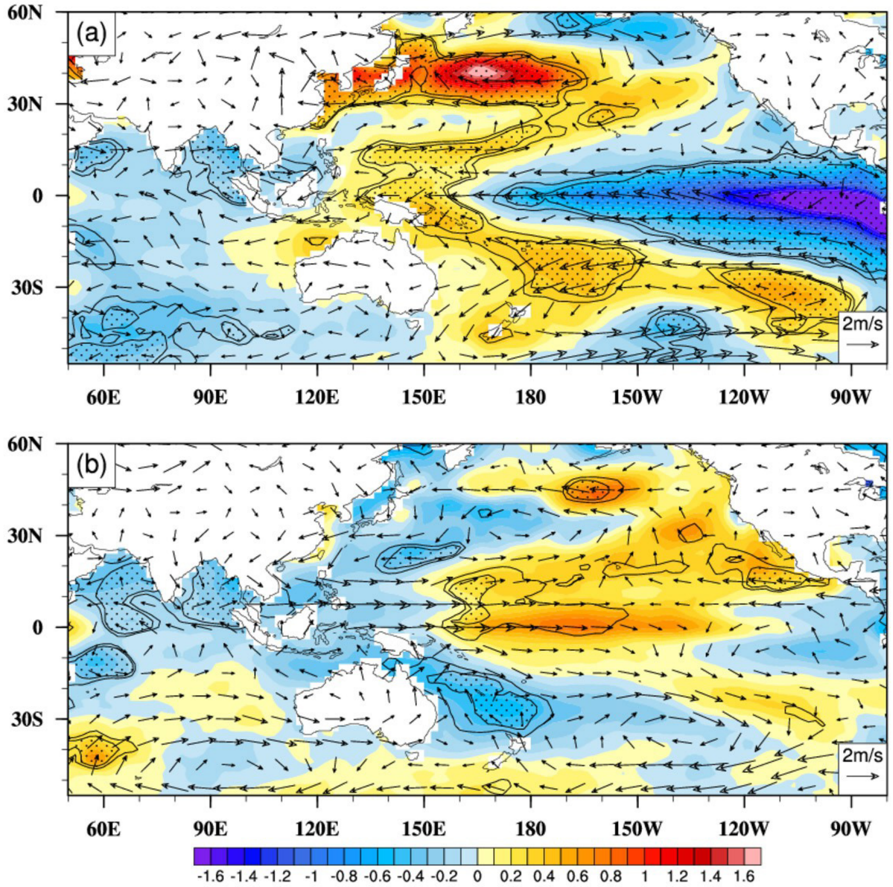

Figure 8. The composite mean difference between the typhoon season SST (shaded contours, units: ℃) and 850hPa wind (vectors, units: m/s) in typical more TCs years and those in typical less TCs years during the separate stages (a) before 1995 and (b) after 1995. The lines enclosed and dotted areas indicate the SST anomalies reaching α=0.10 and α=0.05 significance level, respectively.

The zonal (110°E–180°) vertical section of composite mean difference of typhoon season 5–25°N meridional-mean omega in typical more and less TCs years in the individual stages before and after 1995 is given in Fig.9. Before 1995, the maximum center of anomalous upward movement located at 150°E (Fig.9a) matches the position of warm center of SST anomalies (Fig.8a) in typical more TCs years. After 1995, the upward movement maximum center increases significantly and expands westward (Fig.9b) in the

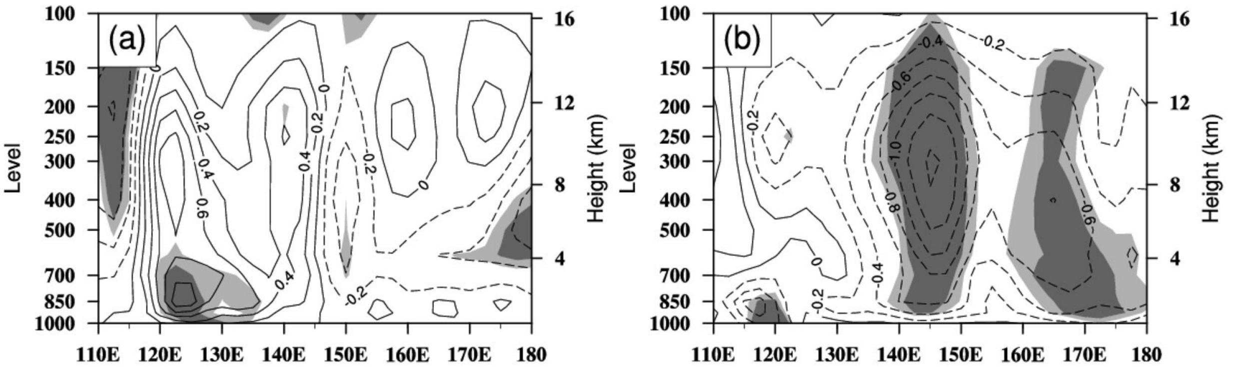

Figure 9. The zonal (110°E–180°) vertical section of composite mean difference of typhoon season 5–25°N meridional-mean omega (units: 10^{-2} Pa/s) in typical more and less TCs years in the separate stages (a) before 1995 and (b) after 1995. The omega data is magnified one hundred times. The deep (shallow) shaded areas represent α=0.05 (0.10) significant level.

typical years when more TCs generate. And the whole TC source region is generally occupied by upward movement anomalies in the typical more TCs years after 1995, especially its marked maximum center at 140°E responding to the anomalous cyclonical circulation and westerlies convergence on 850hPa in Fig. 8b. After 1995, the SST over TC generating area is abnormal below the climatological mean, and the circulation environment in typical years with more TCs is characterized by enhanced upward movement and anomalous cyclonical circulation at the low level. To sum up, the upward movement favored by the interannual generation of TCs is sensitive to the SST anomalies pattern before 1995, whereas the anomalous upward movement in typical more TCs years might be mostly stimulated by the low-level circulation after 1995. Thus we conclude that the atmospheric circulation plays a more prominent role in the interannual generation of TCs during the period after 1995.

5.2 *Relative importance of SST and atmospheric circulation on the interannual variation of TC number*

By the assistance of 11-year running correlation method, we further examine the relative importance of SST and atmospheric circulation for interannual TC generations before and after 1995. We display the zonal (110°E–180°) distributions of 11-year running correlations between typhoon season TC number and 0–30 °N meridional-mean SST, 850hPa zonal wind, 850hPa omega, and tropospheric vertical zonal wind shear in Fig.10.

The running correlation coefficients between TC number and SST is presented in Fig.10a, in which the maximum coefficient reaching +0.6 appears in 150-165°E from 1975 to 1990 evidently, implying that the strongest association between SST and TC number exists within the period of 1975–1990. Probably due to the eastward displacement of sea surface heat source accompanied with El Niño Modoki, the positive correlations originally located at 150°E–180° move eastward by about 30 longitudes abruptly around 1990. During the period after 1990, TC number negatively correlates with tropical SST to the west of 160°E. In Fig.10b, the relationship between TC number and 850hPa tropical zonal wind is weak before the 1990s, whereas the range of positive correlations expands suddenly in 1995, with most areas reaching 95% confidence level after 2000. In coincidence with the features of 850hPa zonal wind in Fig.10b, the high correlation areas of 850hPa omega in Fig.10c and tropospheric vertical zonal wind shear in Fig.10d also shift eastward and expand obviously around 1995, denoting that the upward movement and vertical wind shear could be restricted by the low-level wind to a large extent. The key points of the analyses above are as follows: the SST's association with interannual TC generation is much more significant before the 1990s, while the contribution of atmospheric circulation to interannual changes in TC number is greater after 1990s, accompanying with the weakened positive relationship between TC number and tropical SST from 1990 to 2013.

In conclusion, the main impact factor in TC generation before the mid-1990s is the positive anomalous SST in the warm pole of tropical Pacific (or the tropical Pacific SST anomalies pattern). Specifically, the warmer SST would not only provide the high heat and humidity for TC formation but also stimulate the upward movement that avails the development of convection and the decrease of low-level pressure. After the abrupt change of TC number in 1995, the anomalous westerlies, converged by the cold flow from Southern Hemisphere and the warm flow from Northern Hemisphere, together with the atmospheric circulation environment adapting to this anomalous westerlies, contribute to the enhancement of atmospheric instability, the intensification of convection disturbance, and the anomalous cyclonical circulation on low levels. All these atmospheric circulation factors have much more prominent effects on TC generation relatively.

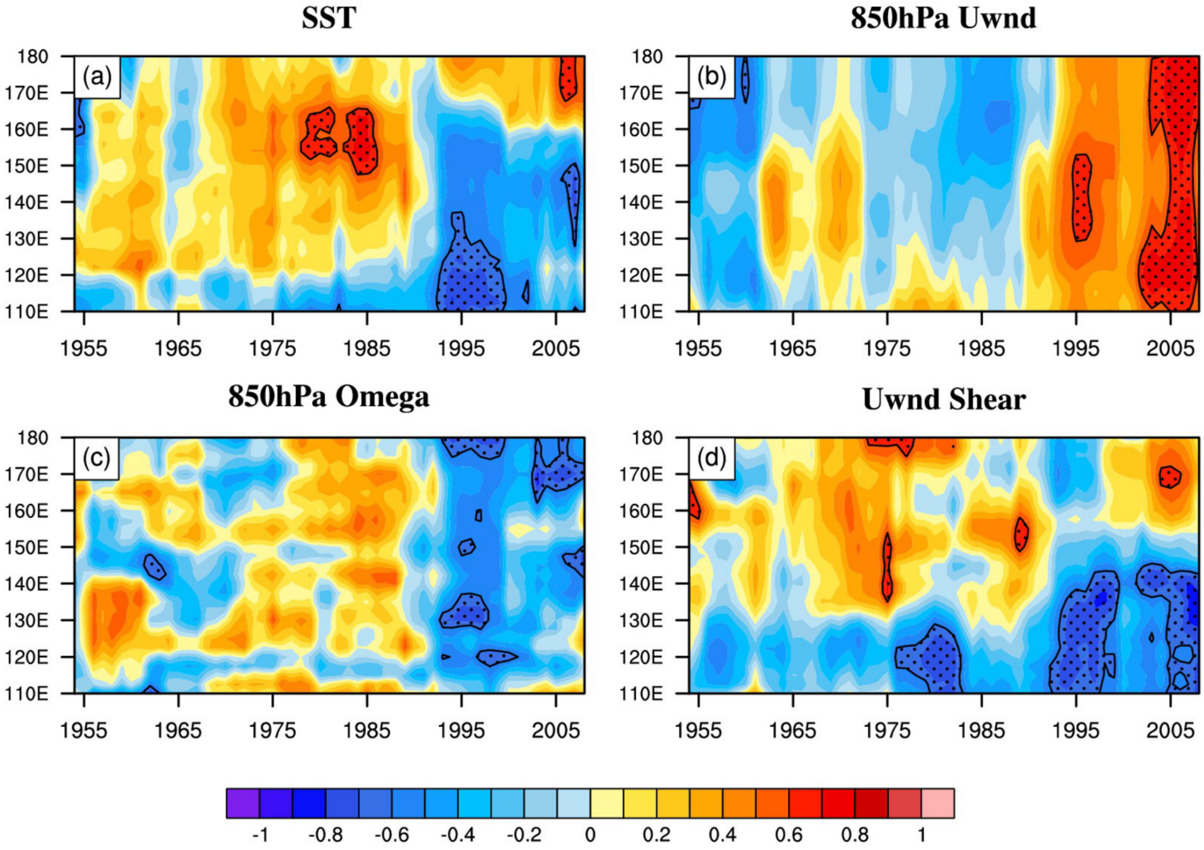

Figure 10. The interannual zonal (110°E–180°) distributions of 11-year running correlation coefficients between typhoon season TC number and 0–30°N meridional-mean (a) SST, (b) 850hPa zonal wind, (c) 850hPa omega, and (d) tropospheric vertical zonal wind shear. The solid and dashed lines respectively represent positive and negative correlation. Dotted areas indicate α=0.05 significant level.

6 CONCLUSION AND DISCUSSION

In this paper, we first find the significant abrupt change year in TC number. Then we focus on the interdecadal variation characteristics of environmental impact factors related to TC generation before and after the abrupt change of TC number. We last examine the different contributions of these environmental factors to the interannual variation of TC number during the individual stages before and after the abrupt change in further detail. The main conclusions of this study are as follows.

(1) The time series of yearly numbered TCs over the western North Pacific including the South China Sea is characterized by pronounced interdecadal variation. The TC number shows a significant abrupt change from more to less around 1995 by the Mann-Kendall test.

(2) After the abrupt change of TC number in 1995, the vertical upward movement decreases, vertical shear of tropospheric zonal wind increases, and sea level pressure rises, all of which are unfavorable to TC generation and work together to make TC number reduce significantly after 1995. Although the warmer SST in western equatorial Pacific and a La Niña-like pattern appear obviously, the TC number still shows an obvious reduction after 1995. These results demonstrate that the influence of tropical Pacific SST anomalies pattern on TC generation is not primary after 1995. Besides, the northwestward shift in TC generating location after 1995 is partly influenced by this La Niña-like pattern.

(3) The comparative studies of interannual variation of TC number during the individual stages before and after 1995 reveal that, the main impact factor in TC generation before 1995 is the SST anomalies pattern in the tropical Pacific, while the atmospheric circulation has much more crucial influence on TC formation after 1995. Thus we conclude that the primary impact factor for the interannual variation of TC generation alters from the SST environment before 1995 into the atmospheric circulation after 1995.

It should be noted that, the environmental factors also experience interdecadal changes in the mid-1990s, which hints that the combined action of these environmental factors might make the TC number change abruptly around 1995. Recent research indicated that an abrupt change of atmospheric circulation also occurs in the 1990s [25, 26, 40-45]. Whether the abrupt change of TC number correlates with the climatological variation is an interesting issue that needs further investigation.

As we know, ENSO is the strongest signal in the interannual global air-sea coupled system, and hence has always been the primary climate forecasting factor. Although numerous studies have reported that the El Niño events correspond to more TC generations, the analyses in this paper point out that the particular role of El Niño Modoki in TC formation in recent years is worthy of attention.

REFERENCES:

[1] CHEN Min, ZHENG Yong-guang. An analysis on tropical cyclone climatic feature in the western North Pacific for recent 50 years (1949-1996) [J]. J Trop Meteor, 1999, 15 (1): 10-16 (in Chinese).

[2] YUMOTO M, MATSUURA T. Interdecadal variability of tropical cyclone activity in the Western North Pacific [J]. J Meteor Soc Japan, 2001, 79(1): 23-35.

[3] CHAN J C L. Interannual and interdecadal variations of tropical cyclone activity over the Western North Pacific [J]. Meteor Atmos Phys, 2005, 89(1-4): 143-152.

[4] PAN Yi-hang. The effect of the thermal state of equatorial eastern Pacific on the frequency of typhoons over western Pacific [J]. J Meteor Res, 1982, 40(1): 24-34 (in Chinese).

[5] LI Chong-yin. A study on the influence of El Niño upon typhoon action over western Pacific [J]. J Meteor Res, 1987, 45(2): 229-236 (in Chinese).

[6] CHEN Guang-hua, HUANG Rong-hui. The effect of Warm Pool thermal states on tropical cyclone in west northwest Pacific [J]. J Trop Meteor, 2006, 22 (6): 527-532 (in Chinese).

[7] CHEN G H, TAM C Y. Different impacts of two kinds of Pacific Ocean warming on tropical cyclone frequency over the western North Pacific [J]. Geophys Res Lett, 2010, 37 (1): L01803.

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

[9] EMANUEL K. Increasing destructiveness of tropical cyclones over the past 30 years [J]. Nature, 2005, 436(7 051): 686-688.

[10] CHAN J C L. Comment on “Changes in tropical cyclone number, duration, and intensity in a warming environment” [J]. Sci, 2006, 311(5768): 1713.

[11] CHEN Lian-shou, DING Yi-hui. Introduction to the Western Pacific typhoon [M]. Beijing: Science Press, 1979 (in Chinese).

[12] DING Yi-hui, WRIGHT E R. The large scale circulation conditions influencing the typhoon formation over the western Pacific [J]. Acta Oceanol Sinica, 1983, 5 (5): 561-574 (in Chinese).

[13] YE Ying, DONG Bo. Interannual change of the severe tropical cyclone activities over the northwest Pacific [J]. Meteor Mon, 1998, 24(7): 29-34 (in Chinese).

[14] ZHANG Qing-yun, PENG Jing-bei. The interannual and interdecadal variations of East Asian summer circulation and its impact on the landing typhoon frequency over China during summer [J]. Chin J Atmos Sci, 2003, 27(1): 97-106 (in Chinese).

[15] LU Qiu-zhen, HU Bang-hui, WANG Xue-zhong, et al. Large scale circulation associated with interdecadal variations of typhoon activity over the western North Pacific [J]. J Trop Meteor, 2008, 23 (6): 629-635 (in Chinese).

[16] SHEN Song-lin, JIANG Jing. Climatic background analysis if abnormal year of typhoons in northwest Pacific [J]. Meteor Mon, 2010, 36(5): 64-70 (in Chinese).

[17] LI Ji, LI Fei, LIN Rong, et al. Interdecadal variations of midsummer northward-going typhoons over East Asia and the relationships with Pacific decadal oscillation [J]. J Trop Meteor, 2011, 27(5): 731-737 (in Chinese).

[18] LAI Fen-fen, JIANG Jing. The inter-annual variation characteristics of the tropical cyclone intensity in the western North Pacific and atmospheric circulation background analysis [J]. J Trop Meteor, 2012, 28 (5): 609-620 (in Chinese).

[19] LI Xian-zhi. The comprehensive theory of the formation of Typhoon [J]. J Meteor Res, 1956, 27 (2): 87-100 (in Chinese).

[20] SUN Shu-qing, LIU Ge, ZHANG Qing-yun. The influence of the circulation anomalies in the Southern Hemisphere on the tropical cyclone frequency in summer over the western Pacific and its mechanism [J]. Chin J Atmos Sci, 2007, 31(6): 1189-1200 (in Chinese).

[21] YANG Xiu-qun, ZHU Yi-min, XIE Qian, et al. Advances in studies of Pacific decadal oscillation [J]. Chin J Atmos Sci, 2004, 28(6): 979-992 (in Chinese).

[22] LIU Xiang-wen, SUN Zhao-bo, LI Wei-jing, et al. The circulation configuration of strong/weak cross-equatorial flow to the north of Australia [J]. Chin J Atmos Sci, 2009, 33(6): 1348-1362 (in Chinese).

[23] TRENBERT K E, HURRELL J W. Decadal atmosphere-ocean variations in the Pacific [J]. Climate Dyn, 1994, 9(6): 303-319.

[24] LV Jun-mei, REN Ju-zhang, JU Jian-hua. The interdecadal variability of East Asia monsoon and its effect on the rainfall over China [J]. J Trop Meteor, 2004, 20(1): 73-80 (in Chinese).

[25] ENGLAND M H, MCGREGOR S, SPENCE P, et al. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus [J]. Nature Climate Change, 2014, 4(3): 222-227.

[26] LIU Hai-wen, ZHOU Tian-jun, ZHU Yu-xiang, et al. The strengthening East Asia summer monsoon since the early 1990s [J]. Chin Sci Bull, 2012, 57 (9): 765-769 (in Chinese).

[27] XIAO Dong, LI Jian-ping. Main decadal abrupt changes and decadal modes in global sea surface temperature field [J]. Chin J Atmos Sci, 2007, 31 (5): 839-854 (in Chinese).

[28] FU Cong-bin, WANG Qiang. The definition and detection of the abrupt climatic change [J]. Chin J Atmos Sci, 1992, 16(4): 482-493 (in Chinese).

[29] WEI Feng-ying. Modern statistical diagnosis and forecasting technique [M]. Beijing: China Meteor Press, 2007: 63-66 (in Chinese).

[30] LIN Xue-chun. The instability of the correlation coefficient in statistics weather forecast [J]. Chin J Atmos Sci, 1978, 2(1): 55-63 (in Chinese).

[31] LI Jian-ping, SHI Jiu-en. The detection and analysis of the abrupt change of the global climate during the last 100 years [J]. Chin J Atmos Sci, 1993, 17 (Suppl):

132-140 (in Chinese).

[32] HE Min, WU Xiao-xi. Relationship between sea level pressure over Northern and Southern Hemispheres and activities of northwest Pacific typhoon [J]. Quart J Appl Meteor, 1998, 9(Suppl): 75-83 (in Chinese).

[33] ZHOU Xue-ming, WEI Ying-zhi, WU Chen-feng. Relationship between summer typhoon frequency anomalies in western Pacific and ENSO events, and the anomalous atmospheric circulation characteristics [J]. J Trop Meteor, 2006, 22(1): 34-40 (in Chinese).

[34] BAI Li-na, HE Min, WANG Yuan, et al. The influence of the vertical wind shear variation on interannual changes in the tropical cyclone activity in the western North Pacific [J]. J Meteor Res, 2010, 68 (6): 877-884 (in Chinese).

[35] YANG Ya-xin, JIANG Jing. The impacts of sea surface temperature anomaly in the equatorial central and eastern Pacific on tropical cyclone in north-west Pacific [J]. J Meteor Sci, 2008, 28(6): 637-643 (in Chinese).

[36] WANG Yong-mei, LI Wei-jing, REN Fu-min, et al. Study on climatic characteristics of China-influencing typhoons and the interrelations between them and their environmental factors [J]. J Meteor Res, 2007, 23 (6): 538-544 (in Chinese).

[37] ZHU Qian-gen, LIN Jin-rui, SHOU Shao-wen, et al. The principles and methods of synoptic meteorology [M]. Beijing: China Meteor Press, 2007: 541-542 (in Chinese).

[38] ZHU Y L, WANG H J, ZHOU W, et al. Recent changes in the summer precipitation pattern in East China and the background circulation [J]. Climate Dyn, 2011, 36 (7): 1463-1473.

[39] XU Ya-mei, WU Rong-sheng. The effects of cold surges from Southern Hemisphere on tropical cyclone formation [J]. J Meteor Res, 2003, 61(5): 540-547 (in Chinese).

[40] KWON M H, JHUN J G, HA K J. Decadal change in east Asian summer monsoon circulation in the mid-1990s [J]. Geophys Res Lett, 2007, 34(21): L21706.

[41] DING Y, SUN Y, WANG Z, et al. Inter-decadal variation of the summer precipitation in China and its association with decreasing Asian summer monsoon Part II: Possible causes [J]. Int J Climatol, 2009, 29(13): 1926-1944.

[42] TU J Y, CHOU C, CHU P S. The abrupt shift of typhoon activity in the vicinity of Taiwan and Its association with Western North Pacific-East Asian climate change [J]. J Climate, 2009, 22(13): 3617-3628.

[43] JI Fei, ZHI Rong, GONG Zhi-qiang, et al. Analysis of temporal and spatial characteristics of correlations between the global circulation systems [J]. J Meteor Res, 2012, 69(6): 1038-1045 (in Chinese).

[44] TANG Jia, WU Bing-yi. Inter-decadal shift of East Asian summer monsoon in the early 1990s [J]. J Appl Meteor Sci, 2012, 23(4): 402-413 (in Chinese).

[45] HUANG Rong-hui, LIU Yong, FENG Tao. Interdecadal change of summer precipitation over Eastern China around the late-1990s and associated circulation anomalies, internal dynamical causes [J]. Chin Sci Bull, 2013, 58(8): 617-628 (in Chinese).

Citation: LI De-lin, XIAO Zi-niu, XIN Fei et al. The abrupt change of tropical cyclone number over the western North Pacific in the mid-1990s [J]. J Trop Meteor, 2017, 23(3): 323-333.