Ⓢ Variability of Tropical Cyclone Landfalls in China✉

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ABSTRACT: The reported decreasing trend of the annual tropical cyclone (TC) landfalls in southern China and increasing trend in southeastern China in recent decades are confirmed to be an abrupt shift occurring at the end of the twentieth century, based on a statistical analysis. The opposite trends in the two adjacent regions are often considered to be a result of tropical cyclone landfalls in southern China being deflected northward. However, it is demonstrated in this study that they are phenomenally independent. In fact, the abrupt decrease of TC landfalls in southern China occurs as a result of an abrupt decrease of the westward events in the postpeak season (October–December), which in turn is a consequence of a significant decrease of the TC genesis frequency in the southeastern part of the western North Pacific (WNP) Ocean basin. On the other hand, the abrupt increase of TC landfalls in southeastern China occurs because of an abrupt increase of the northwest events in the peak season (July–September), as the consequence of a statistically westward shift of TC genesis. The relevant variations of TC genesis are shown to be mainly caused by decreased relative vorticity and increased vertical wind shear, which, however, are intrinsically related to the accelerated zonal atmospheric circulation driven by a La Niña-like sea surface warming pattern over the WNP that developed after the end of twentieth century.

KEYWORDS: Extreme events; Tropical cyclones; Seasonal variability; Sea surface temperature; Climate change

1. Introduction

The overall trend of the tropical cyclone (TC) landfall frequency has been a primary concern of the policymakers since they may need to develop a long-term coastal disaster prevention strategy. The problem has attracted increasing attention in the past quarter century (Wu et al. 2005; Wang and Lee 2008; Park et al. 2011, 2014; Mei and Xie 2016; Li et al. 2017; Yang et al. 2018; Zhou and Lu 2019; Liu and Wang 2020; Liu et al. 2020) because climate change seems to have a substantial impact on it. In particular, a significant number of studies have recently been carried out to discuss the variability of TC landfall frequency along the coast of China (Li et al. 2017; Yang et al. 2018; Liu and Wang 2020; Liu et al. 2020), where residents have been suffering from high landfall frequency of TCs generated in the western North Pacific (WNP) Ocean basin.

Wu et al. (2005) found for the first time that southern China has experienced a decrease while southeastern China an increase of TC landfalls during the TC active season (June–October) over the period 1965–2003. This finding is definitely not trivial because more than 90% of the TC landfalls are concentrated in these two regions in China and any clear trend of variation must thus be taken into consideration when distributing national resources for

coastal disaster prevention. Subsequent studies have further confirmed the fact identified by Wu et al. (2005), and it was further shown that the variation is more likely to be an abrupt change rather than a gradual trend (Tu et al. 2009; Hsu et al. 2017). This is also an important conclusion because an abrupt change may be more reasonably considered as the direct consequence of a climate regime shift. If the mechanism of the relevant climate regime shift can be identified, the future trend of the landfall variation may then be predictable to a large extent.

It is known that most of the TCs that occur in the WNP ocean basin can be classified into a few different types according to the geometry of their tracks (Camargo et al. 2007; Liu and Chan 2008; Chu et al. 2010; Colbert et al. 2015). Those making landfall in southern China are essentially moving straight westward whereas those making landfall in southeastern China are generally moving northwestward when approaching the coast. Variation of the TC landfall frequency in these two regions can thus be considered to be a result of the TC number variation of the relevant type. In fact, the increasing trend of TC landfall in southeastern China has been attributed to the westward shift of TCs with northwestern moving tracks driven by the strengthened westward steering flow, while TC genesis has been found to play a minor role (Wu et al. 2005).

It is natural to consider that the opposite trends of TC landfall frequency variation in southern and southeastern China are due to a common reason (Knutson et al. 2019). Park et al. (2011) and Li et al. (2017) pointed out that there exists a large-scale atmospheric circulation in the cyclonic direction, associated with the westward expansion of the WNP subtropical high, that favors TC landfall in southeastern China through enhancing westerly flows at its northern side and suppresses TC landfall in southern China through weakening westerly flows at its southern side. However, Yang et al. (2018) and Liu et al. (2020)

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recently found that this particular circulation is centered at the east of Taiwan Island in the WNP between 20° and 40°N, and thus strengthens easterly flow at the midlatitudes, but is less influential on the steering flow in the region south of 20°N. Therefore, the abrupt decrease of TC landfall frequency in southern China cannot be explained by the presence of this circulation.

In principle, both spatial and temporal variation of the TC genesis in the WNP ocean basin should also affect the TC landfall frequency along the coast of the East Asian countries including China. Note that there have been a large number of investigations on the variation of TC genesis in the WNP ocean basins in recent years. A significant decrease in TC genesis frequency over the WNP at the end of the twentieth century has been reported in many recent studies (Liu and Chan 2013; Hu et al. 2018). In addition, the abrupt decrease is identified to mainly occur in the postpeak season (October–December) rather than in the peak season (July–September) (Hsu et al. 2014; Shan and Yu 2020a). The physical mechanism for this seasonal inhomogeneity of the abrupt decrease of TC genesis was clarified by Chang et al. (2021), who claimed that significant anomalies of the equatorial easterly wind as well as the anticyclone occurred over the entire WNP and eventually induced an abrupt decrease of TC genesis in the postpeak season. It may be interesting to explore the relationship between the abrupt decrease of TC genesis frequency in the WNP and the variations of the TC landfall frequency along the coast of China.

It is worth mentioning that previous research efforts have been mainly concentrated on the relation between the variations of TC landfall frequency and the environmental factors that may affect TC activities. The underlying mechanism of these variations has received less attention. In the present study, we investigate the variability of TC landfall frequency over southern and southeastern China based on the long-term and reliable data series for the TC landfall events during 1949–2019 but focus on the possible mechanisms behind the variations of TC landfall frequency.

2. Data and methods

Data on TC landfalls in southern and southeastern China during 1949–2019 is available from the tropical cyclone database published by China Meteorological Administration (CMA). As shown in Fig. S1 in the online supplemental material, southern China includes southern mainland China and Hainan Island while southeastern China includes eastern mainland China and Taiwan Island. Since a network of local weather stations, which covers almost the whole region in China affected by TCs, has been operating since early 1950s, the CMA database is likely to be more accurate and complete as compared with other available ones, in terms of the TCs that make landfall in China (Ying et al. 2014).

Since TC landfall frequency in both southern and southeastern China does not show an evident trend of variation before the 1980s, as clarified in the following analysis, we use the TC track data in the WNP from 1979 to 2018, available from the records in IBTrACS (International Best Tracks Archive for

Climate Stewardship) dataset v04 (Knapp et al. 2010), to investigate the mechanism behind the trend of variation of TC landfalls. The multisource corroborated track information in IBTrACS dataset has been widely known for its high reliability.

In this study, TC tracks are classified into three types: (i) the westward track passing through the Philippines and heading for southern China (type C1), (ii) the northwestward track toward southeastern China (type C2), and (iii) the recurring track toward the Korean Peninsula, Japan, and the Pacific Ocean (type C3). The classification method is based on prescribed regions under threat, which is advantageous for relating a TC landfall location to its track. More specifically, we set outgoing boundaries for different types of TCs in the WNP, as shown in Fig. S1 in the online supplemental material. A TC track is classified into a particular type if it first passes through a relevant boundary. Note that TCs that have not reached any of the boundaries and disappeared over the WNP east of 122°E and north of 20°N are classified into type C3. We prefer a relatively small number of track types in this study to ensure a sufficient number of TCs for each type so that statistical analysis is meaningful.

The method of Yokoi and Takayabu (2013) and Hsu et al. (2014) is applied in this study to quantify the relative importance of the TC genesis anomalies and TC track anomalies to the variation of TC occurrence frequency at a particular location. The relevant analysis is performed with $5^\circ \times 5^\circ$ resolution over the entire WNP ocean basin. The relative importance of the TC genesis anomalies is the variation of TC occurrence frequency due to TC genesis anomalies relative to its climatological average while keeping the TC tracks unchanged. On the other hand, the relative importance of the TC track anomalies is the variation of TC occurrence frequency due to TC track anomalies. Since the TC genesis and TC track are not necessarily independent, the nonlinear effect should also be considered.

The moving t test is used in this study to evaluate the statistical significance of an abrupt change (Liu and Chan 2013; Park et al. 2014; Zhao et al. 2018). The Bayesian changepoint analysis (Chu and Zhao 2004, 2011) is also employed to detect a possible abrupt change.

3. Phenomena

a. Overall trend

Variations of the annual TC landfalls in southern and southeastern China during 1949–2019 are plotted in Figs. 1a and 1b, respectively. It is clearly shown that, in recent decades, the annual number of TC landfalls has decreased in southern China but increased in southeastern China. Based on the result of moving t test, as presented in Figs. 1c and 1d, it is found that both the decrease of the annual TC landfalls in southern China and the increase in southeastern China are very likely to be abrupt shifts rather than gradual changes (with a confidence level of 95%). When referring to the posterior probability mass functions for possible occurrence of an abrupt change in the time series of the annual TC landfalls in southern China and in southeastern China, obtained with the Bayesian analysis as

FIG. 1. For (left) southern China and (right) southeastern China, (a),(b) variation of the annual TC landfall numbers (the horizontal dashed lines represent the averaged TC landfall number over different stages); (c),(d) t values obtained from the time series of the annual TC landfall numbers (the dotted lines represent the t -value threshold for a confidence level of 95%); and (e),(f) the posterior probability mass function (label PMF) of changepoints obtained from the time series of the annual TC landfall numbers.

shown in Figs. 1e and 1f, it becomes evident that the most possible changepoints of the landfall decrease in southern China and the landfall increase in southeastern China occurred in 1996 and 2000/01, respectively. From the statistical results, it is reasonable to believe that a climate regime shift, which has a significant impact on the TC landfalls in China, occurred at the end of the twentieth century. In addition, it is found that there is no significant correlation between the annual TC landfalls in southern China and in southeastern China (the correlation coefficient is 0.1), implying that the variations of TC landfall frequency in the two adjacent regions are very likely to be controlled by anomalies of different factors.

Since a TC landfall location is determined by the genesis location and the track geometry of the TC, we investigate the variation in TC track density in the WNP in order to thoroughly understand the variation of the annual TC landfalls along the coast of China. The TC track density in this study is defined by the frequency of TC occurrence—that is, the mean annual number of TCs generated within or passing through a grid element of $2.5^\circ \times 2.5^\circ$ surrounding the position of interest. Note that a TC is counted only once in a particular grid element. The variation in TC track density is to be studied by comparing its values averaged over two stages: the first stage (17 years, from 1979 to 1995) and the second stage (17 years,

from 2002 to 2018). Since the TC landfall numbers in southern and southeastern China are relatively stable from 1949 to the end of the twentieth century, track data before 1979, when satellites had not yet been widely available for TC observations, are not used. A transitional period from 1996 to 2001 is also excluded because the effect of the historically massive 1997/98 El Niño event, which has been reported to have an unusual impact on the TC activities over the WNP ocean basin in this period (Iizuka and Matsuura 2008; Liu and Chan 2018; Wu et al. 2018; Balmaseda et al. 2013; Yao et al. 2020). To confirm the robustness of the results on the differences of TC track density over the WNP before and after the abrupt change at the end of twentieth century, we evaluated the deviation caused by a slightly different choice of the dividing year for the two stages. It is thus confirmed that the spatial patterns of the difference of TC track density are nearly invariant despite an alternative selection of the year for dividing the first and second stages.

The spatial distribution of the difference of the TC occurrence frequency in the WNP between the first and the second stage is presented in Fig. 2a. A noticeable decrease in the TC occurrence frequency over the region south of 20°N is evident, indicating that fewer TCs have opportunities to threaten southern China in recent decades. At the same time, an obvious increase

FIG. 2. Difference of TC track density over the western North Pacific Ocean basin between the first stage (1979–95) and the second stage (2002–18) in (a) all seasons, (b) the prepeak season, (c) the peak season, and (d) the postpeak season. The crosses indicate where the difference is significant at a confidence level of 95%.

in the TC occurrence frequency occurred along the coast of the Northeast Asian region, indicating that more TCs have opportunities to threaten southeastern China and the Pacific side of Japan also. Besides, an evident decrease of the TC occurrence frequency also appeared in the open sea area east of 150°E and north of 20°N.

b. Variation in different seasons

In the WNP, TCs generated in the peak season (July–September), the postpeak season (October–December), and the prepeak season (April–June) account for about 55%, 27%, and 16% of the total number, respectively. Figures 2b, 2c, and 2d demonstrate the spatial distribution of the difference of the TC occurrence frequency in the two stages before and after the climate regime shift, in the prepeak, the peak, and the postpeak seasons, respectively. In the peak season, an obvious increase in the TC occurrence frequency along the coast of the Northeast Asian region a simultaneous appreciable decrease in the open sea area east of 150°E are observed. In the postpeak season, however, a significant decrease of the TC occurrence frequency appears in the tropical region south of 20°N. No evident change is identified during the prepeak season. It is thus certain that the variation of the TC occurrence frequency in the WNP, and thus the variation of

TC landfalls in Asian countries in recent decades, is mainly related to the anomalies of TC activities in the peak season and the postpeak season. In other words, the abrupt increase in the annual TC landfalls in southeastern China in recent decades is very likely to be a consequence of the variability of the TC occurrence frequency in the peak season, while the abrupt decrease in the annual TC landfalls in southern China is basically determined by the variability of the TC occurrence frequency in the postpeak season.

c. Variation of prevailing types

TC tracks in the WNP can be classified into different types by predefineding regions under threat (Liu and Chan 2008; Wang et al. 2013; Colbert et al. 2015; Shan and Yu 2020b). Three prevailing types are considered in this study. Note that similar track classifications were also adopted by Liu and Chan (2008) and Wang et al. (2013). As summarized in Table S1 in the online supplemental material, among all 1066 TC events occurred in the WNP during 1979–2018, 352 TCs belong to the C1 type, 151 TCs belong to the C2 type, 520 TCs belong to the C3 type, and a small number cannot be classified into any type. Note that the C1 and C2 types account for about 50% of all TC events over the WNP with a

FIG. 3. Difference of TC track density between the first stage (1979–95) and the second stage (2002–18) for the (left) C1 type and (right) C2 type in the (a),(b) peak season and (c),(d) postpeak season. The solid lines represent the prevailing TC tracks during the second stage for different TC types, and the dotted lines represent those during the first stage. The total number of TC events during the second stage is shown, and its difference with the first stage is also shown (in parentheses).

landfall rate in China of about 70%. On the other hand, the C3 type account for about 50% of all TC events that do not make landfall in China. It is also clear that the C2 type of TCs mainly occur in the peak season, with the largest number in July.

The difference of total number and occurrence frequency for C1 type and C2 type of the TC events in the WNP between the first and the second stage defined in the present study are presented in Fig. 3. It is clearly shown that the decrease of TC landfalls in southern China is related to the number variation in the C1 type of TCs during the postpeak season, while the increase in southeastern China is related to the number variation in the C2 type of TCs during the peak season. It is also confirmed that the variations both in the TC number of C1 type during the postpeak season and in the TC number of C2 type during the peak season are certainly abrupt changes based on their statistical significance obtained with the moving t test and their posterior probability obtained with the Bayesian changepoint analysis, as presented in Figs. S2 and S3, respectively, in the online supplemental material. Actually, the fact that the total number of TC events in the postpeak season experienced a significant decrease has been

extensively studied (Hsu et al. 2014; Shan and Yu 2020a). It may also be demonstrated that there are nearly no TC events belonging to the C2 type in the postpeak season.

4. Mechanisms

a. Direct correlation

Since the TC landfall location is essentially determined by the genesis location and the track geometry of the TC, we pay a special attention to the relative importance of the TC genesis anomalies and TC track anomalies to the variation of TC landfalls in China. Figures 4a and 4b show the contributions of genesis and track anomalies to the difference of TC track density in the peak season between the two stages defined in the present study. It is found that the effect of TC genesis plays a dominant role in the abrupt increase of the TC occurrence frequency along the coast of southeastern China in the peak season. In contrast, the track effect is negligible.

In Fig. 4, the differences of the TC genesis frequency and the large-scale steering flows in the WNP between the two

FIG. 4. Contributions of (a) genesis anomalies and (b) track anomalies to the difference of TC track density between the first stage (1979–95) and the second stage (2002–18) in the peak season. Differences of TC (c) genesis frequency and (d) steering flow velocity (m s^{-1}) between the first stage (1979–95) and the second stage (2002–18) in the peak season, with black dots and brown crosses indicating TC genesis locations during the first stage and the second stage, respectively. In (d), the solid line and dotted line indicate the 5880-gpm contour of 500-hPa geopotential height during the first stage and second stage, respectively.

stages are also presented. Note that TC tracks are statistically governed by the environmental steering flow and its rate of shear (Shan and Yu 2020b) while the large-scale steering flow is defined as the pressure-weighted tropospheric layer-mean flow from 850 to 300 hPa (Holland 1984; Wu et al. 2005; Chu et al. 2012). In Fig. 4c, an obvious westward shift of the TC genesis is observed over the WNP during the peak season in recent decades, which must be responsible for the abrupt increase of the C2 type of TCs and thus an abrupt increase of TC landfalls in southeastern China.

Figure 5 shows the effects of genesis and track anomalies on the variation of TC occurrence frequency in the postpeak season. It is obvious that the abrupt decrease in the TC occurrence frequency along the coast of southern China is a direct result of the decreased TC genesis in the recent stage in the postpeak season. In contrast, the track effect contributes to the abrupt decrease of the TC occurrence frequency in the open sea area of the WNP. In Fig. 5c, an abrupt decrease of the TC genesis frequency is observed in the

southeastern part of the WNP in recent decades while Fig. 5d implies that effect of the variation of the steering flow condition near the coast is negligibly small. Consequently, the C1 type of TC events decreased significantly in the postpeak season and the TC landfalls in southern China also decreased significantly.

On the basis of the facts resulting from the aforementioned analysis, it is strongly suggested that the abrupt increase in the TC landfall number in southeastern China is related to the westward shift of the TC genesis during the peak season while the abrupt decrease in the TC landfall number in southern China is related to the abrupt decrease of TC genesis number during the postpeak season.

b. Effect of environmental factors

To understand the mechanism behind the variability of TC landfalls in China, it may be necessary to investigate the anomalies of the environmental factors over the WNP ocean basin. Figures S4a and S4b in the online supplemental material

FIG. 5. As in Fig. 4, but in the postpeak season.

present the differences of SST between the two stages defined in the present study in the peak season and in the postpeak season, respectively. It is found that SST increases significantly over the main region of TC genesis, which is favorable for TC genesis in general but not in a particular season. In addition, the SST warming pattern does not show much difference in the two seasons, which is actually in agreement with Chang et al. (2021). In Fig. S5 in the online supplemental material, a significant increase of the relative humidity is observed over the main region of TC genesis in the peak season. In the postpeak season, the relative humidity increases at low latitudes but changes insignificantly at the midlatitudes. It is thus clear that the variations of SST and relative humidity cannot explain the effect of TC genesis on the variability of TC landfalls in China, since they do not support the decrease of TC genesis frequency in the southeast part of WNP in the peak season and the overall decrease of TC genesis frequency in the postpeak season.

Figures 6a and 6c present the difference of the absolute vorticity at 850 hPa between the two stages defined in this study in the peak season and the postpeak season, respectively. It is shown that the absolute vorticity decreases over the tropics in the longitude range of 150°E–180° and with significant changes only in sporadic areas west of 150°E in the peak season. In addition, the absolute vorticity

decreases in the tropics of WNP in the postpeak season, which affects the main region of TC genesis and are responsible for the overall decrease of TC genesis frequency. As shown in Fig. 6b, the vertical wind shear increases significantly in the southeast part of WNP over the longitude range of 150°E–180° in the peak season, which is responsible for the decrease of TC genesis frequency in the southeast part. In the postpeak season, the increase of vertical wind shear affects the region from 135° to the date line along the tropics in Fig. 6d, which contributes to the decrease of TC genesis frequency. These conclusions are consistent with previous studies (Park et al. 2014; Hsu et al. 2014; Chang et al. 2021), which claimed that dynamic factors dominate over thermodynamic factors in TC genesis over the WNP.

c. Effect of La Niña-like sea surface warming

In this study, we try to relate the variability of the TC landfalls in China or the variability of the TC occurrence frequency over the WNP ocean basin to the development of a La Niña-like sea surface warming pattern after the end of twentieth century (Liu and Chan 2013; Hsu et al. 2014; Shan and Yu 2020a). In Fig. 7, it is clearly confirmed that a significant part of the WNP experiences an SST increase between the two stages defined in this study and the warmed

FIG. 6. Difference between the first stage (1979–95) and the second stage (2002–18) of (left) absolute vorticity and (right) vertical wind shear in the (a),(b) peak season and (c),(d) postpeak season. The stippling indicates where the difference is significant at a confidence level of 95%.

area is geometrically analogous to the interannual SST anomalies during La Niña years.

Figures 8a and 8c show that, in the peak season, the 850-hPa westerly winds generally blow over the regions west of 150°E at the low latitudes in the tropical WNP, while the 850-hPa easterly winds generally blow over the regions east of 150°E. The 850-hPa relative vorticity must then reach its maximum along the boundary of the 850-hPa westerly and easterly winds where the largest gradient of the wind speed occurs. The 200-hPa zonal winds, however, show an opposite distribution as demonstrated in Figs. 8b and 8d. In recent decades, the strengthened zonal gradient of the SST associated with the La Niña-like sea surface warming pattern has enhanced the Walker circulation and thus accelerated the zonal atmospheric circulation. Consistently, the 850-hPa easterly winds increase significantly at the regions east of 150°E along the tropical WNP as shown in Fig. 8e. The increased easterly winds weaken the gradient of the horizontal winds and eventually lead to a decreased relative vorticity in the southeastern part of the WNP. This is in agreement with the finding of Chang et al. (2021). In addition, the 200-hPa westerly winds increase significantly in the regions east of 150°E along the tropical WNP as shown in Fig. 8f, which

plays a dominant role in strengthening the vertical wind shear. Note that the increased 850-hPa easterly winds also contribute to the increase of the vertical wind shear but play a less important role due to its small magnitude. It is also identified that the changes of the atmospheric circulation in the peak season mainly occur in the regions east of 150°E.

In the postpeak season, the 850-hPa zonal winds in the tropical WNP are characterized by a distribution with the easterly winds at the low latitudes and the westerly winds at the middle latitudes, as shown in Figs. 9a and 9c, which is different from the distribution in the peak season. Accordingly, the 850-hPa relative vorticity also shows a parallel distribution at the low latitudes. Since the zonal atmospheric circulation has been accelerated by the La Niña-like sea surface warming pattern, the 850-hPa easterly winds increase significantly along the entire tropical WNP from 120°E to the date line as shown in Fig. 9e. As a result, the gradient of the horizontal winds is weakened and the relative vorticity is decreased in the tropical WNP. The 200-hPa westerly winds increase significantly in the region over the tropical WNP extending from 135°E to the date line as shown in Fig. 9f, which induces an increase of the vertical wind shear. When compared with those in the peak

FIG. 7. Schematic representation of a possible mechanism for the variations of TC landfall number in southern and southeastern China in (a) the peak season and (b) the postpeak season.

season, the changes of the atmospheric circulation show larger zonal extension in the postpeak season so that the main regions of TC genesis are influenced.

The fact that the atmospheric circulation has different zonal extension in different seasons was first reported by Chang et al. (2021), who attributed the phenomenon to the difference in the extension of the equatorial easterly wind anomalies and its resulting anticyclone anomalies in the subtropics. In this study, it is further identified that the different zonal extensions of the atmospheric circulation are jointly caused by the effect of a La Niña-like sea surface warming pattern developed after the end of the twentieth century and the Walker circulation, which has a larger zonal extension in the postpeak season than in the peak season.

5. Conclusions

This study focused on the possible mechanisms behind the variations of TC landfall frequency in China. It is confirmed that the annual number of TC landfalls has decreased in

southern China but increased in southeastern China abruptly at the end of the twentieth century, based on statistical analysis of the long-term series for the TC landfalls during 1949–2019. It is demonstrated that the opposite trends of TC landfall frequency change in southern and southeastern China are not simply a deflection of the TC tracks due to a variation of the climate conditions. In fact, the abrupt decrease in the annual number of TC landfalls in southern China is related to the abrupt decrease of TC events with westward track during the postpeak season, while the abrupt increase in southeastern China is related to the abrupt increase of TC events with northwestward track during the peak season.

It is found that, in the postpeak season, there is an abrupt decrease in TC genesis frequency in the southeastern part of the WNP, resulting in the abrupt decrease of TC events with westward tracks, and thus the abrupt decrease in the number of TC landfalls in southern China. On the other hand, a statistically westward shift of the TC genesis has been found during the peak season, which is responsible for the increase of TC events

FIG. 8. The mean values of (left) 850-hPa zonal winds U_{850} and (right) 200-hPa zonal winds U_{200} during the first stage (1979–95) in the peak season and (c),(d) during the second stage (2002–18). The black contours represent 850-hPa relative vorticity in the peak season. Also shown are differences of (e) U_{850} and (f) U_{200} between the two stages in the peak season. Stippling indicates where the difference is significant at a confidence level of 95%.

with northwestward tracks and thus the increase of TC landfalls in southeastern China. The variations of the TC genesis frequency over the WNP ocean basin are shown to be caused by the variations of the atmospheric factors (i.e., a decreased relative vorticity and an increased vertical wind shear in recent

decades). These variations, however, are all related to the accelerated zonal atmospheric circulation in response to the development of a La Niña-like sea surface warming pattern over the WNP ocean basin after the end of twentieth century.

FIG. 9. As in Fig. 8, but in the postpeak season.

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Data availability statement. The data that support the findings of this study are all openly available. In particular, the tropical cyclone landfall data are available at http://tcdata.typhoon.org.cn/dlrdqx_zl.html, and the tropical cyclone

track data are available at <https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access>.

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