The Spatial Variation Characteristics and Mechanism of Landing Tropical Cyclones in China

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Abstract. Based on the tropical cyclone (TC) data from the United States Joint Typhoon Center, this paper analyzes the spatial variation characteristics and possible mechanism of the TC that landed in China during the 65 years from 1951 to 2015. The conclusions are as follows. (1) The TC transformation location moves to southeast in El Niño years, and shifts to northeast in La Niña years. (2) In El Niño years, the frequency of TC affecting the coast of Mainland China is relatively low, while the frequency of TCs affecting Japan is increasing. In La Niña years, the frequency of TCs affecting Japan and the surrounding waters, the Yellow Sea, the Bohai Sea and the South China Sea increased, while that of Taiwan province decreased. (3) The changes in the local circulation in the Northwest Pacific increased the sea temperature, increased convection, increased relative humidity in the middle layer, weakened vertical wind shear, increased low-level vorticity, and increased high-level divergence in the southeastern part of the Northwest Pacific during the El Niño year. The large-scale circulation adjustments provided favorable background conditions for the southeast movement of the TC generating position. The southeast movement of the spawning location makes the landing TC activities have a longer moving distance and thus increases the life history. In La Niña years, the subtropical high weakened and moved eastward. This environment is conducive to generating more TCs to land in China in the La Niña year.

1. Introduction
So far, the physical mechanism of interdecadal climate variability has not been determined. Human activities, low-frequency oscillation of the climate system itself and sea surface temperature anomaly (SSTA) are all possible causes of global warming [1]. Alexander et al. [2] pointed out that the abnormal sea surface temperature caused ENSO to be in a different phase, they think that the abnormal energy during the tropical ocean ENSO period is transferred to the North Pacific, Atlantic and Indian Oceans through the action of atmospheric bridges such as the Walker circulation and Hadley and Rossby waves, which changes the local atmospheric circulation field there and thus affects the climate of the surrounding areas.

The spatial distribution of TC genesis location in the Northwest Pacific has obvious east-west inter-annual oscillation characteristics [3]. Further studies have shown that the inter-annual changes of TCs genesis location are of great significance to the changes in TC activities [4]. Wang et al. [5] think that comparing the TC track, large-scale guided airflow has a greater impact TCs genesis location. The change of TC genesis location in the Northwest Pacific is closely related to the inter-annual variation of ENSO [6]. The Equatorial Middle East Pacific sea temperature anomaly can change the local circulation of the Northwest Pacific through the atmospheric circulation process, and further affect the climate of the Northwest Pacific and East Asia [7]. The change of the local large-scale circulation
corresponding to the warm phase of ENSO can make the TC genesis location move to the southeast direction. TC activity in the Northwest Pacific mainly occur in summer and autumn, when the atmospheric circulation over the Northwest Pacific is mainly monsoon circulation. The lower level is mainly affected by ENSO southwest monsoon flow, monsoon trough and subtropical high pressure circulation system [8]. The monsoon trough is an important part of the tropical monsoon circulation and is mainly located on the southwest side of the subtropical high. The activities of the monsoon trough are closely related to the activities of the southwest monsoon and subtropical high [9]. Chen et al. [10] research shows that more than 70% of TCs in the Northwest Pacific are related to monsoon trough activities. Cao [11] believed that the change of the Northwest Pacific monsoon trough would cause the anomaly of the low-level zonal wind, which would influence the change of the genesis location and the epidemic track of the TCs. Chen et al. [10] found that the monsoon trough can form a large-scale cyclonic vortex structure in the lower troposphere, which is conducive to the formation of TCs. At present, the physical mechanism of how the monsoon trough affects the formation of TCs is unclear. It can be seen that TC activity may be closely related to the anomaly of the tropical Pacific Ocean thermal conditions, but the physical process through which the two are realized still needs further research. Although some studies have explained the mechanism of its connection from the large-scale circulation, this problem has not been solved well.

This article mainly starts with the inter-annual changes of the Walker circulation and Hadly circulation caused by ENSO, and discusses the relationship between the SSTA in the equatorial Eastern Pacific and the TC landing in China and their possible mechanisms.

2. The division of El Niño and La Niña years
We utilized the Joint Typhoon Warning Center (JTWC) (https://metoc.ndbc.noaa.gov/en/web/guest/jtwc/products-and-services-notice) TC best-track data covering the period of 1951-2015. The dataset commonly includes the locations of the TC centers, central pressure, maximum wind speed (1min observed center) and so on. Wu and Zhao [12] point out that the JTWC TC best-track data over the Northwestern Pacific is more reliable than the other data; Chan [13] also argue that JTWC TC intensity data is more reliable. The main typhoon season in China is from May to November, so the TC index in this paper is from May to November.

The SST data from 1951 to 2015 are from HadISST, a dataset provided by the Hadley Center of the UK Met Office (http://hadobs.metoffice.com/hadisst/data/download.html), which has a unique combination of monthly globally complete fields of SST and sea ice concentration on a 1 degree latitude–longitude grid [14].

In the region of Niño-3.4 region (5°North–5°South, 170–120°West), the surface temperature gradient in the equatorial east-west ocean is the largest [15]. In addition, the variation of SST in this region has a good correlation with TC activity in the Northwest Pacific Ocean. For further study the relation between TC activity and sea surface temperature covering the period of 1951–2015, so this paper chooses the SST variation over the Niño-3.4 region to represent the ENSO variation. The ENSO signal is evident during the May–November TC landing activities peak of season. Therefore, the mean value of the SSTA in the Niño 3.4 area from May to November is selected to determine the ENSO change, and the threshold is 0.5°C (-0.5°C) [16]. The monthly SST anomaly comes from the US Weather Service Climate Prediction Center (http://www.cpc.nova.gov/data/indices/) ERSSTv4 extended reconstructed sea surface temperature data [17]. The process yields 16 El Niño years, 15 La Niña years, and 34 ENSO neutral years (Figure 1, Table 1).

![Figure 1](image)

**Figure 1.** The time series of Niño-3.4 SSTA index (°C) for the season May-November in the period 1951–2015. The horizontal lines show Niño-3.4 SSTA index value equal to ±0.5.
Table 1. 1951-2015 El Niño and La Niña year classification results.

| El Niño years | La Niña years | neutral years |
|---------------|---------------|---------------|
| 1951          | 1954          | 1952          |
| 1953          | 1955          | 1956          |
| 1957          | 1964          | 1962          |
| 1958          | 1970          | 1966          |
| 1963          | 1971          | 1978          |
| 1965          | 1973          | 1979          |
| 1969          | 1974          | 1983          |
| 1982          | 1988          | 1990          |
| 1991          | 1999          | 1996          |
| 1997          | 2000          | 2001          |
| 2002          | 2007          | 2008          |
| 2004          | 2010          | 2012          |
| 2009          | 2015          | 2013          |

This paper is based on the 5° latitude×5° longitude box to analyze two parameters of TMLC genesis location and track frequency, then to further study the spatial variation of these two parameters in El Niño years versus neutral years, La Niña years versus neutral years.

3. The relation between the spatial variation of TC genesis location, track frequency and ENSO

3.1. The relation between spatial variation of TC genesis location and ENSO

Figure 2a shows the spatial distribution of TC genesis locations. The geological distribution of every 10a TC frequency generally locates over the Northwestern Pacific 130°–140°E, 10°–20°N and the other area is in the northeast of the South China Sea (115°E, 15°–20°N). Figure 2b shows the contrast between El Niño years and neutral years. From the perspective of spatial distribution, the negative value (green contour line) shows that TC frequency decreased in different spatial location in El Niño years. The most rapidly decreasing regions generally locate on the TC formation regions in neutral years. The increasing regions locate within 150°E, 5°–10°N, which indicates that the formation location shifted toward southeast. This result is in accordance with previous findings [18]. Figure 2c shows that the most rapidly decreasing regions in La Niña years versus in neutral years generally locate on the TC formation regions in neutral years. The increasing regions locate in the center of 140°E, 15°N, southern part of Taiwan province, which indicates that the formation location shifted northeastward.

Figure 2. Geographical distribution of TC formation frequency (number per 10a) in each 5°×5° grid area. (a) Neutral year (b) El Niño year minus Neutral year (c) La Niña year minus Neutral year.

3.2. The relationship between the spatial variation of TC track frequency and ENSO

TC track can be described by TC frequency. The frequency is counted by the number of TC through in each 5°×5° grid area at 6 h intervals, and a TC is only counted once even though it may enter the same grid box several times, which could reflect the chances of being influenced by TC in the region.

In Figure 3a, in a normal year, one of the main track travels westward from the TC to the Philippine Sea and the South China Sea, and another one moves from tropical Pacific northwestward to Korea and Japan influencing the region around East Asia coast. The maximum value of TC frequency occurred over the center region of 118°E, 18°N. Figure 3b of El Niño versus neutral years shows that there are fewer TCs making landfall in China during El Niño years. In Japan, the contours were positive, indicating that more TCs made landfall in Japan in El Niño years. Figure 3c shows that contrasting La Niña years with neutral years, the positive contour lines regions locate the area around Japan Sea, the Yellow Sea, the Bohai Sea and South China Sea, which indicates that TC frequency
increases around the Bohai Sea, Jiao Zhou Peninsular and Southern China coastal area. This means that TC frequency increase around these areas. The contour lines values are negative over the regions of Taiwan province and its surrounding area and Southeastern China coastal area, which indicates that TC frequency decreases around these regions.

Figure 3. Geographical distribution of TC track frequency (number per a) in each 5°×5° grid area. (a) Neutral year (b) El Niño year minus Neutral year (c) La Niña year minus Neutral year.

4. The possible mechanism of ENSO on the changes of landing TC activities in China

4.1 Spatial and temporal distribution of SST anomalies in the tropical Pacific Ocean

Figure 4a shows the spatial distribution characteristics of sea SST in the equatorial Pacific and North Pacific in 1951-2015 (May-November), the SST is in a strip shape and gradually decreases as the latitude increases, the temperature on the west side is higher than that on the east side. The high-value areas are mainly distributed in the Western Pacific (120-180°E, 10°S-15°N), where the average temperature from May to November exceeds 29°C. Figure 4b shows the spatial distribution characteristics of changes in El Niño years compared with normal years, the tropical ocean within 15° north-south latitude presents an east-west SST dipole distribution about 170°E as the axis, the center of the negative (cooling) extreme value of the tropical Western Pacific Ocean is located in the warm pool area centered at 140°E at the equator, and the highest temperature drop is -0.2°C. The center of the positive (warming) extreme value is located in the waters on both sides of the equator in the tropical central and Eastern Pacific, and the highest temperature rise is 0.8°C. Figure 4c shows the spatial distribution characteristics of changes in La Niña years compared with normal years. It can be seen that the centers of positive (warming) extreme values are mainly distributed in the Northwest Pacific (120-130°E, 15-25°N) and parts of the North Pacific (140°E-160°W, 15-45°N), with the warming range of 0.4°C. The center of negative (cooling) extreme value is located in the sea areas on both sides of the equator in the tropical Middle East Pacific, and the maximum cooling range is -0.8°C. In El Niño years, the spatial distribution pattern of equatorial Middle East Pacific is mainly characterized by significant warming, while in La Niña years, the opposite spatial distribution pattern is dominated by significant cooling.

Figure 4. Spatial distribution of SST over the equatorial Pacific and North Pacific from 1951-2015 (May-November). (a) Neutral year (b) El Niño year minus Neutral year (c) La Niña year minus Neutral year.
4.2. Anomalous atmospheric circulation fields associated with SSTA in the tropical Pacific Ocean

The active season of TCs in the Northwest Pacific is from May to November, and their genesis location is the mid-low latitudes within the range of 130-140°E and 10-15°N in the Northwest Pacific. In Fig. 6, the spatial distribution of the flow field shows that there are major circulation systems in the equatorial Pacific and North Pacific regions. The lower troposphere (Figure. 5a) is controlled by the powerful Northwest Pacific Subtropical High on the ocean east of 120°E, the south edge of the subtropical high is easterly wind, and there is a cyclonic trough where east and west wind meet in low-latitude tropical areas (5-20°N), namely the Northwest Pacific monsoon trough; The north side of the monsoon trough is the easterly trade wind, along the monsoon, while the southwest side is the monsoon southwest flow. The upper troposphere (Figure. 5b) is controlled by the anticyclonic circulation of the South Asian high centered on South Asia; Thus, from May to November, there are circulation systems of subtropical high, monsoon trough, southwest monsoon and South Asian high in the Northwest Pacific Ocean.

Figure 5. Atmospheric circulation field and altitude field (shaded area) from 1951-2015 May to November. (a) 850HPA circulation field and height field (unit: M); (b) 200HPA circulation field and height field (unit: M)

4.3 The influence of atmospheric circulation field on landing TC activities

The changes in the large-scale environmental background field are very important for the generation and development of TCs. Figure. 6 shows the resultant difference of physical quantities of El Niño and La Niña annual wind vertical shear, relative vorticity, relative divergence and relative humidity subtropical high. It can be seen from Figure. 6a that in the El Niño year, the vertical wind shear along the eastward extension of the monsoon trough is significantly reduced, and the difference can reach 1.5m/s in the southeast of the Northwest Pacific. The combination of strong upper divergence and low-level cyclonic vortices can promote the development of deep convection, and this background field is conducive to the formation of TCs [19]. Since the monsoon trough itself is the most important cyclonic circulation system in the Northwestern Pacific, there is a significant increase in cyclonic vorticity along the position of the monsoon trough in the El Niño year (Figure. 6b), which is accompanied by an increase in high-level divergence (Figure. 6c). Figure. 6d shows the spatial distribution of the middle-level relative humidity. The relative humidity increases up to 6% in the southeast of the Northwest Pacific Ocean, which is conducive to the generation of TCs under the environment of higher middle relative humidity [19]. Large-scale circulation conditions over the Southeastern Northwest Pacific Ocean have become more favorable for TC formation. The southeast migration of the generative position makes the landfall TC activity have a longer moving distance and thus increase the life history. This change in TC activity in the Northwest Pacific is very likely to be related to the change in the location of TC generation by ENSO [20]. Wu and Wang [20] further pointed out that the change in the location of the TC may have a much greater impact on its path than the large-scale guide airflow, that is to say, the activity change of the TC was probably caused by the change of its formation position. Previous studies have shown that when a TC is generated in the south-eastern part of the Northwest Pacific Ocean, the TC track will tend to turn northeast [20], which is conducive to the development of TCs in low-latitude warm water for a longer time, making them stronger. The ENSO cycle plays an important role in the inter-annual variation of TC activity in the Northwest Pacific Ocean.

Previous studies have shown that when the subtropical high in the Northwest Pacific Ocean rapidly expands westward, the subsidence divergence will cause the low pressure circulation to weaken rapidly, and the landing TC will die out after only maintaining a short track; When the Northwest
Pacific subtropical high weakens and retreats eastward, the convergent upward movement will strengthen or maintain the low-level low-pressure circulation for a long time, and the landing TC can maintain a longer moving track [21]. Moreover, the movement of TCs is guided by environmental airflow, and the guidance role of the middle troposphere is particularly important (Hope and Neumann 1970). The Northwest Pacific Subtropical High is generally in the range of (120-180ºE, 20-40ºN), and its geographic location directly affects the wind field in the western coast of the Northwest Pacific. Because the middle wind field in this area has a significant guiding effect on the TC movement track of landing in China, the offset of the Northwest Pacific subtropical high has a great impact on the TC activity of landing in China. The displacement of the subtropical height of the Northwest Pacific Ocean can be characterized by the longitude of the most westerlies of the 5880GPM isoline in the 500hPa field [22].

The comparison between Figure. 6e and Figure. 6f shows that, compared with El Niño years, the subtropical high in the Northwest Pacific Ocean weakens and the position moves eastward in La Niña years, which is conducive to the generation of more TCs landing in China in La Niña years.

It can be seen that in an El Niño year, TCs in the Northwest Pacific Ocean are generated in the southeast, and more severe TCs in a curved track are active in the Northwest Pacific Ocean east of the Philippines; The number of TCs generated and active in the South China Sea has decreased. Preliminary studies show that the temperature in the equatorial Middle East Pacific has a significant influence on the activity and formation location of TCs, which is probably realized through the change of local circulation in the Northwest Pacific Ocean by ENSO. It can be seen that the influence of ENSO on TC activities is ultimately the result of ENSO's influence on atmospheric circulation changes. The tropical atmospheric circulation was affected earlier, and the degree of influence was also the most obvious. In succession, the atmospheric circulation associated with it at middle and high latitudes also changed accordingly, and the activity of TCs would also change accordingly.

![Figure 6](image)

**Figure 6.** Comparison of circulation field physical quantity between El Niño and La Niña years from 1951-2015 (May to November). (a) 200-850hPa wind vertical shear, unit: ms-1; (b) 850hPa relative vorticity, unit: 10-6 ms-1; (c) 200hPa relative divergence, unit: 10-6 ms-1; (d) 500-700hPa relative humidity, unit: %; (e) El Niño year 500hPa altitude field, unit: gpm; (f) La Niña year 500hPa altitude field, unit: gpm. The blue shaded areas in Figures a, b, c, and d indicate that the significance test of the mean difference has passed (95%) t test.

5. **Conclusion**

By dividing El Niño and La Niña years into temperature anomalies in Nino 3.4 region, the spatial variation characteristics of TC origin, track frequency and observed intensity were analyzed by empirical orthogonal function analysis. The relationship between the spatial variation of TC source,
track frequency, observed intensity and ENSO was discussed. The conclusions are as follows:

1) The TC transformation location moves to southeast in El Niño years, and shifts to northeast in La Niña years.

2) In El Niño years, the frequency of TCs affecting the coast of Mainland China is relatively low, while the frequency of TCs affecting Japan is increasing. In La Niña years, the frequency of TCs affecting Japan and the surrounding waters, the Yellow Sea, the Bohai Sea and the South China Sea increased, while that of Taiwan province decreased.

3) The changes in the local circulation in the Northwest Pacific increased the sea temperature, increased convection, increased relative humidity in the middle layer, weakened vertical wind shear, increased low-level vorticity, and increased high-level divergence in the southeastern part of the Northwest Pacific during the El Niño year. The large-scale circulation adjustments provided favorable background conditions for the southeast movement of the TC generating position. The southeast movement of the spawning location makes the landing TC activities have a longer moving distance and thus increases the life history. In the La Niña year, the subtropical high weakened and moved eastward. This environment is conducive to generating more TCs to land in China in the La Niña year.

6. References

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