

Article

Interannual Characteristics of Tropical Cyclones in Northwestern Pacific Region in Context of Warm Pool and Monsoon Troughs

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Abstract: This study utilizes the typhoon path ensemble dataset from the Marine Science Big Data Center, surface temperature data from NOAA's COBE Sea Surface Temperature dataset, and wind field data from the NCEP/DOE Reanalysis II dataset. It employs analytical techniques such as wavelet analysis, correlation analysis, and the Mann–Kendall test to investigate the temporal and spatial variations in tropical cyclones in the Northwest Pacific, focusing on aspects such as frequency, genesis regions, and Accumulated Cyclone Energy. The research examines the influence of environmental factors, including warm pool thermal conditions and monsoon troughs, on the behavior of tropical cyclones. Findings indicate that over the past 39 years, there has been an upward trend in the frequency of tropical cyclones, whereas ACE has exhibited a slight downward trend. The results of the M-K test suggest that following a period of rapid increase, cyclone frequency experienced a significant shift in 1996, subsequently displaying a downward trend. Notably, the frequency of cyclones aligns with mutation points corresponding to warm pool thermal conditions and the Monsoon Trough Index. Wavelet analysis reveals that cyclone frequency, ACE, warm pool thermal conditions, and MTI exhibit similar small scale periodic variations. The observed differences in the genesis regions of tropical cyclones are attributed to fluctuations in warm pool thermal conditions. Specifically, years characterized by cooler warm pool conditions correspond with a stronger MTI, while warmer conditions are associated with a weaker MTI. The genesis regions of cyclones predominantly lie within the monsoon trough, where environmental conditions favorable for cyclone development are intensified during years of cooler warm pool conditions, resulting in heightened convective activity.

Keywords: warm pool; monsoon troughs; tropical cyclones; interannual variations



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1. Introduction

As one of the world's high sea surface temperature (SST) areas, the Northwest Pacific is one of the main areas for the formation of tropical cyclones (TCs) and typhoons in the world, and according to statistics, about one-third of the world's TCs are generated over this sea area. The study of the TC formation process, intensity, structural change, and activity law has always been a frontier scientific issue in the fields of marine hydrology, meteorology, and geographical environment science. The occurrence and development of TC is affected by the atmospheric environment field over the upper ocean and ocean surface, and the formation and development of TC is the result of complex interactions between

the atmosphere, the ocean, and the structure of the TC itself [1–3]. At the same time, the generation and development trends of TCs are influenced by different physical factors on various time scales. Consequently, research on TC activities ranges from studying the characteristics of individual cyclones to examining the statistical characteristics of changes on seasonal, interannual, and decadal scales [4–6]. Nevertheless, the study of TC activities faces significant challenges due to the scarcity of detailed field observations and the limited accumulation of long-term data pertaining to TCs in the expansive oceanic environment. Additionally, there exists a deficiency in comprehensive and systematic understanding of the physical mechanisms that govern the formation and evolution of TCs.

Approximately 90% of the world's warm sea water is concentrated in the tropical Western Pacific Ocean, making this region the warmest sea area globally. This area, commonly referred to as the warm pool, is characterized by the most intense air–sea interactions in the world and serves as a significant genesis of latent heat release in the global atmosphere [7–9]. Research indicates that over the past few decades, global temperatures have consistently risen, leading to an increase in the temperature of the upper layers of the oceans. As one of the warmest ocean regions on Earth, the sea surface temperature in the warm pool of the Western Pacific Ocean has risen markedly. This area not only represents the upper branch of the Walker circulation but also acts as a strong convergence zone for airflow and water vapor, facilitating the development of intense convective activity and precipitation [8,10,11]. Numerous studies have demonstrated that the Western Pacific warm pool directly influences the thermal and dynamic aspects of tropical cyclone activity in the Northwest Pacific. Furthermore, tropical cyclone activity exhibits significant intra-seasonal, interannual, and interdecadal variations due to the thermal changes occurring in the Western Pacific warm pool [12–14]. There is also a discernible trend of increasing tropical cyclone activity (in terms of frequency, intensity, etc.) in regions where sea surface temperatures are rising [15,16]. Nevertheless, certain research findings suggest that, within the framework of global warming, the intensity of regional TCs has escalated, whereas their frequency may be subject to a potential decline [13,17,18]. There exists a relationship between TC activity and ocean thermodynamic changes; however, regarding interannual variations, the impact of SST changes on TCs may not be the primary influencing factor [16]. Recent research has demonstrated that the thermal regime of the warm pool in the Northwest Pacific affects the monsoon trough, a crucial component of the atmospheric circulation system in the tropics and subtropics, particularly in the Asian monsoon region [18,19]. This phenomenon is closely linked to the monsoon and has significant implications for regional climate, precipitation, and weather systems [20]. Prior research has indicated that the intensity of the Northwest Pacific Monsoon Trough's low-level zonal winds plays a crucial role in determining both the location and path of TCs. Additionally, the Northwest Pacific Monsoon Trough creates vital large-scale environmental conditions that are conducive to the development of TCs [3,15,21]. These conditions include the convergence of airflow, cyclonic relative vorticity, divergence of upper-level airflow, minimal vertical wind shear, and a sufficient supply of water vapor, all of which collectively create a conducive environment for the formation and development of TCs. Given the severe disasters caused by TCs in the Northwest Pacific, many researchers have systematically investigated the generation, structure, development, and movement patterns of TCs in this region [22,23]. As a result, the investigation into the characteristics and mechanisms underlying interannual and interdecadal variations in TC activity in the Northwest Pacific, along with the large-scale alterations in environmental factors stemming from thermal changes in the warm pool, has attracted the interest of Chinese researchers and pertinent scientists.

In this study, we utilized the NOAA extended reconstruction of sea surface temperature data from 1984 to 2022, the NCEP/DOE Reanalysis II dataset (<https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html>, accessed on 1 March 2024), and the typhoon track dataset offshore of China to analyze the spatiotemporal variation characteristics of TCs in the Northwest Pacific over the past 40 years. Additionally, we explored the relationship between TC activity and monsoon trough dynamics in the Western Pacific Ocean, considering the context of changes in the warm pool.

2. Data and Methods

2.1. Data Sources

The tropical cyclone data used in this study is derived from the China Offshore Typhoon Track Ensemble Dataset of the Ocean Science Big Data Center (<https://msdc.qdio.ac.cn/data/metadata-special-detail?id=1422759994058625025>, accessed on 1 March 2024), which includes the dataset of typhoon tracks in China's offshore waters from 1945 to 2023, including the true track information of each typhoon, typhoon intensity, air pressure, central wind speed, moving speed, moving direction.

The sea temperature data comes from NOAA's COBE Sea Surface Temperature dataset (<https://psl.noaa.gov/data/gridded/data.cobe.html>, accessed on 1 March 2024), with a spatial resolution of $1.0^\circ \times 1.0^\circ$. This dataset includes monthly sea surface temperature data from JMA from 1891 to 2023.

Wind field data and relative humidity data are from the monthly average data of NOAA's NCEP/DOE Reanalysis II dataset (<https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html>, accessed on 1 March 2024) with a spatial resolution of $2.5^\circ \times 2.5^\circ$ and a monthly average for the time range from 1979 to 2024.

Longwave radiation data (<https://psl.noaa.gov/data/gridded/data.olrcdr.interp.html>, accessed on 1 March 2024) are derived from NOAA interpolated Outgoing Longwave Radiation (OLR) with a spatial resolution of $2.5^\circ \times 2.5^\circ$.

2.2. Method Introduction

2.2.1. Wavelet Transform Method

Wavelet transform is a method that simultaneously analyzes signals in both the time domain and frequency domain. Wavelet transform can reflect the local variation characteristics of signal frequency in a time series, and it is effective in analyzing the changes in sequences over time. In Matlab (2022a), we can conveniently perform wavelet analysis using the wavelet toolbox or related functions such as "wavelet". This article uses the continuous wavelet transform method to conduct periodic analysis on data such as cyclone occurrence frequency, ACE, Western Pacific warm pool SSTA, and MTI. The main function for wavelet transform is as follows [24,25].

$$WT(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \psi\left(\frac{t-b}{a}\right) dt \quad (1)$$

In the formula, a is the scale, b is the translation parameter, $f(t)$ corresponds to the time series, and ψ represents the wavelet basis function. Here, the Morlet wavelet is selected as the wavelet basis function using the wavelet analysis method.

$$\psi(t) = \pi^{-\frac{1}{4}} \exp\left(-\frac{t^2}{2}\right) \exp(iw_0 t) \quad (2)$$

In the formula, w_0 represents the dimensionless frequency, and the wavelet variance is employed to better characterize the strength of periodic signals in the time series. The calculation formula for wavelet variance is as follows:

$$\text{Var}(a) = \frac{1}{N} \sum_{t=0}^{N-1} (WT(a, t))^2 \quad (3)$$

In the formula, N represents the length of the time series.

2.2.2. Mann–Kendall Method

The Mann–Kendall (M-K) trend test is a non-parametric statistical testing method that is widely used to analyze the long-term trends of various meteorological element time series data. It has advantages such as a simple calculation process, a wide detection range, low interference, and a high degree of quantification. The principle of the M-K test is as follows [26,27]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(X_j - X_i) \quad (4)$$

In the formula, S represents the M-K statistic; sgn is the sign function; n is the number of sample; X_i and X_j are the i -th and j -th data values of the time series, respectively; its variance is calculated as shown in formula (not considering tie cases, that is, $X_i = X_j$) (5).

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18} \quad (5)$$

The Z values corresponding to different S intervals in the M-K statistic formula are as follows:

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{\text{Var}(S)}}, & S > 0 \end{cases} \quad (6)$$

In a two-sided trend test, a positive Z indicates that the sequence has an increasing trend, while a negative Z indicates that the sequence has a decreasing trend. At a given confidence level, if $Z \geq Z_{\alpha/2}$, the trend of the sequence is significant; if $Z \leq -Z_{\alpha/2}$, the trend of the sequence is not significant. The critical values of the statistic Z for significance levels of 0.1, 0.05, and 0.01 are 1.64, 1.96, and 2.58, respectively.

Next, use the M-K method for mutation analysis, structured as follows:

$$S_k = \sum_{i=1}^k \sum_{j=i+1}^n a_{ij}, k = 2, 3, 4, \dots, n \quad (7)$$

$$\text{In the formula, } a_{ij} = \begin{cases} 1, & X_i > X_j \\ 0, & X_i < X_j \end{cases} \quad 1 \leq j \leq i.$$

Assuming the time series is random, the statistics are as follows:

$$UF_K = \frac{|S_k - E(S_k)|}{\sqrt{\text{Var}(S_k)}}, k = 1, 2, 3, 4, \dots, n \quad (8)$$

In the formula, $E(S_k)$ represents the mean, and $\text{Var}(S_k)$ represents the variance, calculated according to Formulas (9) and (10).

$$E(S_k) = \frac{k(k+1)}{4} \quad (9)$$

$$\text{Var}(S_k) = \frac{k(k-1)(2k+5)}{72} \quad (10)$$

According to the time series in reverse order $X_n, X_{n-1}, \dots, X_1$, calculate UB_k using the process described above. Within the confidence interval $|U| \leq 1.96$, if $UF_K = UB_k$, the intersection point is identified as the mutation point of the time series. When $UF_K > 0$, the sequence shows an upward trend; when $UF_K < 0$, the sequence shows a downward trend.

2.2.3. Monsoon Trough Intensity Index

In order to better study the interannual variations in the monsoon trough, this paper adopts the definition of the Monsoon Trough Intensity Index (MTI) proposed by Zhang Xiang et al., which uses MTI to quantify the intensity of monsoon trough activity. The formula is as follows [28]:

$$MTI = \frac{\xi' - \bar{\xi}}{\sqrt{\sigma^2}} \quad (11)$$

In the formula, ξ' represents the average convective low-level 850 hPa relative vorticity over the region of 215–165° E and 5–20° N in the Western Pacific during the autumn (September to November) of a certain year. $\bar{\xi}$ is the climatic average of the convective low-level 850 hPa relative vorticity for this region from 1984 to 2022 during autumn. $\sqrt{\sigma^2}$ is the mean square deviation of the convective low-level 850 hPa relative vorticity for this region. According to the formula, if $MTI > 0$, the Western Pacific Monsoon Trough is stronger; conversely, if $MTI < 0$, the Northwestern Pacific Monsoon Trough is weaker.

3. Results

3.1. Temporal and Spatial Variation Characteristics of Tropical Cyclones in Northwest Pacific

By analyzing the occurrence frequency of tropical cyclones in the Western Pacific over the past 39 years, we identified that their activity is primarily concentrated during the summer and autumn months, spanning from June to November. Consequently, this study focuses on cyclones that attain tropical storm intensity (wind speed ≥ 17.3 m/s) within these seasons. Figure 1 illustrates the interannual distribution of tropical cyclone frequency derived from statistical methods. Specifically, Figure 1a depicts the total frequency of cyclones over the 39-year period, totaling 789 occurrences. The year 1994 recorded the highest frequency with 30 cyclones, while 1998 had the lowest with only 10. From a long-term perspective, the frequency of cyclones exhibits a slight upward trend, increasing at a rate of 0.0623 occurrences per year, though this trend is not statistically significant. Figure 1b shows the trend significance and abrupt changes in the frequency of Western Pacific TCs from 1984 to 2022 based on the M-K test. The results reveal an abrupt change in cyclone frequency in 1986, followed by a significant upward trend between 1993 and 1995, suggesting that the period from 1991 to 1996 was characterized by heightened cyclone activity. However, after the abrupt change in 1996, the frequency of cyclones began to decline, although this decrease is not statistically significant. This lack of significance in the declining trend may be attributed to the substantial short-term fluctuations in cyclone occurrence, which obscure a clear long-term downward trend.

In order to explore the frequency variation cycles of tropical cyclones in summer and autumn in the Northwest Pacific Ocean from 1984 to 2022, the wavelet analysis method was used to obtain the wavelet power spectrum variation diagram (Figure 2a) and the wavelet full spectrum diagram (Figure 2b) of tropical cyclone frequency. The area enclosed by the thick black line in Figure 2a represents the wavelet power that passes the 95% confidence test. The black dashed line indicates the critical line of the cone of influence (COI), and the area below the dashed line represents the region significantly affected by the edge effects of the continuous wavelet transform. In Figure 2b, the red dashed line represents the critical line for the 95% significance level.

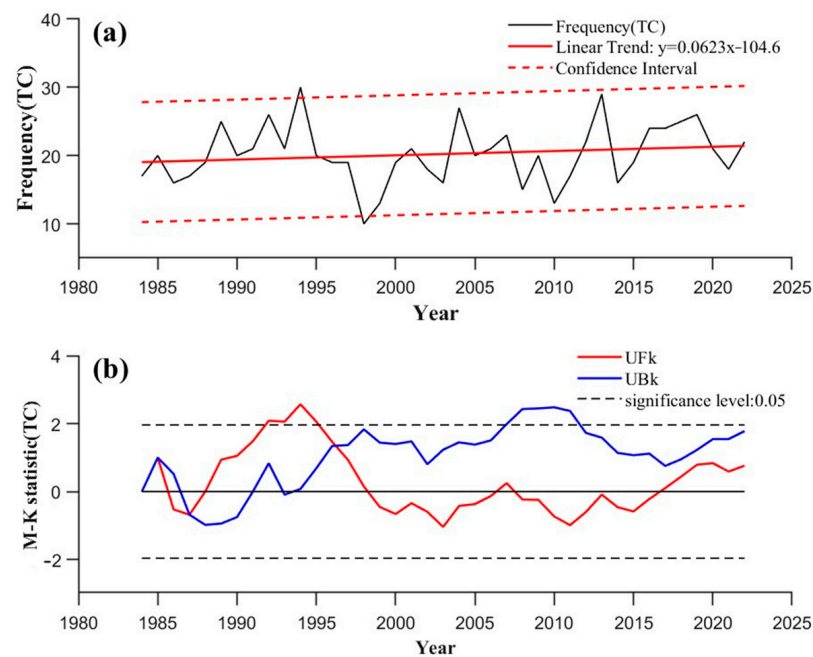


Figure 1. Interannual variation and M-K trend test of frequency of tropical cyclone bottles from 1984 to 2022. (a) is Interannual variation and (b) is M-K trend test.

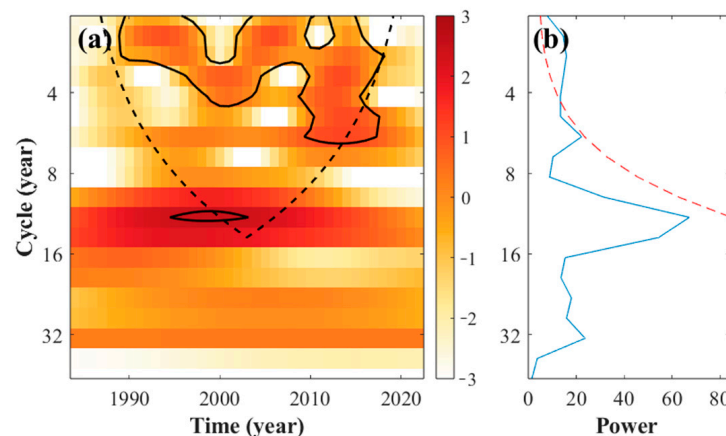


Figure 2. Wavelet power spectrum variation chart and global wavelet power map of tropical cyclone frequency in Northwest Pacific from 1984 to 2022. (a) is wavelet power spectrum variation diagram and (b) is wavelet full spectrum diagram.

You can see from Figure 2a that the tropical cyclone frequency wavelet power change cycle is the most prominent at small size scales, and the TC frequency by the 95% confidence level inspection cycle is roughly 1–3 years and 1 to 6 years, of which 1989–1995 for 1–3 years scale change cycles, and 2011–2018 is characterized by 1–6 years scale change cycles. It can also be seen from the global spectrum of wavelet in Figure 2b that the period of passing the 95% confidence test is mainly within 6 years. It can be concluded that the frequency of tropical cyclones in the Northwest Pacific Ocean in recent 39 years has a small scale periodic change of 1–3 years and 1–6 years [29].

Accumulated Cyclone Energy (ACE) is a quantitative metric for assessing the intensity of tropical cyclones, and was first proposed by Bell in 2000. This measure encompasses all tropical cyclones that exceed the intensity threshold for tropical storms, and it is computed by summing the squares of their maximum wind speeds at six-hour intervals over a designated period [30]. Consequently, compared to studies focusing on single indicators such as tropical cyclone frequency or intensity, the analysis of ACE provides a more

comprehensive understanding of the overall trends in tropical cyclone activity. Therefore, we calculated the ACE values for TCs with an intensity greater than or equal to tropical storm intensity (wind speed of at least 17.2 m/s) over the past 39 years.

The ACE trend and long-term trend of TCs from June to November for the years 1984 to 2022 are illustrated in Figure 3a. This figure reflects the ACE trend of TCs over the past 39 years. The analysis indicates that ACE exhibits a generally negligible downward trend, characterized by a decline rate of $-0.145 \times 10^3 \text{ (m}^2/\text{s}^2)$. The maximum ACE value was recorded in 1994, while the minimum occurred in 1999. According to the M-K test, the average annual ACE of TCs over the 39-year period indicated no significant increase or decrease. There was no notable upward trend in ACE prior to 1998, but there was a non-significant downward trend from 1998 to 2004, from 2007 to 2015, and after 2020. The first mutation point was identified in 1998, after which the ACE displayed a non-significant alternating trend of increases and decreases, with two additional mutation points in 2007 and 2013.

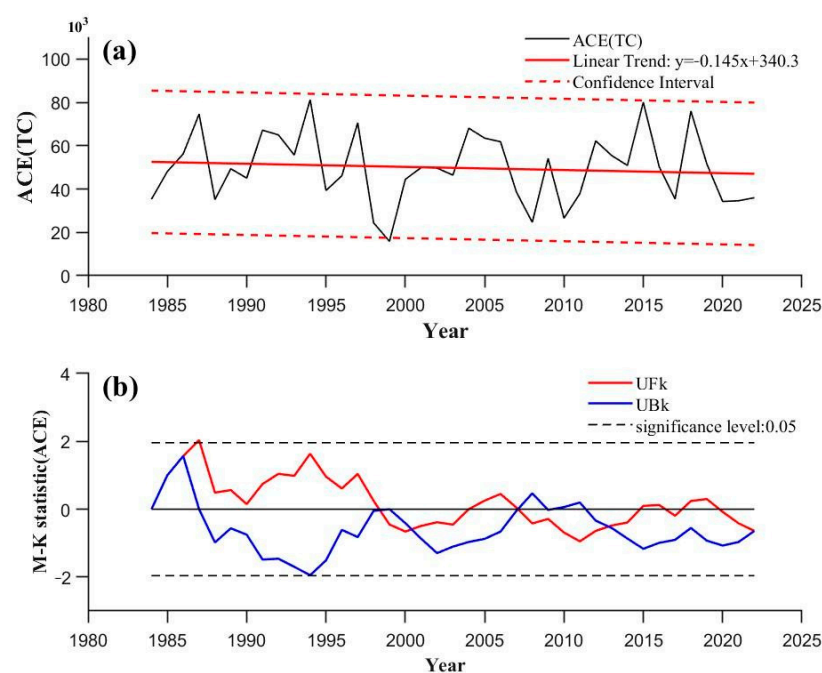


Figure 3. Interannual variation and M-K trend test of ACE from 1984 to 2022. (a) is Interannual variation and (b) is M-K trend test.

Figure 4 illustrates the periodic fluctuations of ACE. As depicted in Figure 4a, there is a notable periodic variation in ACE associated with tropical cyclones on a relatively small scale. The periodicity of ACE for these cyclones, assessed at a 95% confidence level, is identified as occurring within the ranges of 1–5 years and 2–4 years. Specifically, the period from 1987 to 2004 is characterized by a 1–5 year oscillation, whereas the period from 2007 to 2020 is characterized by a 2–4 year oscillation. Furthermore, the global wavelet power spectrum presented in Figure 4b corroborates that the periodicity of ACE, also evaluated at a 95% confidence level, predominantly resides within the 1–5 year range, with a wavelet power peak observed at 2–3 years. This suggests that variations in ACE are particularly pronounced during this timeframe. In conclusion, the ACE of tropical cyclones in the Northwest Pacific over the past 39 years demonstrates low-frequency oscillatory periodic changes of 1–5 years and 2–4 years.

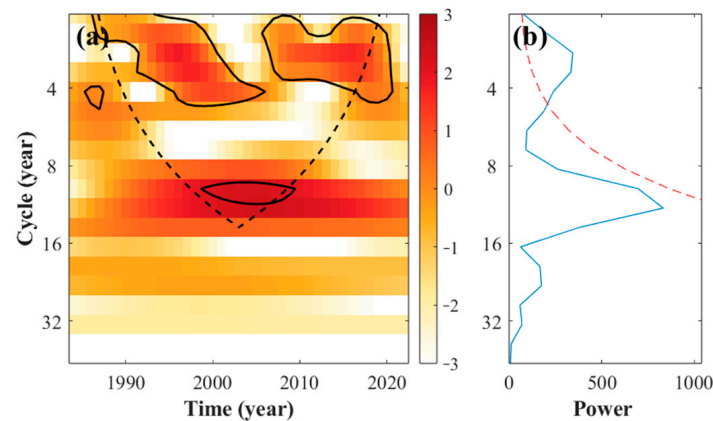


Figure 4. Wavelet power spectrum variation chart and global wavelet power map of ACE in Northwest Pacific from 1984 to 2022. (a) is wavelet power spectrum variation diagram and (b) is wavelet full spectrum diagram.

In order to gain a deeper insight into the spatial distribution patterns of tropical cyclone origins within the Northwest Pacific region, we divided the sea areas between 0 and 40° N and 100 and 160° E into 1° × 1° grids. We then calculated the frequency of TCs in each grid to create a spatial distribution map of tropical cyclone genesis of various categories in the Northwest Pacific from June to November over the past 39 years (Figure 5). The analysis reveals that tropical cyclone geneses are primarily concentrated between 5 and 24° N and 110 and 155° E. Specifically, there are three areas of high tropical cyclone frequency: 10–20° N, 112–120° E; 8–20° N, 125–135° E; and 8–20° N, 140–152° E. The frequencies of TCs in these three areas account for approximately 16%, 24%, and 21% of the total number of TCs, respectively, while the remaining TCs are distributed around these three concentration zones.

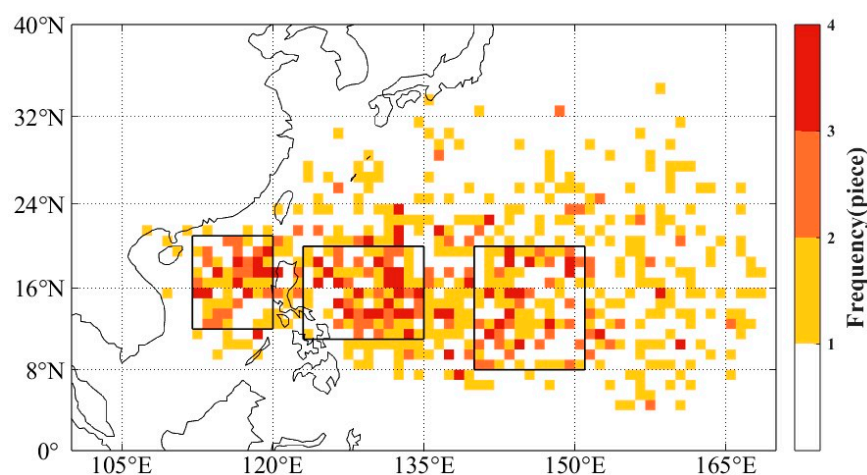


Figure 5. Spatial distribution of tropical cyclone genesis in Western Pacific from 1984 to 2022.

We have classified tropical cyclones that have occurred over the past 39 years in accordance with the classification criteria established by the China Meteorological Administration. The classification of tropical cyclones is predicated on their maximum sustained wind speeds, which are categorized into five distinct classifications: Tropical Storm (TS, with a maximum sustained wind speed exceeding 17.2 m/s), Severe Tropical Storm (STS, with a maximum sustained wind speed exceeding 24.5 m/s), Typhoon (TY, with a maximum sustained wind speed exceeding 32.7 m/s), Severe Typhoon (STY, with a maximum sustained wind speed exceeding 41.5 m/s), and Super Typhoon (Super TY, with a maximum

sustained wind speed exceeding 51.0 m/s). Figure 6 depicts the spatial distribution of the genesis regions for these various categories of tropical cyclones in the Northwest Pacific.

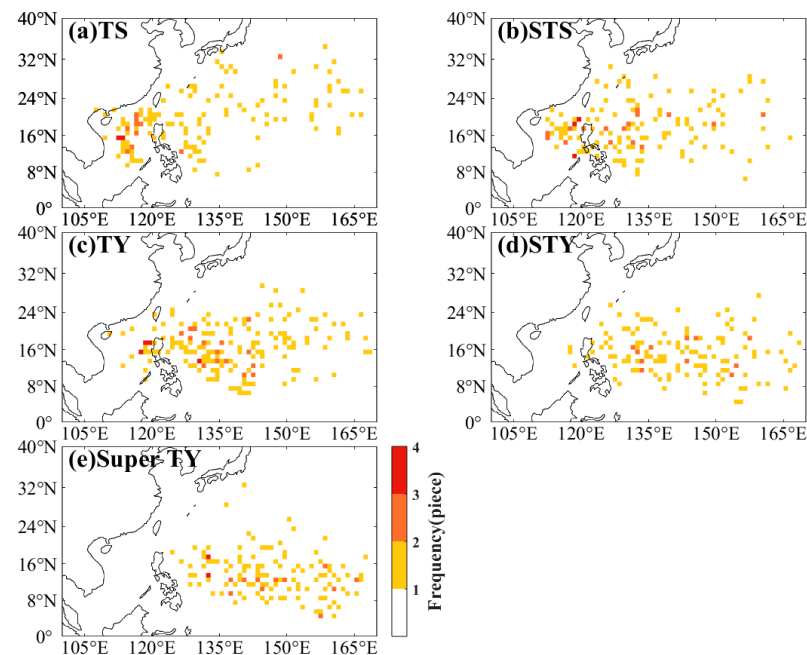


Figure 6. Spatial distribution of tropical cyclone geneses of different grades in Western Pacific from 1984 to 2022.

The analysis presented in Figure 6a indicates that the primary genesis region for TS is located in the South China Sea, with a secondary area of high frequency situated to the east of the Philippine Islands in the Western Pacific Ocean. Figure 6b illustrates the spatial distribution of STS, which predominantly originate from the southern part of the South China Sea, west of the Philippines, and from the Northwestern Pacific Ocean, east of the Philippine Islands. The genesis region for TY is primarily concentrated in the Central Northwestern Pacific Ocean, specifically to the east of the Philippine Islands, with a significant focus in the area defined by the coordinates 8–20° N and 118–150° E (Figure 6c). In the case of STY and Super TY, the genesis regions shift further eastward, with the principal areas of origin located in the eastern part of the Western Pacific, predominantly within the longitudinal range of 120–160° E. As the intensity of tropical cyclones increases, the genesis regions in the South China Sea appear to diminish (Figure 6d,e), while the high-frequency centers progressively migrate eastward. This observation suggests that the South China Sea is less favorable for the formation of high-intensity tropical cyclones.

The following is a statistical analysis of the latitude and longitude distribution of cyclone genesis regions in the Northwest Pacific from 1984 to 2022 (Figures 7 and 8). From Figure 7, it can be clearly observed that the main latitude position of TCs has not changed significantly over the past 39 years, remaining consistently concentrated in the range of 8–20° N. However, from the perspective of longitude distribution (Figure 8), there is a slight westward trend in the generation locations of TCs. Specifically, before 2000, TCs were mainly generated near 125–150° E; during the period from 2000 to 2010, this range slightly shifted eastward to 130–145° E; and from 2010 to 2022, the main generation locations of TCs further shifted westward, concentrating between 120 and 140° E.

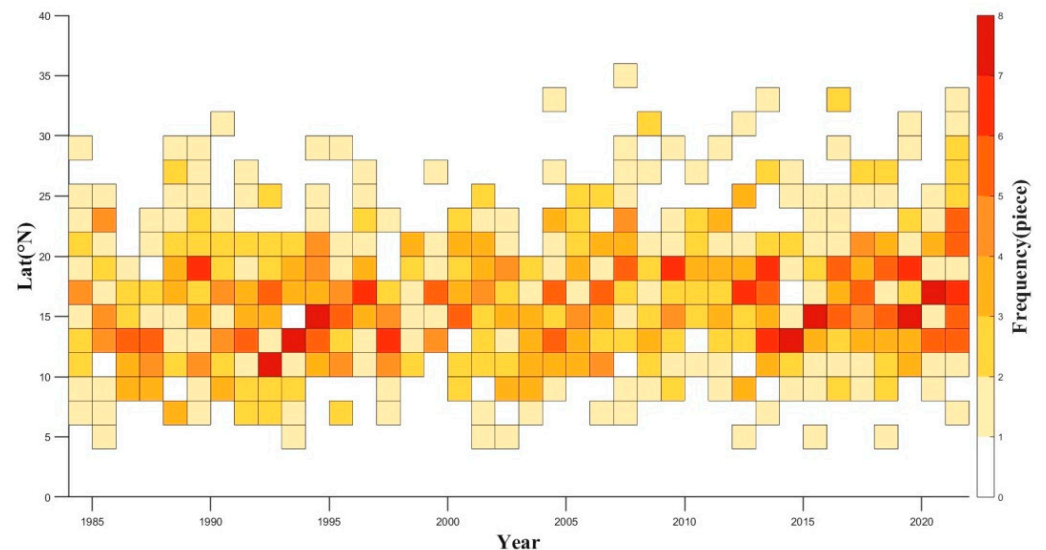


Figure 7. Interannual distribution of latitude of TC origins in Northwest Pacific from 1984 to 2022.

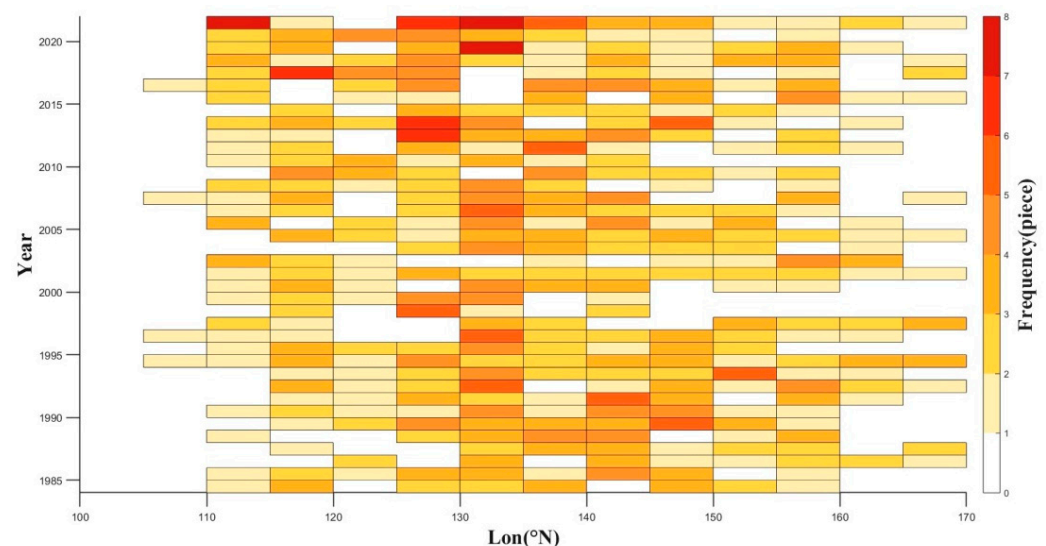


Figure 8. Interannual distribution of longitude of TC origins in Northwest Pacific from 1984 to 2022.

3.2. The Relationship Between Tropical Cyclone Activity in the Northwest Pacific and Temperature Changes in the Warm Pool in the Western Pacific

TC activity demonstrates a substantial correlation with alterations in ocean thermodynamics. Research suggests that the warming anomaly of SST may be a critical factor contributing to the rise in annual tropical cyclone frequency. However, the relationship between tropical cyclone activity and sea surface temperature continues to be a topic of ongoing debate. While warm SSTs create a more favorable environment for TC development, some studies suggest that SST changes are not the primary driver influencing the number of typhoons [16].

The Northwest Pacific Ocean is recognized as one of the principal regions for tropical cyclone genesis globally, primarily attributable to the existence of the Western Pacific warm pool, which is the largest and warmest body of warm water on the planet. The thermal conditions of this warm pool exert a significant influence on the formation and development of TCs in the region. To investigate the relationship between the interannual variability of the warm pool and TC activity in the Western Pacific, a study region within the bounds of 0–16° N and 125–165° E in the Western Pacific Ocean was designated as the warm pool [31,32]. The mean sea surface temperature anomaly (SSTA) from June to

November in this area was calculated and used as an indicator of the thermal state of the warm pool (Figure 9). It is not difficult to see that the warm pool heat conditions in the past 20 years have been warmer compared to the previous 20 years. To better reflect the changes in warm pool heat conditions, this article defines years with warm pool SSTA $> 0.2\text{ }^{\circ}\text{C}$ (SSTA $< -0.2\text{ }^{\circ}\text{C}$) as significantly warm (cold) years. Statistics show that in the past 39 years, there have been 7 significantly warm years and 9 significantly cold years for the warm pool.

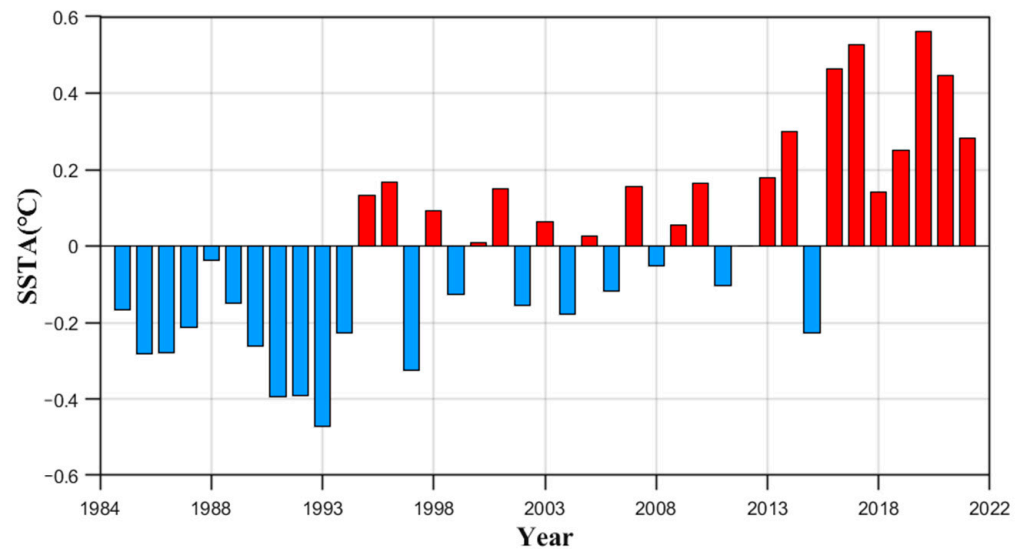


Figure 9. Interannual variability of SSTA in Northwest Pacific warm pool from 1984 to 2022.

The results indicate a significant increase in the thermal environment of the Western Pacific warm pool over the past 39 years, as demonstrated by the interannual variations illustrated in Figure 10a. The sea surface temperature within the warm pool displays a consistent upward trend, rising at an annual rate of $0.0169\text{ }^{\circ}\text{C}$. To gain deeper insights into the thermal state of the warm pool, the long-term trends and potential climate shifts in the SSTA of the warm pool in the Northwest Pacific were analyzed using the M-K test method, as depicted in Figure 10b. The analysis indicates a significant mutation point in the SSTA of the warm pool in 1990, while no notable thermal changes were detected in 1986. From 1986 to 1991, the thermal conditions of the warm pool remained relatively stable, with no significant upward trend observed. Similarly, between 1991 and 1995, there was no substantial decline in the thermal conditions. However, following 1996, the thermal environment of the warm pool has shown a consistent upward trajectory, with a particularly pronounced increase observed after 2006.

Through the application of wavelet analysis, we identified the periodic variations in the SSTA in the Western Pacific warm pool (see Figure 11). The findings suggest that the SSTA in this region demonstrates notable periodic variations on a small scale with cycles of 1–3 years and 2–5 years. From 1996 to 2004, it showed a 1–3 year periodic variation, while from 2011 to 2021, it exhibited a 2–5 year periodic variation (Figure 11a). By observing the wavelet global spectrum (Figure 11b), it can be found that the wavelet power, through confidence testing, has a periodicity of 1–4 years, with a peak at 3 years, indicating that the periodic variation in the warm pool is most significant around 3 years.

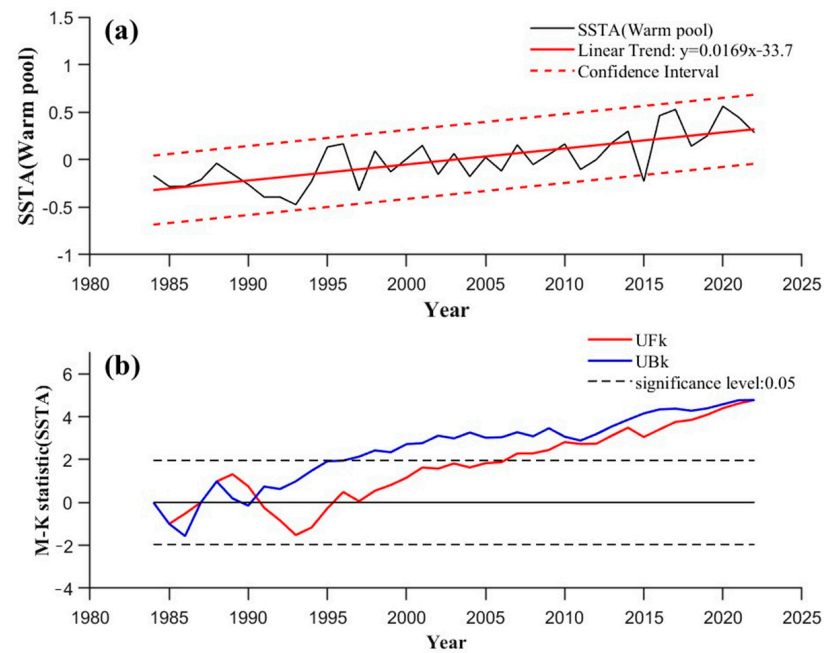


Figure 10. Interannual variation and M-K trend test of the SSTA in Northwest Pacific warm pool from 1984 to 2022. (a) is Interannual variation and (b) is M-K trend test.

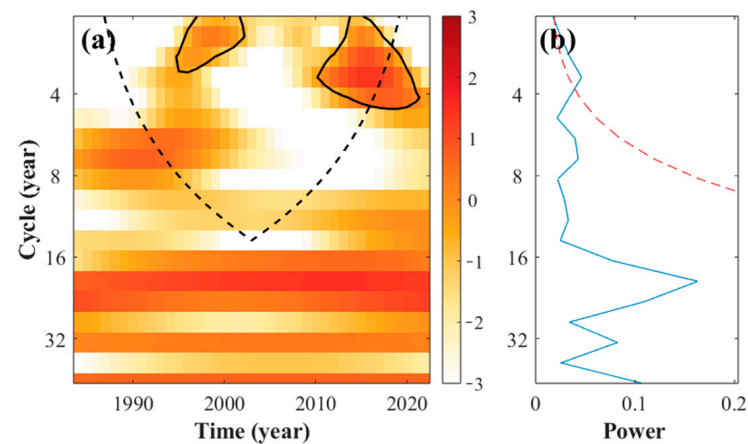


Figure 11. Wavelet power spectrum variation chart and global wavelet power map of SSTA in Northwest Pacific warm pool from 1984 to 2022. (a) is wavelet power spectrum variation diagram and (b) is wavelet full spectrum diagram.

To examine how tropical cyclone activity responds to variations in SSTA within the Northwest Pacific warm pool, we conducted a statistical analysis of TC distribution patterns over the past 39 years under both cold and warm thermal conditions of the warm pool, as illustrated in Figure 12. During years with a warm thermal state of the warm pool, the 29 °C isotherm is positioned approximately at 22° N (Figure 12a), extending across much of the sea areas south of the South China Sea and northwest of the Philippine Islands. The primary genesis regions for TCs are located in the central and western parts of the Northwest Pacific, south of the 29 °C isotherm, which can be roughly categorized into three distinct areas: the South China Sea region (8–20° N, 112–120° E), the sea area west of the Philippine Islands (8–20° N, 125–134° E), and the Northwest Pacific region (10–20° N, 140–145° E).

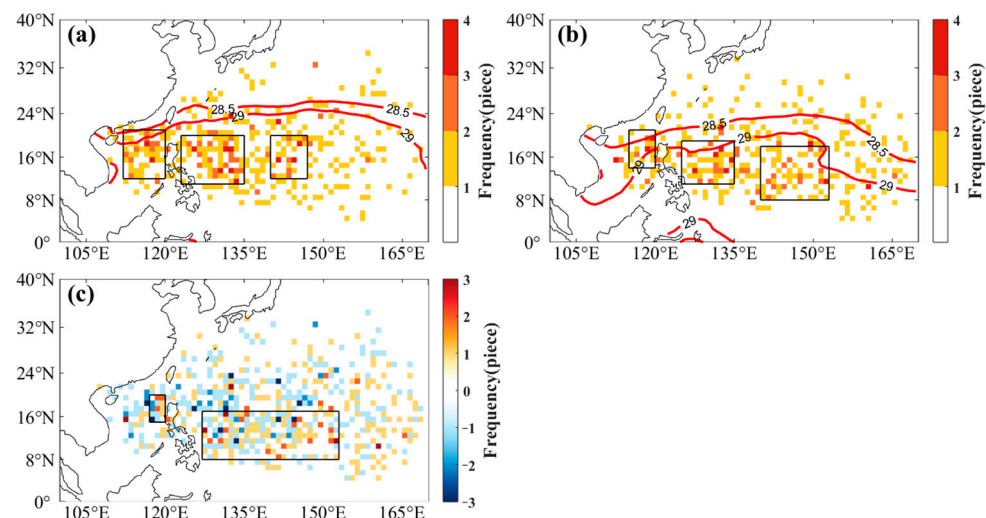


Figure 12. Distribution of cyclone genesis regions and abnormal distribution of cyclone genesis regions in Western Pacific warm pool from 1984 to 2022 (red solid line represents isotherm of warm pool, and black box indicates high-frequency cyclone genesis regions). (a) is the warm pool thermal state in warm years, (b) is the warm pool thermal state in cold years, and (c) is the distribution of cyclone frequency anomalies.

In contrast, during years with a cold thermal state of the warm pool (Figure 12b), the 29 °C isotherm shifts to around 20° N, covering most of the central and western parts of the West Pacific. Under these conditions, the genesis regions for TCs are primarily concentrated south of the 28.5 °C isotherm, with high-frequency areas also located south of the 29 °C isotherm. These regions can be divided into three main areas: the South China Sea region (8–20° N, 112–120° E), the sea area west of the Philippine Islands (5–20° N, 125–135° E), and the Northwest Pacific region (8–20° N, 140–155° E).

Figure 12c highlights the differences in cyclone frequency during anomalous years of warm pool thermal conditions, revealing positive anomalies in a small area of the South China Sea east of the Philippine Islands and in the central–southern part of the Northwest Pacific (8–16° N, 128–155° E). Conversely, negative anomalies are observed in the northern part of the Northwest Pacific region. These findings suggest that during years with a cold thermal state of the warm pool, the genesis regions for cyclones shift further south and east.

3.3. Relationship Between Tropical Cyclone Activity and Monsoon Trough Activity in Northwest Pacific

Given that warm pools are not the primary factor influencing the frequency of TCs, what factors determine the spatial distribution of these phenomena? The prevalence of TCs in the Western Pacific Ocean can be attributed not only to the relatively high surface sea temperatures in the region, which fulfill the thermal requirements for TC formation, but also to the frequent presence of active monsoon troughs during the summer and autumn months. The monsoon trough is an important feature of atmospheric circulation, typically referring to a low-pressure trough that forms in tropical and subtropical regions during the monsoon season (usually summer). It is usually located near the equator and extends northward to the Asian continent. When the monsoon trough develops significantly, it can extend eastward to the Indochinese Peninsula and connect with the near-equatorial trough around the Philippines [28,33]. Relevant studies indicate that approximately 75% of the world's TCs originate within monsoon troughs, with around 80% of the TCs formed in the Northwest Pacific occurring in these troughs [33,34]. Figure 13 shows the interannual variation in the MTI in the Northwest Pacific from 1984 to 2022, calculated using the above definitions and wind field data. To clearly reflect the characteristics of monsoon trough

activity, this paper defines years with $MTI > 1$ ($MTI < -1$) as years with significantly strong (weak) monsoon troughs. It can be seen that in the past 39 years, there have been 6 years with significantly strong monsoon troughs and 5 years with significantly weak monsoon troughs.

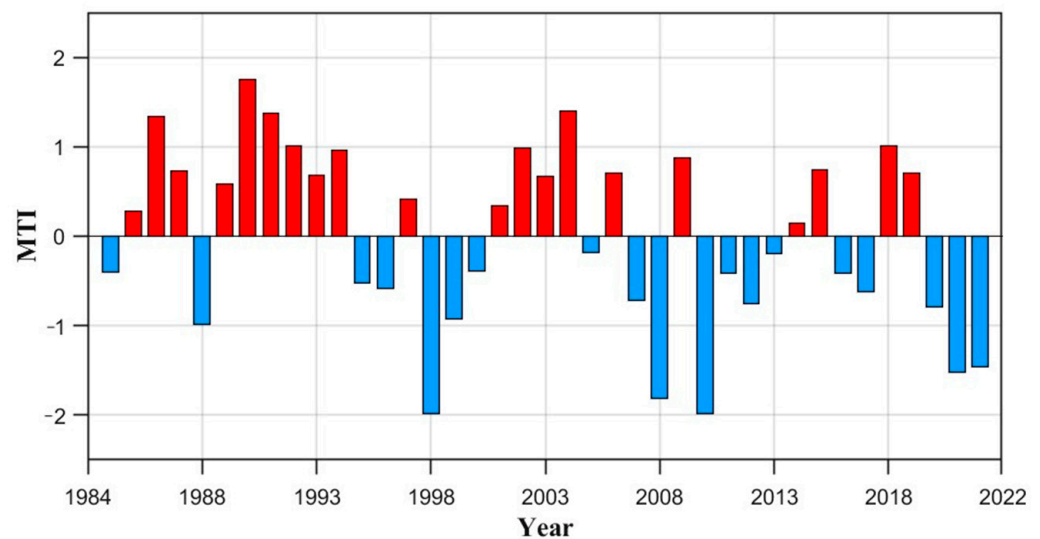


Figure 13. Interannual variation in MTI in Pacific Northwest from 1984 to 2022.

Through a long-term trend study of MTI over the past 39 years, we found that MTI shows a non-significant downward trend; the M-K test indicated a mutation in 1996. Before 1996, the intensity of MTI showed an increasing trend, while after 1996, it mainly exhibited a weakening trend. By employing wavelet analysis, we obtained the wavelet power spectrum change diagram of MTI (Figure 14a) and the global wavelet power diagram (Figure 14b). The results show that the periodicity of MTI, verified at a 95% confidence level, is 1–5 years and 1–6 years. From 1985 to 1993, it exhibited a variation cycle of 3–5 years, from 1993 to 2002, a variation cycle of 1–4 years, from 2007 to 2016, a variation cycle of 1–3 years, and from 2016 to 2021, primarily a variation cycle of 3–6 years. Additionally, there is a relatively significant periodic variation around 2–3 years in MTI.

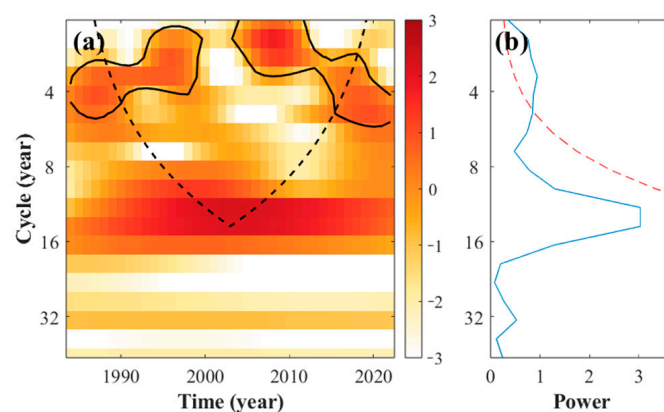


Figure 14. Wavelet power spectrum variation chart and global wavelet power map of MTI in Northwest Pacific from 1984 to 2022. (a) is wavelet power spectrum variation diagram and (b) is wavelet full spectrum diagram.

The results of the aforementioned research demonstrate a discernible weakening trend in the intensity of the monsoon trough in the Northwest Pacific over the past 39 years. Previous research has indicated that the interannual variability of the monsoon trough in this region is predominantly affected by the thermal conditions of the Northwest Pacific

warm pool. Furthermore, the activity of TCs in the Western Pacific is closely linked to the interannual fluctuations in the monsoon trough. To investigate these relationships, we conducted an analysis of the correlations among TC frequency, ACE, SSTA of the warm pool, and MTI [21,24,26]. Figure 15 presents the Pearson correlation coefficients among TC frequency, ACE, warm pool SSTA, and MTI. The analysis reveals that TC frequency is significantly positively correlated with both ACE ($r = 0.4675$) and MTI ($r = 0.4252$) at the 95% confidence level ($p < 0.05$). Additionally, ACE exhibits a strong positive correlation with MTI ($r = 0.7219$, $p < 0.001$), suggesting that MTI has a more substantial influence on both cyclone frequency and ACE. In contrast, warm pool SSTA is significantly negatively correlated with both ACE ($r = -0.4474$, $p < 0.01$) and MTI ($r = -0.5495$, $p < 0.001$), while showing only a weak and insignificant positive correlation with TC frequency. This pattern suggests that the thermal state of the warm pool significantly influences MTI. As the thermal state of the warm pool varies, a potential weakening of MTI may ensue, which could result in a decrease in TC frequency and a reduction in ACE.

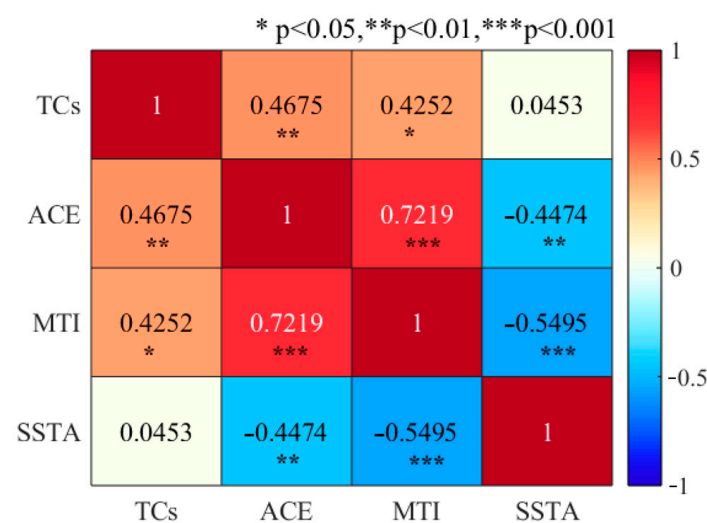


Figure 15. Heatmap of correlation coefficients for tropical cyclone frequency, ACE, SST, and MTI.

In order to better study the activity trends of the monsoon trough under varying conditions of warm pool thermal status, we analyzed the distribution of the monsoon trough under warm and cold thermal conditions of the warm pool. The figure below shows the distribution of the monsoon trough at 850 hPa in the Northwestern Pacific under warm (Figure 16a) and cold (Figure 16b) thermal conditions of the warm pool. Under warm thermal conditions, the 29 °C isotherm is relatively positioned to the north, located around 24° N, covering a vast area of the Northwestern Pacific south of 24° N. At this time, the activity area of the monsoon trough is shifted westward, mainly concentrated west of 130° E, and can extend over the Philippine Islands. In contrast, when the warm pool thermal status is cold, the 29 °C isotherm is positioned further south, around 16° N. In this context, the monsoon trough exhibits a southeastward orientation, with its activity range located between 5° N and 16° N, extending southeastward to 155° E. This distribution characteristic reveals that under cold conditions of the warm pool, the activity area of the monsoon trough is broader, covering most of the southeastern region of the Northwestern Pacific.

In the preceding analysis, it was determined that the thermal conditions of the warm pool exert a significant influence on the activity trends of the monsoon trough. Consequently, it is imperative to investigate whether the activity of TCs exhibits a discernible pattern in response to fluctuations in MTI in the Northwest Pacific. This study aims to examine the variations in the 850 hPa flow field associated with the monsoon trough, as well as the distribution of TC genesis regions from June to September during years

characterized by strong and weak MTI. Since the monsoon trough typically weakens and dissipates in October–November each year, the analysis did not include cyclone activity during this period.

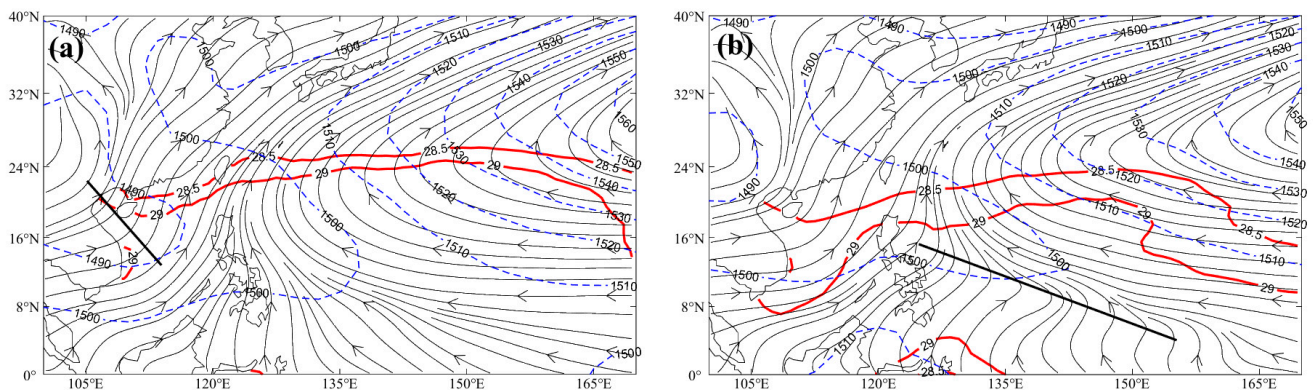


Figure 16. Average distribution of 850 hPa monsoon troughs in warm pool thermal conditions from 1984 to 2022 warm (a) and cold (b) (red solid line is warm pool SST contour, blue dashed line is 850 hPa contour, black streamline is 850 hPa wind field, and heavy black line indicates approximate location of monsoon trough).

In years characterized by a stronger MTI, the monsoon trough extends from the South China Sea to the Central–Western Pacific Ocean at 150° E during the months of June to July, encompassing latitudes between 5° and 16° N, as illustrated in Figure 17a. During this timeframe, the primary regions for TC genesis are situated in the South China Sea and the Western Pacific, specifically to the east of the Philippines, with cyclone formation predominantly occurring within the confines of the monsoon trough. Subsequently, from August to September, the monsoon trough migrates northward, covering the northern portion of the South China Sea and the Northwest Pacific at latitudes ranging from 8° to 24° N, as depicted in Figure 17b. The trough further extends eastward into the Western Pacific at 165° E.

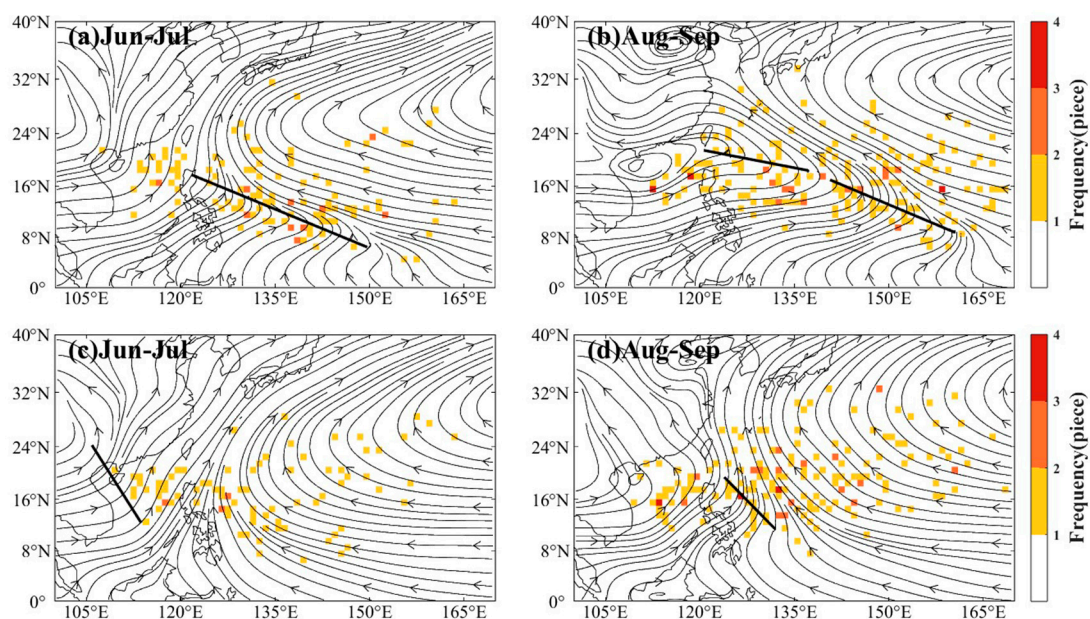


Figure 17. Average distribution of monsoon trough at 850 hPa and distribution of TC genesis from autumn 1984 to 2022.

In contrast, during June and July in years of weak MTI (Figure 17c), the monsoon trough is primarily located over the South China Sea at latitudes of 5° to 16° N, with the main TC genesis regions concentrated in the South China Sea and the Northwest Pacific east of the Philippine Islands. From August to September, the monsoon trough shifts eastward over the Northwest Pacific near longitudes of 120° – 130° E, with the primary TC genesis regions located to the east–southeast of the South China Sea and in the Northwest Pacific near the Philippine Islands.

In summary, during years of strong MTI, the TC genesis regions are predominantly within the monsoon trough. In contrast, during years of weak MTI, TC genesis is more likely to occur in the northward airflow belt, which results from the convergence of the northwesterly equatorial airflow and the airflow from the Eastern Pacific. This observation highlights the strong relationship between tropical cyclone activity and the dynamics of the monsoon trough.

3.4. Characteristics of Environmental Factors Above Northwest Pacific Under Abnormal Warm Pool Heat Conditions

Through a comparative analysis, it is evident that the thermal conditions of the warm pool significantly influence the spatial distribution and activity trends of the monsoon trough (Figure 16). Specifically, during warmer warm pool conditions, the monsoon trough's activity is primarily confined to the western and northern parts of the South China Sea. In contrast, during colder warm pool conditions, the monsoon trough shifts to the central–eastern regions of the Northwest Pacific, expanding in a southeastern direction. These findings provide essential insights into the relationship between the thermal state of the warm pool and the dynamics of the monsoon trough. Prior research has emphasized a substantial connection between the monsoon trough and cyclone activity. One key question remains: why do cyclones frequently form within the monsoon trough? Outgoing Longwave Radiation (OLR) is a crucial metric for assessing convective activity, with lower OLR values typically indicating intense convection and high cloud tops, while higher OLR values suggest weaker convection. By examining the distribution and variability of OLR within the monsoon trough, we can gain deeper insights into the underlying mechanisms connecting monsoon trough activity to cyclone formation and development [28,34].

Figure 18 provides the 850 hPa streamlines and the composite distribution of OLR (W m^{-2}) over the Northwest Pacific during June–July, August–September, and October–November in years characterized by strong and weak monsoon troughs. Figure 18a illustrates that in strong MTI years, the monsoon trough extends eastward from the South China Sea to the Central Northwest Pacific during the months of June and July, spanning approximately 5° – 24° N, with heightened convective activity in this region. By August–September (Figure 18b), the monsoon trough shifts significantly northward, covering latitudes of 10° – 20° N over the South China Sea and the Northwest Pacific, and extends eastward over the Eastern Northwest Pacific near 165° E. Convective activity also migrates northward, reaching the South China Sea and the Northwest Pacific at latitudes of 10° – 18° N and longitudes of 110° – 160° E. Figure 18c depicts the monsoon trough's variation from October to November, showing a gradual weakening and southward movement due to the westward expansion of the easterly airflow. During this period, the monsoon trough transitions into a cyclonic vortex centered over the Northwest Pacific near 10° N, 135° E.

Figure 18d–f illustrates the average 850 hPa streamlines and OLR over the Northwest Pacific during the periods of June–July, August–September, and October–November in years characterized by weak MTI. Specifically, Figure 18d indicates that during weak MTI years, the monsoon trough is predominantly situated over the western part of the South China Sea and the Northwest Pacific, at latitudes ranging from 8° to 20° N, during the months of June and July, with notable convective activity in this area. From August to

September (Figure 18e), the monsoon trough shifts southward, covering the South China Sea and the Northwest Pacific at latitudes of 8–18° N, and extends eastward over the Central Northwest Pacific near 140° E. Convective activity also migrates northward, affecting the South China Sea and the Northwest Pacific at latitudes of 8–18° N and longitudes of 110–140° E. Figure 18f reveals that from October to November, the monsoon trough experiences a weakening along the southern boundary of the Western Pacific subtropical high and subsequently shifts southward in conjunction with the easterly airflow, evolving into a cyclonic vortex centered over the western part of the Northwest Pacific near 8° N, 115° E.

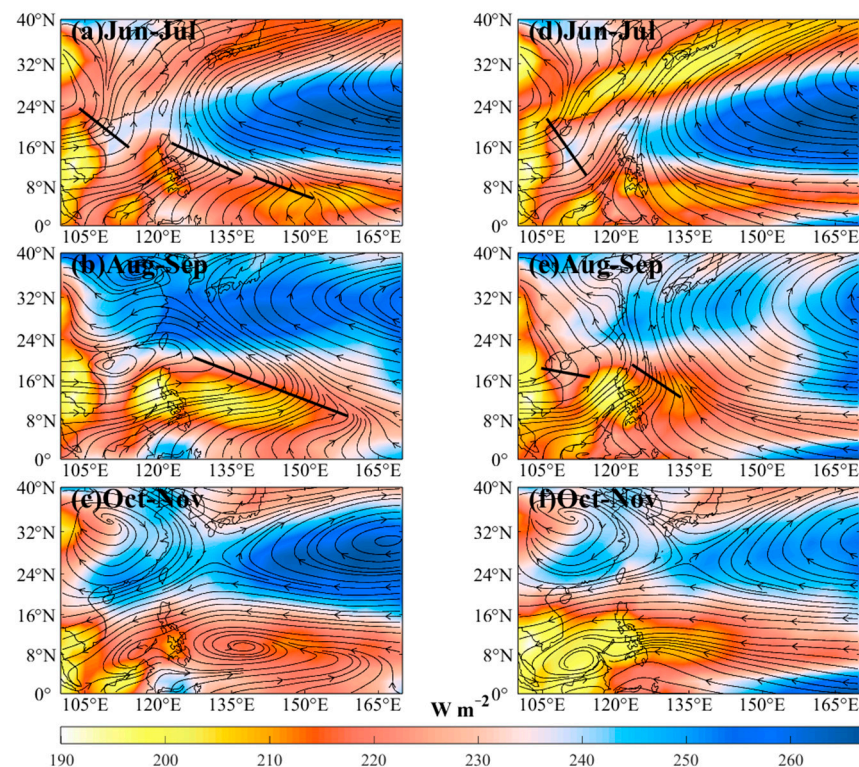


Figure 18. Average distribution of 850 hPa monsoon trough and OLR distribution during strong (a–c) and weak (d–f) MTI years in summer and autumn from 1984 to 2022 (shaded areas, unit: W m^{-2}).

In summary, during strong MTI years, the monsoon trough exhibits greater intensity, with its activity range expanding northward and eastward. The trough line tends to be positioned more northerly or easterly, resulting in broader coverage over the eastern part of the Western Pacific, particularly in the Central Western Pacific, where convective activity may be more vigorous. Conversely, in weak MTI years, the monsoon trough's intensity diminishes, and its activity range contracts westward, predominantly shifting northwestward during years characterized by cold warm pool conditions, particularly affecting the South China Sea and the Philippine Islands. Furthermore, convective activity is notably more pronounced in the South China Sea and the West–Northwest Pacific region, indicating a weaker MTI and reduced monsoon trough activity, whereas during warm of warm pool years, the monsoon trough develops more eastward, reflecting a stronger monsoon trough.

The intensified cyclone activity within the monsoon trough can be explained by several interconnected factors. Key among these is the SST in the Western Pacific warm pool, which typically exceeds 28.5 °C beneath the monsoon trough, providing the necessary thermal foundation for cyclone development [4,11]. Moreover, the persistent presence of the monsoon trough over this warm pool during the summer months creates an envi-

ronment characterized by favorable dynamic and thermal conditions, further promoting cyclone formation. First, the relative vorticity associated with atmospheric convergence and cyclonic characteristics within the monsoon trough is particularly strong at the 850 hPa level, supplying the rotational energy required for cyclone genesis. Second, the relatively low vertical wind shear within the monsoon trough enhances the stability of convective and circulation structures, facilitating the development and intensification of cyclones [11,21,32]. Additionally, the monsoon trough plays a critical role in supplying abundant water vapor, which is essential for the initiation and sustenance of cyclones. The continuous transport of warm, humid air toward the cyclone center supports robust convective activity. Simultaneously, the divergence at the 200 hPa level within the monsoon trough aids in the outward transport of heat and kinetic energy from the cyclone, supporting its ongoing development and intensification [28,29]. To obtain insights into the spatial and intensity variations in the Northwest Pacific Monsoon Trough, as well as the large-scale environmental factors influencing cyclone formation during the warm and cold periods of the Western Pacific warm pool, several atmospheric parameters must be considered (shown in Figure 19). The parameters considered included relative vorticity at 850 hPa, relative divergence at 200 hPa, vertical wind shear between 200 hPa and 850 hPa, and average relative humidity between 500 hPa and 700 hPa within the lower troposphere over the Northwest Pacific.

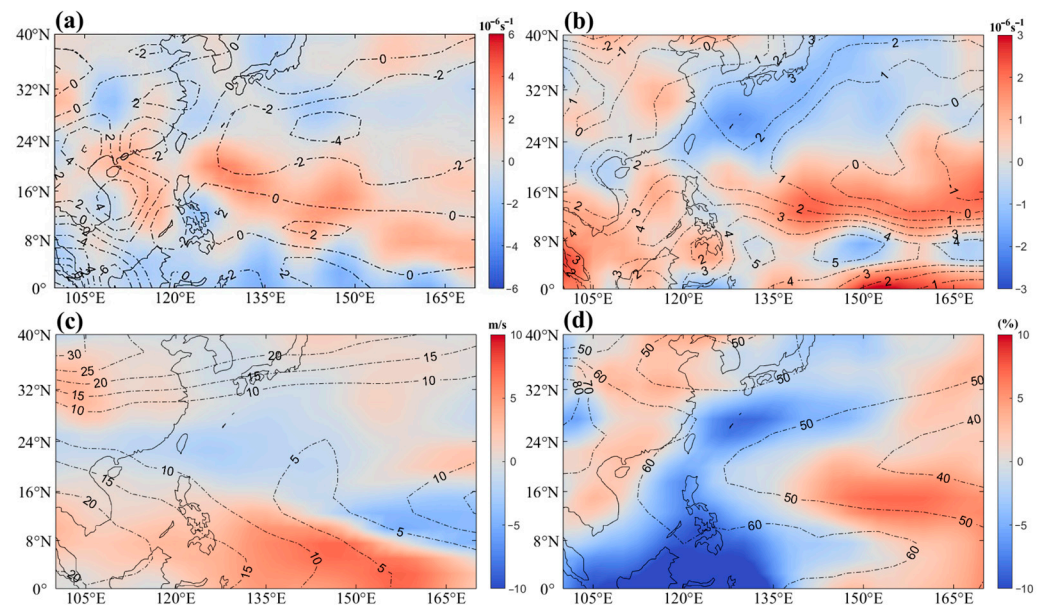


Figure 19. Abnormal distribution of environmental factors (colored) and climate mean state for warm pool heat status anomaly years from 1984 to 2022 ((a) is relative vorticity at 850 hPa, (b) is relative divergence at 200 hPa, (c) is wind shear between 850 hPa and 200 hPa, (d) is average relative humidity between 500 hPa and 700 hPa, with contour lines representing climate mean state).

Figure 19a illustrates the relative vorticity at 850 hPa during the anomalous years characterized by the warm pool's thermal conditions, in comparison to the climatological average. In the average state, positive relative vorticity exists in the central and eastern areas of the Northwest Pacific (8–16° N, 125–160° E). Positive anomalies also appear in this region and the eastern part of the South China Sea, signifying enhanced relative vorticity in colder years. It implies that the cyclonic relative vorticity at 850 hPa in the central to eastern regions of the Northwest Pacific is stronger in colder years than in warmer years, reflecting more intense airflow convergence in these areas under colder conditions. Figure 19b shows the relative divergence at 200 hPa during the abnormal years of the warm pool's thermal conditions relative to the climatological average. In the average state, positive divergence is observed in the central and eastern regions of the Northwest Pacific.

Additionally, positive divergence anomalies are present in the eastern part of the South China Sea and the eastern section of the Northwest Pacific ($8\text{--}16^\circ\text{ N}$, $125\text{--}170^\circ\text{ E}$), indicating enhanced divergence in colder years. This indicates that the circulation divergence at 200 hPa over the South China Sea, as well as in the western and central-eastern regions of the Northwest Pacific, is enhanced during colder years, thereby promoting increased convective activity. The climatological mean of the vertical wind shear between 250 hPa and 850 hPa demonstrates minimal shear in the central and southeastern areas of the Northwest Pacific (Figure 19c). Negative anomalies were identified in the central and southeastern regions of the Western Pacific, suggesting a reduction in wind shear during colder years. This observation indicates that vertical wind shear in the central and southeastern areas of the Northwest Pacific is diminished in colder years. Furthermore, an analysis of the climatological mean of relative humidity between 500 hPa and 700 hPa is warranted to understand the implications of these findings (Figure 19d); there is sufficient moisture in the South China Sea and the southern part of the Western Pacific ($5\text{--}12^\circ\text{ N}$, $120\text{--}150^\circ\text{ E}$). Negative anomalies are detected near the Philippine Islands and the surrounding sea areas, indicating reduced moisture content in colder years. On the contrary, positive anomalies are seen in the eastern part of the Western Pacific, suggesting adequate moisture availability in this region during colder years.

In summary, during the cold phase of the warm pool thermal conditions, anomalies in relative vorticity, positive relative divergence, and wind shear were predominantly observed over the eastern part of the South China Sea and the central to eastern regions of the Northwest Pacific. Additionally, a positive anomaly in relative humidity was primarily observed in the Northeastern Pacific Ocean. Most of these positive anomalies were concentrated in the maritime area bounded by $8\text{--}16^\circ\text{ N}$ and $125\text{--}160^\circ\text{ E}$, corresponding to the active region of the monsoon trough during both warm and cold years. These findings indicate that convective activity within the operational range of the monsoon trough is notably vigorous, significantly enhancing the formation and intensification of cyclones. This phenomenon explains the increased frequency of cyclones occurring within the monsoon trough.

4. Conclusions

Through the analysis of the interannual variation characteristics of TC activity in the Northwest Pacific from 1984 to 2022, as well as the ACE and generation genesis, it was found that the frequency of TCs exhibits significant interannual variation characteristics, with a slight upward trend. The M-K test analysis revealed a mutation in cyclone frequency around 1996, and a mutation in ACE intensity occurred around 1998, with both showing a downward trend. By studying the thermal conditions of the warm pool and MTI, we found that the thermal conditions of the warm pool have been on the rise since 1996, with a significant increase after 2006, while MTI showed a downward trend after the mutation in 1996. Using wavelet analysis, we discovered that the frequency of TCs, ACE, warm pool SSTA, and MTI all exhibit similar low-scale periodic variations. Taking 2001–2005 as a dividing point, the significant periodicity of cyclone frequency in 2001 was 1–3 years, ACE had a significant periodicity of 1–6 years, warm pool SSTA had a periodicity of 1–3 years, and MTI had a periodicity of 1–4 years. After 2005, the significant periodicity of TCs frequency was 1–7 years, ACE had a significant periodicity of 1–4 years, the warm pool had a periodicity of 1–6 years, and MTI had a periodicity of 1–6 years. From the analysis of cyclone generation genesis over the 39 years, it was found that there are three main generation geneses, and the longitudinal position of the TC occurrence genesis has shifted westward.

Through our investigation into the correlation between the warm pool in the Western Pacific and the frequency of cyclone occurrences, we discovered that the origins of cyclones are frequently situated in regions of the ocean characterized by high sea surface temperatures. In years when the warm pool's thermal conditions are above or below average, we observed that during warmer (or cooler) years, the MTI may be weaker (or stronger). There exists a substantial negative correlation between the thermal conditions of the warm pool and MTI. In years characterized by elevated thermal conditions in the warm pool, the monsoon trough may extend as far as the South China Sea and the western region of the Northwestern Pacific at 130° E, while in cooler years, it can extend to the eastern part of the Northwestern Pacific at 160° E. This trend of monsoon trough activity is consistent with years of stronger or weaker MTI. In our study of the activity trends during years of stronger and weaker monsoon troughs, we found that the activity of the monsoon trough is generally accompanied by stronger convective activity, and the main generation areas for tropical cyclones are primarily located within the monsoon trough. In years characterized by a weaker monsoon trough, the primary regions for tropical cyclone formation are not limited to the monsoon trough itself; rather, they also more frequently arise within the northward airflow produced by the convergence of the northwesterly flow and the airflow originating from the Eastern Pacific.

Finally, we focused on analyzing the activity of environmental factors under different thermal conditions of the warm pool. In years when the warm pool is relatively cool, there are positive anomalies of relative vorticity and relative divergence over the eastern part of the South China Sea and the central and eastern regions of the Northwest Pacific. The positive anomaly of relative humidity is mainly concentrated over the eastern part of the Northwest Pacific. Most of these positive anomalies of environmental factors occur in the sea area between 8 and 16° N and 125 and 160° E, while wind shear shows a negative anomaly. The appearance of these anomalies indicates an enhancement of environmental factors in this region, which is more conducive to the development of convective activity. This area corresponds to the activity range of the monsoon trough during years when the warm pool is relatively cool. Within the monsoon trough's activity range, convective activity is particularly intense, and under strong convective conditions, the occurrence and development of cyclones are more favorable.

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