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Spatial and temporal variation of north-west pacific tropical cyclone under the background of upper ocean warming

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Under the background of global warming, the activities of north-west pacific (NWP) tropical cyclones (TCs) are undergoing significant changes. The TC frequencies have been characterized by an initial slow increase followed by a rapid increase and then a decrease, the past 33 years. During the 21st century, the TC frequency of the NWP has clearly decreased. However, the three TC origin types in the NWP have experienced different types of changes. The TC frequencies of origin 1 (10°~22°N,110°~120°E) and origin 2 (8°~20°N,125°~145°E) are both increasing, but the TC frequency of origin 3 (5°~20°N,145°~155°E) is decreasing. Under the background of upper ocean warming, the average TC duration has shown a decreasing trend (-0.27d/10a), while the TC mean and maximum intensity has increased (0.93 m/s/10a and 1.57 m/s/10a, respectively). Therefore, the potential threats of TC activities to NWP coastal countries are likely to intensify. The changes in the thermal state of the upper ocean have many effects on TC activities. Sea surface temperature is not the main factor affecting the frequency of TCs. However, the response of TCs to the upper ocean heat content is obvious.

[**Keywords:** North-west pacific; Tropical cyclone; Thermal state of upper Ocean; Global warming]

Introduction

The upper ocean has been warming for the past 40 years[1]. Therefore, trends in the activities (frequency, origin, and intensity) of tropical cyclones (hereinafter referred to as TCs), have become a hot topic in the areas of typhoon prediction and disaster reduction and prevention.

According to previous theoretical analyses, TC intensity and sea surface temperature (SST) show a positive correlation; thus, with the warming climate [illegible] enhanced[2,4]. Further research has suggested that the overall frequency of TCs has decreased despite increase in the TC intensity of individual regions[5]. Although TC activities are partially related to thermal changes in the ocean, SST change is not the main influencing factor in terms of interdecadal variations[6]. Other models have predicted that with the continuation of global warming, the TC frequencies might be reduced or remain unchanged at the global scale. However, the prediction results of these models are not highly reliable[1]. Several studies have indicated that SST only represents the shallow surface temperature of the ocean and the dynamic processes of the ocean's thermal state have not been adequately expressed[7]. In addition, TC activities in the western Pacific are strongly influenced by ENSO[8,9], and the thermal state of the upper ocean directly reflects the variation tendency of ENSO[10,13]. Therefore, it is necessary to consider the influence of the ocean on TCs based on the thermal variations in the upper ocean.

Since 1970s, TC activities in the Atlantic Ocean have clearly strengthened[1]. However, it is still unclear [illegible] est pacific (NWP) will change with global warming[1]. Therefore, this study analyzed the spatial and temporal variations in TCs in the NWP and explored the relation between TCs and changes in the thermal status of the upper ocean.

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Materials and Methods

The research region is located between 0° and 30°N within 105° to 155°E (Fig. 1). The TCs that affect China mainly occur in the NWP, which has one of the highest concentrations of TCs globally[14]. Approximately 30 TCs are generated in the NWP each year, representing a third of the world's total[15,16].

We utilized TC best-track data from the Joint Typhoon Warning Center (JTWC) covering the period of 1982-2014 in the NWP basin. The data sets commonly include the locations of the TC centers and maximum sustained wind speeds at 6 h intervals.

The SST data used was the NOAA Optimum Interpolation 1/4 Degree Daily SST Analysis V2.0 data. These data cover a time range of 1982.01–2014.12, at a spatial resolution of 0.25°×0.25° and include both SSTs and SST anomalies (ftp://eclipse.ncdc.noaa.gov/pub/OI-daily v2/netcdf-uncompress).

The heat content data for the upper 700 m of the ocean came from the United States National Oceanic Data Center (NODC) covering the period of 1982-2014 and had a spatial resolution of 1°×1°.

Method: Empirical orthogonal function

The empirical orthogonal function (EOF) is a method of analyzing the structural features of matrix data and extracting the main data feature quantities. Lorenz first introduced EOF to meteorological and climate studies in the 1950s[17], and now EOF method has a range of applications. The analysis steps are as follows:

(1) Data are first preprocessed and transformed to their anomaly form, producing a data matrix of $X m\times n$.

(2) The intersection product of matrix X and its transposed matrix X^T is computed, so the matrix is as follows:

$$C_{m\times m} = \frac{1}{n} X \times X^T \qquad \ldots (1)$$

(3) The characteristic roots (λ 1, …λ m) and mode ($Vm\times m$) of matrix C are computed with the following equation:

$$C_{m\times m} \times V_{m\times m} = V_{m\times m} \times \Lambda_{m\times m} \qquad \ldots (2)$$

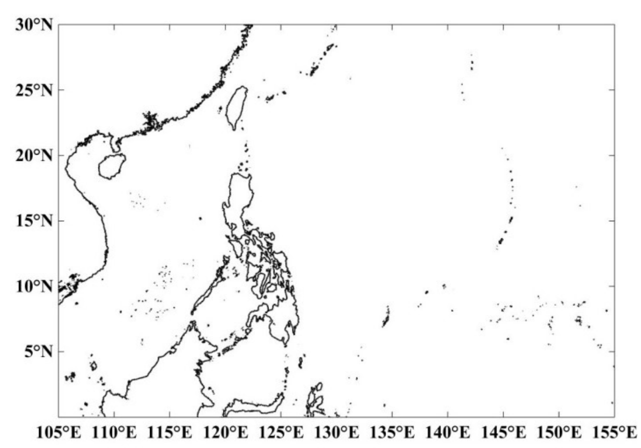

Fig. 1 — Research region (North-west Pacific, 0°-30°N, 105°E-155°E)

where Λ is the $m\times m$ diagonal matrix while the diagonal values are the characteristic roots. The column vectors of $V_{m\times m}$ are the mode values of each characteristic root, which is the EOF.

(4) The principal components are computed. By projecting the EOF onto matrix X, we can get all time-varying coefficients (principal components). This is written as:

$$PC_{m\times n} = V\,T_{m\times m} \times X_{m\times n} \qquad \ldots (3)$$

where each row value in PC corresponds to the time-varying coefficient of each mode.

(5) The significance test is conducted. The error range of characteristic roots must be computed for the significance test. The error range of the characteristic roots λ_j can be calculated as:

$$ej = \lambda j(\frac{2}{n})\,\frac{1}{2} \qquad \ldots (4)$$

where n is the sample size. When the characteristic roots meet the condition $\lambda_j - \lambda_{j+1} \geq e_j$, the corresponding EOF is valuable.

Results and Discussion

According to the monthly TC distribution statistics for 1982–2014 (Fig. 2), TCs occurred throughout the year in the NWP. The highest TC concentration occurred from June to October, accounting for 80.1% of the total number of TCs in the year. Figure 3 shows the monthly changes in the TC frequency for the period, 1982 to 2014. Overall, from January to April, the TC frequency was low and showed no obvious changes. The monthly TC frequencies showed

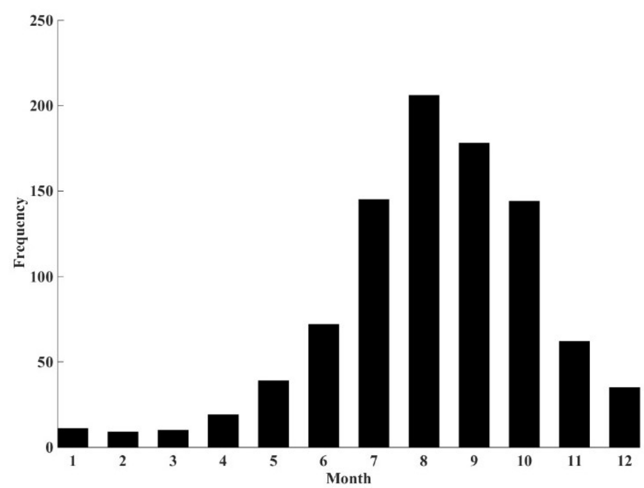

Fig. 2 — Cumulative monthly frequency distribution of TCs in the NWP (month 1 = January and month 12 = December)

decreasing trends from June to October. In contrast, the monthly TC frequencies showed increasing trends in May, November and December.

From 1982 to 2014, the total number of TCs was 930, corresponding to an average of 28 TCs per year. The most TCs occurred in 1996 (44), and the least TCs occurred in 2014 (20). Obvious interannual variations in the TC frequency were observed in this 33-year period: 1994, 1996, 1999, and 2000 were high-frequency years, whereas 1986, 1987, 1987, 2006, 2010, and 2014 were low-frequency years (Fig.4). The TC frequency showed an increasing trend from 1982 to 1991 and 1992 to 2002 and a decreasing trend from 2003 to 2014.

Figure 5 shows the monthly latitudinal and longitudinal distributions of TCs in the NWP. The

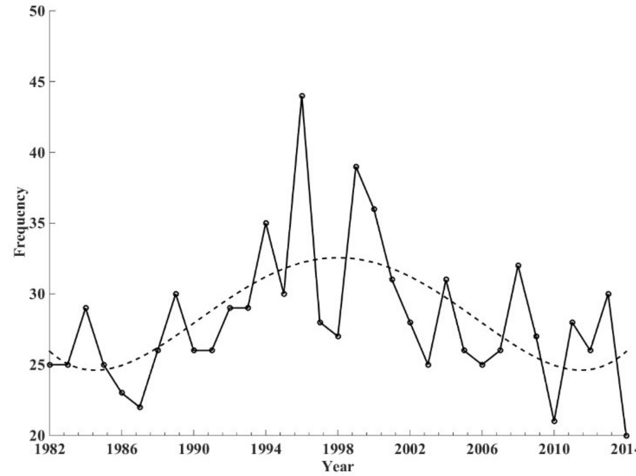

Fig. 4 — Interannual changes in TC frequency in the NWP

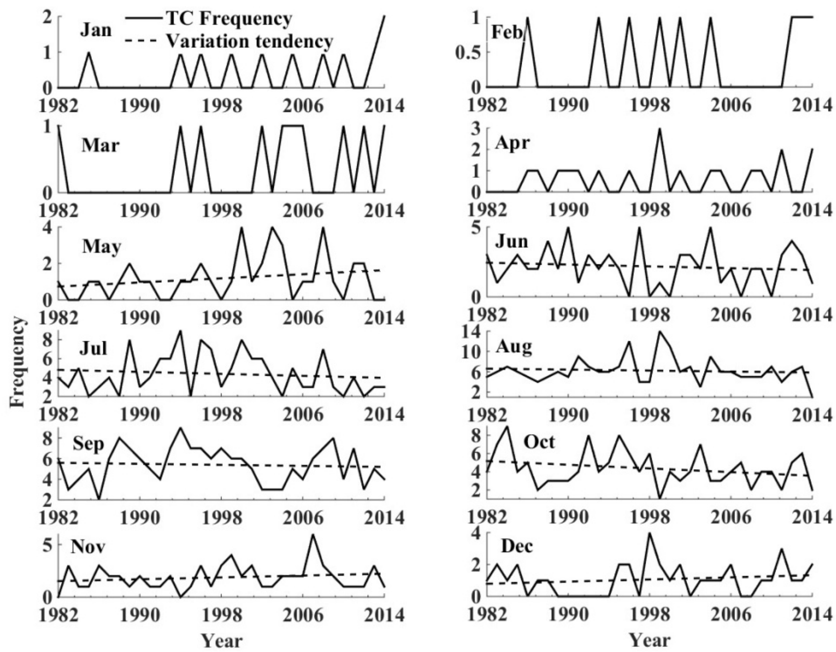

Fig. 3 — Changes in TC frequency in the NWP during each month

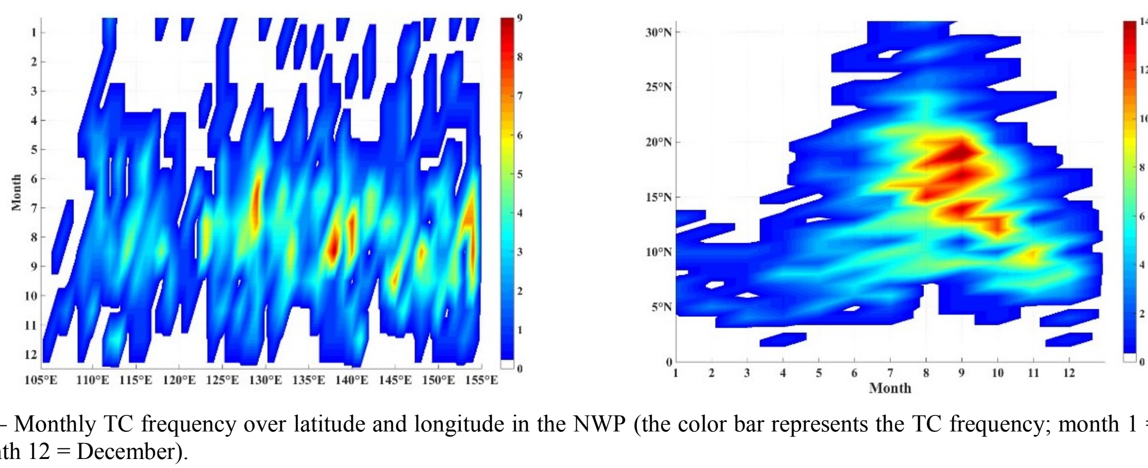

Fig. 5 — Monthly TC frequency over latitude and longitude in the NWP (the color bar represents the TC frequency; month 1 = January, and month 12 = December).

locations of the TC origins demonstrated obvious inter-monthly variations. From January to April, the TC origins were more scattered and tended to be located in the south (2° to 15°N). After April, the TC origins moved toward the north-west. In July, TCs mainly originated from 5° to 20°N, 110° to 155°E. From August to September, the area in which TCs originated moved to the west and north, at the same time the TC frequency was maximized. TCs mainly originated from 8° to 25°N, 112° to 155°E in August and from 12° to 22°N, 112° to 155°E in September. In October, the TC origins began to move south as the TC frequency gradually decreased; the TCs in this month originated primarily from 6° to 18°N, 112° to 155°E. In November and December, the TC origins moved further south (2° to 15°N), and the TC frequency decreased significantly.

According to the 1°×1° bins of the TC distribution in the NWP from 1982 to 2014, representing a range of approximately 0° to 30°N, 105° to 155°E, we can obtain the spatial distribution of the TC origins (Fig. 6). The TC origins were concentrated in 5° to 22°N, 110° to 155°E, and there were three main origins, origin 1 (10°-22°N, 110°-120°E), origin 2 (8°-20°N, 125°-145°E) and origin 3 (5°-20°N, 145°-155°E), which accounted for 27%, 46%, and 21% of the total TCs in the region, respectively. The TC origins were concentrated south of the 27 °C isotherm, and more than 87% of the TCs originated between the 28 °C and 29 °C isotherms.

Figure 7 shows the interannual average duration, average intensity and maximum intensity of TCs in the NWP. In the past 33 years, the average duration of TCs has decreased, while the average intensity and maximum intensity of TCs has increased. This means that the duration of TCs is decreasing, but the intensity of TCs is increasing. The odds of a super TC occurrence are likely to increase, and the TC potential threat may intensify.

The EOF method was used to analyze the spatial distribution of SSTs in the NWP. The variance

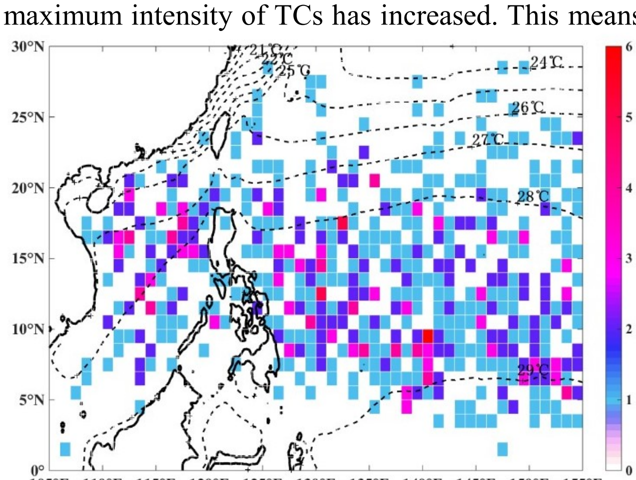

Fig. 6 — Spatial distribution of TC origins and its relationship with SST

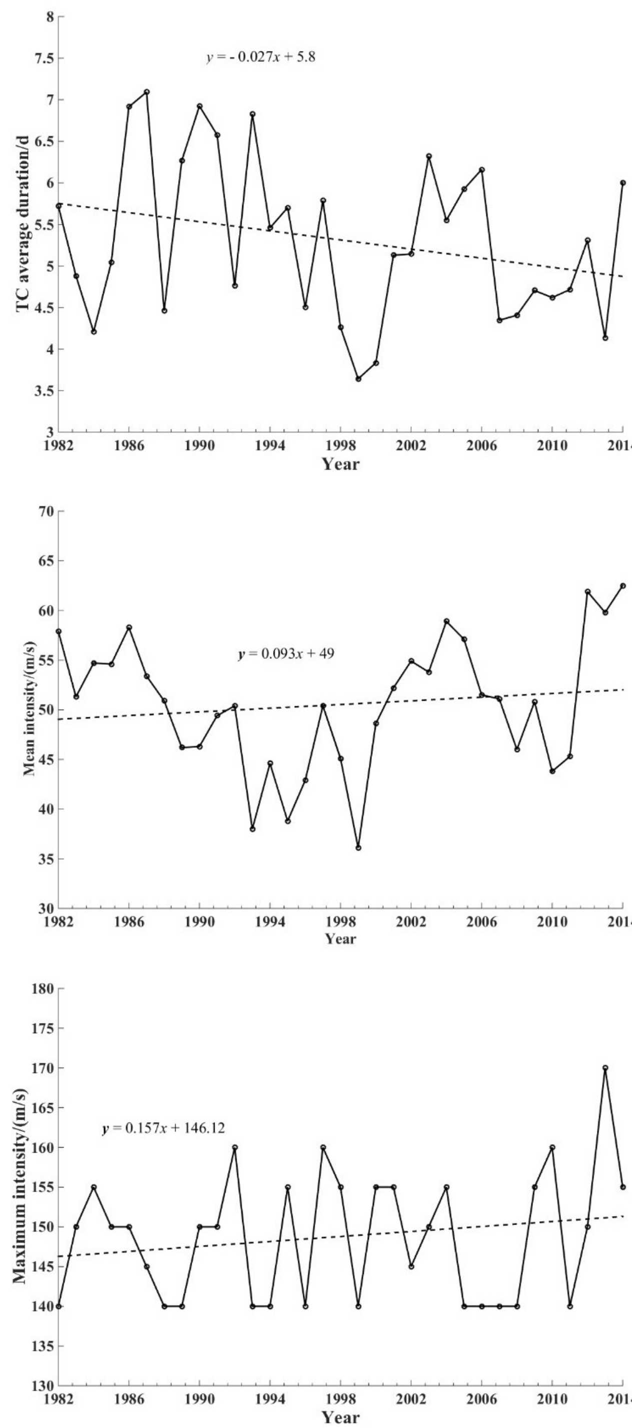

Fig. 7—Changes in the interannual average and maximum intensities of TCs in the NWP from 1982 to 2014

contribution rates of the first four modes were 55.84%, 17.64%, 7.15% and 3.75%. Figure 8 shows the first EOF mode of the SST. The first mode is positively correlated in the whole research area, which shows that the SST has an obvious overall consistency in its spatial variations. We can see that the East China Sea and the NWP warm pool show the most significant changes in SST. SST has generally increased in the NWP over the past 33 years in the range of 0~1.6 °C (Fig. 9), with the East China Sea and the NWP warm pool being the places where SST has increased most rapidly.

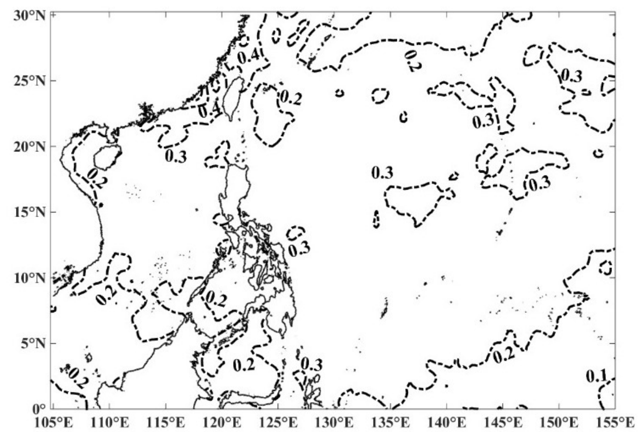

Fig. 8—The spatial distribution of the first mode of the EOF of SST in the NWP

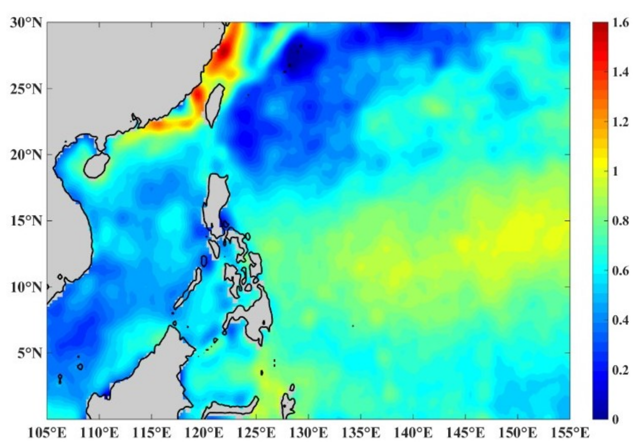

Fig. 9—The SST warming situation in the NWP (The color bar represents the warming amplitude of SST)

The frequency, average duration, average intensity and maximum intensity of the TCs and SST were analyzed by the lead-lag method, and the results are shown in Table 1. When SST leads the TCs by one year, TC frequency is positively correlated with SST, with a correlation coefficient of 0.35. This means that an increase in SST accumulates energy for the production of TCs. When SST lags behind the TCs by one year, the TC frequency is negatively correlated with SST (correlation coefficient -0.31), indicating that SST drops due to the effect of TC activities. When SST is contemporaneous to the TCs, the average TC duration is negatively correlated with SST (correlation coefficient -0.45). This means that with the increase in SST, the average TC duration is likely to decrease.

The TC frequencies for the three TC origins have different variation trends with increases in SST (Fig. 10). The TC frequencies of origin 1 and origin 2 are positively correlated with SST, which means that TC frequency is likely to increase as SST increases. In contrast, the TC frequencies of origin 3 are negatively correlated with SST. Based on the above analysis of different trends in the three TC origins, we can conclude that, in addition to thermodynamic factors, dynamic factors have significant effects on TC activities. Previous studies have suggested that spatial differences in the dynamic environment have changed the mode of TC activities in recent decades. Global warming has led to a greater temperature gradient in the western Pacific and middle east pacific, which has strengthened the Walker circulation, which in turn can strengthen the vertical wind shear and the relative vortices in the NWP and eventually influence TC activities[18]. Other studies have reported that the vertical wind shear and relative vortices have shown significant decreasing trends in the low latitudes of the Central Pacific in recent years[19]. In addition, these are likely to be the main factors reducing the TC frequency of origin 3. With the rising trends in TC frequency of origin 1 and origin 2, the potential threats of TC activities to NWP coastal countries are likely to intensify.

Table 1 — The analysis between frequency, duration, average intensity, and maximum intensity of TCs and SST in the NWP

	SST ahead of TC by 1 year	Contemporaneous	SST lagging behind TC by 1 year
TC frequency	0.35	0.02	-0.31
TC duration	-0.44	-0.45	-0.14
TC average intensity	-0.15	-0.1	0.24
TC maximum intensity	-0.03	0.24	0.26

Note: The red values did not pass the 95% confidence test, while the black values passed the 95% confidence test.

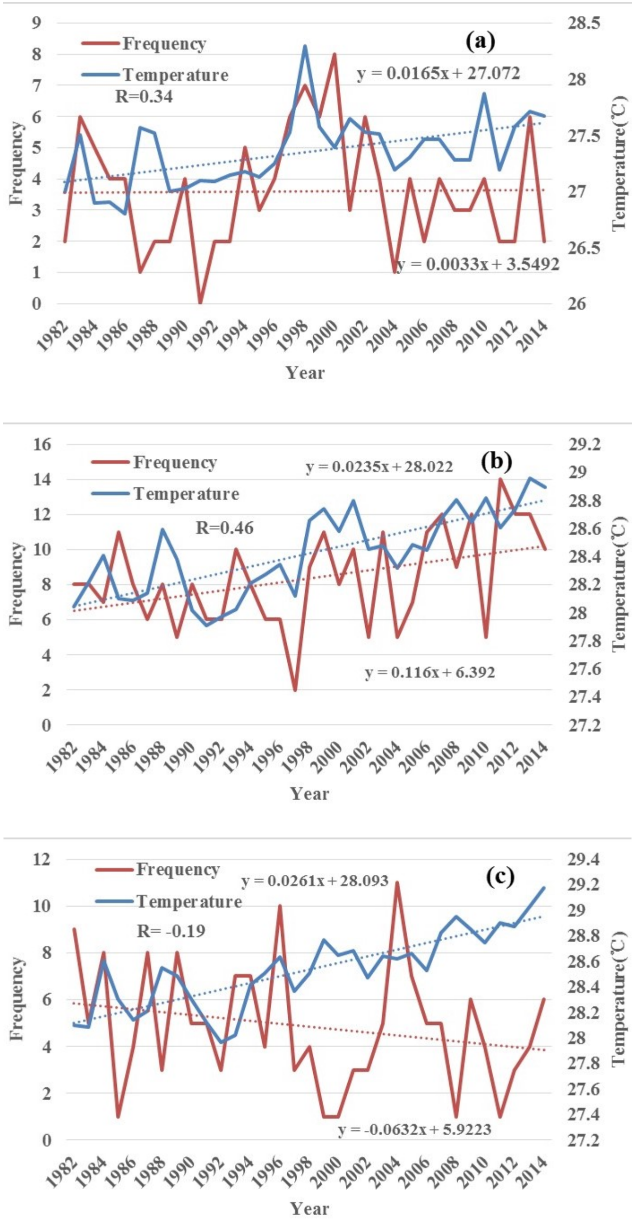

Fig. 10— The spatial distribution of each TC origin and SST in the NWP (Fig (a), (b), and (c) represent origin 1, origin 2, and origin 3, respectively)

In the past 33 years, the upper ocean heat content (UOHC) in the NWP has been on the rise, and this was the most obvious south of 15°N (Fig. 11). The frequency, average duration, average intensity, and maximum intensity of TCs and the UOHC were analyzed by the lead-lag method, and the results are shown in Table 2. When UOHC is contemporaneous with TC frequency, the correlation coefficient is 0.53. This means that the increase in UOHC may lead to an increase in the TC frequency. When UOHC is contemporaneous with the average TC duration, the

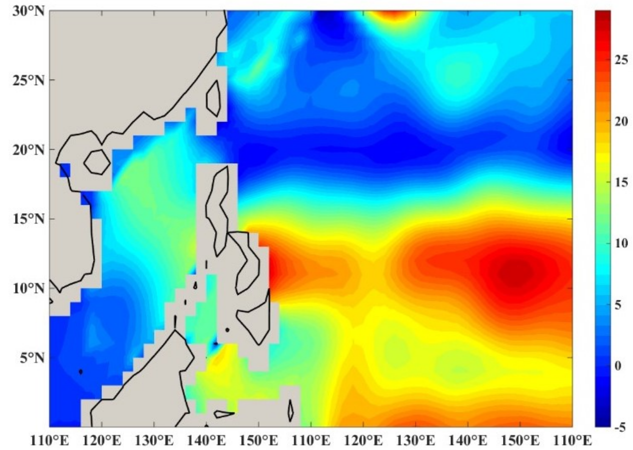

Fig. 11—The annual rate of change of UOHC in the NWP (the color bar represents UOHC, unit: 10^18J/a)

Table 2 — The analysis between the frequency, duration, and maximum and mean intensities of TCs and the UOHC in the NWP

	UOHC ahead of TC by 1 year	Contemporaneous	UOHC lagging behind TC by 1 year
TC frequency	-0.16	0.53	0.14
TC duration	-0.2	-0.68	-0.5
TC average intensity	0.48	-0.21	-0.25
TC maximum intensity	0.4	-0.26	-0.32

Note: The red values did not pass the 95% confidence test, while the black values passed the 95% confidence test.

two are negatively correlated (correlation coefficient of -0.68). Thus, with the rise in UOHC, the TC average duration is likely to decrease. When UOHC lags behind TC by one year, the correlation coefficient is -0.5. Therefore, the increase in UOHC will decrease the influence of TC activities. When UOHC leads TC by one year, the average and maximum intensities of TC are positively correlated with UOHC (correlation coefficients of 0.48 and 0.4, respectively). This means that the rise in UOHC will accumulate energy for the production of TC, and the intensity of TCs will increase significantly. Therefore, it can be inferred that the number of TCs and the probability that a super TC will occur are likely to increase significantly.

Conclusion

Under the background of upper ocean warming, the average TC duration is likely to decrease, but the TC intensity is likely to increase. The number of TCs and the probability that a super TC will occur are likely to increase significantly. The TC frequencies of origin

1 and origin 2 are increasing. In general, the potential threat of TC activities to NWP coastal countries is likely to intensify.

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