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Oscillation in frequency of tropical cyclones passing Taiwan and Hainan Islands and the relationship with summer monsoon*

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Abstract The temporal variations in the frequency of tropical cyclones (TCs) traversing the Taiwan and Hainan Islands (TH islands), were analyzed using a best-track TC dataset from the Joint Typhoon Warning Center for the period 1945–2007. Results show that the oscillations were interannual and interdecadal on the timescales of 2–8 and 8–12 years, respectively. It is also shown that the number of TCs formed in the western North Pacific basin (WNP) and of those traversing the TH islands varied intraseasonally. These results also held for typhoons traversing the TH islands, although the oscillations were less apparent. This study identified interrelationships between the frequency of TCs making landfall on the TH islands and the East Asia summer monsoon (EASM), the South Asia summer monsoon (SASM), and the South China Sea summer monsoon (SCSSM). The SCSSM significantly influenced the number of TCs traversing Hainan Island, but had little influence on the number of TCs traversing Taiwan Island. By contrast, the SASM influenced the numbers of TCs traversing both of the TH islands, shown by correlation coefficients of 0.41 for Taiwan Island and -0.25 for Hainan Island. In addition, the frequency of TC landfall on Taiwan Island increased during years of enhanced EASM, as indicated by a correlation coefficient of 0.4.

Keyword: tropical cyclone; oscillation; monsoon

1 INTRODUCTION

Over the past several decades, against a backdrop of climate change associated with global warming, an increasing frequency of extreme weather has been observed (Wu et al., 2004, 2005). For example, the frequency of tropical cyclone (TC) occurrence in the western North Pacific basin (WNP) has increased in recent decades (Chan, 1996, 2006). Also, the number and destructiveness of typhoons in the WNP have shown an uptrend during the past 30 years (Emanuel, 2005; Webster et al., 2005). China is among those countries most affected by TCs. Approximately 7–8 TCs make landfall in China each year from Liaoning Province in the north to Hainan Island in the south. The regions of China most prone to landfalling TCs are: the eastern coast of Taiwan Island, the coastal region from Fujian Province to Leizhou Peninsula, and the eastern coast of the Hainan Island (Li et al., 2006; Ren et al., 2006). Many previous studies have calculated statistics of TC landfalls on the mainland of China and the islands of Taiwan and Hainan (TH islands). For example, the impacts of TC and typhoon activity in the vicinity of the Taiwan Island have been studied by Tu et al. (2009), and the impacts of TC and typhoon activity in the vicinity of the Hainan Island by have been studied by Wu et al. (2007). More

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recently, Chen et al. (2010) and Chen and Chen (2011) examined the interannual and interdecadal variability of TC activity- and monsoon- induced rainfall in Taiwan Island over the past 5 decades. However, relatively little attention has been paid to the interannual and interdecadal variability in the number of TCs making landfall on the TH islands, or their interrelationship with the variability of the summer monsoon. This study applied a wavelet analysis to explore fluctuations in the number of TCs making landfall on the TH islands.

A number of previous studies have identified interannual and interdecadal variations in TC intensity, track, and frequency of occurrence in the WNP (Chan, 1985, 2005; Chan and Shi, 1996; Fogarty et al., 2006). These variations have been related to fluctuations in monsoon variability, the El Niño-Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) among other factors (Chan, 1985; Lander, 1994; Chen et al., 1998; Wu, 2004; Fudeyasu et al., 2006). Monsoon gyres establish an environment that favors TC genesis (Gray, 1998; Chen et al., 2004). Wang and Ding (2006) reported that intraseasonal oscillations of monsoon troughs associated with the WNP summer monsoon affect the occurrence of TC genesis in the WNP. The monsoon trough is one of the most important factors controlling TC genesis in the WNP which is equal in importance to that of sea surface temperature (Gray, 1998). The monsoon trough satisfies the dynamic conditions required to generate TCs by promoting the occurrence of deep convection, which in turn supplies an initial perturbation that favors TC genesis (McBride, 1995). Sun and Duan (2003) suggested that the East Asia summer monsoon (EASM) plays a crucial role in determining the frequency of TC genesis in the WNP: the stronger the EASM, the more TCs occur in the WNP. Similarly, Gao et al. (2008) found that the frequency of typhoon occurrence in the WNP is strongly correlated with the intensity of the monsoon trough, especially in the South China Sea. However, the relationship between the summer monsoon and the frequency of TCs that make landfall on the TH islands and mainland China is still unclear. We hypothesize that variations in the summer monsoon impact the number of TC landfalls on the TH islands, as these variations have been shown to be closely related with TC genesis and track. We focus in particular on the relationships between the number of TCs traversing the TH islands and the three sub-systems of the Asian monsoon system: the EASM, the South Asia summer monsoon (SASM), and the South China Sea summer monsoon (SCSSM). The outbreak of the SCSSM marks the arrival of the EASM and the rainy season in South China.

Figure 1 shows the areas of interest to this study: the Taiwan Island to the northeast, and Hainan to the southwest. These are two of the regions that are most frequently and seriously affected by TCs in China. These areas of focus differ from that of most papers

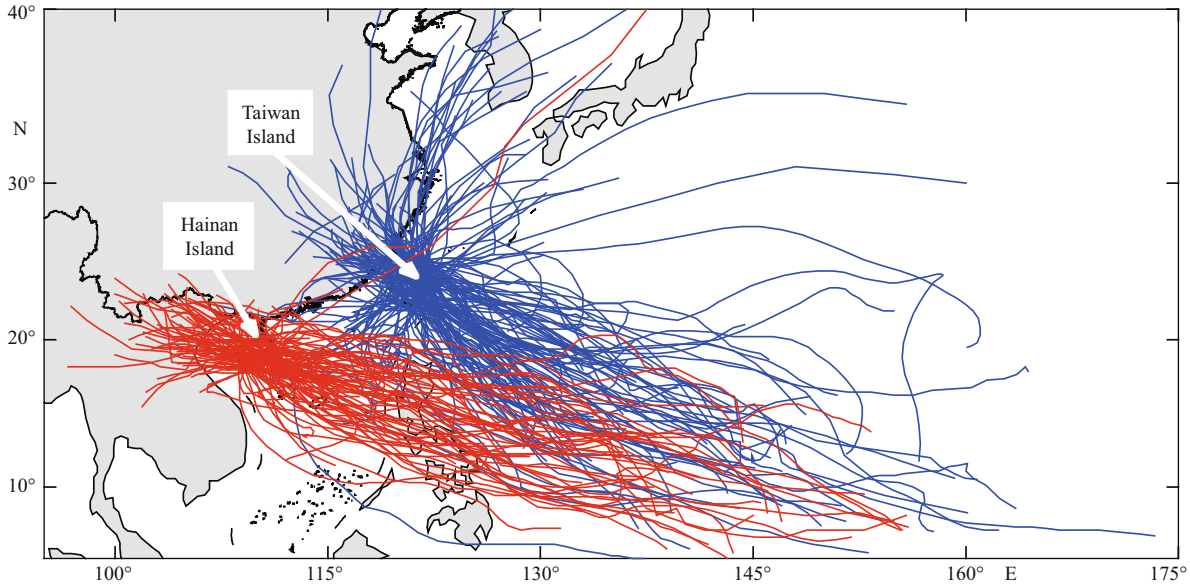

Fig.1 Locations of the areas targeted by this study

The Taiwan Island to the northeast and Hainan Island to the southwest and tracks of TCs stroke HT islands.

which have typically looked at landfalling TCs in all of China, all of East Asia, or even the entire WNP. From Fig.1, it is interesting to see that basically TCs follow two types of tracks: northward recurving and northwestward straight, which is consistent with the findings of Harr and Elsberry (1991, 1995) who reported that the type of TC track has a relationship with the TC genesis location and is regulated by large-scale circulations over the WNP.

2 DATA AND METHOD

The frequency of TCs traversing the TH islands is counted for the period 1945–2007 using best-track data from the Joint Typhoon Warning Center (JTWC) (http://metocph.nmci.navy.mil/jtwc/best_tracks/wpindex.html). Although the total number of typhoons before 1960 is generally less than post-1961, the typhoon dataset has little influence on the correlation analysis, in statistical terms, over a long-term period (about 6 decades). The TC count includes storms that form within the South China Sea (SCS) and also storms that enter the SCS after forming in the WNP. A monsoon index: the dynamical normalized seasonality (DNS) index, is employed in this paper and is given by: $\delta_{i,j}=\frac{\left\|\overline{V_1}-V_{i,j}\right\|}{\left\|\overline{V}\right\|}-2$, where: $\overline{V_1}$ and $\overline{V}$ are the January climatological wind vector and the mean of the January and July climatological wind vectors, $V_{i,j}$ is the monthly wind vector for the year j and month i. Connections between the frequencies of TC genesis and landfall, and the EASM, SASM, and SCSSM are examined using an EASM index defined as a seasonal (JJA) mean of DNS at 850 hPa averaged over the East Asian monsoon domain (10°–40°N, 110°–140°E), an SCSSM index defined as a seasonal (JJAS) mean of DNS at 925 hPa averaged over the South China Sea monsoon domain (0°–25°N, 100°–125°E), and SASM index defined as a seasonal (JJAS) mean of DNS at 850 hPa averaged over the South Asian monsoon domain (5°–22.5°N, 35°–97.5°E) (Li and Zeng, 2002, 2003, 2005). These indices reflect the monsoon circulation activity very well and have been adopted by National Oceanic and Atmospheric Administration to monitor in real-time, and to predict the Asia monsoon. Additionally, these monsoon indices perform better when compared with Wang's SCS monsoon index (Wang et al., 2009) and the monsoon indices from China Monsoon Net (http://www.itmm.gov.cn/grapes/ncep/jfjc.asp), in terms of the variation of the monsoon trough (Zhang and Guan, in press). The interannual and interdecadal variability of the frequency of TCs making landfall on the TH islands and forming in the WNP, is examined by applying a wavelet analysis using the Morlet wave transform.

3 RESULT

3.1 Interannual and interdecadal variability

The occurrence of TCs over the WNP increased during the period 1945–2009 (Fig.2a). This result is consistent with that of Webster et al. (2005), who reported that the occurrence of typhoons in the WNP increased from 1970 to 2004. However, there is no significant trend in the frequency of TCs traversing the TH islands (Fig.2c, d). Chan et al. (2009) reported that the number of TCs making landfall over Southeast Asia (including South China, Vietnam, and the Philippines) did not significantly change during the period of 1945–2004. However, Ren et al. (2006, 2008) noted that the frequency of TCs making landfall over mainland China and the TH islands decreased slightly from 1951 to 2004, although they only found the trend for Hainan Island to be statistically significant. This slight difference between those results and the results reported here appears to be due to the difference in the time span analyzed. Figure 2b shows that the frequency of TC genesis in the WNP and the frequency of TCs making landfall over Taiwan Island are positively correlated (correlation coefficient of 0.23, greater than 90% confidence level), whereas the correlation between the frequency of TC genesis in the WNP and TCs making landfall over Hainan Island is poor. This poor correlation may be attributable to the attenuation of some TCs that formed in the WNP by the Philippine island chain prior to their arrival at Hainan Island. It may also be because TCs traversing Hainan Island form in both the WNP and the SCS, while the TCs traversing Taiwan Island are mainly formed in the WNP.

The frequency of TCs traversing Taiwan Island is anti-correlated with the frequency of TCs traversing Hainan (correlation coefficient of -0.34 at 95% significant level). This anti-correlation indicates that the number of TCs traversing Taiwan Island is reduced when the number of TCs traversing Hainan is enhanced. This finding is consistent with the results of Fogarty et al. (2006), who identified a north-south anti-correlation in yearly TC activity; for example,

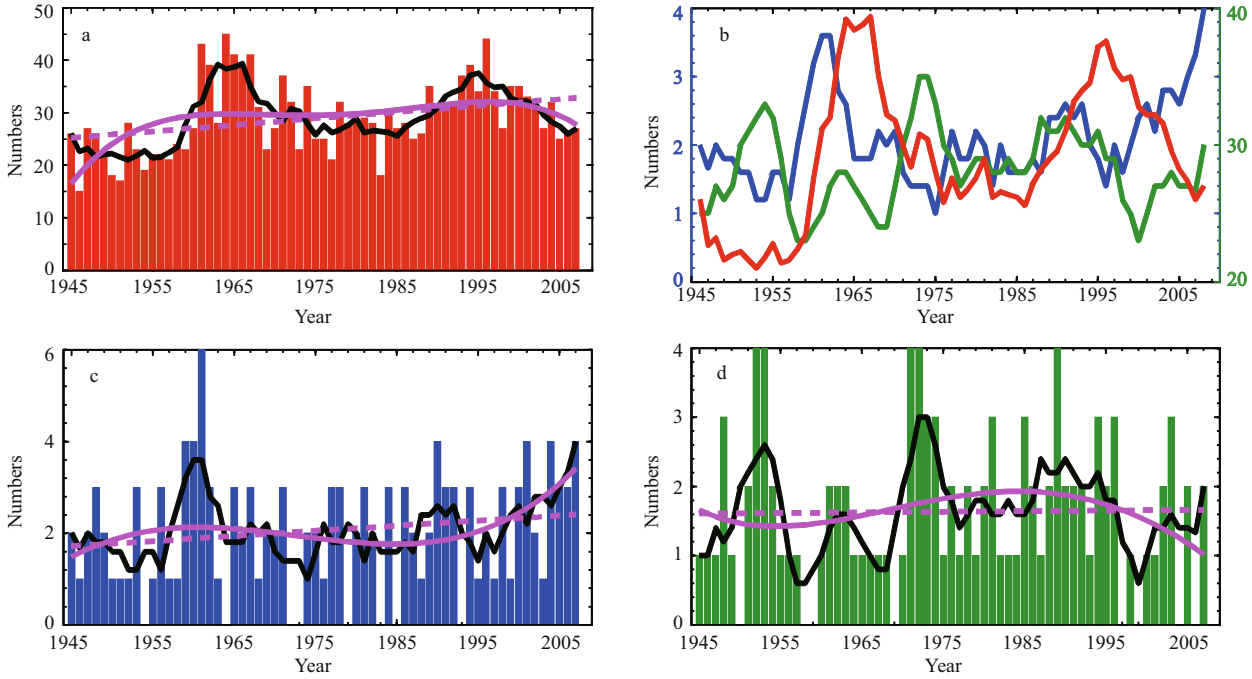

Fig.2 a. Number of tropical cyclones (TCs) formed annually in the western North Pacific (WNP). The black line denotes the 5-a running mean, the solid purple line is the fourth-order fit to the data, and the dashed purple line is the linear trend; b. Five-year running means of TCs formed in the WNP (red), TCs traversing Taiwan Island (blue), and TCs traversing Hainan Island (green); c. As in (a), but for TCs traversing Taiwan Island; d. As in (a), but for TCs traversing Hainan Island

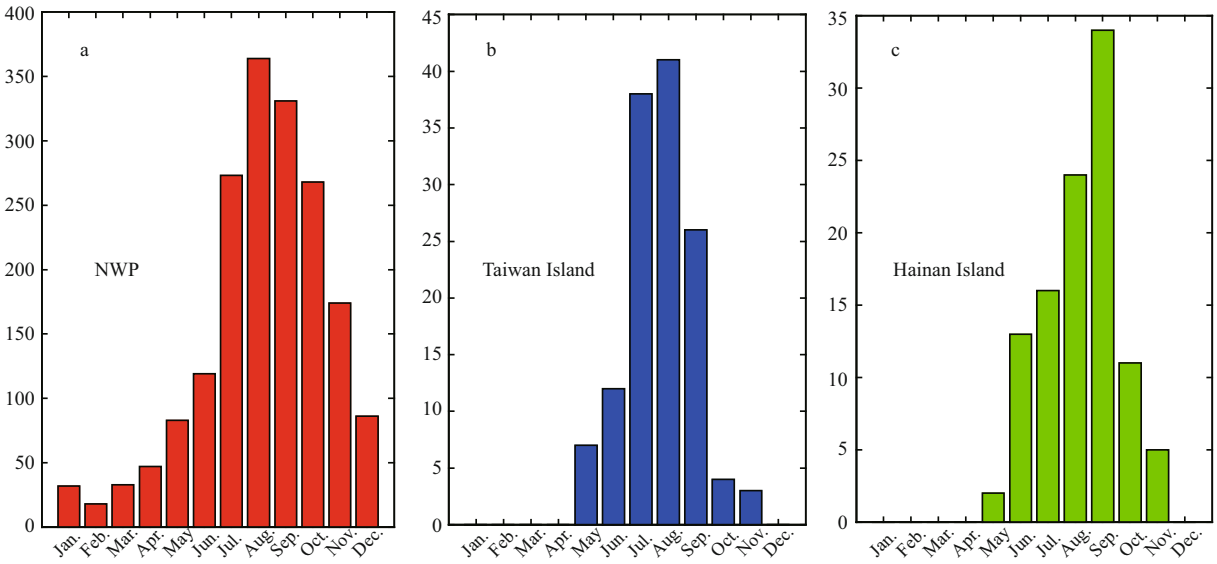

Fig.3 Monthly mean frequencies of tropical cyclones (a) forming in the WNP, (b) traversing Taiwan Island, and (c) traversing Hainan Island

when cyclone activity over the province of Guangdong is high, it tends to be low over the province of Fujian, and vice versa. This may be because TCs traversing the TH islands are primarily affected by shifts between two different positions of the prevailing TC track in the WNP; when the TC tracks shift westward, the occurrence of TCs increases over subtropical East Asia and decreases over the SCS (Wu et al., 2005).

The monthly frequency of the occurrence of TCs in the WNP and TH islands has also been counted separately (Fig.3). TCs traverse the TH islands between May and November, and especially between July and

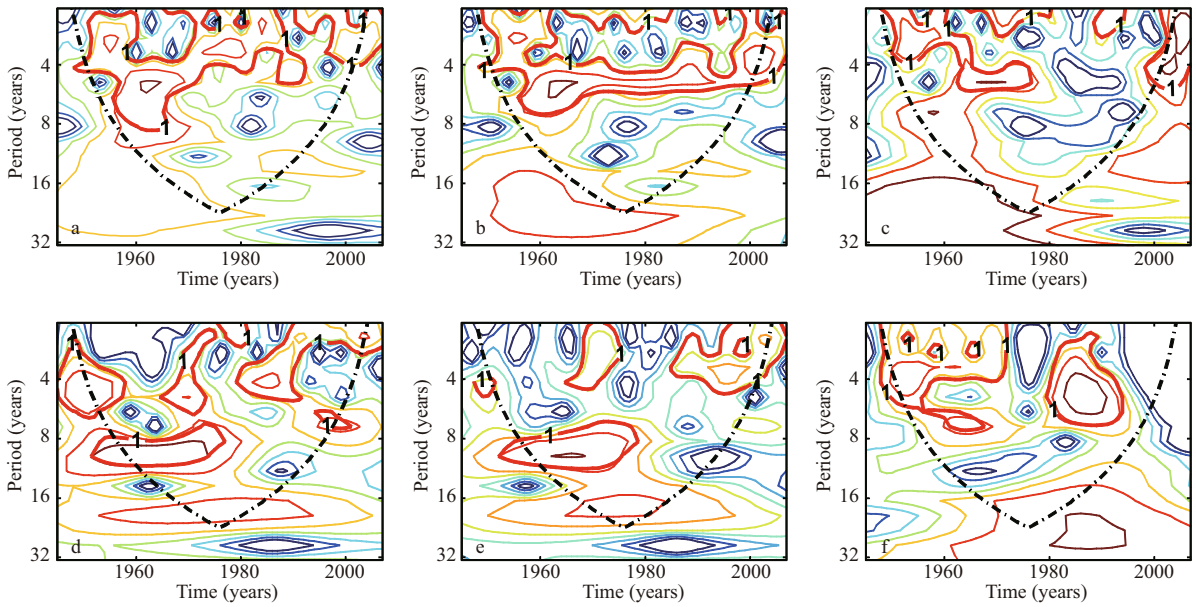

Fig.4 Wavelet power spectrum for the frequency of (a) all tropical cyclones (TCs), (b) total typhoons, and (c) intense typhoons traversing Taiwan Island

d–f as in a–c but for TCs passing Hainan Island.

September. 83% of TCs traversing Taiwan Island and 89% of TCs traversing Hainan Island occur during the summer monsoon season (June–September). Ren (2008) reported a similar result for the shorter period of 1951–2004. TC genesis in the WNP region spans the entire year, but is concentrated in July-September.

The 5-year-running-mean and fourth-order-fit lines shown in Fig.2 indicate that the frequency of TCs forming in the WNP varies on interannual and interdecadal timescales. The frequency of TCs traversing the TH islands appears to vary on interannual, rather than interdecadal scales.

3.2 Wavelet analyses

A wavelet analysis has been applied to the time series of the frequency of TCs traversing the TH islands to better characterize the periods at which these time series oscillate. Figure 4 shows the normalized wavelet power spectrum. The red contour lines enclose regions in which statistical confidence exceeds 95%. For the total number of TCs passing Taiwan Island (Fig.4a), most of the power is concentrated at timescales of 2–8 years. The 4–8 year timescale is particularly prominent from 1955 to 1976. Chan (2009) examined variations in TCs making landfall over East Asia, and reported a concentration of power at timescales of 2–8 years. The strength of the signal at these timescales indicates that TC activity is likely to be modulated by ENSO variability (Goh et al., 2010). For typhoons traversing Taiwan Island, the significant regions are clustered at timescales of 4–7 years during almost the entire analysis period (Fig.4b). This result indicates that the frequency of typhoons traversing Taiwan Island oscillates at a quasi-5-year period. A band of concentrated power also occurs at timescales of 2–4 years around 1956. From 1955 to 1995, the dominant period for both landfalling TCs and landfalling typhoons decreased slightly, from approximately 8 years to approximately 4 years (Fig.4a, b). The frequency of intense typhoons traversing Taiwan Island oscillates at a 4-year timescale during 1953–1963, and at a quasi-5-year timescale during 1964–1977.

The variations in the frequencies of TCs, typhoons, and intense typhoons traversing Hainan Island are apparent in Fig.4. From 1957 to 1981, the power is concentrated at timescales of 8–12 years for both TCs and typhoons traversing Hainan Island. This result indicates that the frequency of TCs and typhoons traversing Hainan Island oscillates at the decadal timescale during 1957–1981. This frequency also oscillates at a timescale of 2–4 years during the periods 1965–1975 and 1985–2000 (Fig.4d, e). Landfall of intense typhoons on Hainan varies on timescales of 2–5 years during 1947–1974 and 2–8 years during 1980–1995. A small area of strong power indicates that landfall of intense typhoons on

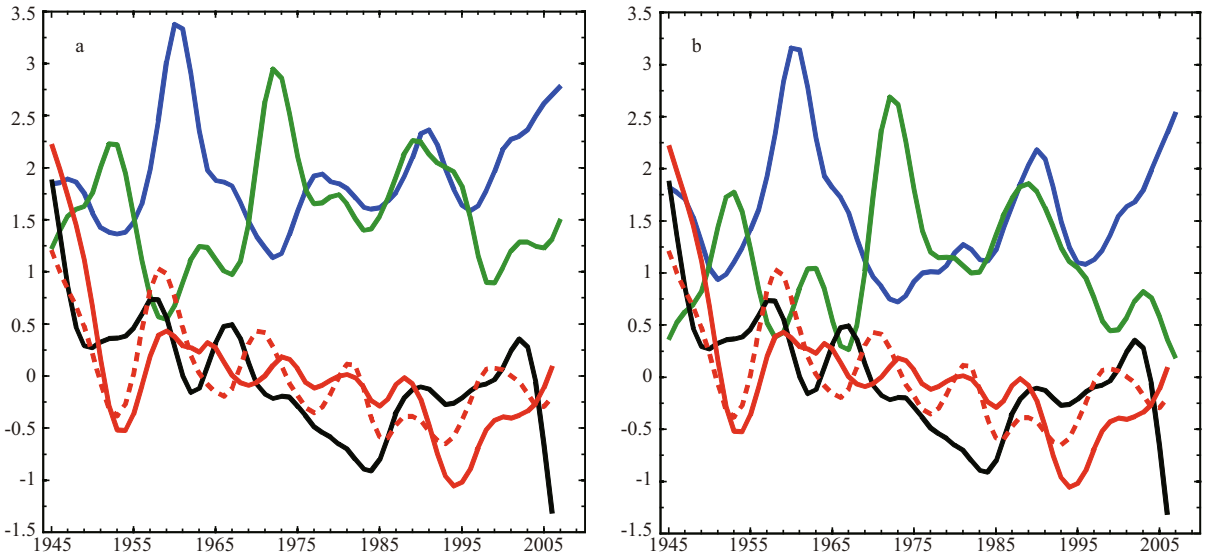

Fig.5 a. South China Sea Summer Monsoon (SCSSM) index (red solid), East Asia Summer Monsoon (EASM) index (red dash), South Asia Summer Monsoon (SASM) index (black), frequency of TCs traversing Taiwan Island (blue), and frequency of TCs traversing Hainan Island (green). All the time series have been processed with a Gaussian-type filter. The left ordinate corresponds to the index value and the right ordinate to the number of TCs; b. Same as (a), but for total typhoons

Hainan also oscillates at a quasi-7-year timescale around 1956.

3.3 Relationships with EASM, SCSSM, and SASM

A Gaussian-type low pass filter has been used to remove noise signals, which means that the correlation analysis for the frequency of TCs traversing the TH islands, and the EASM, SCSSM, and SASM based on the smoothed time series, is more reliable than on the original time series. This filter also strengthens the anti-correlation between the frequency of TCs traversing Taiwan Island and the frequency of TCs traversing Hainan, as the correlation coefficient decreases from -0.34 to -0.58. Figure 5 shows that the monsoon indices trend downwards throughout the analysis period with rates of: -0.015 for the EASM index, -0.023 for the SCSSM index, and -0.019 for the SASM index. These trends are removed before evaluating the relationships between the monsoon indices and the frequency of TCs traversing the TH islands. Tables 1 and 2 list the correlation coefficients between the frequency of TCs and typhoons passing the TH islands and the EASM index, the SCSSM index, and the SASMI index. The results of statistical significance test marked in tables are based on the effective degrees of freedom of the Gaussian-type filtered time series by the Student's *t*-test. As seen from Table 1, the EASM index and the number of TCs traversing Taiwan Island are positively correlated

Table 1 Summary of the correlation coefficients between the frequency of tropical cyclones (TCs) traversing the Taiwan Island and Hainan Island, and EASM SCSSM, and SASM indices

	EASMI	SCSSMI	SASMI
Taiwan Island TCs	0.40**	0.03	0.41**
Hainan Island TCs	-0.11	0.26*	-0.25*

* denotes statistical significance at the 90% confidence level;
** denotes statistical significance at the 95% confidence level.

Table 2 As in Table 1, but for typhoons

	EASMI	SCSSMI	SASMI
Taiwan Island typhoons	0.28**	-0.06	0.33**
Hainan Island typhoons	-0.09	0.05	-0.39**

* denotes statistical significance at the 90% confidence level;
** denotes statistical significance at the 95% confidence level.

(correlation coefficient of 0.40). This result is consistent with previous conclusions, which state that TCs occur more frequently during strong monsoon years (Sun, 2003; Gao et al., 2008). By compositing the 850-hPa geopotential height field for the ten strongest- and weakest-EASM years (Fig.6), we found that the subtropical high in the WNP is enhanced and displaces southwestwards in strong EASM years, which favors TC genesis in the WNP transferring northwestwards straight towards Taiwan Island because of the southeasterly wind to the west of the high center ('H' in Fig.6). In addition, there exists an

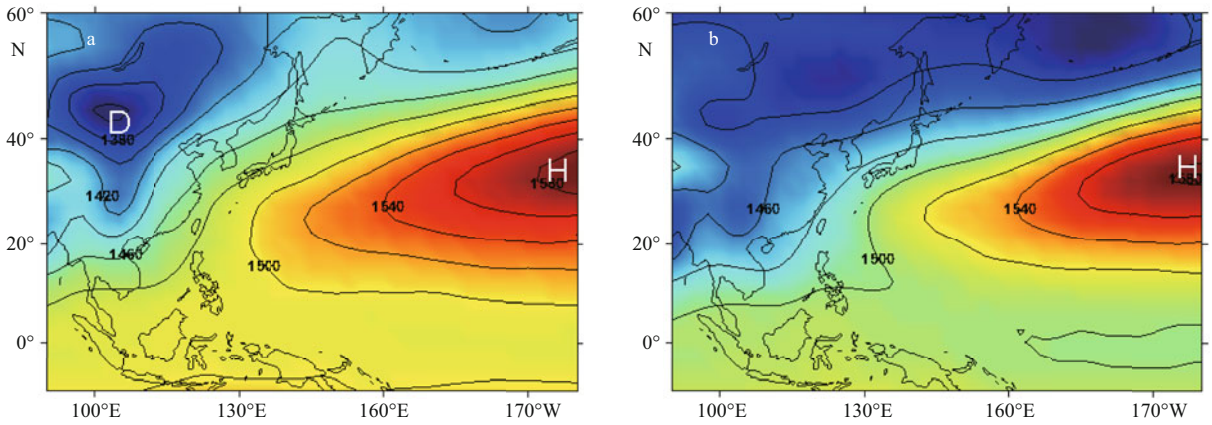

Fig.6 a. Composite 850-hPa geopotential height field for the ten strongest EASM years; b. Same as (a) but for the weakest EASM years

'D' represents the low-pressure center; 'H' is the high-pressure center.

enhanced low-pressure center ('D' in Fig.6) over the mainland with a southwesterly wind to the east of the low center, which can advance TCs in the SCS towards Taiwan Island. However, Chen et al. (2010) and Chen and Chen (2011) demonstrated that recently TC- and monsoon-induced rainfall tends to vary reversely in Taiwan Island on both interannual and interdecadal timescales. The rainfall induced by TCs and the monsoon in Taiwan Island is not only based on the frequency of TCs landfall and the intensity of the monsoon system, but also on the TCs strength and the local and environmental circulation in and around Taiwan Island; such as the anomalous cyclone over the island or to the southeast, or the anomalous Pacific subtropical high over the WNP, which may be the reason for the inconsistent findings. The SCSSM impacts the frequency with which TCs traverse Hainan Island (correlation coefficient of 0.26, significant at the 90% level), but appears to have little impact on the frequency of TC landfall over Taiwan Island. By contrast, the SASM is significantly positively correlated with TCs traversing Taiwan Island (correlation coefficient of 0.4), but negatively correlated with TCs traversing Hainan Island (correlation coefficient of -0.25). The compositions of the 850-hPa geopotential height field for the ten strongest- and weakest-SASM years are the same as in Fig.6 and have been omitted. The results for typhoons traversing the TH islands are similar, except that the SASM is associated more closely with the number of typhoons making landfall over Hainan Island. The mechanisms underlying why the EASM, SCSSM and SASM have a differing influence over TCs traversing the TH islands will be explored further in future work.

4 SUMMARY

The frequency of TCs traversing the TH islands and forming in the WNP was counted for the years 1945–2007, and interannual and interdecadal variations in this frequency were identified. Relationships between the frequencies of TCs and typhoons traversing the TH islands and the EASM, SCSSM, and SASM were also explored. The major results are as follows:

1. The frequency of TCs traversing Taiwan Island is anti-correlated with the frequency of TCs traversing Hainan Island, with a correlation coefficient of -0.34 (-0.58 when a Gaussian-type filter is applied). When the number of TCs making landfall on Taiwan Island is enhanced, the number of TCs making landfall on Hainan is reduced, and vice versa;

2. The number of TCs formed in the WNP is significantly positively correlated with the number of TCs making landfall on Taiwan Island (correlation coefficient of 0.23), but is not significantly correlated with the number of TCs making landfall on Hainan;

3. The number of TCs traversing Taiwan Island varies interannually on a 2–8 year timescale during the entire analysis period, especially for typhoon-strength TCs. However, the number of TCs traversing Hainan Island varies on both interannual and interdecadal (8–12 years) timescales before 1981;

4. The SCSSM plays a crucial role in determining the number of TCs traversing Hainan Island, but does not play an important role in determining the number of TCs traversing Taiwan Island. In contrast, the SASM appears to be related to both the number of TCs traversing Taiwan Island (correlation coefficient of 0.41) and the number of TCs traversing Hainan

(correlation coefficient of -0.25). In addition, the frequency of TC landfall on Taiwan Island increases during enhanced EASM years with a correlation coefficient of 0.4 at 95% significant level.

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