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Effects of the East Asian Summer Monsoon on Tropical Cyclone Genesis over the South China Sea on an Interdecadal Time Scale

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ABSTRACT

Tropical cyclone (TC) genesis over the South China Sea (SCS) during 1965–2004 was analyzed. The locations of TC genesis display evident seasonal changes, with the mean position of formation situated north of 15°N in summer (June–July–August) and south of 15°N in autumn (September–October–November). The TC genesis in summer underwent dramatic interdecadal variations, with more and less TC frequency during 1965–1974/1995–2004 and 1979–1993, respectively. In contrast, a significant interannual variation of TC genesis with a period of ∼4 years was observed in autumn.

This study investigated the relationship of SCS TC genesis to the East Asian jet stream (EAJS) and the western North Pacific subtropical high (WNPSH) on an interdecadal time scale. Analysis and comparison of the impacts of the EAJS and the WNPSH on vertical wind shear changes indicate that changes in the WNPSH and EAJS intensity rather than EAJS meridional location are responsible for changes in TC genesis on an interdecadal time scale. Corresponding to a weaker EAJS, anomalous Rossby wave energy at upper levels displays equatorward propagation at midlatitudes and poleward propagation in the subtropics. This induces anomalous convergence and divergence of wave activity fluxes in East Asia around 30°N and the SCS, respectively. The anomalous divergence of wave activity fluxes reduces easterlies at upper levels over the SCS, which is favorable to TC genesis.

Key words: tropical cyclone, subtropical jet stream, South China Sea

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1. Introduction

As a marginal sea, the South China Sea (SCS) is located in Southeast Asia roughly between the equator and 22°N and from 105°E to 120°E. The SCS is a region with a high frequency of tropical cyclone (TC) genesis (Camargo et al., 2007; Wang et al., 2007), and much effort has been given to studying TC activity over the SCS (Lee et al., 2006; Zuki and Lupo, 2008; Goh and Chan, 2009; Kim et al., 2010). Recently, Wang et al. (2009c) suggested that TCs over the SCS might greatly influence the seasonal variabil-

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ity of large-scale and mesoscale SCS ocean circulations.

TC genesis over the SCS shows climate variability on multiple time scales. Because the SCS is under its influence (Ding et al., 2004), the seasonal change of TC genesis location over the SCS is largely attributed to the East Asian monsoon (Wang et al., 2007). Many studies have demonstrated that the interannual variability of TC genesis over the SCS is to some extent associated with El Niño-Southern Oscillation (ENSO; Lee et al., 2006, Camargo et al., 2007, Wang et al., 2007). The frequency of TC genesis in boreal winter is much greater during La Niña (Wang et al., 2007). Zuki and Lupo (2008) revealed that there is more TC activity over the southern SCS in La Niña years and less during El Niño years during 1960–2006. Although extensive studies on the variability of TC activity have been reported, relatively less research effort has been spent on the long-term variability of the frequency of TC genesis over the SCS. Lee et al. (2006) suggested an increasing trend of annual TC activity over the SCS. Recently, Kim et al. (2010) indicated a dipole oscillation of boreal summer TC genesis between the Philippine Sea and the northern SCS that is characterized by an obvious interdecadal variability. The explanation for the interdecadal variation of TC genesis over the SCS is still an open issue. Goh and Chan (2009) suggested that it is related to Pacific Decadal Oscillation (PDO). The positive phase of the PDO generally favors less TC genesis and the negative phase generally favors more TC genesis. Kim et al. (2010) demonstrated that the decadal variation of the anomalous zonal SST gradient associated with ENSO Modoki events could force and modulate decadal patterns of TC genesis over the Philippine Sea and the northern SCS.

Because of their proximity, the variability of TC genesis over the western North Pacific (WNP) could help to explain that over the SCS. Within the WNP, TC activity is variable on an interdecadal time scale (Chan and Shi, 1996; Matsuura et al., 2003; Ho et al., 2004; Chan, 2006). Yumoto and Matsuura (2001) suggested that the variability of SST in the Pacific and of large-scale atmospheric circulation are the main causes of the interdecadal variability of TC activity over the WNP. The interdecadal changes in typhoon tracks over the WNP are attributed to the PDO signal (Liu and Chan, 2008). Matsuura et al. (2003) attributed the interdecadal variability of TC activity over the WNP to long-term variations in atmosphere–ocean coupling in the North Pacific tropical. Wu et al. (2009) found that the East Asian summer monsoon (EASM) could greatly influence TC activity over the WNP. Lee et al. (2006) reported a linkage between the mei-yu front in East Asia and TCs over the SCS in the months of May and June during 1972–2002. The westward expansion of the western North Pacific subtropical high (WNPSH) in the late 1970s, which is one of the components of the EASM, may have resulted in the interdecadal changes in typhoon tracks over the WNP (Ho et al., 2004). The boreal summer Pacific-Japan (PJ) teleconnection pattern related to the EASM variability, an anomalous meridional dipole circulation between the subtropics and mid-latitude over the WNP (Nitta, 1986; Chan and Zhou, 2005; Zhou and Chan, 2005, 2007; Zhou et al., 2006, 2007a, b; Yuan et al., 2008; Wang et al., 2009a,b; Gu et al., 2009; Zhou et al., 2009a,b), has a significant influence on TC activity over the WNP (Choi et al., 2010). The genesis locations and tracks of TCs over the WNP are obviously different during positive and negative PJ phases. These results of previous studies motivated us to study the interdecadal variations of TC genesis over the SCS in terms of the EASM.

In this study, evidence of interdecadal change in TC genesis over the SCS was gathered, and the impacts of the EASM were investigated. The paper is organized as follows. Section 2 introduces datasets used in the paper. Section 3 shows the climatology of TC genesis over the SCS. The interdecadal variations of TC genesis over the SCS are examined in section 4. In section 5, the relationships between the EASM and TC genesis over the SCS are given, and a possible mechanism of the EASM impact on the TC genesis over the SCS on an interdecadal time scale is presented. Discussion and summary are presented in section 6.

2. Datasets

Data regarding TC genesis over the South China Sea since 1858 were acquired from the website of the International Best Track Archive for Climate Stewardship (IBTrACS) Project (http://www.ncdc.noaa/gov/oa/ibtracs/). The domain of the SCS was selected to be 0°–22°N, 105°–120°E. In this study, TC genesis occurred when the position first of maximum sustained wind speed >34 knots recorded in the IBTrACS dataset fell within this domain. Although the TC data from the 20th century are available, the data reliability is rather low in the pre-satellite era (i.e., prior to the early 1960s). To avoid this data problem, only the TC data in the weather satellite era (1965–2004) was used in this study, which is similar to the work of Wang and Chan (2002) and Kim et al. (2010). We also used the monthly horizontal wind, geopotential height, and air temperature data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset

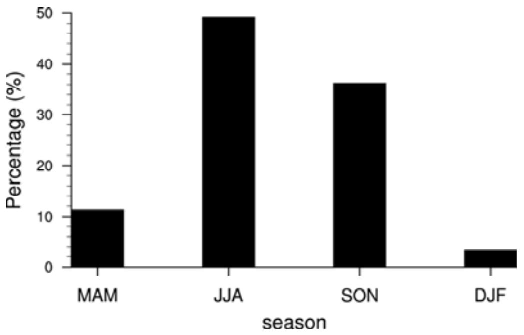

Fig. 1. The seasonal percentage of TC genesis over the SCS (0°–22°N, 105°–120°E) during 1965–2004.

(Kistler et al., 2001) from 1965 to 2004.

3. Climatology of TC genesis over the SCS

The active TC season in the SCS is from May to November (Lee et al., 2006; Wang et al., 2007). Figure 1 shows the seasonal variations of TC genesis over the SCS (0°–22°N, 105°–120°E) during 1965–2004. About half of TCs (49.2%) form in boreal summer (June–July–August, JJA). Following summer, 36.3% of TCs occur in autumn (September–October–November, SON). Less frequent TC genesis occurs in winter and spring, during which only ∼3% and 11% of TCs occur, respectively. Figure 2 illustrates the location of TC genesis over the SCS during summer and autumn. As shown in Fig. 2, ∼82% of TCs form north of 15°N in summer, and 66.7% of TCs form south of 15°N in autumn, which is similar to results of previous studies (cf., Lee et al., 2006; Wang et al., 2007). This latitudinal variation has been suggested to closely relate to the meridional shift of the East Asia monsoon (Wang et al., 2007). Because of this seasonal change in genesis location of TCs over the SCS, in this study we separated the two seasons of summer and autumn, which is different than previous studies that analyzed the SCS TC activity during the entire TC season (May through November) (Lee et al., 2006; Zuki and Lupo, 2008; Goh and Chan, 2009; Kim et al., 2010).

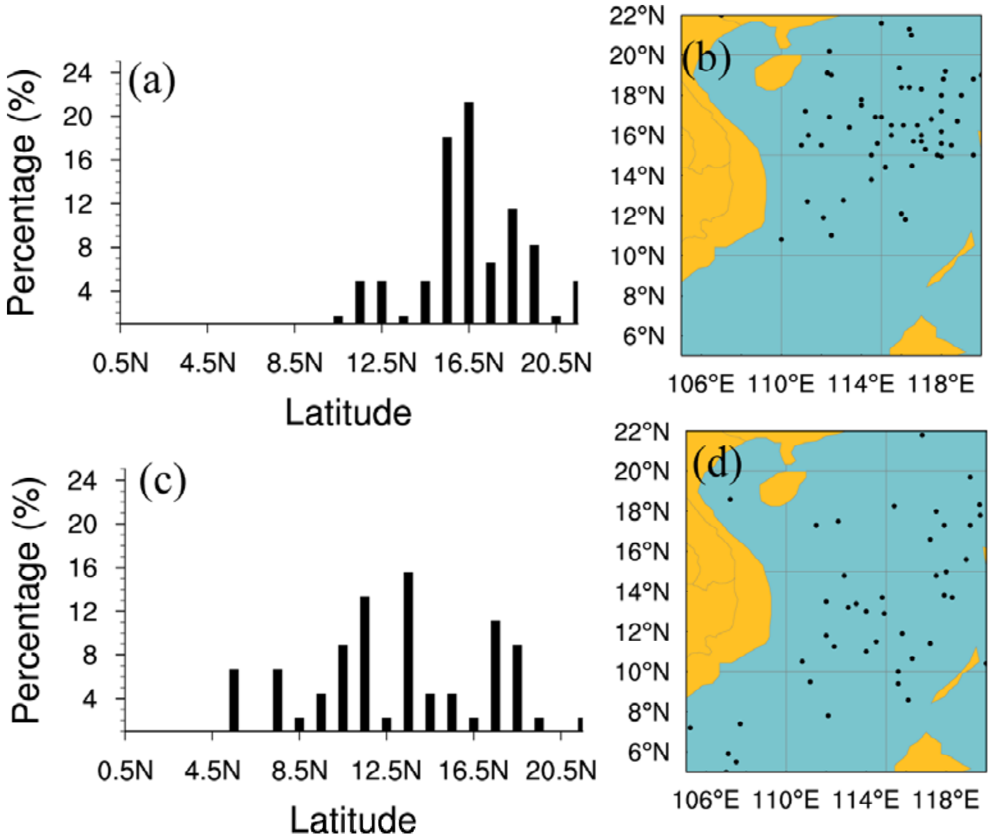

Fig. 2. The latitudinal distribution (average per 1° latitude, 16.5°N means between 16° and 16.9°N) of TC genesis over the SCS in JJA (a) and SON (c). (b) and (d) are the TC genesis locations over the SCS in JJA and SON.

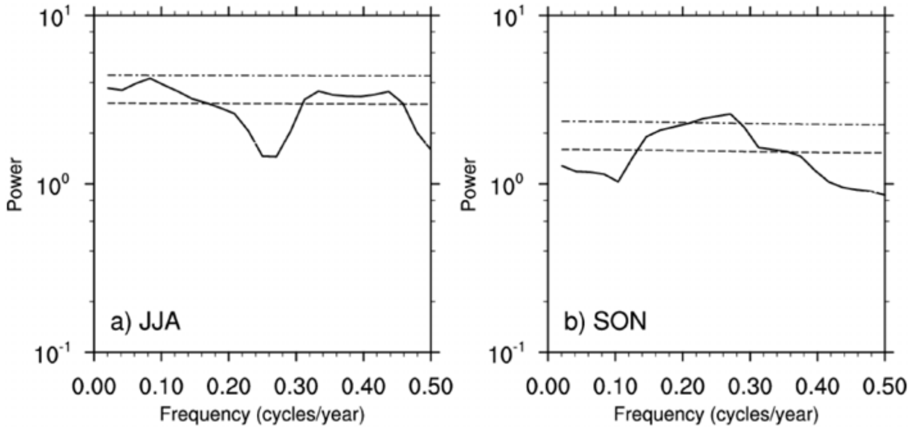

Fig. 3. The spectrum analysis for JJA-mean (a) and SON-mean (b) TC genesis, respectively. The dashed and dash-dotted lines represent Markov red noise spectrum and 90% confidence level.

4. Interdecadal changes in TC genesis over the SCS

The temporal variations of the SCS TC genesis during summer and autumn were analyzed using spectral analysis (Fig. 3). The spectral analysis results of the SCS TC genesis in summer display the spectral peak in an ∼10-year period (Fig. 3a). However, the frequency of TC genesis over the SCS in SON displays a significant (>90% level) interannual variability with a ∼4-year period (Fig. 3b). Therefore, the interdecadal changes in TC genesis over the SCS occur during summer. Most summer TC genesis occurs north of 15°N (Figs. 2a and b); the time series of summer TC frequency anomalies over the northern SCS are shown in Fig. 4a. The variations of 11-yr running means indicate that TC genesis frequency is above normal prior to the early 1970s and below normal after the mid-1970s (during 1973–1994).

To confirm the interdecadal changes in summer, the Lepage test statistic (a nonparametric, distribution-free, two-sample test for significant difference between two samples) was used to identify the statistical significance of interdecadal changes in this study. The Lepage statistic was certified to be more powerful and useful than other tests (i.e., Wilcoxon-Mann-Whitney test, t-test, chi-squared test, and others) by Hirakawa (1974), and thus it has been applied to climate studies by many researchers (e.g., Yonetani, 1992; Liu et al., 2011). More details about the Lepage test can be found in Yonetani (1992).

Because most summer SCS TC genesis is located in the north of 15°N (Fig. 2a), the Lepage statistic was applied to the time series of TC genesis in the northern SCS during summer. As shown in Fig. 4b, the values with >95% confidence level occur during 1974 and the mid-1990s, indicating that summer TC genesis changes remarkably on an interdecadal time scale during this season. In summary, TC genesis over the SCS changes seasonally in terms of location and temporal variation. In summer (JJA), TCs form mostly north of 15°N and display significant interdecadal variations.

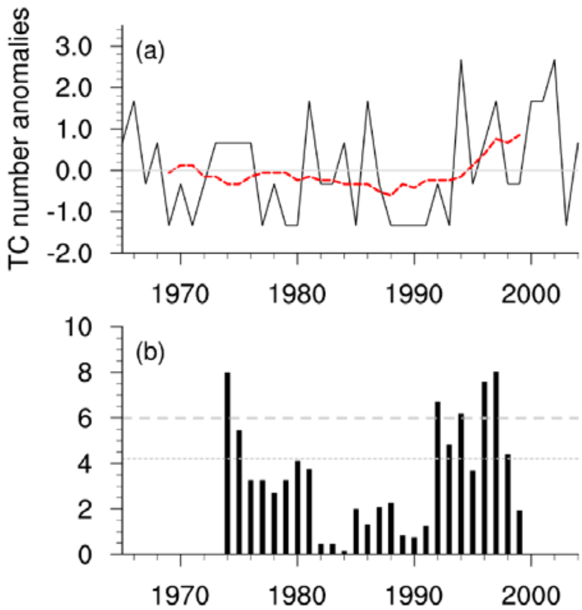

Fig. 4. (a) The time series of summer TC number anomalies (solid) and 11-yr means (dashed) over the northern South China Sea (north of 15°N); (b) The Lepage test statistics of the summer TC genesis over the northern South China Sea (north of 15°N). The dotted and dashed lines denote the Lepage test exceeding confidence level of 90% and 95%, respectively. The year (Yc) exceeding confidence level indicates that the 9-year mean TC genesis starting in Yc shows significant difference with that prior to the Yc.

In contrast, in autumn (SON) TCs occur frequently south of 15°N and show significant interannual variability. The temporal variations of TC genesis are distinct in summer and autumn. In this study, we focused on the variations of summer TC genesis over the SCS.

Figure 4b shows the significant interdecadal changes of summer TC genesis in the SCS during 1974 and the mid-1990s. In addition, the EASM underwent two major shifts in the late 1970s (Hu, 1997; Chang et al., 2000; Li et al., 2006; Zhou et al., 2007a, b, c; Zhou and Chan, 2007; Zhou et al., 2009a,b; Li et al., 2010) and 1993–1994 (Wu et al., 2010). Therefore, the time frames of 1975–1978 as well as 1994 were omitted. The analysis period was thus divided into TC genesis periods of more frequency (1965–1974 and 1995–2004) and less frequency (1979–1993) in summer. The annual mean frequencies of TC genesis in summer during 1965–1974, 1979–1993, and 1995–2004 are 1.9, 0.8, and 2, respectively. The changes of the annual means between 1965–1974 (and 1995–2004) and 1979–1993 are significant at the 95% confidence level using the Student's t-test. Our results are in agreement with the results of Lee et al. (2006), which suggested a possible increasing trend of annual TC frequency over the SCS during 1972–2002.

Chan (2009) pointed out that only in the Atlantic are thermodynamic factors responsible for the climate variations of intense TCs; in other ocean basins, the dynamic factors are much more dominant. Therefore, the primary dynamic control on the TC genesis suggested by Gray (1979) was addressed in this study to illustrate the large-scale circulations favoring TC genesis over the SCS (Fig. 5). According to Fig. 5a, the summer frequency of TC genesis over the SCS is related to the vertical wind shear over the northern SCS (north of 15°N); that is, the weaker vertical wind shear over the northern SCS tends to result in increasing TC genesis over the SCS. This significantly weaker vertical wind shear over the northern SCS is consistent with the above description of the summer TC frequently occurring north of 15°N. Simultaneously, the significantly negative vertical wind shear associated with summer TC genesis over the SCS also occurs across the mid-latitude of the East Asia (30°–40°N, 80°–150°E). The regression pattern of vertical wind shear in mid- and lower latitudes (Fig. 5a) is similar to a Rossby wave-like pattern, indicating that the vertical wind shear anomalies over the SCS seem to be related to mid-latitude processes, which is demonstrated in section 5. Choi et al. (2010) suggested that the PJ teleconnection pattern could greatly influence tracks of boreal summer TC over the WNP. Different from the regression of vertical wind shear (Fig. 5a), the summer frequency of TC genesis over the SCS does

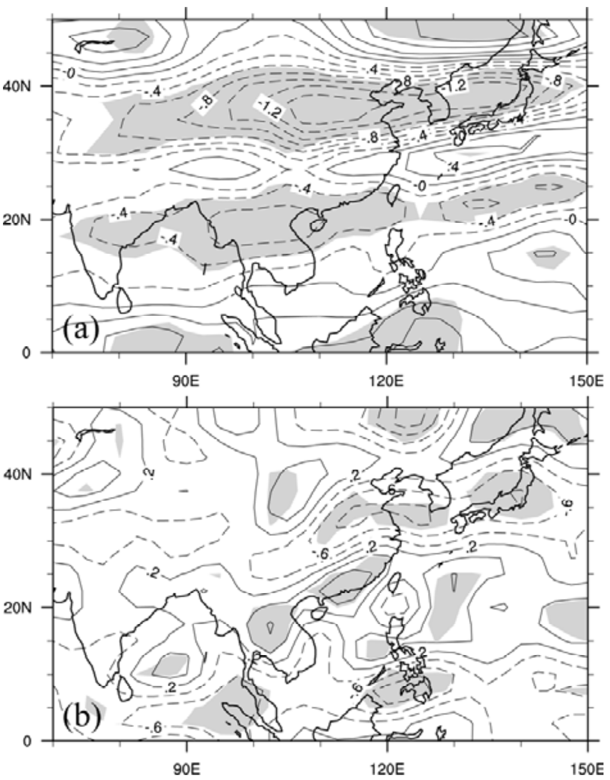

Fig. 5. The regression coefficients of the vertical wind shear (a) and the relative vorticity at 850-hPa (b) against the annual summer frequency of TC genesis over the SCS during 1965–2004. The vertical wind shear was calculated as the magnitude of the vector difference between wind at 200 hPa and 850 hPa. Shading denotes regions reaching the 90% confidence level.

not show significant relationship with the relative vorticity at 850 hPa (Fig. 5b), indicating that the lower-level relative vorticity contributes less to TC genesis over the SCS than does vertical wind shear. In addition, there was no significant signal in the regression of SST in the SCS with respect to summer TC genesis (figure not shown), which coincides with the results of Chan (2009). Therefore, the vertical wind shear could be considered to be the most important dynamic control on the change in TC genesis over the SCS.

To illustrate the interdecadal variations of TC genesis over the SCS, the differences of the vertical wind shear between periods of TC genesis of more frequency (1965–1974/1995–2004) and less frequency (1979–1993) are shown in Fig. 6. Here, we first computed the mean of 1965–1974 and 1995–2004, and then calculated the difference from the mean of 1979–1993. That is, the differences between 20-year means (1965–1974 and 1995–2004) and 15-year means (1979–1993) were calculated. The Student's t-test was used to estimate statistical significance. The pattern of difference

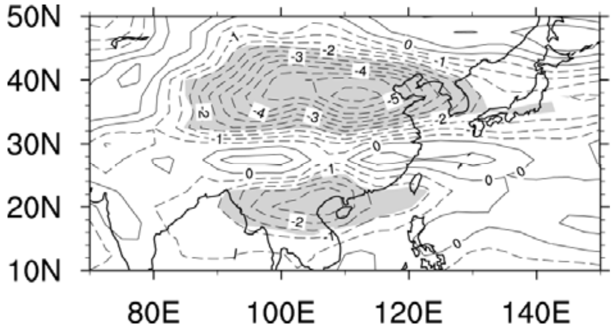

Fig. 6. The differences of 200–850 hPa vertical wind shear (unit: m s^{-1}) between summers of greater TC frequency (1965–1974/1995–2004) and less TC frequency (1979–1993). The shadings indicates areas that exceed 90% significant level.

on an interdecadal time scale reveals the significantly weaker vertical wind shear over the northern SCS and mid-latitude of the East Asia during the period with higher TC frequency over the SCS (Fig. 6), which is similar to the pattern shown in Fig. 5a. Notably, the vertical wind shear difference pattern between 1965–1974 and 1979–1993 is identical to that between 1995–2004 and 1979–1993 (figures not shown), both of which are similar to those shown in Fig. 6.

5. Effects of the East Asian summer monsoon

Many studies have suggested that the EASM system impacts TC activity over the WNP (Lee et al., 2006; Choi et al., 2010). The EASM exhibits interdecadal variations from the mid-1950s to the early 21st century, including southward shift of the East Asian Jet Stream (EAJS) and expansion of the WNPSH (Li et al., 2010). Therefore, a question arises as to whether there is a close linkage between the EASM and summer TC genesis over the SCS on an interdecadal time scale. To answer this question, we analyzed the relationships between TC genesis and the EASM, and we addressed distinct influences of EASM components on vertical wind shear over the SCS on an interdecadal time scale.

5.1 *Components of the EASM*

The EAJS is one important component of the EASM; it is largely associated with climate changes over East Asia (Lu, 2004; Li et al., 2006; Yu and Zhou, 2007; Zhang et al., 2008). To identify changes in the EAJS, empirical orthogonal function (EOF) analysis was applied to data of the summer zonal wind at 200 hPa, as in previous studies (e.g., Gong and Ho, 2003; Lu, 2004; Lin and Lu, 2005; Zhang and Guo, 2005; Zhang et al., 2008). The first leading mode (Fig. 7a) of upper-level zonal wind (explaining 34% variance) exhibits a meridional dipole structure with the zero line located around 40°N, consistent with previous results, implying that the summer EAJS undergoes meridional displacement (Gong and Ho, 2003; Lu, 2004; Lin and Lu, 2005; Zhang et al., 2008). The interannual and interdecadal variations of corresponding principal components (PCs) of the first leading mode are shown in Fig. 8; a positive value indicates poleward displacement. The 11-yr-mean PC of the first leading mode (PC1) shows evident interdecadal variation, shifting

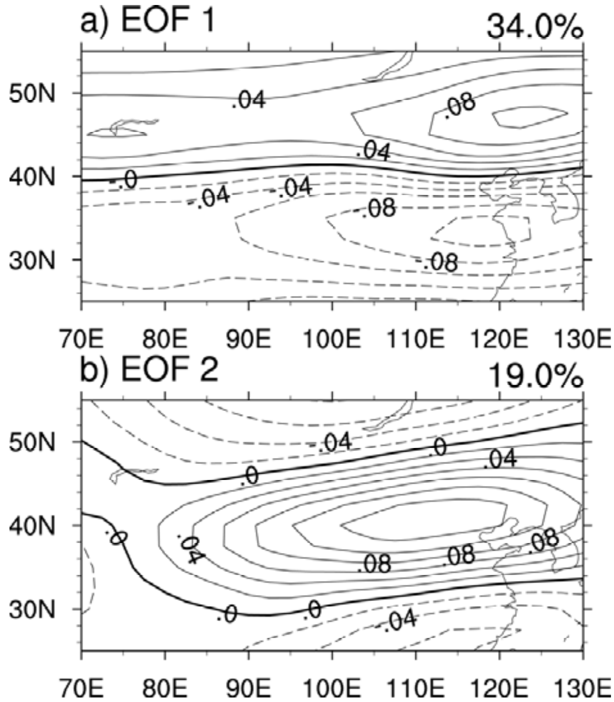

Fig. 7. Panels (a) and (b) show the first two leading EOF modes of summer zonal wind at 200-hPa in JJA.

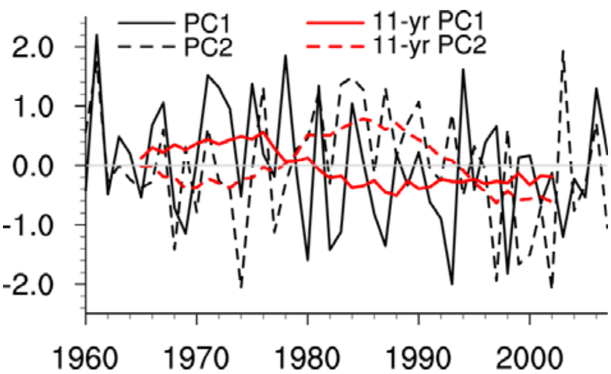

Fig. 8. The normalized corresponding principal components of the EOF modes in Fig. 5. The red lines are the 11-year means.

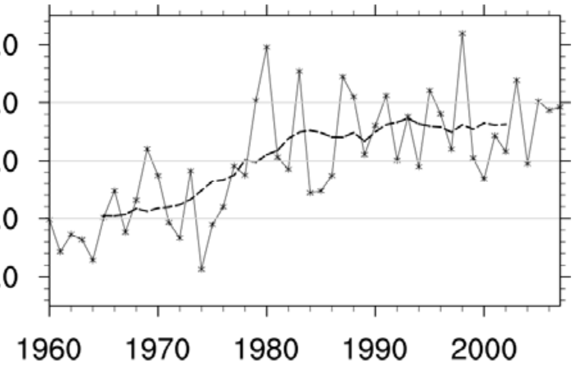

Fig. 9. The summer WNPSH index and its 11-year running average during 1960–2007.

equatorward since the late 1970s (Fig. 8). The second leading mode (PC2; explaining 19% of variance) shows a sandwich-like structure in the meridional direction, with positive loading in the region of 30°–45°N, 80°–130°E and two negative loadings to the south and north (Fig. 7b). Apparently, this pattern of the zonal wind at 200 hPa exhibits the EAJS intensity changes and also implies a strong trough-ridge system in the meridional direction over East Asia. PC2 also displays interdecadal changes, with stronger EAJS during 1979–1993 and weaker EAJS during 1965–1974 and 1995–2003 (Fig. 8). This result coincides with the results of Archer and Caldeira (2008), who showed that the wind speed over East Asia weakened during the summers of 1979–2001. In our study, PC1 and PC2 are regarded as the indices representing the changes in meridional location and intensity of EAJS, respectively. The WNPSH index, which is defined as the area mean (10°–30°N, 120°–140°E) 500-hPa geopotential height anomaly, was used to represent WNPSH changes (Sui et al., 2007). Figure 9 shows an interdecadal increase of the WNPSH index in the late 1970s, indicating a westward extension of the WNPSH.

5.2 *Relationships between the EASM components and TC genesis*

Comparing the correlation coefficients of SCS TC genesis with the EAJS, WNPSH, and the SCS SST (Table 1), the WNPSH and locations and intensity changes in the EAJS relate significantly to TC genesis over the SCS during 1965–2004, while the SCS SST data do not. Vertical wind shear is the most dominant dynamic control on TC genesis over the SCS (Figs. 5 and 6). Figure 10 shows the vertical wind shear patterns associated with the changes in the EAJS and the WNPSH. Although the WNPSH and location and intensity of the EAJS led to significant changes of vertical wind shear over the SCS, the associated vertical wind shear patterns showed some differences. Compared with Figs. 5a and 6, the significant regressed vertical wind shear against the EAJS meridional location (PC1) is centered over the central SCS, between 10°N and 17°N in the SCS (Fig. 10a), and that against the WNPSH is mainly located east of the SCS (east of 115°E, Fig. 10c). Only the regression pattern against EAJS intensity (PC2) displays a sandwich structure in mid-latitude and northern SCS (Fig. 10b), which is identical to that shown in Figs. 5a and 6. Given that the TC genesis over the SCS usually occurs over the northern SCS (north of 15°N) in summer (Fig. 2a), our hypothesis suggests that the interdecadal variations of TC genesis over the SCS can be largely attributed to the changes in intensity of EAJS, which leads to the dynamic control of vertical wind shear responsible for TC genesis.

5.3 *Intedecadal changes in relationships between the EASM components and TC genesis*

To clearly investigate the relationships of TC genesis over the SCS with the EAJS and WNPSH on an interdecadal time scale, Table 1 presents data related to these relationships in the periods of greater TC frequency (1965–1974, 1995–2003) and less TC frequency (1979–1993). Tropical cyclone genesis is significantly related to the EAJS meridional location during 1995–2004, to the EAJS intensity during 1965–1974 and 1995–2004, and to the WNPSH since the late 1970s. This implies that the effects of the EASM components on TC genesis are different on an interdecadal time scale. To determine the components of the EASM that most effectively influenced SCS TC genesis, the standardized regression coefficients calculated from partial regression coefficients were directly compared (Table 2); they represent the partial regression coefficients in units of standard deviation. As shown in Table 2, the changes in the EAJS meridional location contribute less to TC genesis over the SCS in each time period (1965–1974, 1979–1993, and 1995–2003) than those of EAJS intensity and WNPSH. The influence of the EAJS intensity was the largest during 1965–1974 and 1995–2004, whereas the effect of the WNPSH was strongest during 1979–1993. Notably, during the overall study period (1965–2004), the contribution of the EAJS intensity to TC genesis over the SCS was the largest (Table 2), which confirms our proposed hypothesis regarding the remarkable contribution of EAJS intensity to TC genesis. Lu (2004) has shown that the East Asian summer climate relates more significantly to the meridional location variations of the EAJS than to EAJS intensity. In our study, for summer TC genesis over the SCS, the effect of EAJS intensity variation is much more important.

Table 1. Correlation coefficients of TC genesis over the SCS with the EAJS meridional location (PC1), EAJS intensity (PC2), and WNPSH during 1965–2004 and summer SCS-averaged SST (10°–22°N, 110°–120°E) during 1965–2003. The bold italic font indicates that the value exceeds the 90% confidence level. Monthly UK Met Office's Hadley Centre's Sea Ice and SST (HadISST1) data (Rayner et al., 2003) for 1965 to 2003 were used.

	1965–1974	1979–1993	1995–2004	1965–2004 (for SST 1965–2003)
PC1	−0.16	0.33	***0.53***	***0.34***
PC2	***−0.52***	0.09	***−0.79***	***−0.48***
WNPSH	−0.05	***−0.45***	***−0.64***	***−0.37***
SCS SST	0.26	−0.26	−0.35	−0.08

Table 2. The standardized regression coefficients calculated from partial regression coefficients for regression of numbers of TC genesis over the SCS. The bold italic font indicates the largest coefficients in three variables.

	1965–1974	1979–1993	1995–2004	1965–2004
PC1	0.25	0.14	−0.12	0.24
PC2	***−0.7***	0.05	***−0.82***	***−0.42***
WNPSH	0.22	***−0.39***	−0.1	−0.1

It is well known that TC activity over the WNP (including the SCS) is largely related to WNPSH (Matsuura et al., 2003; Ho et al., 2004; Choi et al., 2010; Kim et al., 2010), which apparently has extended westward since the late 1970s (Fig. 9). When the WNPSH was centered east of 135°E during 1965–1974 (Fig. 11a, red and dashed contour), the frequency of TC genesis over the SCS was above normal and was less when the WNPSH reached ∼120°E during 1979–1993 (Fig. 11b, red contour). This result is consistent with the out-of-phase relationship between the location of WNPSH and TC numbers (Table 1). However, although the WNPSH extended westward during 1995–2004 as well as during 1979–1993 (Fig. 11a, red and solid contour), the frequency of TC genesis over the SCS was greater. Table 2 also shows that the contribution of WNPSH to TC genesis over the SCS was the largest during 1979–1993 and the least during 1965–1974 and 1995–2003. All of these results are indirect manifestations of the important influence of EAJS intensity on TC genesis over the SCS. Data listed in Table 3 highlights the changes in influence of the EAJS intensity and WNPSH on vertical wind shear over the SCS in the late 1970s with WNPSH extending westward. During 1979–1993 with stronger EAJS intensity (Figs. 8 and 11b; Table 3), the impact of the WNPSH on vertical wind shear over the SCS was larger, whereas after that, the impact of weaker EAJS (Figs. 8 and 11a) on vertical wind shear was larger than that of the WNPSH.

Table 3. The standardized regression coefficients calculated from partial regression coefficients for regression of area-averaged vertical wind shear average over (15°–22°N, 110°–120°E). The bold italic font indicates the largest coefficients in two variables.

	1979–1993	1995–2004
PC2	−0.08	***0.43***
WNPSH	***0.3***	−0.1

5.4 *Physical mechanism of how EAJS intensity influences TC genesis*

As previously demonstrated, the contribution of EAJS intensity to TC genesis over the SCS is crucial. The associated physical mechanism is presented in this subsection. The vertical wind shear patterns related to TC genesis over the SCS (Fig. 5a) and associated with EAJS intensity (Fig. 10b) show a Rossby wave-like pattern, which inspired us to analyze the aspects of planetary Rossby wave energy propagation (Wang et al., 2011). Here, wave activity flux was used to identify three-dimensional (3D) propagation and the source of stationary wave activity (Plumb, 1985). The wave activity flux, F_s (Plumb, 1985), is given as

$$F_s = p\cos\phi \times \begin{pmatrix} v'^2 - \dfrac{1}{2\Omega a\sin 2\phi}\dfrac{\partial(v'\Phi')}{\partial\lambda} \\ -u'v' + \dfrac{1}{2\Omega a\sin 2\phi}\dfrac{\partial(u'\Phi')}{\partial\lambda} \\ \dfrac{2\Omega\sin\phi}{S}\left[v'T' - \dfrac{1}{2\Omega a\sin 2\phi}\dfrac{\partial(T'\Phi')}{\partial\lambda}\right] \end{pmatrix}$$

where

$$S = \frac{\partial\hat{T}}{\partial z} + \frac{\kappa\hat{T}}{H}$$

is the static stability, the caret indicates an areal average over the area north of 20°N, p is the pressure, a is the radius of the earth, ϕ and λ are latitude and lon-

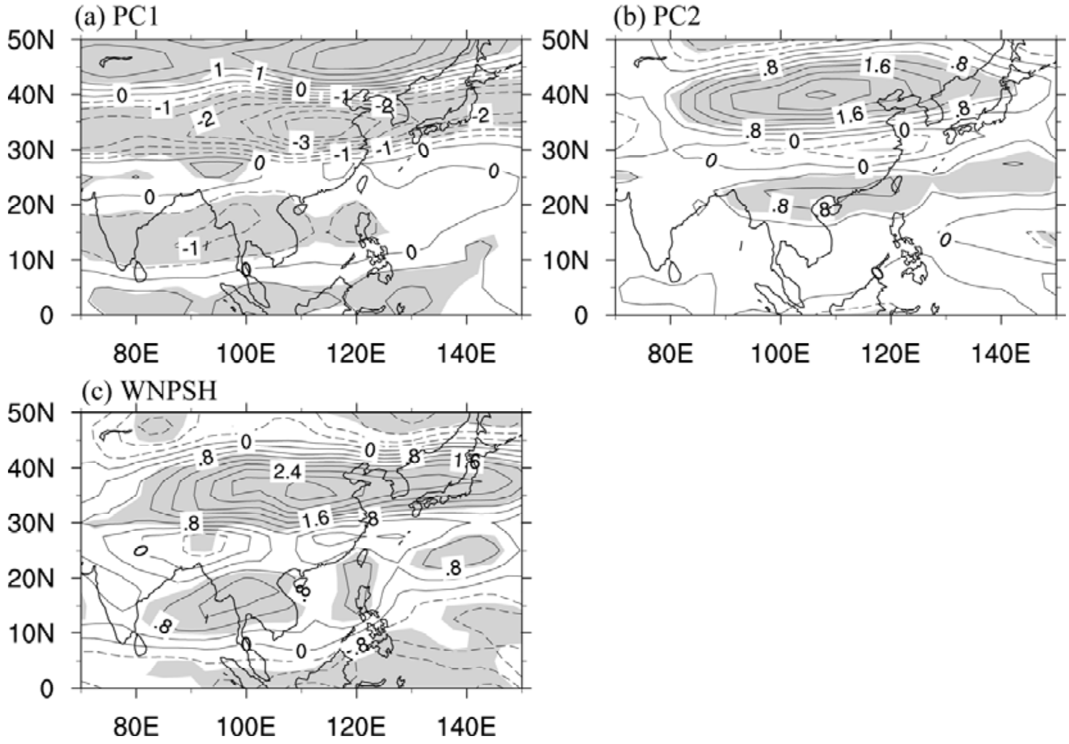

Fig. 10. The regression coefficient of summer vertical wind shear with respect to PC1 (a), PC2 (b) and WNPSH (c) during 1965–2004. The shading indicates areas that exceed the 90% confidence level.

gitude, Φ is geopotential height, and Ω is the Earth's rotation rate. The prime denotes deviation from the zonal mean.

Figure 11 shows 200-hPa wave activity flux and its horizontal divergence during periods of greater TC frequency (1965–1974 and 1995–2004) and lesser TC frequency (1979–1993). It is obvious that the EAJS intensity is much weaker in periods of more frequent TC genesis than in periods of less frequent TC genesis (Figs. 11a and b). Because the mid-latitude westerlies act as a Rossby wave-guide (Hoskins and Ambrizzi, 1993), the wave energy propagates along the westerlies eastward to East Asia (Figs. 11a and 11b). The differences of wave activity flux and its divergence between periods of greater and lesser TC frequency are shown in Fig. 11c. The anomalous wave activity flux at 200 hPa propagates equatorward in mid-latitudes and poleward in subtropical regions between 100°E and 120°E during periods of more frequent TC genesis, which could result in significant convergence and divergence anomalies of wave activity flux around East Asia at 30°N and the northern SCS. The propagation of Rossby waves entails a momentum flux directed opposite the wave motion. As a result, zones of mean wave dissipation (and thus of wave activity convergence) are also regions of zonal-mean deceleration. Therefore, the anomalous divergence of wave activity flux over the SCS around 20°N, indicating the dissipation of wave energy, could lead to weakening of 200-hPa easterlies over the SCS, and thus the vertical wind shear is weakened in favor of TC genesis over the SCS. The regression pattern of vertical wind shear with respect to the EAJS intensity in Fig. 12 is similar to that in Fig. 11c except with reverse signs, indicating that the large-scale circulation changes associated with EAJS intensity are mostly responsible for the interdecadal variations of TC genesis over the SCS. According to Figs. 11 and 12, the weaker EAJS could result in the significant divergence anomalies of wave activity flux in the upper troposphere over the SCS during 1965–1974 and 1995–2004; thus the zonal-average easterlies decrease in the upper troposphere over the SCS. Therefore, the vertical wind shear over the SCS tends to be attenuated, and thus more TC genesis is observed over the SCS.

Rossby wave accumulation in the troposphere may be an important mechanism for the development of tropical synoptic-scale disturbances (Sobel and Bretherton, 1999). However, their wave sources have not been conclusively identified, though planetary-scale equatorial Rossby waves have been diagnosed (Wheeler and Kiladis, 1999). Our results suggest that

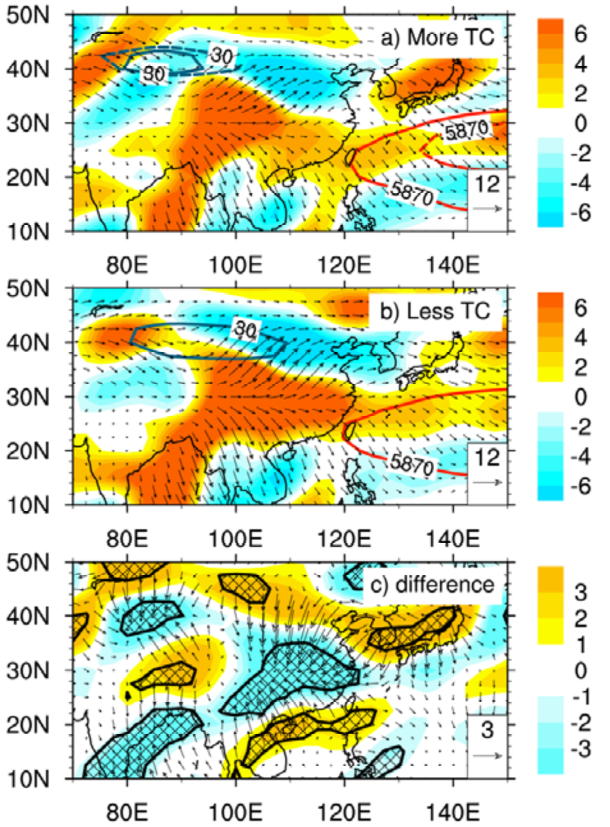

Fig. 11. The 200-hPa wave activity flux (vector) and divergence (shading) average with summer more (a, 1965–1974 and 1995–2004) and less (b, 1979–1993) TC genesis periods. The red and blue contours are 5870 gpm and 200-hPa 30 m s^{-1} zonal wind. The solid and dashed contours in panel (a) are averages in 1995–2002 and 1965–73. Panel (c) shows their differences (more minus less). The cross-hatchings indicate areas that exceed the 90% confidence level.

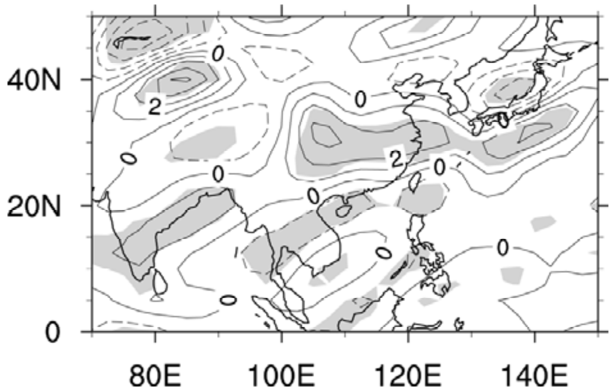

Fig. 12. The regression coefficient of 200-hPa wave activity flux divergence against PC2 during 1965–2004. The shadings indicate areas that exceed the 90% confidence level.

the Rossby wave energy associated with EAJS intensity changes, which originates from mid-latitudes, could influence TC development over the SCS. That is, the summer climate over the SCS is directly related to variations in the subtropics.

6. Conclusions and discussions

6.1 *Conclusions*

Different from previous studies (e.g., Lee et al., 2006; Zuki and Lupo, 2008; Goh and Chan, 2009; Kim et al., 2010), this study separates TC genesis over the SCS in boreal summer from autumn during 1965–2004 because of seasonal changes of TC genesis positions. TC genesis over the SCS usually occurs north of 15°N in summer and south of 15°N in autumn (Fig. 2). In addition, the temporal variation of TC genesis over the SCS in summer is distinct from that in autumn. Summer TC genesis shows a remarkable interdecadal variation with more and less TC frequency during 1965–1974/1995–2004 and 1979–1993, whereas a significant interannual variation (∼4-year oscillation) appears in autumn. In this study, the interdecadal variation of TC genesis over the SCS in summer was our concern. The details regarding interannual changes in TC genesis in autumn are beyond the scope of this article but will be discussed in future papers.

Currently, the cause of interdecadal variations of TC genesis over the SCS is not yet clear. Many studies have revealed the apparent interdecadal variation of EASM (e.g., Chang et al., 2000; Yu and Zhou, 2007; Zhou et al., 2009a,b; Li et al., 2010). In this study, the linkage between the summer TC genesis over the SCS and EASM on an interdecadal time scale was investigated. We focused on the effects of the EAJS and WNPSH, which are important components of the EASM. Based on correlation and regression analysis, the interdecadal variations of TC genesis over the SCS can be attributed to combined influences of long-term changes in the EAJS intensity and WNPSH. In contrast, the contributions of EAJS meridional location changes to TC genesis are less. Through vertical wind shear anomalies over the SCS, the EAJS intensity and the WNPSH could impact the TC genesis over the SCS. The weaker EAJS is the key factor influencing TC genesis over the SCS during 1965–1973 and 1995–2002; it reduced vertical wind shear and thus favored more TC genesis. In contrast, in 1979–1993 with stronger EAJS, the westward extending WNPSH was in control of anomalous strong vertical wind shear over the SCS, and thus was responsible for fewer TC genesis anomalies. Notably, although the WNPSH extended westward around 120°E during 1995–2002, the impact of EAJS intensity on TC genesis over the SCS was much stronger than that of WNPSH.

Due to the remarkable roles of the EAJS intensity on summer TC genesis over the SCS on an interdecadal time scale, we identified a possible mechanism of how the EAJS intensity influences TC genesis over the SCS. Our results show that the EAJS intensity could significantly impact the important TC dynamic condition of vertical wind shear over the SCS, which in turn affects TC genesis over the SCS. The weaker EAJS intensity during 1965–1973 and 1995–2002 induced anomalous Rossby wave energy propagation at high levels, with equatorward propagation at mid-latitudes and poleward in subtropics over East Asia. The resulting convergence and divergence of wave activity flux around East Asia at 30°N and the SCS were expected. Because of anomalous wave activity flux divergence over the SCS, the SCS zonally averaged easterlies at high levels were reduced, and vertical wind shear was accordingly weakened, which provided the favorable dynamic condition for TC genesis over the SCS.

There has been some debate about the impact of global warming on TC genesis, mainly concerning warming of the ocean surface (Chan and Liu, 2004; Webster et al., 2005; Chan, 2006). The SCS has also shown a long-term warming trend (Wang et al., 2009e). Our results show that the mid-latitude jet stream in the upper troposphere could influence TC genesis over the SCS on an interdecadal time scale. The jet stream near the tropopause has shown long-term change (Archer and Caldeira, 2008). Analyzing the output from climate models participating in the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report, Lorenz and DeWeaver (2007) found a strengthening of the tropospheric zonal jets in response to global warming. Therefore, in addition to the warming sea surface, the impact of EAJS intensity changes should be considered for studies with regard to future climate changes and TC genesis over the SCS.

6.2 *Discussions*

The influence of ENSO on seasonal TC activity over the WNP was reviewed by Chu (2004). The results of Chan and his colleague (Chan and Liu, 2004; Chan, 2009) found negative correlations between the frequency of occurrence of intense TCs in the WNP and SST, reflecting the fact that the frequency of occurrence of intense TCs in the WNP is strongly influenced by ENSO. As early as the 1980s, Li (1988) pointed out that TC frequency over the WNP and SCS was less during El Niño years. Recently, Du et al. (2011) suggested that El Niño-induced tropical Indian Ocean warming could also impact TC frequency over the SCS and WNP. Here, the ENSO impact on TC genesis over the SCS was also found. Although summer TC frequency over the SCS shows interdecadal variation, there was no TC formation in particular El Niño years, even during periods of greater TC frequency (i.e., in 1969 and 2003). In a period of lesser TC frequency (1979–1993), TC frequency during La Niña years (i.e., in 1984 and 1986) was higher than average during 1965–2004. Moreover, the difference in summer TC frequency between El Niño and La Niña years exceeded the 95% confidence level, which suggests the ENSO impact on TC genesis over the SCS in summer. El Niño usually occurs in summer, and thus it greatly influences the SCS TC genesis in autumn (Chu, 2004; Wang et al., 2007; Zuki and Lupo, 2008). The results of spectral analysis on autumn TC genesis over the SCS (Fig. 3b) indicate a significant (exceeding 90% confidence level) interannual variability, suggesting a closer relationship with ENSO. Currently, a number of studies reveal a type of El Niño different from the canonical El Niño, known as "El Niño Modoki" (Ashok et al., 2007), "CP El Niño" (Yu and Kao, 2007), or "Warm pool El Niño" (Kug et al., 2009), which has different impacts on East Asian weather and climate (Kao et al., 2009; Weng et al., 2009). Moreover, ENSO occurrences have undergone interdecadal change in the past century (Wang et al., 2009d), and the intensity of warm-pool El Niño has tended to be stronger in the past three decades (Lee and McPhaden, 2010). The impact of ENSO changes on seasonal TC genesis over the SCS is not yet clear, but this impact will be investigated in future studies.

Our results show that EAJS intensity dominated TC genesis throughout 1965–1974 and again during 1995–2004, whereas the WNPSH played a more important role in TC genesis during 1979–1993. A question is thus raised: Why are the respective roles of the EAJS and WNPSH in TC genesis over the SCS distinct during different time periods? The distinction may result from the relative intensity of the EAJS and WNPSH. To further investigate this relationship, a series of model experiments are needed; we plan to study this question in the future.

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