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Out-of-phase relationship between tropical cyclones generated locally in the South China Sea and non-locally from the Northwest Pacific Ocean

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Abstract Tropical cyclones (TCs) in the South China Sea (SCS) are either generated locally or formed non-locally in the Northwest Pacific Ocean (NWP) and entered into the SCS. Here, it is found that local TCs vary out-of-phase with non-local TCs in summer. That is, if fewer (more) TCs enter into the SCS from the NWP, more (fewer) TCs are generated over the SCS. Further analyses show that variability of the western Pacific subtropical high (WPSH) is responsible for the out-of-phase relationship. As the WPSH shifts eastward (westward), fewer (more) non-local TCs formed in the NWP can enter into the SCS because TCs are recurved northward (moved westward). Due to the eastward (westward) movement of the WPSH, positive (negative) low-level vorticity anomalies, weak (strong) vertical wind shear between the upper and lower troposphere, and anomalous upward (downward) motion in the middle troposphere are induced in the northern SCS. The changes in the relative vorticity, vertical wind shear and vertical velocity are favorable (unfavorable) for the local TC genesis in the SCS. These variations of non-local and local TCs result in an out-of-phase relationship between TCs formed locally in the SCS and non-locally in the NWP.

Keywords Tropical cyclone · South China Sea · Northwest Pacific · Out-of-phase relationship · Western Pacific subtropical high

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1 Introduction

As one of the most destructive nature hazards in the world, tropical cyclones (TCs) can cause injury, loss of life and great economic damage when TCs make landfall. The destructiveness of TCs has been increased since the recent decades associated with the warming trend of sea surface temperature (SST) (Emanuel 2005). As shown in Fig. 1, the Northwest Pacific Ocean (NWP) and the South China Sea (SCS) are the active areas for the formation and development of TCs.

The SCS is one of the largest semi-enclosed marginal seas in the world ocean. Most of TCs in the SCS make landfall in its surrounding countries, and thus the understanding of TC activity in the SCS is both scientifically and socially important (Liu et al. 2001). TCs in the SCS can be formed locally, or formed non-locally in the NWP and then entered into the SCS. The ocean and atmosphere circulation in the SCS are strongly affected by TCs formed in the NWP and SCS (Chu et al. 2000; Wang et al. 2009; Ling et al. 2011). According to the "best track data" from Japanese Meteorological Agency (1951–2011), 7.1 TCs among 23.5 TCs can enter into the SCS from the NWP, and about three TCs can be generated locally over the SCS each year (TCs in this study are defined by maximum sustained wind speed being equal to 34 knots or larger).

For TCs generated over the NWP, their movements are strongly associated with the large-scale atmospheric circulation, particularly the position of the western Pacific subtropical high (WPSH) (Chan and Gray 1982; Holland 1983; Harr and Elsberry 1991; Wang and Wang 2013). Many studies have investigated the linkage between the WPSH and TC tracks (George and Gray 1976; Chen 2009; Wang et al. 2013a, b). Generally, they can be classified into three cases: Firstly, as the WPSH shifts more eastward than the

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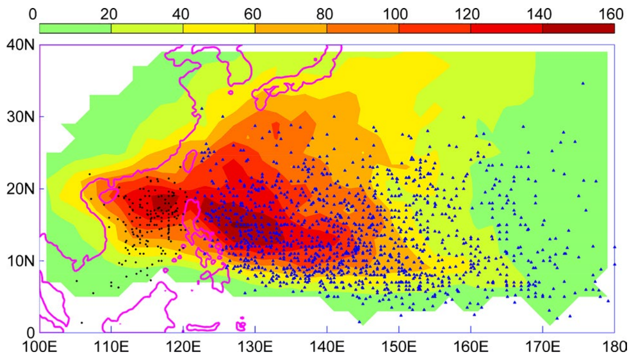

Fig. 1 The frequency of occurrence of tropical cyclones in the NWP and SCS from 1951 to 2011. The TCs generated from the SCS and NWP are represented by *black solid circles* and *blue solid triangles*, respectively

normal, the tracks of NWP TCs are northward; Secondly, as the WPSH extends much more westward, the tracks of NWP TCs are westward; Thirdly, the tracks of NWP TCs are westward first and then northward when the WPSH moves eastward and breaks near 160°E (Ren et al. 2007).

For those of TCs generated locally over the SCS, they were generated over the northern SCS in summer, while over the southeastern SCS in winter (Liang 1991; Liang et al. 1998). The TC genesis is strongly associated with changes of both dynamical and thermodynamical factors in the SCS. The dynamical factors include low-level vorticity, vertical shear of the horizontal wind and Coriolis force, while the thermodynamical factors include the SST, ocean mixed layer depth and relative humidity in the mid-troposphere (Emanuel 2003). Wang et al. (2007) found that the dynamical factors are favorable for the TC genesis over the northern SCS in summer, but both dynamical and thermodynamical factors are favorable for the TC genesis over the southeastern SCS in winter. Besides the above six dynamical and thermodynamical factors, others such as the vertical velocity in the middle troposphere may be also important for the cyclogenesis (McBride and Zehr 1981; Held and Zhao 2011; Wang and Pan 2012). In addition, although it is believed that the mixed layer depth is an important parameter to characterize the upper ocean thermal structure, many recent studies showed that the TC heat potential plays a significant role for the development of TCs (Akiyoshi and Norihisa 2007; Lin et al. 2009).

Although TCs formed in the NWP and SCS have been largely studied (Chan 1995; Wang et al. 2008; Zuki and Lupo 2008; Goh and Chan 2010; Li and Zhou 2014), their linkage has not been explored. Because the genesis and tracks of local TCs are strongly associated with monsoon and SCS ocean environment, while the tracks of non-local TCs are strongly associated with the WPSH, it is useful to separate TCs into local and non-local for discussing their relationship. The purpose of the present paper is to document an out-of-phase relationship between TCs formed locally in the SCS and non-locally in the NWP, and to investigate what cause this relationship.

2 Data sets

The TC data set named 'best track data' is from Japan Meteorological Agency. The data set provides the information of TCs with at least tropical storm intensity, such as the 6 hourly location, minimum sea-level pressure, 10-min averaged maximum wind. The data period from 1951 to 2011 is used in this study.

The wind, geopotential height and relative humidity are from the European Centre for Medium-Range Weather Forecasts, which are available from 1958 to the present. The monthly reanalysis fields have a 2.5° × 2.5° grid for the period from 1958 to 1978 and 0.75° × 0.75° grid for the period from 1979 to the present, and the data from 1958 to 1978 are interpolated to 0.75° × 0.75° grid by using linear interpolation. The 500 hPa geopotential height is used to examine variability of the WPSH. The wind fields at 200 and 850 hPa are used to calculate the vertical wind shear as in other studies (e.g. Wang and Lee 2008). The vertical integrated pressure-weight flow from 850 to 200 hPa is used to represent the TC steering flow (e.g., Wang et al. 2011; Yang et al. 2014). The relative humidity at 500 hPa is to characterize the mid-troposphere relative humidity. The vertical velocity at 500 hPa is used to represent the vertical motion of the middle troposphere.

SST during 1951–2011 is obtained from the dataset of the Hadley Center (Rayner et al. 2003). Its temporal and spatial resolution are monthly and 1°, respectively. The monthly ocean temperature dataset (Ishii and Kimoto 2009) with a 1° × 1° grid is used to calculate the tropical cyclone heat potential (TCHP). The TCHP is calculated as done by Lin et al. (2009):

$$\mathrm{TCHP} = C_p \rho \sum_{i=1}^{n} \Delta T(x, y, z_i, t) \Delta Z_i, \tag{1}$$

where C_p is the heat capacity at constant pressure, ρ is the density of sea water, ΔT is the temperature difference between $T(z_i)$ and 26 °C, ΔZ_i is the thickness of the ith layer and n is the layer number from the surface to the 26 °C isothermal depth. In this study, we take the C_p and ρ as 4,178 J kg^{-1} °C^{-1} and 1,026 kg m^{-3}, respectively.

3 Results

3.1 Out-of-phase relationship between TCs formed in the SCS and NWP

TCs in the SCS are either formed locally (local TCs hereafter) or formed non-locally in the NWP and move into the

Table 1 The number of TCs for each month from year 1951 to 2011

Month	1	2	3	4	5	6	7	8	9	10	11	12
Number of local TCs	0	1	0	2	22	22	25	37	33	22	14	4
Number of non-local TCs	6	0	8	10	10	33	67	55	74	71	71	27
Total number	6	1	8	12	32	55	92	92	107	93	85	31

SCS (non-local TCs hereafter). As shown in Table 1, TCs are active in the SCS from May to December. The correlation calculations show that local TCs have a good correlation (coefficient is −0.46) with non-local TCs in summer (June–August), while there is no correlaiton (coefficient is −0.006) from September to December. In this paper, we will thus focus on the relationship between local TCs and non-local TCs during summer.

Figure 2a and b show the numbers of non-local and local TCs during summer, respectively. On average, there are 2.54 non-local TCs and 1.38 local TCs in each summer from 1951 to 2011. An important feature of these two time series is an out-of-phase relationship between local and non-local TCs. That is, as more (fewer) TCs are formed in the NWP and move into the SCS, fewer (more) TCs are formed locally in the SCS. The correlation coefficient between non-local TCs' number and local TCs' number is −0.46 at the 99.98 % confidence level. If we only consider the period after 1979 when TCs can be seen from satellites, the correlation coefficient is increased to −0.52 at the 99.83 % confidence level. As shown in Fig. 2, the inter-annual and decadal variability in both non-local and local TCs are robust. More non-local TCs affected the SCS in the periods of 1960–1972, 1978–1983, and 1988–1994, while fewer in the other periods.

To better understand the out-of-phase relationship between local and non-local TCs in the SCS, we take the difference between the numbers of local TCs and non-local TCs (local minus non-local) as an index to measure variability of the relationship (Fig. 2c), which is called "TCs–SCS–NWP" index. If this TCs–SCS–NWP index is positive (negative), the number of local TCs is more (less) than that of non-local TCs. The correlation coefficients between the TCs–SCS–NWP index and the numbers of local TCs and non-local TCs are 0.82 and −0.89, respectively. Note that the out-of-phase variation between local TCs and non-local TCs does not mean that the total number of local and non-local TCs is constant. In contrast, because the number of non-local TCs is about twice that of local TCs, the total number of TCs over the SCS has similar inter-annual and decadal variability to non-local TCs (the correlation coefficient is 0.66).

To understand the mechanism of the out-of-phase variation, we choose the years of out-of-phase Type A (B) if the TCs–SCS–NWP index is larger (less) than its mean plus (minus) one standard deviation for further analyses. Totally,

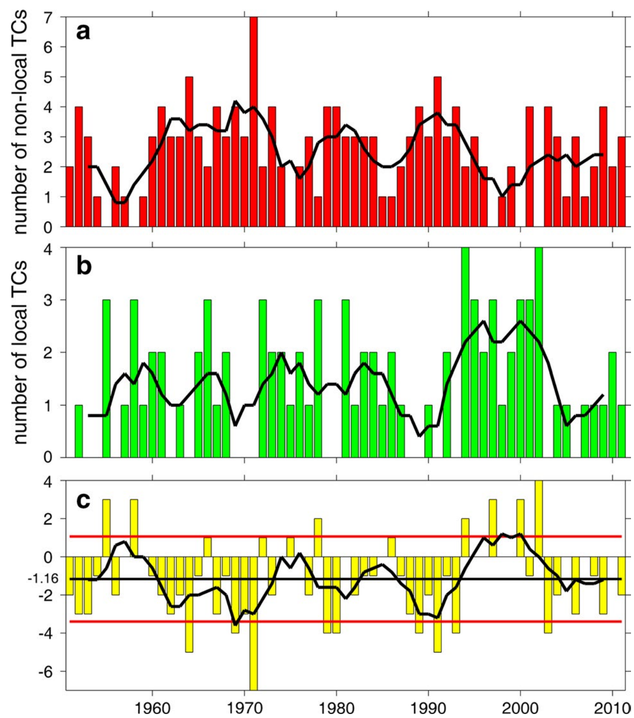

Fig. 2 The number of TCs in the SCS during summer from 1951 to 2011. The *top panel* of **a** is TCs formed in the NWP and entered into the SCS. The *middle panel* of **b** is TCs generated locally in the SCS. The *bottom panel* of **c** is the TCs–SCS–NWP index defined as the difference between local and non-local numbers of TCs (**b** minus **a**). In (**c**), the *black line* indicates the mean value of the TCs–SCS–NWP index and the two *red horizontal lines* represent one standard deviation. The *solid black curves* are the numbers smoothed by a 5-year filter

16 years have been chosen from 1951 to 2011, which satisfy this criterion. As shown in Fig. 3, few non-local TCs (3 of 80) entered into the SCS, while 23 local TCs generated in the years of Type A: 1955, 1958, 1978, 1994, 1997, 2000 and 2002. Much more non-local TCs (42 of 94) entered into the SCS, while no local TC formed in the years of Type B: 1964, 1969, 1971, 1979, 1980, 1989, 1991, 1993 and 2003.

3.2 Mechanisms of out-of-phase relationship

To understand why local TCs vary out-of-phase with non-local TCs, we examine the composited atmospheric and oceanic variables for the years of Types A and B. For Type A, the composited years include 1958, 1978, 1994, 1997,

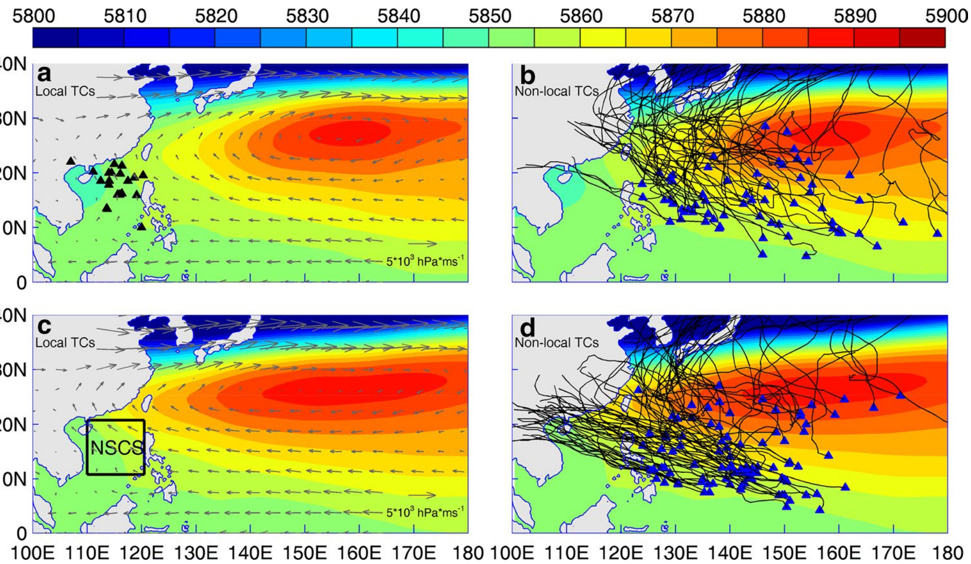

Fig. 3 The composite maps of the 500 hPa geopotential height (*meter*) and TCs in the years of Type A (*Panels* **a** and **b**) and Type B (*Panels* **c** and **d**). The years for out-of-phase Type A (B) are chosen if the TCs–SCS–NWP index in Fig. 2c is larger (*less*) than its mean plus (*minus*) one standard deviation. *Black* and *blue triangles* represent the genesis locations of local TCs and non-local TCs, respectively. *Black lines* in Panels **b** and **d** represent the tracks of TCs formed in the NWP

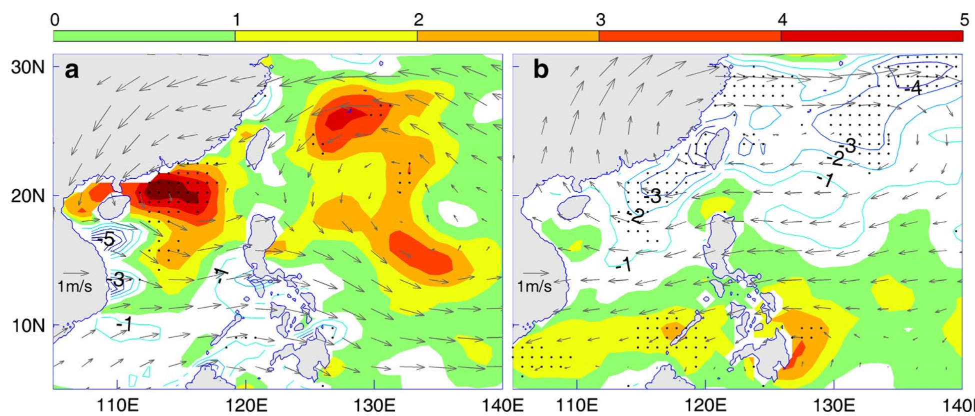

Fig. 4 The composite maps of anomalous 850 hPa wind (*vector*) and 850 hPa relative vorticity anomalies (10^{-6} s^{-1}). **a** is for years of Type A and **b** for years of Type B. The negative (*positive*) values are in contour (*shading*). The *stippling* indicates the statistical significance at the 90 % confidence level

2000 and 2002 (the year of 1955 is removed because there is no data), while for Type B the composites are based on the years of 1964, 1969, 1971, 1979, 1980, 1989, 1991, 1993 and 2003.

The WPSH, as seen from the 500 hPa geopotential height, is shown in Fig. 3 for the two cases. For Type A, the WPSH is more eastward (Fig. 3a and b), then the easterly wind south of the WPSH becomes weak over the SCS and turns to northward around Luzon strait, resulting in more northward tracks of NWP TCs. Among 80 non-local TCs during the years of Type A, only three non-local TCs enter into the SCS. For Type B, the mean position of the 5,865-m contour line extends westward into the interior SCS, the easterly wind south of the WPSH is strong in the northern SCS, thus more non-local TCs can be steered into the SCS. Quantitatively, among 94 non-local TCs during the years of Type B, 42 non-local TCs enter into the SCS (Fig. 3d).

Although the TC steering flow associated with the WPSH can explain why fewer (more) non-local TCs can enter into the SCS during the years of Type A (B), it is not clear why more (fewer) TCs are generated over the SCS at the same time. We further examine the dynamical and thermodynamical factors which affect the TC genesis in the SCS. Figure 4a and b show the relative vorticity at 850 hPa for the years of Types A and B, respectively. For Types A and B, the anomalous relative vorticity in the northern SCS is positive and negative, respectively. Quantitatively, compared to the climatological mean value, the relative vorticity in the northern SCS (NSCS; the box of 110°E–120°E and 12.5°N–22.5°N) increases (reduces) 49.55 % (28.58 %) for Type A (B). The positive (negative)

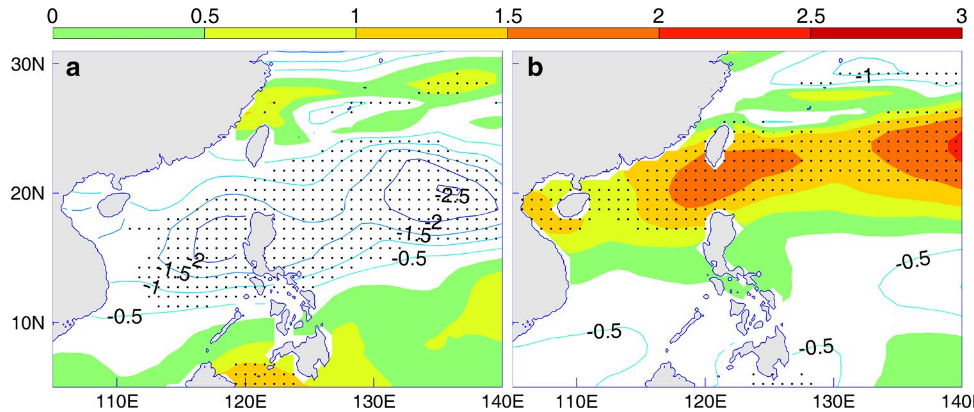

Fig. 5 The composite maps of 200–850 hPa vertical wind shear anomalies (m s^{-1}). **a** is for years of Type A and **b** is for years of Type B. The negative (*positive*) values are in contour (*shading*). The *stippling* indicates the statistical significance at the 90 % confidence level

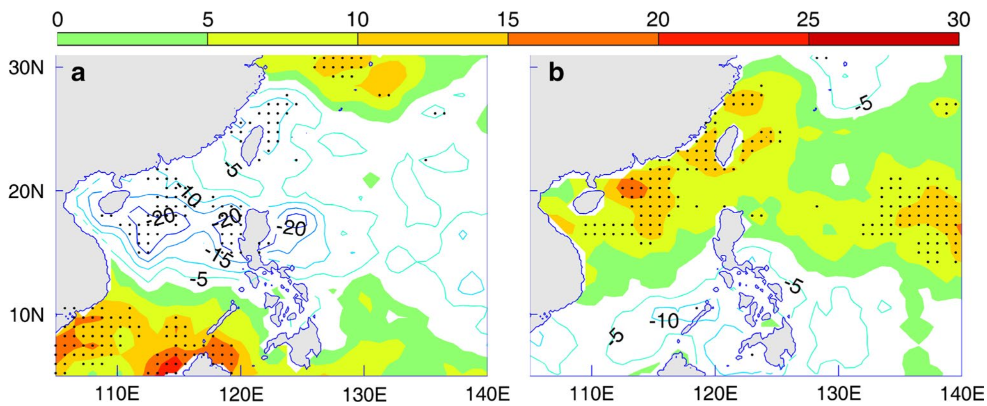

Fig. 6 The composite maps of pressure vertical velocity anomalies at 500 hPa (10^{-3} Pa s^{-1}). **a** is for years of Type A and **b** is for years of Type B. The negative (*positive*) values are in contour (*shading*). The *stippling* indicates the statistical significance at the 90 % confidence level

relative vorticity anomalies are favorable (unfavorable) for the genesis of SCS TCs. The change of relative vorticity is associated with the shift of the WPSH. Because the WPSH is a system with strong negative vorticity, the positive (negative) relative vorticity anomaly is produced in the northern SCS when the WPSH shifts eastward (westward).

The vertical wind shear is another important dynamical factor affecting the TC genesis, and its composites in the SCS during the years of Types A and B are respectively shown in Fig. 5a and b. The anomalous vertical wind shear is negative and positive for Type A and B, respectively. Compared to the climatological mean, the vertical wind shear decreases (increases) 25.56 % (14.70 %) for Type A (B). The weakening (enhancing) of the wind shear during Type A (B) in the SCS is favorable (unfavorable) for the genesis of local TCs in the SCS. As the WPSH shifts westward (eastward), the South Asia high in the upper troposphere moves eastward (westward) accordingly (Zhang et al. 2003; Tao and Zhu 1964; Yu and Qian 1992), resulting in weakening (strengthening) of the wind at 850 hPa and strengthening (weakening) of the wind at 200 hPa over the northern SCS (not shown). As a result, the vertical wind shear between the upper and lower troposphere becomes more stronger (weaker) during the years of Type B (A).

In the middle troposphere, the anomalous upward (downward) motion appears in the northern SCS during the years of Type A (B) (Fig. 6), which is favorable (unfavorable) for the genesis of local TCs in the SCS. Compared to the climatological summer mean, the upward motion in the NSCS increases (decreases) 25.67 % (15.11 %) in the years of Type A (B). The changes of vertical velocity are also associated with the shift of WPSH: When the WPSH shifts westward (eastward), the southwest monsoon is weakened (intensified) (Yang and Sun 2003), resulting in weakening (strengthening) of the convergence in the lower troposphere in the northern SCS (not shown). Thus, the upward motion in the mid-troposphere is also weakened (strengthened) during the years of Type B (A).

The composites of the SST, TCHP and relative humidity anomalies are shown in Fig. 7. The change of SST is less than 0.1 °C for both the years of Types A and B. This suggests that the SST variation is not important for the TC genesis in the SCS, given the high climatological SST in the SCS. The same is true for the changes of the TCHP and relative humidity. Quantitatively, the TCHP increased (reduced) 2.17 % (0.73 %) and the relative humidity is slightly increased (decreased) 3.83 % (0.83 %) during the years of Type A (B) in the northern SCS.

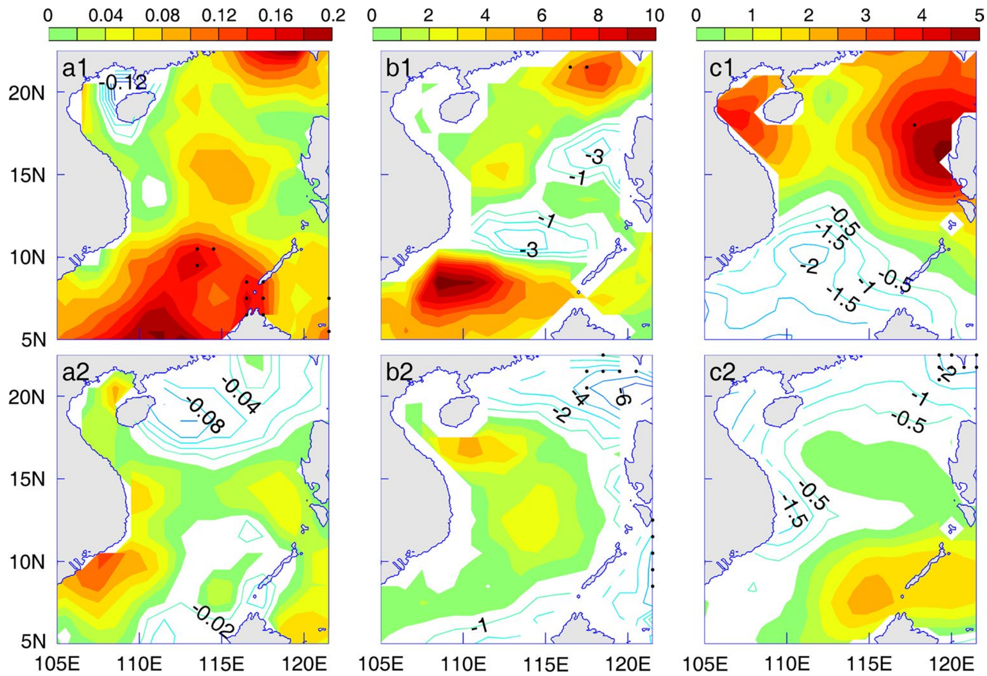

Fig. 7 The composite maps of the **a** SST anomalies (°C), **b** TCHP anomalies (kJ cm^{-2}), and **c** 500 hPa relative humidity anomalies (%). "1" is for years of Type A and "2" is for years of Type B. The negative (*positive*) values are in contour (*shading*). The *stippling* indicates the statistical significance at the 90 % confidence level

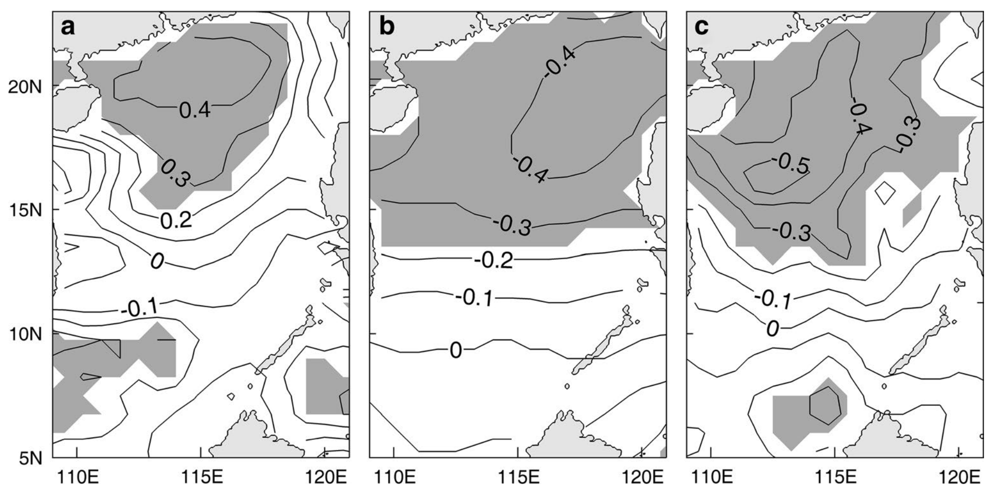

Fig. 8 The correlation maps between the TCs–SCS–NWP index and the **a** 850 hPa relative vorticity, **b** 200–850 hPa vertical wind shear, and **c** 500 hPa vertical velocity. The shaded areas denote the correlation exceeding the 90 % significance level

To further see whether the out-of-phase relationship results from the changes of the relative vorticity, vertical wind shear and vertical velocity, we calculate the correlations between the TCs–SCS–NWP index (defined as the difference between the numbers of local and non-local TCs) and these three variables (Fig. 8). All correlation coefficients are larger than 0.3 in the northern SCS above the 90 % confidence levels. In contrast, the mean correlation coefficients in the northern SCS between the TCs–SCS–NWP index and the SST, TCHP and relative humidity anomalies are only −0.09, −0.03 and −0.21 respectively. This suggests that the out-of-phase relationship between local and non-local TCs is strongly related to the dynamical factors of the relative vorticity, vertical wind shear and vertical velocity, but not the thermodynamical factors.

The above results suggest that local TCs and non-local TCs in the SCS can link together by the change of atmospheric circulation. As the WPSH moved more eastward (westward), there are two ways to affect TC activity. Firstly, the southeasterly wind in the south side of the WPSH is more eastward (westward), which is favorable for TCs to take the northward (westward) track. Thus, fewer (more) non-local TCs can be steered into the SCS. Secondly, associated with the eastward (westward) movement of the WPSH are positive (negative) low level relative vorticity anomalies, negative (positive) vertical shear anomalies between the upper and lower troposphere and anomalous upward (downward) motion in the middle troposphere in the northern SCS, all of which are favorable (unfavorable) for the genesis of local TCs in the SCS.

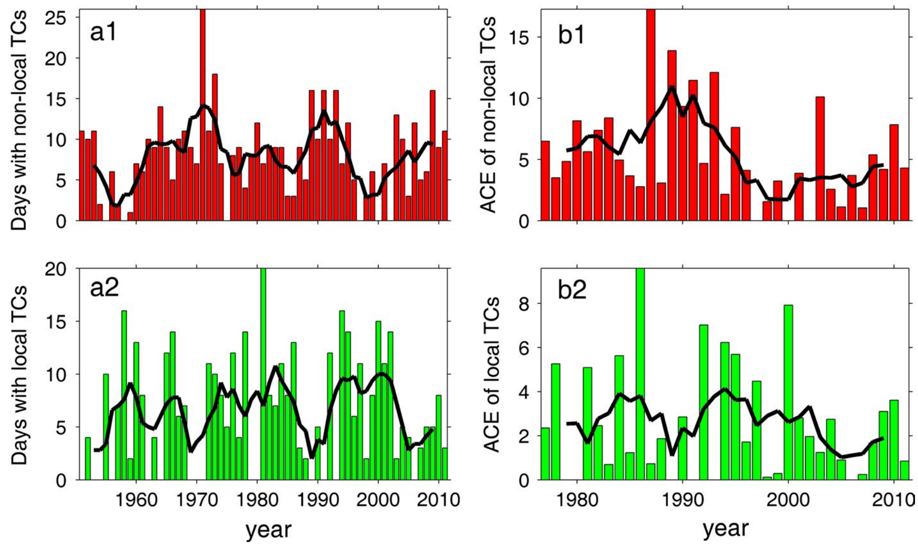

Fig. 9 The TCs' days (**a**) and ACE (**b**, unit: 10^4 knot^2) of local and non-local TCs during summer in the SCS. "1" is for non-local TCs, "2" is for local TCs. The *solid black curves* are the values smoothed by a 5-year filter

4 Summary and discussion

The understanding of TC activity over the SCS is both scientifically and socially important since most of them make landfall in its surrounding countries. TCs over the SCS are either from the NWP or are generated locally. The present paper found that local TCs vary out-of-phase with TCs formed non-locally in the NWP. If more (fewer) local TCs are generated over the SCS, fewer (more) non-local TCs enter into the SCS. It is also noted that both the accumulated cyclone energy (ACE) and the TCs' days demonstrate a similiar out-of phase relationship (Fig. 9). This suggests that the out-of-phase relationship is robust.

Further analyses show the WPSH variation is responsible for the out-of-phase relationship. When the WPSH shifts eastward (westward), fewer (more) non-local TCs can enter into the SCS because the southeasterly wind in the south side of the WPSH is more eastward (westward) and non-local TCs are favorable to take the northward (westward) track. Because of the eastward (westward) movement of the WPSH, positive (negative) low-level relative vorticity anomalies in the lower troposphere, weak (strong) vertical wind shear between the upper and lower troposphere, and strong (weak) upward motion in the middle troposphere are induced in the northern SCS. All these changes of the relative vorticity, vertical wind shear and vertical velocity are favorable (unfavorable) for the local TCs genesis in the SCS. Because of the variations of both non-local TCs and local TCs associated with the WPSH changes, an out-of-phase relationship between local TCs and non-local TCs is produced.

The shift and intensity of the WPSH are linked to climatic phenomena such as ENSO, Pacific decadal oscillation (PDO), Indian ocean dipole (IOD) and the western Pacific warm pool (Li and Mu 2001; Lu and Dong 2001; Chan and Zhou 2005; Sui et al. 2007). To test the influences of these large scale phenomena on the out-of-phase relationship, we repeat to calculate the correlation coefficient between local and non-local TCs by removing the top and lowerest 10 % years for ENSO, IOD, PDO and the western Pacific warm pool individually based on their summer indices. Take ENSO as an example, the strong El Niño years of 1965, 1972, 1982, 1987, 1991, 1997 and strong La Niña years of 1970, 1973, 1975, 1988, 1999, 2010 are removed with the criteria. The correlation coefficients between local and non-local TCs are −0.46, −0.42, −0.51 and −0.47 after removing the years with extreme ENSO, PDO, IOD and warm pool events, respectively. All these correlation coefficients are very close to the original correlation coefficient (−0.46), suggesting that these large scale phenomena can not influence the out-of-phase relationship significantly. The dynamical and thermodynamical processes about the linkages between large scale climatic phenomena and the out-of-phase relationship need to be further explored in the future.

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