Reasons for the Weakening of Tropical Depressions in the South China Sea

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ABSTRACT

The frequency and location distribution of tropical depressions (TDs) from 1979 to 2017 in the South China Sea (SCS) are statistically analyzed based on the best track data of tropical cyclones (TCs) from the Shanghai Typhoon Institute, China Meteorological Administration (CMA-STI). ECMWF interim reanalysis data (ERA-Interim) are used to investigate the reasons for the weakening of TDs in this study. The results show that there are 4.8 TDs formed in the SCS per year, and these TDs can be separated into 3.2 developing cases (DTDs) and 1.6 nondeveloping cases (NTDs) according to whether they intensify into tropical storms. Further objective classification by the multivariable-time empirical orthogonal function (MVT-EOF) method finds that the weakening cases in the positive-PC1 (the first principle component) mode occur in May–September, with the reason for weakening being a shortage of moisture. The decrease of westerly wind south of the NTDs reduces the water vapor transportation from the Indian Ocean. Binary TCs in the northwestern Pacific acquire water vapor from the eastern boundary of the SCS NTDs. Meanwhile, the weak high-level divergence and low-level convergence are not enough for the accumulation of local moisture and maintaining local convections inside the NTDs. The weakening cases in negative-PC1 mode occur in October–December with the reason for weakening being the invasion of cold air from the north. Strong cold air advection in the lower troposphere increases the vertical wind shear in front of the NTDs, and sharply reduce sensible and latent heat flux as well. Seasonal dependence exists in the causes of the SCS NTDs weakening.

1. Introduction

The South China Sea (SCS) is considered to be one of the high-risk areas for tropical cyclones (TCs) in the world, which cause serious economic losses and casualties to surrounding countries and regions every year. According to the formation location, SCS TCs can be divided into two categories: TCs that cross the Philippine Islands into the SCS after forming in the tropical western Pacific, and TCs that form locally in the SCS. The latter is called the

SCS typhoon or the disastrous typhoon of the SCS (Wu et al. 2005).

Usually, TCs can be further divided into six classes based on the 2-min mean maximum wind speed (MSW): tropical depression (TD; $10.8 \leq \text{MSW} \leq 17.1 \text{ m s}^{-1}$), tropical storm (TS; $17.2 \leq \text{MSW} \leq 24.4 \text{ m s}^{-1}$), strong tropical storm (STS; $24.5 \leq \text{MSW} \leq 32.6 \text{ m s}^{-1}$), typhoon (TY; $32.7 \leq \text{MSW} \leq 41.4 \text{ m s}^{-1}$), strong typhoon (STY; $41.5 \leq \text{MSW} \leq 50.9 \text{ m s}^{-1}$), and super typhoon (SuperTY; $\text{MSW} \geq 51 \text{ m s}^{-1}$). When a TD strengthens into a TS, it is named and tracked as a “typhoon.”

The prediction of typhoon formation and intensity has always been the central issue of operational forecasting departments and is one of the challenging topics in the field of numerical forecasting (Wang 2013). However,

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the intensity prediction of TCs is limited by the insufficiency of ocean observation data, the low resolution of the model and the errors of the initial field. Fundamentally, the mechanisms controlling the intensity change (physical factors and influence process) are not well understood (Yu 2012). Previous studies on TC intensity prediction have been carried out extensively over the SCS (Kong et al. 2006; Lin et al. 2013; Chen et al. 2015; Fudeyasu and Yoshida 2018). In recent years, the rapid development of ensemble forecasting has significantly improved the forecasting skills of typhoon formation and development (Snyder et al. 2011). However, the improvement of intensity prediction is only for TCs that have developed into typhoons. There are few studies on nondeveloping TDs (NTDs), which are often neglected for not reaching TS strength during their lifetime. And this kind of TD is usually defined as the nondeveloping TDs. Predevelopment statistics found that approximately 10% of TDs in the northwestern Pacific (WNP) and 35% of TDs in the SCS do not develop into TSs. NTDs can cause disasters as great as those from typhoons, which deserve further attention and research (Chen et al. 2016).

A large number of previous studies have shown that large-scale circulation and marine environments are very important external factors affecting the intensity of TCs (Huang and Lei 2010). The influence of large-scale circulation on TC intensity is controlled by the position and shape of the subtropical high (Lee et al. 2010), the intensity of cross-equatorial flow and the subtropical high (Ding et al. 2016), and the intraseasonal oscillation of intertropical convergence zone (ITCZ) intensity (Liu et al. 2009). In addition, the influence of environmental factors should not be ignored. When the vertical wind shear (VWS) between 300 and 1000 hPa is less than $7\text{--}9\text{ m s}^{-1}$ or the VWS between 850 and 1000 hPa is less than $2\text{--}2.5\text{ m s}^{-1}$, a TC is more likely to develop and intensify, while it tends to weaken when the moving speed is greater than 12 m s^{-1} (Wang et al. 2015). The role of thermodynamic factors also deserves attention. Yang et al. (2017) found that TCs strengthen when the sea surface temperature (SST) is $27^{\circ}\text{--}30^{\circ}\text{C}$, and most of them weaken under a low SST. Strong dry and cold air, which is not conducive to its occurrence and development, can destroy the convective instability of the second kind (CISK) mechanism (Charney and Eliassen 1964), while moderate intensity cold air activities can strengthen the TCs (Li 1983). In addition, TC intensification and weakening are also quite different in terms of relative humidity and divergence of the middle and upper troposphere (Hendricks et al. 2010). Due to the special geographical location of the SCS in the East Asian monsoon region, the impact of environmental

factors on TC intensity is particularly complex. Environmental factors cannot be independent of each other. The adverse changes in a single factor cannot dominate the future development of a TC. It is now agreed that the dynamic factors are more important than the thermodynamic factors in TC genesis in the WNP (Fu et al. 2012).

To sum up, the circulation factors that affect the change in TC intensity has been systematically studied and summarized by predecessors, and the processes of TC formation and intensification have always been hot topics (Hu et al. 2014). However, the study of TC weakening and dissipation is still limited to the analysis of special cases. The objective classification and study of the mechanisms of the causes of TDs weakening can make up for the deficiencies in case studies. It is helpful to understand the physical mechanisms of typhoon formation and carry out early warnings and disaster prevention works by investigating the changes in circulation and environmental factors in the life history of the NTDs.

In this paper, an objective classification method will be used to investigate the reasons for the weakening of different types of the SCS NTDs. Then, the weakening circulation patterns of various NTDs and the mechanisms leading to the TDs weakening are analyzed in detail. The rest of this paper is organized as follows. Section 2 introduces the data and methods. Section 3 statistically analyzes the spatial and temporal distribution characteristics of the SCS NTDs. Section 4 objectively classifies the weakening cases over the sea by using the multivariable-time empirical orthogonal function (MVT-EOF) analysis method and then studies the causes of different types of the TDs weakening in detail. Section 5 summarizes and discusses the results.

2. Data and methods

a. TC case selection

The data of TC in the SCS are from the best track dataset of TCs from 1979 to 2017 compiled by the Shanghai Typhoon Institute, China Meteorological Administration (CMA-STI). CMA-STI TC best track dataset records the time, strength, latitude, longitude, center minimum pressure, and 2-min center maximum wind speed for the TCs formed in the WNP (contain SCS) every 6 h. Especially, the TDs that do not intensify into TSs during their lifetime are also recorded in this dataset. This dataset has good accuracy in the position and intensity of TC in the SCS. But there are some subcenter TC data in CMA-STI best track dataset, which do not conclude by other dataset. One TC will separate into two TCs under some special conditions

during its life period. The TC occur later is called subcenter TC. They have the same ID number in the dataset. Usually, the center of the subcenter TC is close to the main TC (the stronger one) and most of them can develop as an independent TC in the future.

After removing the subcenter TC cases from the CMA-STI best track dataset, TDs that will intensify into TSs are classified as developing tropical depressions (DTDs), while the remaining that begin to weaken in TD stage and dissipate before reaching the TS level are classified as nondeveloping tropical depressions (NTDs). DTDs and NTDs will be numbered in the order of the TD formation time (the first record in TD stage) in this paper because the NTDs lack of ID number in original CMA-STI best track dataset. The TDs formed in the SCS (0° – 25° N, 100° – 120° E) are further selected with the rule that the TC should be located in the SCS during the whole TD stage in order to remove the cases that formed in the WNP but strengthened in the SCS.

b. Environmental data analysis

Atmospheric and oceanic factors from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) data, which have a spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$ and a 6-h time resolution from 1979 to 2017. The atmospheric specific humidity at 2 m used for calculating latent heat flux is derived from the National Centers for Environment Prediction–National Center for Atmospheric Research (NCEP–NCAR) 6-h Gauss point reanalysis data. To maintain consistency among the calculated grid points, the standard grid is interpolated in the use process. Daily Madden–Julian oscillation (MJO) phases are obtained from Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004) provided by the Australian Meteorological Agency (<http://www.bom.gov.au/climate/mjo/>) and oceanic Niño index (ONI) from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center is used to discriminate the warm and cold events of El Niño–Southern Oscillation (ENSO).

For objectively classifying the cases of the SCS NTDs, a new empirical orthogonal function (EOF) analysis method (MVT-EOF) is selected using the key factors of the TC development in the SCS. This method refers to the multivariable EOF (MV-EOF) method proposed by Wang (1992) and the seasonal EOF (S-EOF) method proposed by Wang and An (2005). By skillfully arranging the data matrix for EOF, we can simultaneously get the eigenvector values of each factor and its change within 6 h of weakening. The former can help to find out the factors with large differences between individual cases, while the latter can grasp the changes of these factors. Besides, we can get some “time

coefficient” for each TC cases. This parameter is similar between the TC cases that have similar change of factors, corresponding to different weakening reasons. Therefore, we can separate the NTDs into different kinds objectively through the combination change of several factors. The MVT-EOF factors selection and calculation range are shown in Table 1. Factors are standardized before calculation.

The formulas for calculating some environmental factors in Table 1 are as follows:

- 1) The sensible and latent heat flux caused by turbulence at the atmosphere–ocean interface are estimated by the following formulas:

$$H_s = -c_p c_H V (T_a - SST),$$

$$Le = -L c_q V (q_a - q_{sea}),$$

where H_s and Le represent sensible and latent heat flux, conveyed upward from the sea; V is the surface wind speed, where the TC maximum wind speed is used instead in the TC center; and T_a and T_{sst} represent atmospheric temperature at 2 m and the SST. Atmospheric absolute humidity at 2 m and absolute humidity close to the sea surface are denoted as q_a and q_{sea} in the formulas. The latent heat constant of condensation is $L = 2.5 \times 10^6 \text{ J kg}^{-1}$. The specific heat at constant pressure is c_p . The dimensionless exchange coefficients of sensible heat and latent heat are c_H and c_q .

- 2) Vertical wind shear is the magnitude of the horizontal wind difference between the upper and lower troposphere, such as 300–1000 hPa wind shear:

$$VMS_{3001000} = \sqrt{(u_{300} - u_{1000})^2 + (v_{300} - v_{1000})^2}.$$

- 3) Zonal and meridional moisture flux formulas are as follows:

$$MF_u = u \times q,$$

$$MF_v = v \times q.$$

MF_u is the zonal moisture flux, MF_v is the meridional moisture flux, and q is the specific humidity.

3. Statistical classification of TDs in the SCS

a. Spatial–temporal distribution characteristics

During 1979–2017, the average annual number of TDs formed in the SCS was 4.8, of which 3.2 cases intensified into TS and 1.6 cases did not develop. Before and after 2003, the number of TDs has changed from 5.5 to 3.8 on

TABLE 1. The factors used in MVT-EOF method.

Factor	Calculation area	Unit
Sea surface temperature	$1^{\circ} \times 1^{\circ}$ Average	$^{\circ}\text{C}$
Sensible heat flux	$1^{\circ} \times 1^{\circ}$ Average	J kg^{-1}
Latent heat flux	$1^{\circ} \times 1^{\circ}$ Average	J kg^{-1}
300 hPa air temperature	$6^{\circ} \times 6^{\circ}$ Average	$^{\circ}\text{C}$
500–850 hPa temperature difference	$6^{\circ} \times 6^{\circ}$ Average	$^{\circ}\text{C}$
200–850 hPa temperature difference	$6^{\circ} \times 6^{\circ}$ Average	$^{\circ}\text{C}$
600 hPa relative humidity	$6^{\circ} \times 6^{\circ}$ Average	%
400 ~ 925 hPa moisture flux	$6^{\circ} \times 6^{\circ}$ Average	$\text{kg m}^{-1} \text{s}^{-1}$
850 hPa relative vorticity	$6^{\circ} \times 6^{\circ}$ Extremum	s^{-1}
300–1000 hPa vertical wind shear	$6^{\circ} \times 6^{\circ}$ Average	m s^{-1}
850–1000 hPa vertical wind shear	$6^{\circ} \times 6^{\circ}$ Average	m s^{-1}
200 hPa divergence	$6^{\circ} \times 6^{\circ}$ Average	s^{-1}
925 hPa divergence	$6^{\circ} \times 6^{\circ}$ Average	s^{-1}

average (Fig. 1a). This may be due to the anomalous subsidence over the SCS caused by the SST warming in the north Indian Ocean (NIO) and WNP during 2003–10. This anomalous circulation suppresses the development

of synoptic-scale disturbances and leads to a decrease in TCs in the SCS (Ha and Zhong 2015). The development rate (DTD number divided by TD number) in Fig. 1b shows that the number of DTDs is greater than the number of NTDs in most years, except for 1979, 1980, 2006, and 2011, along with a slight upward trend without significance. In terms of seasonal variation in frequency, the SCS TCs are mainly formed in May–December (98% of the total) and peak in September (22% of the total), while the peak of the NTDs is in October. The development rate peaks in July (83%).

The weakening of the NTDs in the SCS is closely related to its location. Figure 3 shows the frequency distribution of the DTDs and NTDs in their TD stage. Figure 2 gives an example of the DTDs/NTDs track and marks the special time point along the track. It can be found that the genesis location of both DTDs and NTDs are concentrated over the west side of the Philippine islands (15° – 20°N , 115° – 120°E) (Figs. 3a,c). The growth of TCs is accompanied by the westward shift in the high-density area. Obviously, the average position of the NTDs reaching their maximum intensity in TD stage is west of the DTDs (Figs. 3b,d). In other words, NTDs

FIG. 1. (a) The annual variations of the TD number (black line), DTD number (red line), and NTD number (blue line) that formed locally in the SCS. (b) The annual variations of development rate (DR): DTDs number divided by TDs number. (c) The seasonal variations of the TD (black column), DTD (blue column), and NTD (blue column) that formed locally in the SCS. Development rate is shown with orange line.

FIG. 2. An example of the DTD and NTD track. The intensity of the TC is coded by the color bar on the right side. The first record in TD stage is regarded as “TD genesis.” Maximum strength for DTD is the max TD strength. The weakening moment is 6 h after the strongest moment. The last record is regarded as “dissipation time.”

have adjacent average formation positions with DTDs, but they move over longer distances when they reach their maximum TD intensity. When further calculating the time taken by DTDs/NTDs from the TD genesis to the max TD strength, we found that it takes 32 h for DTDs on average and 48 h for NTDs and the difference between them passes the 95% significance test, which fully shows that the environmental condition of the NTDs does not favor their intensification. In addition, 50% of the NTD cases (32/64) began to weaken in shallow waters entering the continental shelf after reaching maximum strength and eventually dissipated in the Beibu Gulf and the eastern coast of Vietnam. But there are still quite a few cases that began to weaken over the sea and dissipated far away from land. The surface friction is always the common reason for the weakening of most landing cases (Yan et al. 2005). However, the reasons for the weakening cases over the sea are more complex. Not only consider the influence of oceanic factors but we must consider the specific weather system. The intensity prediction of the TCs over the sea is more difficult than that of the landfall cases. Therefore, it is necessary to further analyze the changes in the circulation and environmental factors during the transition from intensification to decline of the NTDs over the sea.

b. The leading modes of environmental factors

We employ the MVT-EOF method to decompose the dominant features of the environmental factors of 32 NTD cases over the sea. The result shows that the explained variance of the first leading mode (EOF-1) is approximately 32% (Fig. 4a) and that of the second leading mode (EOF-2) is 20% (Fig. 4b). In EOF-1, the divergence in the upper and lower troposphere and the vorticity at 850 hPa are larger than other factors.

The moisture flux and the air temperature follow in second place. The values of the SST and temperature are smaller than those of divergence, vorticity, and other dynamic factors, which indicate that the dynamic factors dominate the first mode. The perennial high SST and relative humidity in the west Pacific warm pool may not be the reason for restricting the NTDs, while dynamic factors play an important role in it. This is consistent with Fu et al. (2012). In the second mode, the thermodynamic factors such as SST, sensible and latent heat flux, relative humidity and several air temperature related factors are much larger than the other dynamic factors, implying that thermodynamic factors dominate the EOF-2.

In addition, the MVT-EOF method considers the comparison of the factor at the strongest moment and the first 6 h of weakening, represented by the red and blue bars in each mode. The latent heat flux, divergence at 925 hPa, and relative vorticity at 850 hPa change considerably in EOF-1, while the other factors have small changes. In the second mode, the temperature difference and sensible heat flux in the upper and lower troposphere change greatly. After 6 h of evolution, a different background circulation or weather system increases or decreases the difference between these factors. The changes in EOF-1 and EOF-2 within 6 h can distinguish the influence system that causes the different changed factor fields to some extent.

c. Case classification

To further investigate the causes of the NTDs weakening and extinction, PC1 and PC2 are used to classify the cases. As shown in Fig. 5, the scatter distribution in the figure can be initially regarded as four types of cases clustered near the positive and negative coordinate axes of PC1–PC2.

Previous studies have shown that the atmospheric circulation and environmental factors anomalies caused by MJO and ENSO have a greater impact on TCs in the SCS, so we analyzed their effects, respectively. The cases occurring during El Niño events (9.4%) are concentrated in PC1+ and PC2+ quadrant, while the cases occurring during La Niña events (31.3%) are distributed in other quadrants. However, there are more NTDs formed in normal years (59.3%), so the ENSO phase may not be the most important factor restricting the development of TDs in the SCS. A similar analysis of the MJO shows that the impact of the MJO can be ignored in classification.

Besides, we found that 18 of 32 (56%) NTDs were accompanied by binary typhoons. This means that more than half of the NTDs will have another TC in the western Pacific at the same period. Figure 6a classifies

FIG. 3. Distribution of the DTDs/NTDs location density in the SCS: (a) DTDs genesis location, where the blue point is the average location; (b) maximum intensity location of the DTD in TD stage; (c) NTDs genesis location; (d) maximum intensity location of the NTDs; (e) weakening location of the NTDs; and (f) dissipation location of the NTDs. The number of samples of each graph is marked after the title.

FIG. 4. The result of MVT-EOF (a) EOF-1 (32.71%) and (b) EOF-2 (20.35%). The normalized eigenvector for each factor in strongest moment is shown by red column and that in the weakening moment is shown by blue column.

the NTDs into binary (yellow), nonbinary (blue), and direct impact (red) cases. Real-time weather charts were used to calculate the distance between the binary typhoons in the WNP and SCS NTDs. Cases were considered direct impact if the distance between NTDs and the other WNP TC was less than 18° latitude ($d \leq 18^\circ$). Usually, when the center distance between the two typhoons is within 20° latitude ($d \leq 20^\circ$), the mutual rotation phenomenon (Fujiwara effect) will gradually become apparent (Ruan et al. 1985). The effects of binary TC interactions are depended on the distance

between them (Carr and Elsberry 1998). In this study, 18° latitude is a relatively modest indicator used to distinguish whether another typhoon has impact on the NTDs. After coloring the scatter points separately, it can be found that the cases accompanied by binary typhoons can be separated well using a PC1–PC2 scatterplot. Therefore, the effect of binary typhoons should be considered. Furthermore, the cases in late season (October–December) have negative values of PC1, while those in the TC season (May–September) have positive values of PC1 (Fig. 6b).

FIG. 5. PC1–PC2 scatterplot. The values of PC1 and PC2 are the result of MVT-EOF, using 64 NTDs cases in the SCS. Each NTD case would have a scatter in the PC1–PC2 scatterplot. The number of samples is marked after the title.

This seasonal difference is also reflected in the track and average SST (Fig. 7). Positive-PC1 cases are mostly formed in the northern part of the SCS with a northwest movement. Negative-PC1 cases mostly occur in the southern part of the SCS with a westward track. For these cases (Fig. 7b), there is a cold tongue in the SCS along the eastern coast of Vietnam. When TDs move to the cold tongue area, most cases begin to weaken or even dissipated, indicating that the cold tongue here may has a significant impact on the development of TDs in the SCS. Thus, we classify cases according to the month of formation and the influence of binary typhoons. Most positive-PC1 cases formed during May to September are binary typhoon related, we define this kind of NTDs as summer-binary NTDs. Most negative-PC1 cases formed during October to December are not binary typhoon related. We define this kind of NTDs as winter-nonbinary NTDs.

4. Reasons for the weakening of the SCS NTDs

The development of a cyclone requires the cooperation of thermodynamic and dynamic factors. The upper ocean is the energy source of TCs, and the SST determines the sensible and latent heat flux, which affects the strength of TCs. A slowly moving TC obtains less energy from the upper ocean due to the cooling of the mixing layer caused by the entrainment process, which can further decrease the strength of the TCs (Han et al. 2012). At the same time, large vertical wind shear destroys the warm core structure of the TCs and inhibits

FIG. 6. Classification of cases from PC1–PC2 scatterplot: (a) binary or nonbinary typhoon related cases and (b) seasonal difference of NTD genesis time.

their development, which is also a cause of many TC dissipations (Wu et al. 2016). The mismatch of thermodynamic and dynamic factors is the most reliable reason for the discontinuation of the positive feedback mechanism, leading to the weakening of the NTDs.

In the previous sections, there are different reasons for weakening between the cases near the PC1 positive and negative axes, which can be reflected by the differences in the factors in each mode (Fig. 4). To confirm the specific influence mechanism of environmental factors in the weakening process of the TCs, a dynamic synthesis of factor fields was carried out for the summer-binary NTDs and winter-nonbinary NTDs. The list of the NTD cases that used in the composition is shown in Table 2.

a. Summer-binary NTDs

For the summer-binary NTDs (Fig. 8), the strongest moments of the TCs are located south of the South Asian high at the 200 hPa level and are dominated by

FIG. 7. The track for (a) positive-PC1 cases and (b) negative-PC1 cases. The intensification stage during the TD stage is marked in red dots and the weaken stage is marked in blue dots. The shaded is the mean SST of all the NTD cases shown in the tracks at the maximum moment (SST data resource: ERA-Interim).

northeasterly winds. There is an asymmetric distribution of the divergence around the TCs. The positive center is located south of the cyclone center, corresponding to a strong divergent airflow. The negative center is located at the north side of the cyclone center, where there is a weak convergence region. The asymmetric distribution of divergence also persists at the weakening moment. During the weakening stage, the divergence center at 200 hPa at the south side moves slightly to the southwest part of the TC, while its intensity changes slightly. When the NTD reaches its maximum intensity, its average center is on the southwest side of the subtropical high at the 500 hPa level. The ridge line of the subtropical high is approximately 10°N of the cyclone center corresponding to the weak turning flow. In addition, there is a weak VWS region roughly along the average forward direction of the NTD, while the VWS south of the cyclone center is more than 12 m s^{-1} . Notably, 83% (10/12) of summer-binary NTDs accompany with a low value center west of the TC center in geopotential height of 850 hPa (Fig. 9). In addition, there is another TC in the WNP within 18° latitude of the summer-binary NTD center, which can have a direct impact on the SCS NTDs.

The low-level circulation and water vapor flux are shown in Figs. 8c and 8f. When the NTD reaches its strongest location in the SCS, the lower-level water

vapor flux channel on the south side of the center is over $40\text{ kg m}^{-1}\text{ s}^{-1}$. The development of convection on the west side cuts off the water vapor transport channel from the Indian Ocean to the SCS. The water vapor flux is increased in the low pressure center west to the NTDs, while the water vapor flux in the downstream is decreased (Fig. 10). Further investigation demonstrated that the weakening of zonal wind is the main reason for the decrease in the moisture flux (Fig. 10b). There is a negative belt in u component the same as the moisture flux change in Fig. 10a. But it is not an exit in v component (Fig. 10c) and specific humidity (Fig. 10d). It means that the other calculated components of moisture flux such as meridional wind and specific humidity have less contribution on the change of moisture flux. Meanwhile, by synthesizing the anomalous wind in the mid- and lower levels, it is found that the decrease in the westerly wind south of the SCS NTD is due to the weakening of the westerly jet in the southwest side (Fig. 11a). In addition, there is an obvious anomalous northeastward wind on the east side of the SCS NTD, indicating that the WNP TC can attract water vapor transport and make the water vapor belt shift eastward. The water vapor transport to the SCS NTD is intercepted, resulting in a reduction in water vapor entering the SCS NTD. Li et al. (2018) noted that the eastern boundary is the main source of typhoon water vapor

TABLE 2. The list of composite NTD cases.

Strongest moment		Genesis month	Quantity of the binary TCs
Summer-binary NTDs ID number			
7905*	1979052006	5	1
7914*	1979080618	8	2
8017*	1980082800	8	1
8123	1981092300	9	2
8509	1985070112	7	1
8513*	1985081318	8	1
8810	1988080112	8	1
8908	1989062506	6	1
8917	1989081000	8	1
0113	2001081912	8	1
0405*	2004051700	5	2
0614	2006082500	8	1
Winter-Nonbinary NTDs ID number			
8031	1980111500	11	0
8128	1981111000	11	0
8528	1985101100	10	0
9030	1990101306	10	0
9523	1995121400	12	0
9927	1999121018	12	0
1125	2011110800	11	0
1126	2011121212	12	0

The case with an asterisk means that it is influenced by another TC to a certain extent. The distance between them is less than 18° latitude.

transport and plays an important role in the development and maintenance of typhoon intensity. Therefore, the decrease in water vapor flux on the east and south sides of the SCS NTD caused by binary typhoons is an important factor restricting development.

Further comparing the SST and velocity of the summer-binary NTDs (Fig. 11c), the average SST of these cases from 24 h before to 12 h after the weakening moment are warmer than 28.5°C. In addition, the moving speed increases slowly to 15 m s⁻¹, which is basically consistent with the average wind speed in TD stage. This shows that such a weak TD is less affected by cold sea temperature and upturned seawater. However, this does not mean that the energy supply from the ocean is not important during this period. The latent heat flux from the ocean to the atmosphere decreases sharply within 6 h, from 180 to 140 J kg⁻¹, while the sensible heat flux maintained at the level of 20 J kg⁻¹ due to the slight change in the SST difference. The decrease in the heat transfer from the ocean to the atmosphere is not conducive to maintaining the warm core of the TC.

In addition, the shallow shear (850–1000 hPa VWS) (Fig. 11e), which is better related to the weak TC intensity, was maintained. Although the deep shear (300–1000 hPa VWS) increased, it still remained below 10 m s⁻¹. Therefore, the VWS may not be a major

limiting factor for the development of the TDs. Meanwhile, the absolute divergence value of the upper and lower troposphere is small (Fig. 11f). It is unfavorable for the upward vertical motion. The divergence at 200 hPa begins to decrease noticeably 12 h ahead of time and is close to zero at the end, which indicates that the TDs do not have good conditions for high-level divergence at this time and is unfavorable for further development.

To sum up, the reason for weakening of the summer-binary cases is the shortage of water vapor transport. The decrease of westerly wind in the south of the NTD center and the abnormal wind field caused by binary typhoons in the WNP reduce the water vapor transport outside the NTDs. At the same time, the weaker convergence and divergence conditions are further weakened, affecting the accumulation of local moisture inside the NTDs (Fig. 11b). The moisture supply is insufficient to maintain the positive feedback mechanism of convection, thus entering the stage of weakening.

b. Winter-nonbinary NTDs

For the winter-nonbinary NTDs, the circulation backgrounds are quite different from those of the summer-binary cases. The cyclone is located in the subtropical high at the 200 hPa level under the control of the southeasterly wind (Fig. 12a). The large divergence area is located at the north side of the cyclone, and the divergence intensity does not change within 6 h. Moreover, the cyclone is located at the southwest side of the subtropical high at the 500 hPa level, and the ridge line of the subtropical high is located near 7° to the north side of the cyclone center (Fig. 12b). The north side of the cyclone is undergoing a larger VWS that is greater than 20 m s⁻¹ and extends to the inner core of the cyclone. There is a large VWS area (> 12 m s⁻¹) in the forward direction of the cyclone. The north side of the cyclone center has a large geopotential height gradient (Fig. 12c). Strong cold air advection enters the inner core of the cyclone and enlarges the VWS in the forward direction of the NTDs. Besides, the cold air advection will reduce the temperature difference between the upper and lower troposphere, followed by the weakening of the convection.

The changes in each factor are examined synthetically. The temperature of the upper and midlevels (200–500 hPa) and the lower levels (850–1000 hPa) of the TD both decrease but the temperature at 600 hPa increases (Fig. 13a). The air temperature at 850 hPa decreases after the maximum TD strength (Fig. 13b). At the same time, SST is decreasing continuously, which is related to the movement of the TD into the cold tongue area along the eastern coast of Vietnam. The latent heat flux

FIG. 8. The synthetic circulation background of 12 summer-binary cases. (a) 200 hPa (contour: geopotential height, vector: wind, shading: divergence, black dot: synthetic NTD center, black triangle: relative position of the WNP TC, the same as below); (b) 500 hPa (shading: 300–1000 hPa VWS); and (c) 850 hPa (shading: 400–925 hPa moisture flux). (a)–(c) The strongest moment and (d)–(f) the weakening moment (6 h after the strongest moment).

decreases by approximately 50% compared with that 24 h prior, and the decrease in the sensible heat flux is closely related to the decrease in the SST. Focusing on the VWS (Fig. 13e), both deep shear and shallow shear increase synchronously and maintain a large value. This shows that the VWS restricts such kinds of NTDs more persistently, and even if the upper divergence conditions are good, they still cannot develop.

In summary, the weakening of winter-nonbinary cases results from the increase in the VWS caused by the invasion of cold air on the north side in the lower troposphere and the sharply decrease in the sensible and latent heat flux caused by the cold underlying surface. The increase in the VWS forces an asymmetry in vertical motion and convection in the eyewall and a quasi-steady downshear left tilt of the vortex center. The favorable convergence and divergence conditions did not

FIG. 9. The geopotential height in 850 hPa level of 12 summer-binary cases. Blue dot: the SCS NTD; red dots: binary typhoons in the WNP. Green dot: binary typhoon in the north Indian ocean (Bay of Bengal).

FIG. 10. The difference of (a) 400–925 hPa moisture flux (shading) between the strongest moment and the weakening moment. The vector is the 850 hPa wind at strongest moment; The factors in (b)–(f) are three calculated components of moisture flux. (b) 400–925 hPa mean zonal wind (shading); (c) 400–925 hPa mean meridional wind (shading); and (d) 400–925 hPa mean specific humidity (shading). The black dot is the synthetic NTD center.

product a stable deep convection because of the ventilation effect. In addition, movement into the cold sea region and the reduction in the SST are also important reasons for its weakening. The combined effect of the cold underlying surface and the VWS make it impossible for these TDs to maintain a stable vertical circulation structure and intensify continually.

5. Summary and discussion

Based on the tropical cyclone best track data from CMA-STI and ERA-Interim reanalysis data from 1979 to 2017, this paper makes a statistical analysis of the NTDs in the SCS. During this period, the annual average number of TDs formed in the SCS is 4.8. This number can be divided into 3.2 DTDs and 1.6 NTDs. These TDs formed in a similar location, but the NTDs are closer to land when they reached their maximum TD strength. The strengthening time from TD genesis to maximum TD strength is also significantly longer for the NTDs compared to the DTDs. Through the MVT-EOF method, the reasons for the weakening of

different types of NTDs are further classified. The conclusions are as follows:

The first type of cases mainly occurred in May–September with a northwest track. The main reason for their failure in developing into TSs is the insufficiency of water vapor transport. This kind of NTD is usually accompanied by binary typhoons. Another TC nearby will affect the circulation of water vapor transport of the NTDs in the SCS. The low pressure center west of the NTDs leads to a decrease in the water vapor flux in the downstream SCS, and the WNP TC near the northeastern side may seize part of the water vapor from the eastern border of the SCS TD. At the initial stage of this kind of TD, due to the insufficient water vapor supply outside the NTDs and the weak convergence and divergence condition inside the NTDs, less water vapor is obtained by the SCS NTDs, which ultimately is not enough to provide the energy needed for positive convection feedback.

The second kind of cases mainly occurred in October–December with a westward track. The main reason for

FIG. 11. (a) The difference (weakening minus strongest) in wind (vector) between the strongest moment and the weakening moment of 12 summer-binary cases in average, the relative positions of the WNP TC are shown in red point (strongest moment) and blue point (weakening moment); (b) time series of moisture flux divergence. It shows the mean result of 12 summer-binary cases. The following factors are the same: (c) SST (red line, left axis), air temperature at 2 m (blue line, left axis), speed (black line, right axis); (d) sensible heat flux (red line, left axis), latent heat flux (blue line, right axis); (e) 300–1000 hPa VWS (blue line), 850–1000 hPa VWS (red line); and (f) 200 hPa divergence (blue line) and 925 hPa divergence (red line). The VWS and divergence are $3^{\circ} \times 3^{\circ}$ regional average with the TC center but moisture flux, and sensible and latent heat flux are $1^{\circ} \times 1^{\circ}$ regional average.

FIG. 12. The synthetic circulation background of 8 winter-nonbinary cases. (a) 200 hPa (contour: geopotential height, vector: wind, shading: divergence, black dot: synthetic TD center, the same as below); (b) 500 hPa (shading: 300–1000 hPa VWS); and (c) 850 hPa (shading: 850–1000 hPa temperature advection). (a)–(c) The strongest moment and (d)–(f) the weakening moment (6 h after the strongest moment).

weakening was the invasion of strong cold air from the north. Strong northeasterly winds at low levels and southwesterly winds at high levels formed a large area of VWS along the direction of the TDs. The ventilation effect destroyed the warm core of the TDs, and the convergence and divergence conditions did not play a positive role. In addition, these cases were also significantly affected by the SST. When most cases move into the cold tongue area close to eastern Vietnam,

the intensity began to weaken, and the latent heat at the air–sea interface decreased sharply as well. On the other hand, the slowdown of TD velocity also enhanced the negative effect of the cold sea surface temperature.

Through the MVT-EOF method, the NTDs in the SCS are well classified and their weakening reasons are clearer after synthetic analysis of the environmental factors. But it is worth noting that most of the factors

FIG. 13. (a) -24 to $+12$ h wind vectors of each layer, where shading is the temperature from -24 to $+12$ h minus the temperature of the same layer at the strongest moment. The time series of the factors in (a)–(f) are calculated by the average of 8 winter-nonbinary cases; (b) 300 hPa temperature (red line, left axis), 850 hPa temperature (blue line, right axis); (c) SST (red line, left axis), air temperature at 2 m (blue line, left axis), speed (black line, right axis); (d) sensible heat flux (red line, left axis), latent heat flux (blue line, right axis); (e) 300–1000 hPa VWS (blue line), 850–1000 hPa VWS (red line); and (f) 200 hPa divergence (blue line) and 925 hPa divergence (red line). The calculation area of the factors is the same as Fig. 11, especially, the air temperature is $3^{\circ} \times 3^{\circ}$ regional average with the TC center.

used in this study are atmospheric factors. The ocean factors only consider the influence of the SST. Obviously, it is not sufficient to analyze the cases near the positive and negative axes of PC2 even if their numbers are small. The reasons for the weakening of these cases may

correspond to the dynamic process of the ocean. In addition, the influences of the TD structure, vortex Rossby waves and internal mesoscale and small-scale systems will also lead to the weakening of the TD and need further study.

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