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Role of surface warming in the northward shift of tropical cyclone tracks over the South China Sea in November

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Abstract

Tropical cyclones (TCs) formed in the Northwest Pacific Ocean (NWP) can cross the South China Sea (SCS) sometimes. It is found that the TC tracks in the SCS in November are shifted to the north after 1980 compared with those before 1980. Both data analyses and numerical simulations show that the surface warming in the SCS may contribute to this more northward shift. The warming produces a cyclonic atmosphere circulation anomaly in the northwestern SCS and an associated southerly in the central SCS steering the TCs to the north.

Key words: tropical cyclone, track, South China Sea, sea surface temperature

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1 Introduction

The South China Sea (SCS) is a semi-enclosed marginal sea surrounded by continent and islands. It is one of the regions that suffer from serious disasters caused by tropical cyclones (TCs). Some TCs formed over the Northwest Pacific Ocean (NWP), and then moved into the SCS. The tracks of these TCs in the SCS exhibited significant variability from intra seasonal to interdecadal change (Chen and Ding, 1979; Chan, 1995, 2000; Chia and Ropelewski, 2002).

The TC track is generally determined by the large-scale steering flow, beta effect and terrain effect (Chan and Gray, 1982; Holland, 1983; Wang et al., 1998; Chan, 2005; Wu et al., 2005; Wang and Holland, 1996a, b). The ocean also plays a role in the TC track by affecting a large-scale steering flow through air-sea interaction (Wu and Wang 2005; Wu et al., 2005; Tu et al., 2009; Wang et al., 2011) or by changing the horizontal advection of the local cyclonic vortex under certain topographic effect (Yun et al., 2012; Choi et al., 2013). For example, Wang and Holland(1996a, b) talked about the beta drift in both adiabatic and diabatic baroclinic vortices and revealed the important role of beta gyres in controlling TC northwestward movement. The higher SST may induce stronger TC intensity and larger beta-drift. Wu et al. (2005) found that the westward expansion and strengthening of the subtropical high due to climate change resulted in a westward shift of typhoon tracks in the NWP. A warmer SST can induce a local circulation anomaly and further affect TC movement (Yun et al., 2012).

It has been discussed that the TC tracks exhibit quite different characteristics in different months over the NWP (Chen and Ding, 1979). In November, the TCs from the NWP usually move westward, travel across the SCS Basin, and make landfall in Vietnam (Fig. 1). The latitudes of these TCs' landfall were usually from 6°N to 16°N while some typhoons shifted their tracks to the northwest (Hainan Island) after they moved into the SCS. Besides, no significant track shift is found in other months. Are there any robust features in these TC tracks in November? Does the SCS play an important role in causing these features? In this study, these two questions are investigated using observations and numerical models.

2 Data, models and methods

The monthly SST data with 1°×1° resolution is from the UK Met Office Hadley Centre sea ice and sea surface temperature (HadISST). The best-track data from the Japan Meteorological Agency (JMA) includes tropical cyclone position, time and intensity (such as 10 min averaged maximum wind speed and the TC central minimum sea level pressure, MSLP) every 6 h. Daily 700 hPa wind speed with 2.5°×2.5° resolution is from the Nation-

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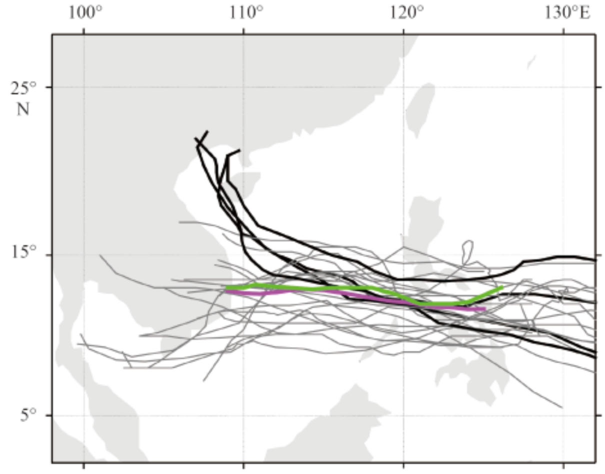

Fig. 1. Tracks of TCs crossed the SCS in November. The thick gray line denotes the four unusual TCs and the thin gray line is for the others. The magenta and green lines are the tracks for the ensemble mean, TC Joan and simulated TC Joan, respectively.

al Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis. In this study, we used the above data sets from 1951 to 2013.

The weather research and forecasting (WRF) model Version 3.5 is used in this study. Two nested grids are designed for a TC simulation, covering the area of (0°–30°N, 100°–170°E) and (5°–25°N, 105°–140°E), respectively. A horizontal resolution for the outer domain is 30 km with (245×106) grids, and that for the inner domain is 10 km with (358×220) grids. There are 30 sigma levels in the vertical, and the top level is set to 50 hPa. The initial and boundary conditions are constructed from the NCEP final (FNL) operational global analysis data, including 6 h reanalysis data with horizontal resolution of 1°×1°. For realistic simulations, the basic state of the atmosphere and the initial/boundary conditions of experiments were taken from those for TC Joan (1964), Skip (8829) and Haiyan (1330). Experiments were designed in this study to test the SST role in a TC track shift, namely, the control experiment and a warming/cooling experiment. The SST was increased/decreased by 0.5°C in the SCS Basin uniformly only in the warming/cooling experiment to see if TC movement is affected by the change (based on an observational result in Section 3.1). More details will be given in Section 3.2. Main model parameterizations are shown in Table 1.

To study the north-south shift of the TC tracks in the SCS, the TCs that entered the SCS along 120°E and left the basin along 109°E in November were selected. We calculated the latitude difference (φ) of TC tracks between 120°E and 109°E as follows:

$$S_{\rm ns} = \varphi_{109} - \varphi_{120}, \qquad (1)$$

Table 1. Model parameterizations used in the WRF

Physics	Parameterization scheme
Microphysics	Lin et al. scheme
Long wave radiation	RRTM scheme
Short wave radiation	Dubhia scheme
Surface layer	MM5 similarity
Planetary boundary layer	Yonsei University scheme
Cumulus parameterization	GD ensemble scheme

where φ_{120} and φ_{109} are the latitudes when a TC moves across 120°E and 109°E, respectively, and $S_{\rm ns}$ represents the north-south shift (NSS) of the TC. The positive (negative) NSS denotes that a TC moves to the north (south) in the SCS. The selected TCs and their *NSS*s are listed in Table 2.

3 Results

3.1 *Results based on observations*

To reveal the shift of the TC tracks, we use two periods: the first one from 1951 to 1979, and the second one from 1980 to 2013. The two periods are chosen because all of the four unusual TCs whose northward shift was larger than 5.7° happened after 1980. The four TCs are Hazen (1981), Mike (1990), Nepartak (2003), and Haiyan (2013). On average, the NSS from 1951 to 2013, in the first period and the second period was 1.30°, –0.14° and 2.36°, respectively, which means that the TC track shift in the second period was 2.52° more to the north compared with that in the first period (Fig. 2a), when the four unusual TCs are included. Even after removing the four unusual TCs, the TC track shift after 1980 was still about 0.82° to the north of that in the first period (Fig. 2b).

Why did the TCs after 1980 move more northward in November than those before 1980? The steering flow (750 hPa wind field) of the November climatology mean in the two periods is shown in Figs 3a and b. The steering flow in the central SCS was easterly and a little northerly in both these two periods, explaining the westward movement of the TC considering the beta effect. But the difference is that the steering flow is significantly weakened in the second period than in the first one, which is less than and more than 5 m/s, respectively. The differences between these two periods are shown in Fig. 3c, which demonstrates a significant southerly and westerly anomaly (about 1–2 m/s) in the central SCS from the southwest to the northeast. There also existed a weak cyclonic circulation anomaly in the northwestern SCS. It is indicated in the previous studies that the TC movement is controlled by the combination of the environmental steering flow and the beta effect. The increase of the southerly and the decrease of the easterly could both make the TCs to move more northward as the results of the strengthened steering effect and

Table 2. NSSs of selected TCs

Year	TC name, number and NSS/(°)									
Before 1980	Wanda 5 119 –0.2	Tilda 5 422 –0.9	Lucy 6 229 –0.6	Joan 6 429 0.4	Freda 6 736 2.7	Mamie 6 825 1.8	Niña 6 826 –0.5	Opal 7 024 –3.1	Patsy 7025 1.8	Hester 7 429 –0.6	Helen 7 518 –2.3
After 1980	**Hazen** **8 125** **7.5**	Herbert 8 623 1.8	Maury 8 721 0.5	Skip 8 829 3.0	Tess 8 830 2.2	**Mike** **9 025** **5.8**	Thelma 9 125 –0.9	Kyle 9 325 1.2	Elvis 9 814 3.0	Lingling 0 123 1.0	**Nepartak** **0 320** **9.0**
After 1980	Nuifa 0 425 –3.5	Durian 0 621 –2.7	**Haiyan** **1 330** **5.7**	Zoraida 1 331 1.8							

Note: Bold font is used for the four TCs of unusual northward shift.

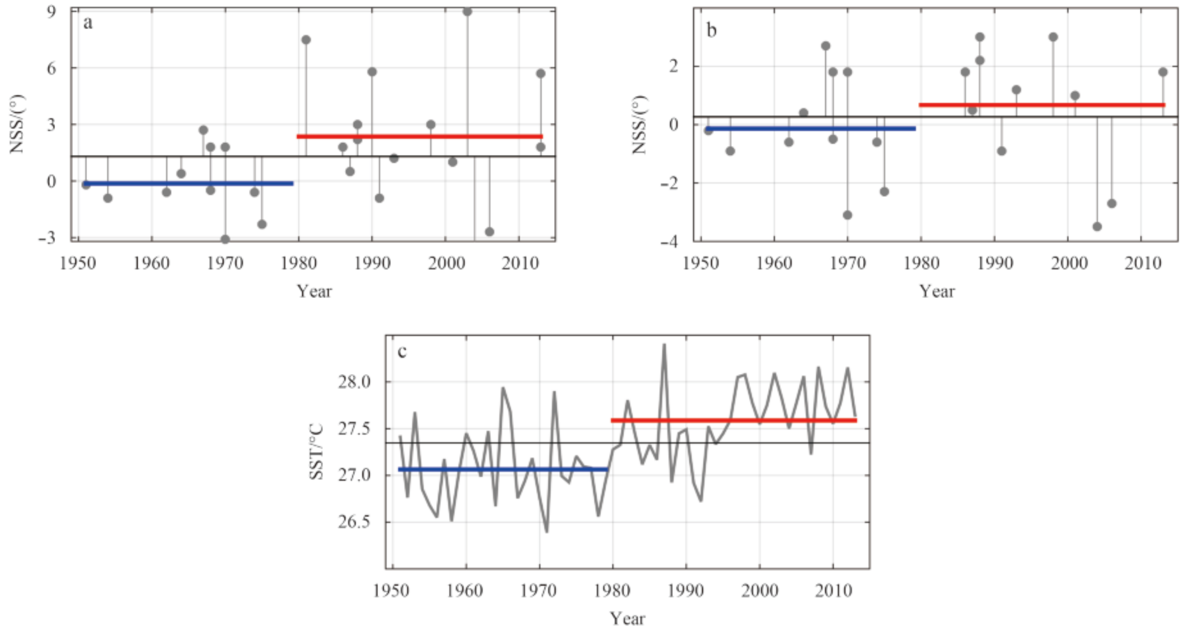

Fig. 2. The north-south shift of tracks for the TCs from 1951 to 2013 (a), same as Fig. 2a, except for the four unusual TCs (b) and SCS-averaged SST in November from 1951 to 2013 (c). Black thin, blue and red lines denote the averages of the periods from 1951 to 2013, 1951 to 1979 and 1980 to 2013, respectively.

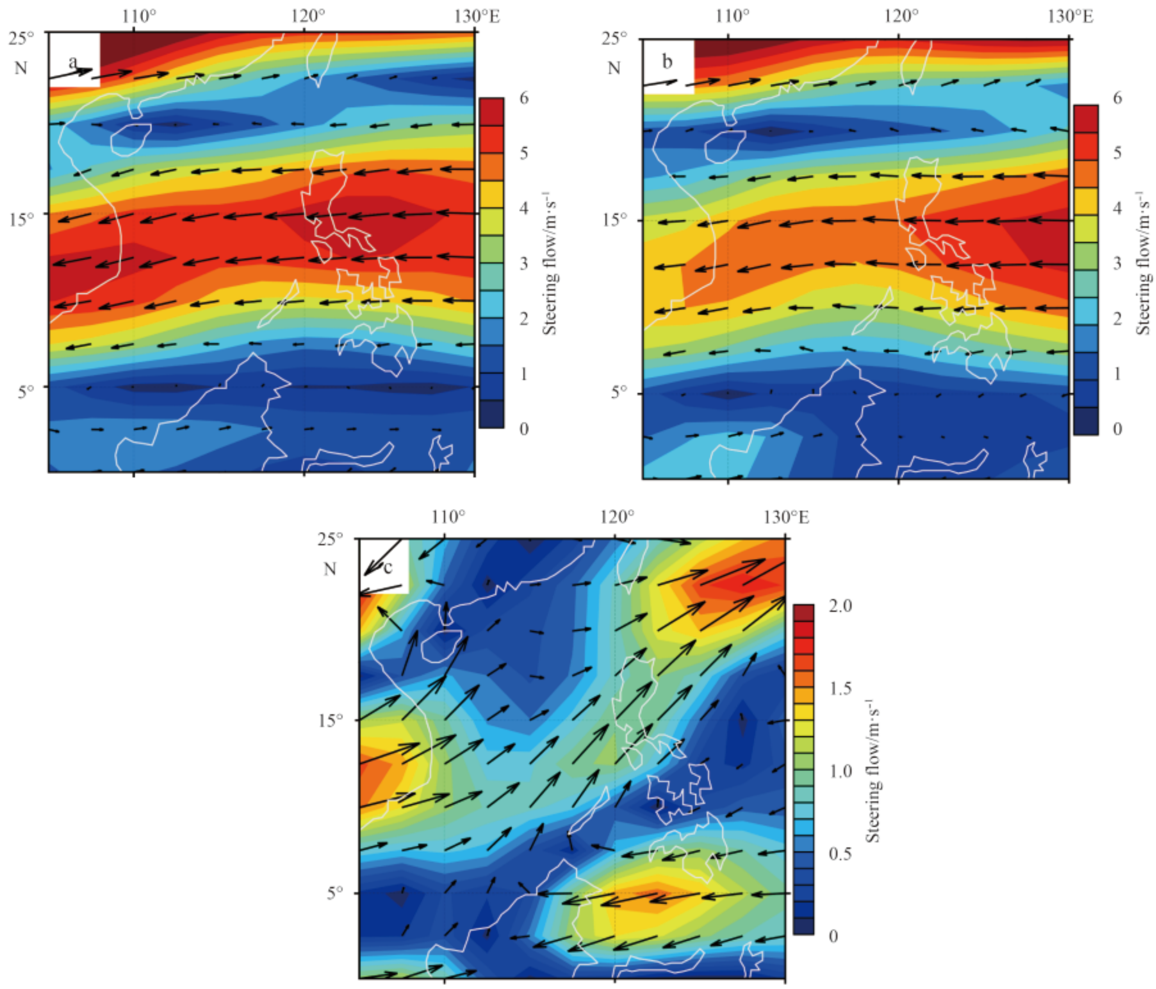

Fig. 3. Steering flows at 700 hPa of the November climatology mean in the first and the second period, respectively (a, b) and the change of the steering flow in the second period compared with that in the first one (c).

the more acting time of the beta effect, respectively.

As is well known, 1979 was the year when the global warming rate significantly increased (IPCC, 2007; Hansen et al., 2010). The shift was also significant in the SCS, which was mentioned by several studies (Huang et al., 2007; Liang et al., 2007; Wang et al., 2009). The average SSTs in the SCS before and after 1980 were 27.1 and 27.6°C (Fig. 2c), respectively. Considering both the warming and more northward track occurred around 1980, we hypothesize that the SST variation may have contributed to the northward shift of the TC tracks. Can the SCS warming induce a southerly anomaly in the central SCS and contribute to the northward shift of the TC tracks? To answer this question, we turn to numerical simulations.

3.2 *Numerical model results*

To test whether the SCS warming can result in more northward shift of the TCs or not, two kinds of TCs were chosen: (1) TC Joan (1964) and Skip (8829) and (2) Haiyan (2013) . This choice was made with the following reasons: (1) Tracks of TC Joan was similar to the ensemble-mean track of the TCs in November (Fig. 1); (2) the SCS SST before TC Joan and Skip entered the SCS were both comparable to the mean SST (27.1°C) from 1951 to 1979, which were 26.7 and 26.9°C, respectively; (3) TC Haiyan was one of the four unusual TCs, shifted 5.7° northward in the SCS and the SCS SST before it entered the SCS was 27.6°C, which was equal to the mean SST (27.6°C) in the second period. The full physics model WRF was adopted in the study and three sensitivity experiments were designed to investigate the role of the SCS SST in TC movement (Table 3). The SCS SST was increased by 0.5°C in experiment J-SCS and S-SCS to check if their tracks in the SCS would exhibit more northward shift caused by the SCS warming. H-SCS was to see if the track will shift southward when the SCS warming was removed. Considering the different SST forcing conditions in these experiments, we divided these experiments into two kinds: and the cooling experiments (J-CTL, S-CTL and H-SCS) and the warming experiments (J-SCS, S-SCS and H-CTL).

The NSSs of the simulated TC tracks in experiments J-CTL and S-CTL were 0.96° and 1.27°, respectively, which were comparable to their actual shift and quite similar to the ensemble mean (1.30°) (Fig. 1). After the SST was increased by 0.5°C in the SCS Basin uniformly in the warming experiments, the simulated track of J-SCS and S-SCS both exhibited a significant northward shift. Their northward movement reached 1.81° and 3.30° (Fig. 4), supporting our hypothesis that the SCS SST plays an important

Table 3. WRF experiments design for TC Joan, Skip and Haiyan

TC	Control experiment	Sensitive experiment	Details
Joan	J-CTL	J-SCS	the SST in the SCS is increased by 0.5°C
Skip	S-CTL	S-SCS	the SST in the SCS is increased by 0.5°C
Haiyan	H-CTL	H-SCS	the SST in the SCS is decreased by 0.5°C

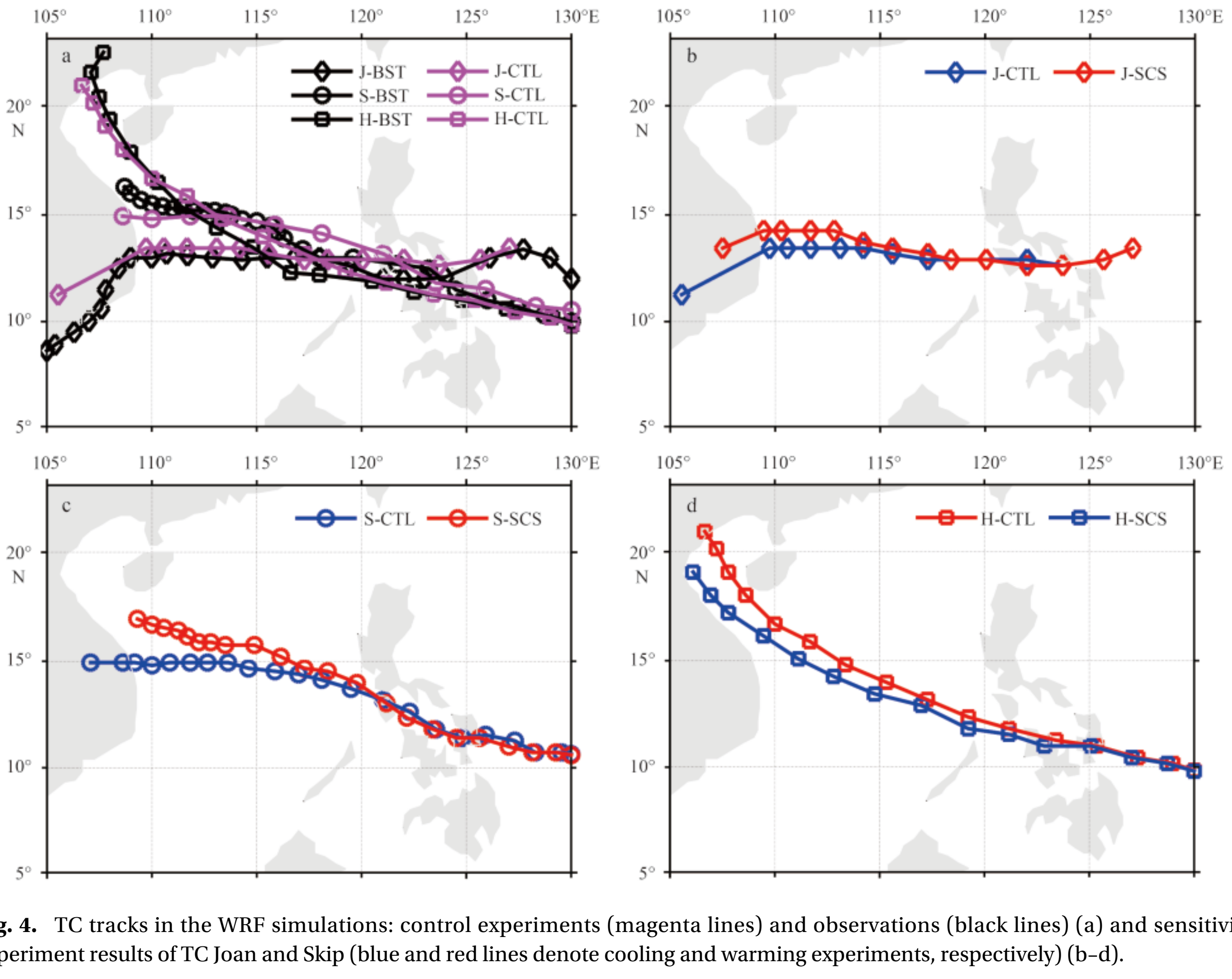

Fig. 4. TC tracks in the WRF simulations: control experiments (magenta lines) and observations (black lines) (a) and sensitivity experiment results of TC Joan and Skip (blue and red lines denote cooling and warming experiments, respectively) (b–d).

role in the northward shift of the SCS TC tracks. Comparing H-CTL and its cooling experiment H-SCS, the simulated track of Haiyan exhibited a southward shift when the SCS SST decreased by 0.5°C: NSSs in these two experiments were 5.50° and 4.52°, respectively. This indicates that the SCS warming contribute to the northward shift of TC Haiyan, further supporting the hypothesis that the SCS SST plays an important role in the northward shift of the SCS TC tracks.

The steering flow in these six experiments is calculated and the differences between the warming and cooling experiments are shown in Fig. 5. It is clear that the steering flow in the SCS exhibited significant change after the SCS was warmed up by 0.5°C.

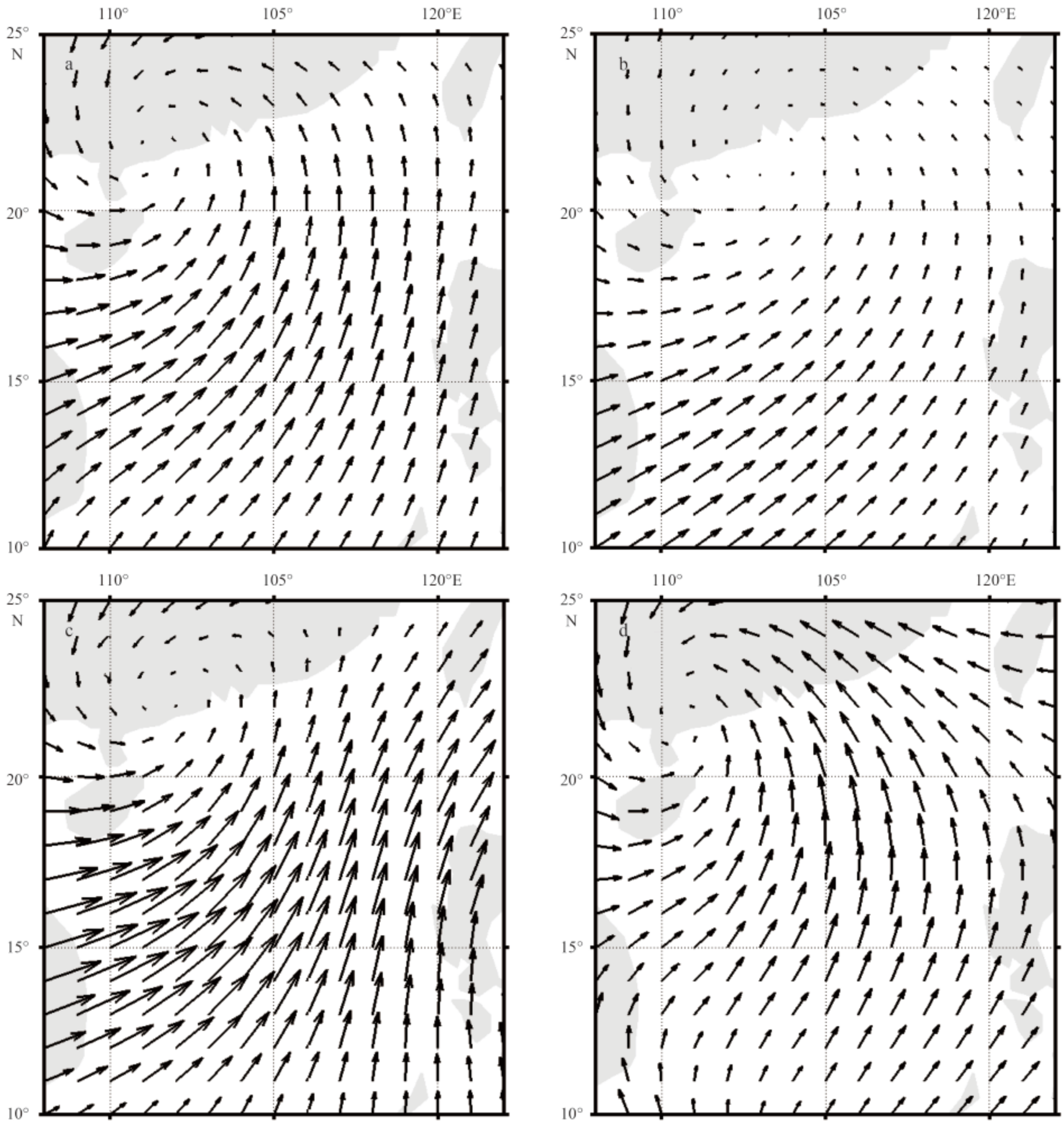

Fig. 5. The change of the steering flow between the warming and cooling experiments: ensemble mean of Joan, Skip and Haiyan (a) and Joan, Skip and Haiyan (b–d), respectively.

The ensemble mean difference gives a quite similar pattern with the observation (Fig. 3c): there also exist a cyclonic circulation in the northwestern SCS and the southwesterly in the central SCS from the southwest to the northeast. This response to the SCS warming makes a contribution to the northward drift of TC motion. The beta drift is also calculated but the beta gyres are not clear in neither cooling nor warming experiments (figure not shown), indicating that the beta effect may have little effect on the northward shift of the TCs in November after 1980.

Why does the warming over the SCS cause a cyclonic anomaly in the northwestern SCS? This can be explained by Gill's (1980) theory. The vorticity balance requires the southerly wind anomaly over the heating region and the return flow being situated farther west associated with the Rossby wave response; hence, a cyclonic anomaly appears on the northwestern flank of the forcing region.

4 Conclusions

The tracks of the SCS TCs in November show more northward shift after 1980. Both observations and numerical simulations suggest that the SCS warming plays an important role in this more northward shift: the warming in the SCS can induce a cyclonic anomaly in the northwestern SCS, and its associated southerly anomaly in the central SCS can make the TC to move further to the north in the SCS.

Our study indicates that the SST in the SCS Basin plays a role in TC movement in the meridional direction. Since the dynamic processes of the atmospheric circulation are not fully considered in this study, for example, teleconnections between the SCS large scale steering flow and the global atmospheric circulation, further studies are needed to deepen our understanding of the TC track shift over the SCS.

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