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Role of ocean upper layer warm water in the rapid intensification of tropical cyclones: A case study of typhoon Rammasun (1409)

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Abstract

Rammasun intensified rapidly from tropical storm to super typhoon in the northern South China Sea (NSCS) before its landfall on Hainan Island. Analysis of observed data shows that the anomalous ocean upper layer warm water (WW) is important to the rapid intensification of Rammasun. During the period of Rammasun, sea surface temperature (SST) in the NSCS was much warmer than the climatological SST. The anomalous WW supplied more energy to Rammasun, resulting in its rapid intensification. Numerical simulations further confirm that the NSCS WW plays an important role in the rapid intensification of Rammasun. As the WW is removed, the intensification of Rammasun is only 25 hPa, which is 58.1% of that in the original SST-forced run.

Key words: tropical cyclone, Rammasun, rapid intensification, warm water, sea surface temperature

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1 Introduction

Tropical cyclone (TC) periodically produces devastating natural disasters, causing great losses of human and property. TC intensity, especially just before landfall, is very important for disaster prevention. However, due to the complexity of atmosphere and ocean conditions, it is difficult to forecast TC intensity, especially the rapid intensification (Kaplan and DeMaria, 2003; Elsberry et al., 2007; Wang and Zhou, 2008).

Previous studies have shown that TC intensification is significantly affected by sea surface temperature (SST) (DeMaria and Pickle, 1988; Wang and Wu, 2004; Duan et al., 2013), and 1°C SST change will lead to 5–20 hPa minimum sea level pressure (MSLP) change (Evans, 1993; Schade and Emanuel, 1999; Chan et al., 2001; Wu et al., 2005). This is because the warm SST provides enough energy through surface heat flux for TC intensification to overcome frictional dissipation in the boundary layer and at large radii in the outflow (Emanuel, 1986). Besides, with the surface wind speed increase near TC core region induced by the warm SST, TC can draw more energy from ocean as a positive feedback, further causing TC intensification (Emanuel, 1986; Rotunno and Emanuel, 1987; Sun et al., 2013). Recently, TC rapid intensification is more concerned by scientists, but the mechanism is still not clear (Wang and Wu, 2004; Cangialosi and Franklin, 2014). Lin et al. (2005, 2008, 2009, 2013) discussed the oceanic effect on TC rapid intensification, and emphasized the important role of upper ocean heat content in the rapid intensification of TCs.

The South China Sea (SCS) is an unique semi-enclosed marginal sea. Most of TCs in the SCS make landfall on surrounding countries, such as China, Vietnam and Philippines. Thus, understanding the development of the TCs in the SCS is very important for disaster prevention. Rammasun is the ninth TC generated over the Northwest Pacific Ocean (NWP), and the first one crossed the SCS in the year of 2014. Its intensity decreased when it just entered the SCS, but then it rapidly intensified to super typhoon before landfall on Hainan Island, with its maximum wind speed (10-min averaged) increased by 15.8 m/s from 31.7 m/s to 47.5 m/s and MSLP decreased by 35 hPa from 970 hPa to 935 hPa in 36 hours (Fig. 1). This rapid intensification of Rammasun made it the most severe landfall typhoon (on South China) in the past 41 years and brought great disaster to China, causing 62 people deaths and 33.65 billion yuan RMB in direct economic losses. So far, the reason of this rapid intensification process is not clear yet. But we notice that SST in the northern SCS (NSCS, north of 15°N) was abnormally warmer than climatological value during the time of Rammasun passing through the SCS, which may play an important role in the rapid intensification of Rammasun. In this paper, the effect of NSCS upper layer warm water (WW) on rapid intensification of Rammasun is examined by using a series of observations and numerical simulations.

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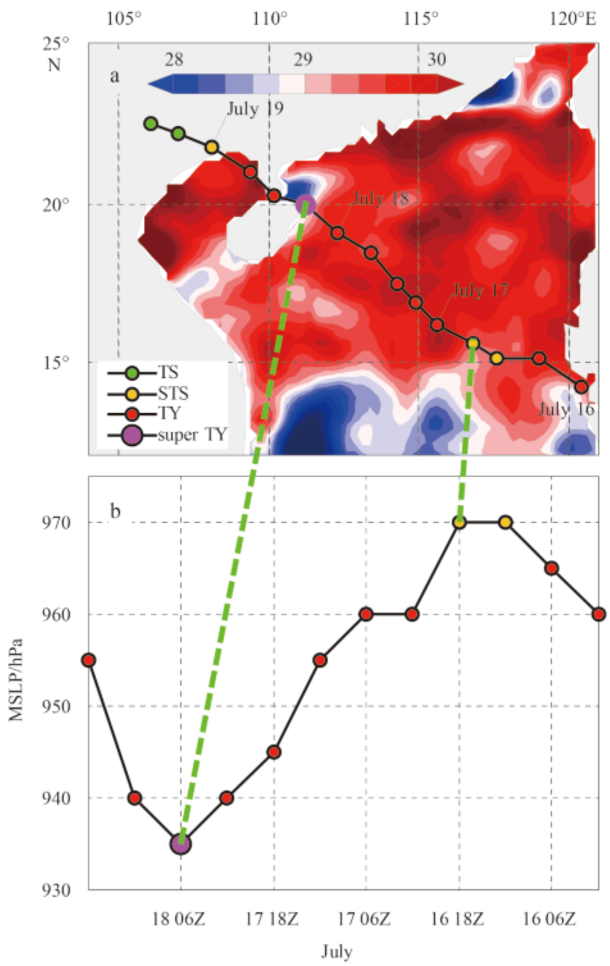

Fig. 1. Rammasun track (6-hourly TC center positions, colored circle line) and SST on July 16, 2014 (shaded color, unit: °C) (a), and Rammasun intensity (MSLP, unit: hPa) (b).

2 Data and model

2.1 *Data*

The TC dataset named "best track data" from Japan Meteorological Agency (JMA) is used. This dataset provides 6-hourly tropical cyclone center position and intensity (including 10-min averaged maximum wind speed and MSLP) and is used from 1982 to 2014. Best track data provided by China Meteorological Administration (CMA) is also used for the verification of Rammasun simulation.

National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center Optimum Interpolation Sea Surface Temperature analysis (NCDC-OISST) data are used to get NSCS average SST. The daily SST dataset with 0.25°×0.25° spatial resolution is available from 1981 September 1 to present. We use the data from 1982 to 2014.

Daily surface flux data, including latent heat flux (LHF) and sensible heat flux (SHF), is derived from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis 1 project. We use the data from July 16 to July 20 of the year 2014 during the time of Rammasun.

2.2 *Model*

WRF version 3.5 is used for typhoon Rammasun simulation. Doubly nested grid is adopted and the horizontal resolution is 30/10 km with (245×106)/(358×220) grids, covering (0°–30°N, 100°–170°E) and (5°–25°N, 105°–140°E), respectively. Thirty full-sigma levels are set in vertical, and the model top layer is set as 50 hPa. Detailed model parameterization used in this study is shown in Table 1. The initial and boundary conditions are constructed from NCEP Final Operational Global Analysis data. In this study, we focus on the process when Rammasun is in the NSCS. Thus, the model is integrated from July 14, which is 48 hours before Rammasun landfall on Philippines, and then integrated 7 days to July 21.

Table 1. Model parameterization configuration in WRF 3.5 model

Physics process	Parameterization scheme
Microphysics	Lin et al. scheme
Cumulus parameterization	Kain-Fritsch scheme
Upper layer	MM5 similarity
Planetary boundary layer	Yonsei University scheme
Longwave radiation	RRTM scheme
Shortwave radiation	Dubhia scheme

3 Results

3.1 *Observations*

Rammasun is generated over the NWP on July 7, 2014, moved westward with its intensity increasing, made landfall on Philippines on July 15, and then weakened to tropical storm at (15.6°N, 116.8°E) in the NSCS. After that, Rammasun rapidly intensified by 35 hPa and 15.8 m/s in 36 hours to be super typhoon and made landfall on Hainan Island with its maximum intensity (Fig. 1). This rapid intensification of Rammasun made it the most severe landfall typhoon (on South China) in the past 41 years.

To reveal the difference of intensification between Rammasun and other TCs in the SCS, 18 TCs that entered the SCS at 120°E and left the SCS at 110°E in July from 1982 to 2013 are selected (Table 2). Figure 2 shows the tracks and intensity changes of the 19 TCs. It is found that all TCs entered the SCS from Philippines Islands and left from the northwestern SCS (Fig. 2a), but their intensity change and intensification rate are quite different (Fig. 2b). Generally, TCs kept intensifying after they entered the SCS, until they made landfall on Hainan Island or left the SCS. On average, TC kept intensifying after entering the SCS and their maximum MSLP decrease in the SCS can be 11 hPa. In contrast, Rammasun intensified after the first weakening stage, and its maximum MSLP decrease in the SCS reached 35 hPa, which is 24 hPa stronger than the average intensification, and its intensifica-

Table 2. Numbers and names of the selected 18 TCs from 1982 to 2013

TC No. and name			
8208# (Winona)	8303# (Vera)	8404# (Betty)	8907# (Faye)
8910# (Irving)	9106# (Zeke)	9205# (Eli)	9207# (Gary)
9303# (Lewis)	0107# (Yutu)	0307# (Imbudo)	0308# (Koni)
0606# (Prapiroon)	0905# (Soudelor)	1002# (Conson)	1003# (Chanthu)
1108# (Nock-ten)	1309# (Jebi)		

tion rate is the rapidest among all the selected TCs.

Because TC intensification is significantly affected by SST (DeMaria and Pickle, 1988; Wang and Wu, 2004; Duan et al., 2013), we first take a look at the SST in the NSCS. As shown in Fig. 1, before Rammasun entered the SCS, a WW mass was located in the NSCS. The SST was higher than 30°C in almost the whole NSCS, which was 1–2°C higher than the climatological value in July (Fig. 3). When Rammasun moved to the top of the preexisting WW, it stopped weakening and began to intensify rapidly, suggesting that the NSCS anomalous WW may play an important role in the rapid intensification of Rammasun. Thus, we examine the relationship between the NSCS average SST and intensification of the selected TCs. The result shows that TC intensification increases with the NSCS average SST increasing, and 1°C SST increase can lead to 8.4 hPa MSLP decrease (Fig. 4), further suggesting that higher SST may contribute to more intensification of TC in the NSCS.

Previous studies verified that higher SST can enhance TC through supplying more heat energy to TC (Malkus and Riehl, 1960; Black and Holland, 1995; Xu and Wang, 2010; Sun et al., 2013). In this part, we are going to examine the effect of the NSCS anomalous WW on the Rammasun rapid intensification through surface heat flux. As shown in Fig. 5, surface heat flux from ocean to atmosphere began to increase when Rammasun entered the SCS (July 16). Then the increased surface heat flux intensified Rammasun rapidly. On July 18, just before landfall, the surface heat flux and Rammasun intensity reached their maximum values: 268.7 W/m^2 and 935 hPa (MSLP), respectively. Due to the heat loss to the atmosphere, the NSCS average SST decreased from 29.8°C to about 29.0°C. However, the NSCS average SST was always higher than the climatological value (29.0°C) throughout the entire intensifying process, making it possible to provide more energy for Rammasun than the other TCs, and causing the rapid intensification of Rammasun in the SCS.

3.2 *Numerical simulation*

To examine the effect of the NSCS upper layer WW on Rammasun rapid intensification, Rammasun is simulated by WRF 3.5 model. As shown in Fig. 6a, the model succeeds in reproducing the motion of Rammasun in the NSCS, considering the error of the best track data and the spatial resolution in the model. The simulated maximum intensity is 925 hPa and is 10 hPa lower and 37 hPa higher than the JMA and CMA best track data, respectively, and is able to reproduce Rammasun rapid intensification before landfall on Hainan Island in the SCS (Figs 6b and c), although the on-land intensification stage on Philippines Islands is weak, which may be a result of the model parameterization scheme. We focus on Rammasun rapid intensification in the SCS,

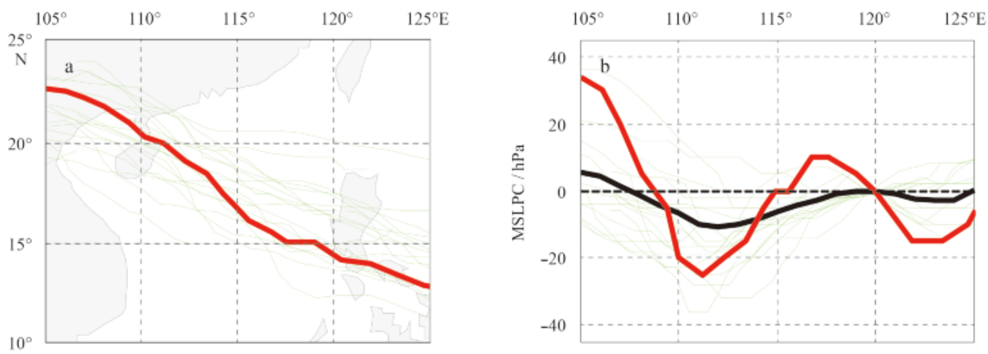

Fig. 2. selected 18 TCs Tracks (green lines), red line represent the track of Rammasun (a); and selected 18 TCs MSLP change (MSLPC) (green line, unit: hPa), their average MSLPC (black line) and Rammasun MSLPC (red line) (b). MSLPC means MSLP change comparing to MSLP at 120°E.

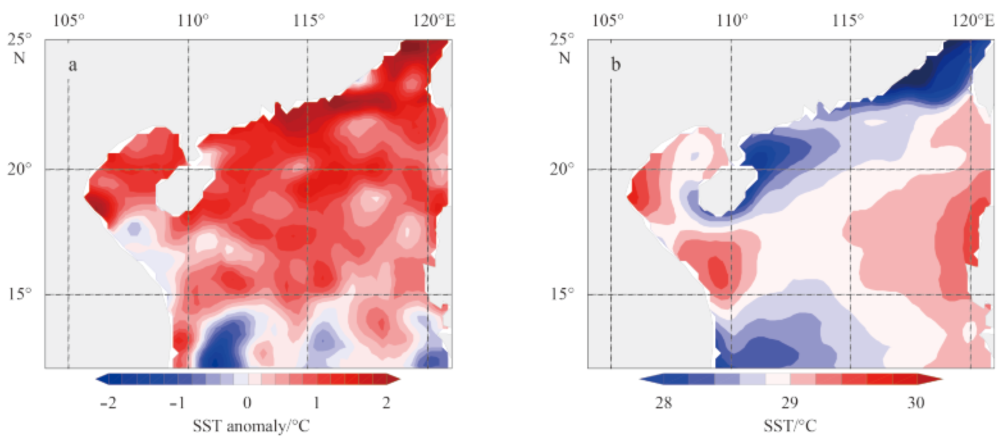

Fig. 3. SST anomaly (unit: °C) on July 16, 2014 (a), and climatological SST (unit: °C) in July (b).

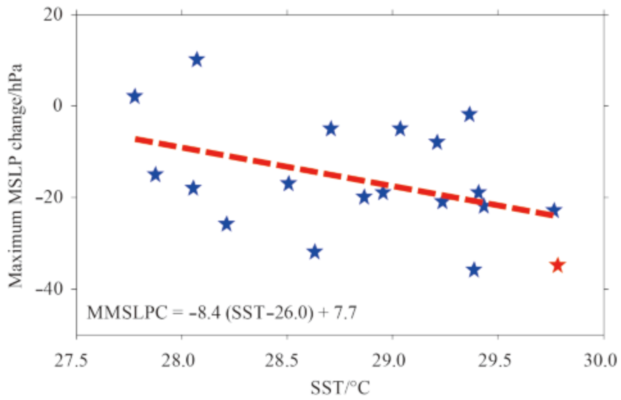

Fig. 4. Maximum MSLP change (MMSLPC) in SCS and average SST ofNSCS when TC entered SCS. Blue stars denote TCs in July from 1982 to 2013, red star denotes Rammasun, red dashed line denotes linear fitting.

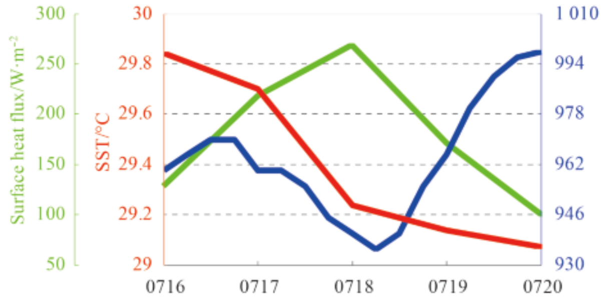

Fig. 5. NSCS average SST (red line, unit: °C), surface heat flux (green line, unit: W/m^2) and Rammasun MSLP (blue line, unit: hPa) from July 16 to 20 of 2014.

where Rammasun can be well replicated by WRF, thus it can be used for further mechanism discussion.

In order to quantitatively evaluate the role of the NSCS upper layer WW on the rapid intensification of Rammasun, three sensitive experiments with WRF 3.5 model are carried out. In these three experiments, different SST magnitudes are given in the NSCS and SST condition is not changed in other areas (Table 3). In Exp. 1, SST higher than 30.0°C is suppressed to 30.0°C. Considering that the NSCS climatological SST in July is 29.0°C, SST higher than 29.0°C in the NSCS is suppressed to 29.0°C in Exp. 2. Because SST is warmer than 29.0°C in nearly the whole NSCS (Fig. 1a), the NSCS SST condition in Exp. 2 is almost uniform in horizontal (29.0°C). In Exp. 3, SST climatology in July is used. Since the mean NSCS SST in Exps 2 and 3 are almost the same, the two experiments can be used to examine the effect of SST spatial pattern on TC intensification.

The results of sensitivity experiments show that TC track is not much affected by the NSCS WW, but its intensity is very sensitive to the magnitude of the NSCS WW (Figs 7a and b). With the NSCS average SST decreased from CTRL to Exp3, the simulated Rammasun intensity becomes weaker and weaker. As shown in Table 4, in the NSCS, the simulated intensity increases by 43, 35, 26 (25) hPa to 925, 933, 942 (943) hPa in experiments CTRL, Exp. 1 and Exp. 2 (Exp. 3), respectively. In Exp. 3, when the NSCS WW is removed, Rammasun intensification is only 58.1% of that in CTRL run, indicating the NSCS WW is important to the rapid intensification of Rammasun. Also, the intensification difference between Exps 2 and 3 indicates that the different spatial distribution of the NSCS SST (see Fig. 1b) can also affect TC intensity: the cold water in the northwest SCS may slightly weaken TC before its landfall.

In the Carnot heat engine theory (Emanuel, 1986), the ocean provides energy for TC intensification through surface heat flux, including the LHF and SHF, and both of them are affected by SST (Large and Pond, 1982). As shown in Figs 7c and d, both the LHF and SHF decrease with the initial SST decreasing from CTRL to Exp. 3. The maximum LHF from CTRL to Exp. 3 are 900, 640, 490, 400 W/m^2 and maximum SHF are 280, 205, 105, 100 W/m^2 (Table 4), respectively. The reduction in surface heat flux then leads to the weakening of TC intensification (Fig. 7b). The TC intensification in Exp. 3 reduces by 41.9% than that in CTRL run, when the SHF and LHF in Exp. 3 reduce by 64.3% and 55.6% than that in CTRL run, respectively. It suggests that the NSCS anomalous WW

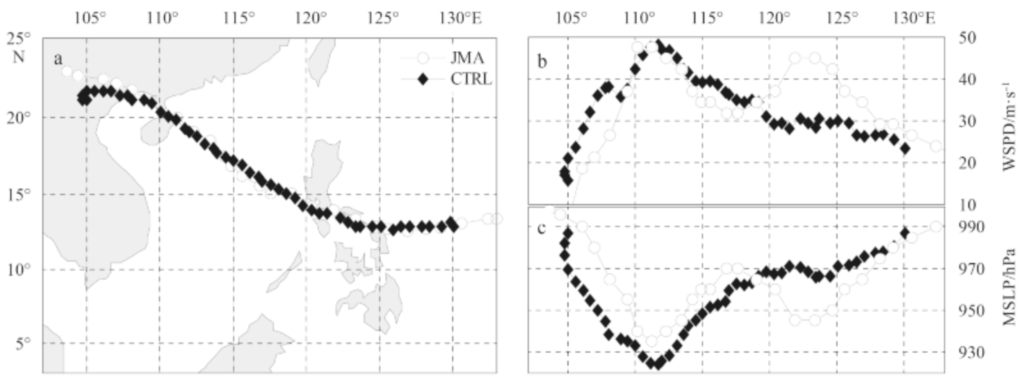

Fig. 6. Control experiment results of Rammasun simulation (white circle line is JMA data; black diamond line is WRF simulation result): track (a), 10 m wind speed (unit: m/s) (b), MSLP (unit: hPa) (c).

during the period of Rammasun causes its rapid intensification through supplying more energy to atmosphere.

To further confirm the effect of the NSCS anomalous WW on Rammasun rapid intensification, warm core (WC) of Rammasun in these experiments are shown in Fig. 8. TC WC is an indicator to describe TC structure and development (Willoughby, 1995), which is calculated by subtracting the average temperature value of each pressure levels from the TC center (within a radius of 50

Table 3. SST condition configuration for WRF 3.5 model in sensitive experiments

Experiments	SST condition
CTRL	daily SST
Exp. 1	SST higher than 30.0°C in the NSCS is set to 30.0°C
Exp. 2	SST higher than 29.0°C in the NSCS is set to 29.0°C
Exp. 3	climatology July SST

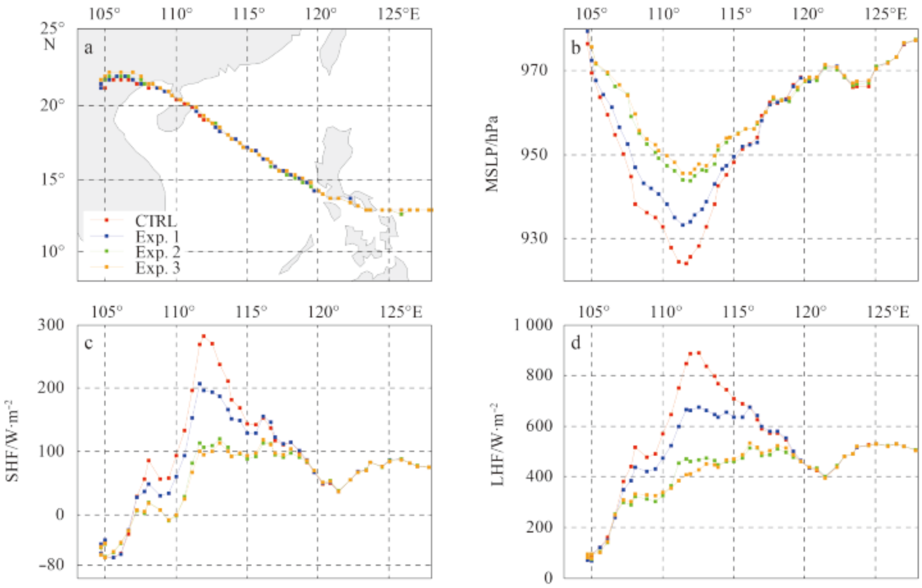

Fig. 7. Simulated track (a), intensity (MSLP, unit: hPa) (b), SHF (unit: W/m^2) (c), and LHF (unit: W/m^2) in CTRL and sensitive experiments (d).

Table 4. Simulated maximum intensity (MI), intensification (ITF), SHF and LHF in each experiment (The numbers in the blankets denote percent of the CTRL result)

Experiments	MI/hPa	ITF/hPa	ITF decrease/hPa	SHF/W·m^{-2}	LHF/W·m^{-2}
CTRL	925	43 (–%)	–(–%)	280 (–%)	900 (–%)
Exp. 1	933	35 (81.4%)	8 (18.6%)	205 (73.2%)	640 (71.1%)
Exp. 2	942	26 (60.4%)	17 (40.6%)	105 (37.5%)	490 (54.4%)
Exp. 3	943	25 (58.1%)	18 (41.9%)	100 (35.7%)	400 (44.4%)

km) regional averaged value in the study. In these sensitive experiments, TC WC east of 120°E are almost the same. However, after Rammasun enters the SCS, WC development is quite different (Fig. 8). WC development of Rammasun in experiment CTRL is the rapidest during its time in the NSCS, especially west of 117°E. When the magnitude of the NSCS WW decreases, WC development rate distinctly slows down (Fig. 8). The sensitivity of WC structure to the magnitude of the WW further confirms that the NSCS upper layer WW is crucial to the rapid intensification of Rammasun.

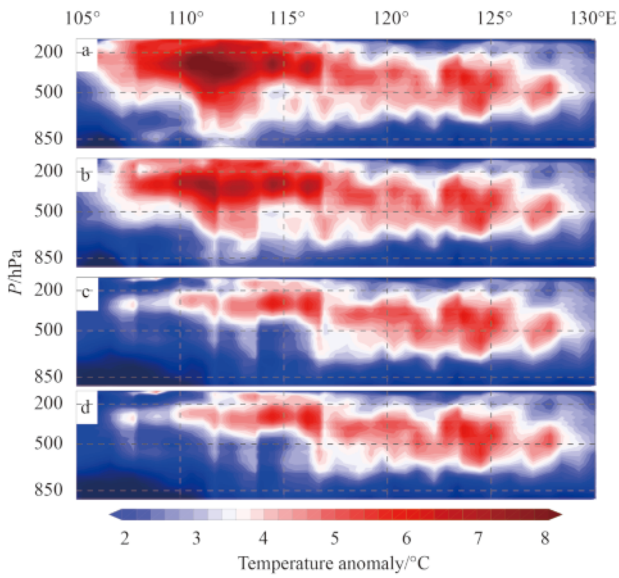

Fig. 8. Simulated potential temperature anomalies (unit: °C) in each experiment (in *P*-coordinate (hPa)): CTRL (a), Exp. 1 (b), Exp. 2 (c), and Exp. 3 (d).

4 Summary and discussion

The role of the ocean upper layer WW in the TC intensification in the July SCS is investigated in this study. The results show there is a good relationship between the intensification of TCs and SST in NSCS: The MSLP of TC will decrease 8.4 hPa with 1°C SST increasing. Then the rapidest intensified TC Rammasun is selected to study the mechanism of the effect of the WW on the intensification of TCs.

Rammasun intensified rapidly before its landfall on Hainan Island, and became the most severe landfall typhoon (on South China) in the past 41 years. Satellite observed SST shows that SST in the NSCS during Rammasun time was about 1–2°C warmer than the climatological value (29°C). Further analysis suggests that the anomalous WW in the NSCS may play a major role in the rapid intensification of Rammasun by supplying more energy. Numerical simulations confirm that its intensity is very sensitive to the magnitude of the NSCS WW. As the WW is removed, LHF and SHF reduce 55.6% and 64.3% respectively, and Rammasun only intensifies by 25 hPa, which is 58.1% of that in the original

SST-forced run.

Typhoon intensity prediction is very important, but it is still a challenge to improve. Ocean environments are complex before TC landfall and have great effects on TC motion and intensity. Abnormal WW is capable to cause TC rapid intensification, and should be paid more attention in TC forecast business.

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