A Diagnostic and Numerical Study on a Rainstorm in South China Induced by a Northward-Propagating Tropical System*

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ABSTRACT

A strong cyclonic wind perturbation generated in the northern South China Sea (SCS) moved northward quickly and developed into a mesoscale vortex in southwest Guangdong Province, and then merged with a southward-moving shear line from mid latitudes in the period of 21–22 May 2006, during which three strong mesoscale convective systems (MCSs) formed and brought about torrential rain or even cloudburst in South China.

With the $1^{\circ}\times1^{\circ}$ NCEP (National Centers for Environment Prediction) reanalysis data and the Weather and Research Forecast (WRF) mesoscale model, a numerical simulation, a potential vorticity inversion analysis, and some sensitivity experiments are carried out to reveal the formation mechanism of this rainfall event. In the meantime, conventional observations, satellite images, and the WRF model outputs are also utilized to perform a preliminary dynamic and thermodynamic diagnostic analysis of the rainstorm systems.

It is found that the torrential rain occurred in favorable synoptic conditions such as warm and moist environment, low lifting condensation level, and high convective instability. The moisture transport by strong southerly winds associated with the rapid northward advance of the cyclonic wind perturbation over the northern SCS provided the warm and moist condition for the formation of the excessive rain. Under the dynamic steering of a southwesterly flow ahead of a north trough and that on the southwest side of the West Pacific subtropical high, the mesoscale vortex (or the cyclonic wind perturbation), after its genesis, moved northward and brought about enormous rain in most parts of Guangdong Province through providing certain lifting forcing for the triggering of mesoscale convection. During the development of the mesoscale vortex, heavy rainfall was to a certain extent enhanced by the mesoscale topography of the Yunwu Mountain in Guangdong. The effect of the Yunwu Mountain is found to vary under different prevailing wind directions and intensities. The location of the heavy rainfall was in a degree determined by the trumpet-shaped topography of the Zhujiang Delta. It is identified that the topographic effect on precipitation depends on the relative position between the terrain and the mesoscale storm systems. The short distance from the SCS to South China facilitates the moisture transport, which offers ease for the heavy rain to form in South China.

Finally, the role played by land-sea contrast in the fast intensification of the MCSs in South China is not yet clear, and the interaction between the MCSs and the mesoscale vortex needs to be clarified as well.

Key words: rainstorm in South China, mesoscale vortex, topography, potential vorticity inversion, mesoscale convective system (MCS)

1. Introduction

South China, which is close to the South China Sea (SCS) in the south and leans the Nanling Mountain in the north, is in a special geographic environment, where the meso- and small-scale geography is complicated. Every year the flooding season comes early and the rainfall is not only subject to the westerly systems, but also influenced by the northward-migrating tropical systems. Rainstorms occur frequently and usually result in serious flooding disasters in the region. There have been a lot of documents and research concerning the early-summer rainstorms in South China. Meteorologists have investigated not only the large-scale background related to the rainstorm from the points such as monsoon, subtropical high, and middle-high latitude atmospheric circulations, etc. (Tao, 1980; Huang, 1986; Xue, 1999), but also the characteristics of the mesoscale convective

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systems (MCSs) triggering rainstorms and their possible formation mechanisms (Zhou, 2000; Zhao et al., 2004) by mesoscale analysis and numerical modeling. It has been found in the research and operational forecast that the systems resulting in the South China rainstorms are mainly three types: the westerly systems associated the fronts, the northward propagating tropical systems, and the local thermal forcing convective systems. For the first category, if in a stable large-scale background, the frontal system will be in a quasi-stationary state when going down to South China and usually causes rainstorms lasting several days (like South China continuous rainstorms in June 2005). But if the frontal systems move quickly southward to the SCS, it will only result in a short-lived rainstorm. In the meantime, there usually occur rainstorms or even extremely exceptional rainstorms in the prefrontal warm area (about 200–300 km ahead of the surface front), which presents a great difficulty to operational forecasting. The second category includes typhoon, tropical depression, and perturbations in the tropics. As to this category, the forecast capability of mesoscale numerical models is very low and the model usually gives empty forecasts or fails to give forecasts in real operation because of sparse observations available in the wide ocean. Especially the rainstorm triggered by northward-translating tropical perturbations from the SCS is very hard to forecast accurately because its forecast signal or clue is rather weak. The third category is the most difficult to forecast and operational forecasts usually fail. But sometimes the local thermal convection in the high warm-moist environment may develop into mesoscale convective complex (MCC) and leads to a wide-range of rainstorms under the role of the local sea-breeze circulations. Therefore, it is necessary to carry out separate research on these rainstorms for understanding their thermodynamic structure and physical formation mechanism, which is beneficial to the operational forecast and the improvement of mesoscale numerical models.

A strong cyclonic wind perturbation from the SCS moved northward quickly and developed into a mesoscale vortex in South China during the period of 0800 BT 21 to 0800 BT 22 May 2006. Under the vortex influence, there occurred rainstorms in most parts of Guangdong Province and even extremely exceptionally heavy rainstorms in its east coast. The strong rain mass was located in the Zhujiang Delta (Fig.1). The observed rainfall was over 50 and 100 mm respectively in 49 and 17 county stations. There even appeared extremely exceptional rainstorms in Taishan and Xinhui, with a rainfall of 232 and 229 mm, respectively. Moreover, the heavy rainfall occurred in a short time and was of obvious mesoscale characteristics, with 1-h maximum rainfall of 54 mm (Dongguan) and 6-h maximum 164 mm (Taishan). The strong rainfall mass was of meso-β scale structure. The rainstorm belongs to the so-called second category rainstorm mentioned above. In the following, this rainfall event will be taken as an example to investigate the physical mechanism of this type of rainstorms through diagnostic analyses and numerical simulations, for deepening the understanding of this kind of rainstorms and providing a scientific basis for operational forecast.

2. Synoptic conditions and mesoscale environment

2.1 Synoptic scale conditions

At 0800 BT 21 May 2006, an upper-air trough was located in the west of North China at 500-hPa height (Fig.2a), with the trough bottom in Sichuan Basin. A temperature trough was obviously lagged behind of the height trough. At 850 hPa, a shear line was in an NE-SW orientation and located in the middle valleys of Yangtze River. The upper-air trough cloud clusters indicated by TBB (black-body temperature) cloud

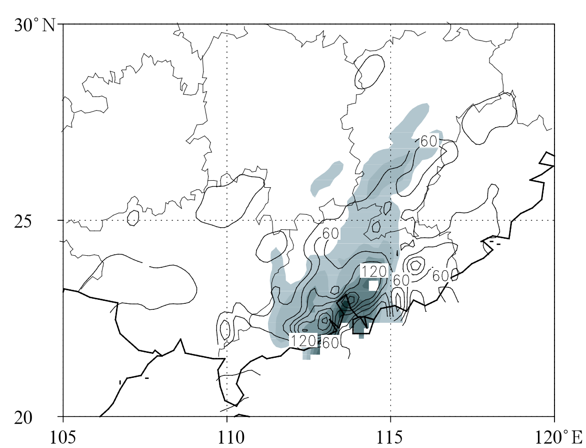

Fig.1. Observed 24-h accumulative precipitation (mm) at 0800 BT 22 May 2006. Shaded area is for simulated precipitation greater than 25 mm.

images were in front of the 500-hPa trough and the north side of 850-hPa shear line. This weather system was obviously of baroclinicity when viewed from the allocation of height and temperature fields and the system's situation in the upper and lower levels. A south branch trough was over the Bay of Bengal and a vortex circulation was developing at

850 hPa. The West Pacific subtropical high was in a quasi-WE orientation and extended westward into the SCS, with its ridge line at about 18°N. A strong cyclonic wind perturbation in the north of the SCS began to land the southern coast of Guangdong Province, with intensive convective clouds developing in the surroundings of strong wind axis. On the 850-hPa pseudo-equivalent potential temperature ($\theta_{\rm se}$) field (Fig.2b), there were two fronts in the north and south branch, respectively, one in front of the north branch trough and the other in the south of Yangtze River, with a dry area between them. There was an area with high pseudo-potential temperature over 340 K in the south of South China. The intensive wind perturbation in the north of the SCS was corresponding with strong relative vorticity and divergence.

At 2000 BT 21, the upper-air north trough was slightly strengthened and moved eastward to the central and west of North China (Fig.2c). At 850 hPa, the shear line also moved eastward slightly with it. The north $\theta_{\rm se}$ front pushed southward while the south front moved northward with a dry area still maintaining between them (Fig.2d). Due to the cut-off of the moisture transportation by the dry area, the upper-air trough did not make obvious rainfall in the middle valleys of Yangtze River. At this time, a strong cyclonic wind perturbation landed the Yunwu Mountain in Guangdong Province and developed into a mesoscale vortex (the relative vorticity at 850 hPa indicates the vortex's position, but its formation time is not clear). With the activity of the vortex, strong convective clouds developed in the east of Guangdong Province and brought about intensive rainfall. At 0800 BT 22, the upper-air trough moved SE-ward further (Fig.2e). At 850 hPa, the northwest winds in the north side of the shear line pushed quickly southward to influence Guangxi Region and the south of Jiangxi Province (Fig.2f). Lastly, the shear line merged with the vortex and the south front merged with the north one. The TBB cloud images also indicated that the upper-air trough clouds met with the convective clouds in South China, where might exit an interaction between the middle-latitude and tropical systems. However, due to the temporal sparseness of the observational data, the time is not clear when the southward-moving shear line merged with the mesoscale vortex in South China. Viewed from the variation of hourly cloud images, the two systems were merged with each other at about 0400 BT 22. It can be deduced according to the system's baroclinicity that the shear line may merge with the mesoscale vortex although the clouds in the rear of the upper-air trough are in the middle valleys of Yangtze River. Therefore the main weather systems triggering heavy rainfall in Guangdong Province include the mesoscale vortex formed by northward-moving cyclonic wind perturbation from the north of the SCS after its landing Guangdong and SE-ward-moving middle-latitude shear line steered by the north branch trough. Correspondingly, the rainfall includes two stages, one the vortex rainfall and the other the shear-line rainfall.

2.2 *Mesoscale environment, mesoscale convection and topography*

2.2.1 *Mesoscale environment*

The physical variables before and after the heavy rainfall are calculated with the data from three sounding stations (Table 1). It can be seen, before the heavy rainfall, that the atmospheric column precipitable water is low (41 mm at Qingyuan), the total totals and K index are low, the lifting condensation level is high (911 hPa at Qingyuan), and the surface relative humidity is less than 90%. This implies that, before the heavy rainfall, neither the moisture nor the lifting condition is beneficial to the rainstorm formation. But the atmosphere is in an unstable state, that is, the convective instable energy is accumulating, which is favorable for the rainstorm's formation. During the period of heavy rainfall (0800 BT 21–0800 BT 22),

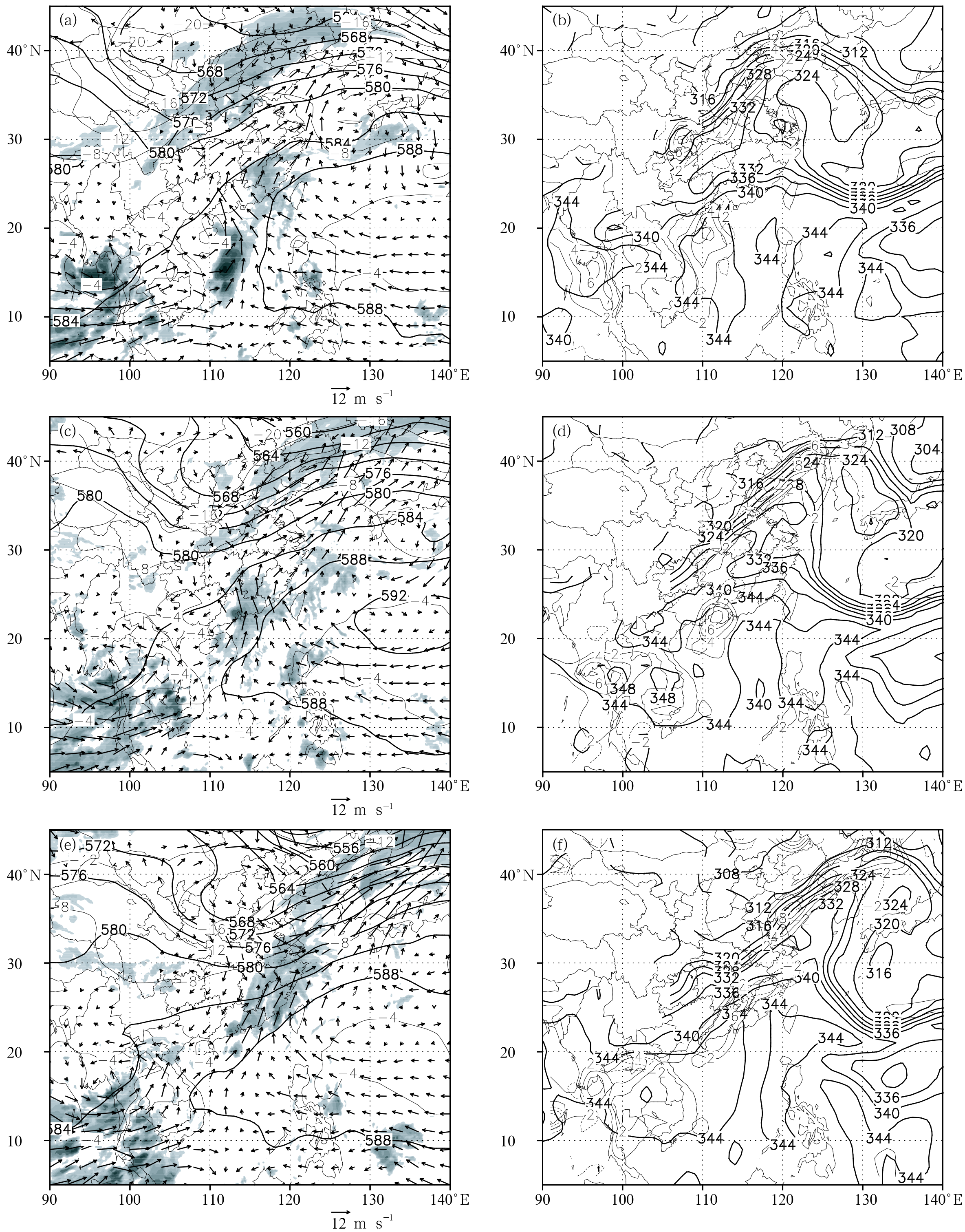

Fig.2. 500-hPa geopotential height (thick solid line, dagpm), temperature field (thin solid line, °C), 850-hPa wind field (vectors, m s^{-1}), and TBB detected by Fengyun Satellite (shaded area)(left panels: a, c, e); 850-hPa pseudo-equivalent potential temperature (thick solid line, K), relative vorticity (thin solid line, 10^{-5} s^{-1}), and divergence (thin dashed line, 10^{-5} s^{-1})(right panels: b, d, f). The top, middle, and bottom panels are for 0800, 2000 BT 21, and 0800 BT 22 May 2006, respectively, and shaded area in a, c, e indicates TBB less than -10°C.

the atmospheric column precipitable water increased quickly (65 mm in Hongkong), the surface relative humidity was saturated (relative humidity was 100%) with the surface θ_{se} 351 K, the lifting condensation level became low, the total totals index was 44°C and K index was 38°C, with the low surface lifting index, which are beneficial to the low-level parcel lifting. All of these show that the environment of high warm and moist air and low lifting condensation level is very beneficial to the convection outbreak and rainstorm formation. In this period, the convective available potential energy (CAPE) was released totally with the CAPE value near 0, but the analysis of the atmospheric instability shows that the atmosphere was in a conditional instable state with dry R_i number in the middle-lower troposphere greater than 0 while the moist R_i number less than 0. If there is a lifting forcing mechanism, the upward motion will further trigger convection and leads to heavy rainfall (obviously the mesoscale vortex in Guangdong Province provides the upward forcing). It is necessary to be noted that there is no very high CAPE calculated from the soundings. It may be due to the temporal sparseness of sounding observations and the soundings do not capture the accumulation and release of high CAPE. Even if there exist high resolution soundings, the accumulation and release of high CAPE may not be captured. It can be deduced from Hong Kong's soundings (Hong Kong is not in the center of heavy rainfall) that there appear the accumulation and release of high CAPE. The CAPE was 115 J kg^{-1} before the heavy rainfall and accumulated to 826 J kg^{-1} in the later period of heavy rainfall.

Table 1. Precipitable water (P_W), total totals index (T_T), surface lifting index (L_I), convective inhibition energy (C_{IN}), convective available potential energy (E_{CAP}), lifting condensation level (H_{LCL}), K index (K_I), surface vapor mixing ratio (Q), surface pseudo-equivalent potential temperature (θ_{se}), and surface relative humidity (R_H) calculated from soundings in Guangdong and Hong Kong

Time	Station	P_W (mm)	T_T (K)	L_I (°C)	E_{CIN} (J kg^{-1})	E_{CAP} (J kg^{-1})	H_{LCL} (hPa)	K_I (°C)	Q (g kg^{-1})	θ_{se} (K)	R_H (%)
2000 BT	HK	48	32	2	7	115	961	24	16	341	83
20 May	QY	41	39	0	14	99	911	23	15	341	65
	YJ	52	37	2	13	12	972	30	16	340	88
0800 BT	HK	56	42	2	41	7	1004	35	17	341	100
21 May	QY	52	43	6	0	0	953	34	13	330	78
	YJ	62	40	2	0	0	999	35	16	338	100
2000 BT	HK	65	43	-2	12	6	1002	38	19	350	100
21 May	QY	62	40	2	0	0	1007	35	16	341	100
	YJ	59	44	1	102	4	984	38	17	343	94
0800 BT	HK	57	43	-3	9	826	989	36	19	351	94
22 May	QY	58	45	0	192	4	993	36	16	342	94
	YJ	59	42	2	0	0	984	36	17	343	94

HK means Hong Kong, QY indicates Qingyuan, and YJ represents Yangjiang.

How was the warm-moist environment in the rainstorm area formed? It is found when analyzing 6-h NCEP (National Centers for Environment Prediction) data that a southerly low level jet migrated northward and transported moisture to the north with the cyclonic wind perturbation moving northward. Therefore, the high θ_{se} air was transported to the rainstorm area and the warm-moist environment was formed. Figure 3 shows the variation of specified contours for physical variables at 850 hPa before and after the rainstorm. It can be seen that a large relative vorticity (strong cyclonic wind perturbation) was located in the northern SCS at 2000 BT 20 May, the specified contour pushed northward to the south of Yunwu Mountains at 0200 BT 21 May and later it moved further northward. This indicates that a cyclonic wind pertu-

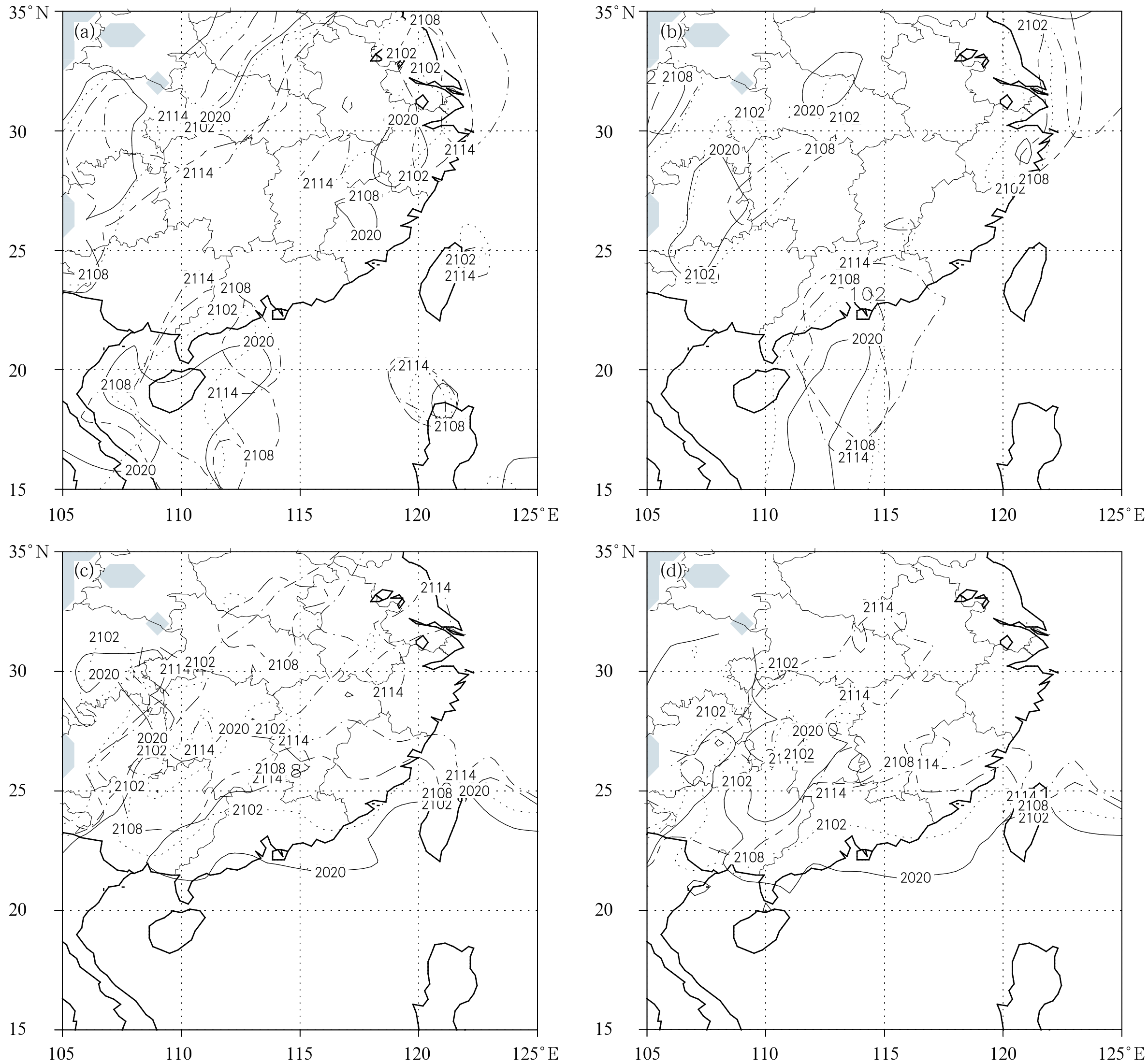

Fig.3. Temporal evolution of specified contours of physical variables at 850 hPa during the period of heavy rainfall formation and development. Contour mark “2114” represents 1400 BT 21 May, and reason out the rest by analogy. (a) Relative vorticity contour of 2×10^{-5} s^{-1}; (b) wind velocity contour of 12 m s^{-1}; (c) specific humidity contour of 10 g kg^{-1}; and (d) pseudo-equivalent potential temperature contour of 334 K.

rbation moved northward to influence Guangdong Province (Fig.3a). The variation of 12-m s^{-1} full velocity contour shows that the southerly low level jet was in the north of the SCS at 2000 BT 20 May, moved to the Zhujiang Delta at 0200 BT 21 May, and then further moved northward (Fig.3b). It can be seen that the southerly strong winds in the east of the cyclonic wind perturbation moved northward with the perturbation system. The variation of 10-g kg^{-1} specified moisture contour indicates that it was in the north of SCS at 2000 BT 20 and quickly pushed northward to the north of Guangdong at 0200 BT 21, with no obvious rainfall in the north of Guangdong (Fig.3c). Then it moved further northward later and Guangdong was all in a high moisture environment at 0800 BT 21, with 17 mm/6 h rainfall there. It translated northward to northern Fujian Province at 1400 BT 21. When analyzing the variation of 90% relative humidity contour, it is found that, at 2000 BT 20, the relative humidity was lower than 60% in most parts of Guangdong and the air was in a low moist condition. At 0200 BT 21, it was in a high relative humidity environment in the coast of southern Guangdong, that is, the air was near saturated. The whole Guandong was in a high relative humidity condition at 0800 BT 21. At 2000 BT 20, the 334-K θ_{se} contour was in the northern SCS. It moved to the north of Guandong at 0200 BT 21. At 0800 BT 21, Guangdong was in a high θ_{se} environment. The specified line was pushed to the northern Fujian at 1400 BT 21 (Fig.3d). It is seen that the pushing northward of high θ_{se} contour was basically in a same phase as relative humidity. Therefore, the formation of high θ_{se} environment is mainly due to moisture increase. It shows from the above analysis that, with the northward pushing of strong cyclonic wind perturbation from the north of SCS, the southerly low level jet translated northward and transported moisture (high θ_{se} air) northward to the heavy rain area, which led to the moisture increasing and the quick formation of the high moisture environment before the heavy rainfall. There was no heavy rainfall though the air started to be saturated. During the beginning of the heavy rain, the moisture increased further and the air became saturated. The heavy rain occurred in a high θ_{se} air area.

2.2.2 Mesoscale convection

Although the soundings do not catch the convective instability energy accumulation and the outburst of strong mesoscale convective system, it is found in the analysis of hourly TBB data (Fig.4) that the heavy rainfall in Guangdong mainly results from the activities of three strong convective systems, with two of them coming from tropical area and another locally generated. There existed an MCC to the south of 20°N in the tropical SCS at 0800 BT 21. The temperature of the MCC cloud top was about −70°C. It moved to the north of 20°N at 0900 BT and became a little weaker with its cloud top temperature about −60°C. At 1000 BT 21 (Fig.4a), a little cloud mass with cloud top temperature lower than −40°C began to develop about 40 km to the south of Zhuhai City. At the same time, a cloud mass was formed away about 170 km to the south of Yangjiang. Later, the two cloud masses developed quickly with their cloud area enlarging and cloud top temperature lowering. At 1300 BT (Fig.4b), the two clouds merged into a mesoscale convective cluster with its cloud top temperature about −70°C. It moved NE-ward to influence Guangdong. At 1600 BT 21 (Fig.4c), the MCC in the tropical SCS began to split. The separated convective cloud cluster began to move northward slowly while the convective cloud cluster over Guangdong became weak. At 2000 BT, the separated cloud cluster from the MCC became the main convective clouds over Guangdong and it moved NE-ward slowly with the former convective cloud cluster in the northeast of Guangdong weakening and dissipating basically. The analysis of synoptic chart indicates that the activity of the two translating convective systems is related to the northward movement of cyclonic wind perturbation in the north of the SCS. At 0400 BT 22 (Fig.4d), convective clouds were formed locally around Yangchun and Heshan. Later, these clouds were strengthened step by step and formed a convective cloud band in an NE-SW orientation. It maintained for a long time, became weak and dissipated till 1200 BT 22. These convective clouds were associated with southward-moving shear line from the middle latitudes and possibly triggered by the intruding of northwest winds in the north of the shear line. It was noted that the convective systems were strengthened quickly when they moved to the coast of Guangdong, which indicates that the land-sea contrast may play a certain role in the strengthening of the convective systems.

2.2.3 Topography

The topography is very complicated in South China, especially in Guangdong, where the topography is high in the north and low in the south, tilting from east to west. There are a lot of mesoscale terrains, like Yunwu and Yunkai Mountains in the southwest, Lianhua Mountains in the northeast, Jiulian and Qingyun Mountains in the north, and Weishan and Dadong Mountains in the northwest. It is relatively flat in the Zhujiang Delta and the whole topography is trumpet-like. The complicated topography may play an important role in the formation of the heavy rainfall. The topography mainly plays a role dynamically and thermodynamically. The dynamic role includes the triggering of the convection, the enhancement of

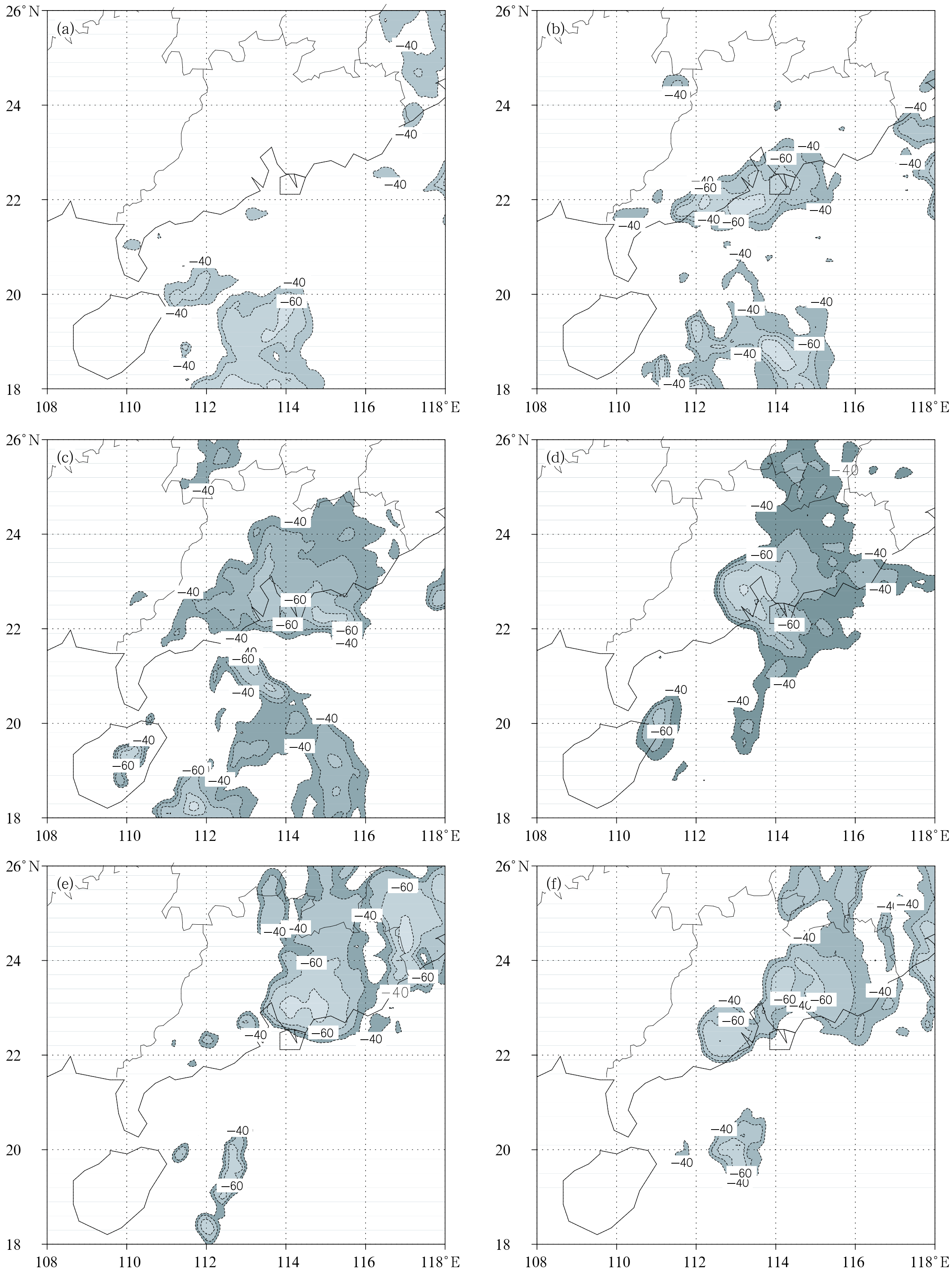

Fig.4. Black-body temperature (TBB; °C) at cloud top detected by Fengyun Satellite at (a) 1000 BT 21; (b) 1300 BT 21; (c) 1600 BT 21; (d) 2000 BT 21; (e) 0400 BT 22; and (f) 0700 BT 22 May 2006.

the convection and rainfall due to blocking and the convergence in the lee side (Cui et al., 2002; Chiao et al., 2004; Yeh et al., 2004; Galewsky and Adam, 2005). As a cooling or heating source, the topography may result in local thermal circulation. The cloud seeder-feeder by topography is also an important affecting mechanism on rainfall (Carruthers and Choularton, 1983). Furthermore, the topographical rainfall is influenced by the intensity and direction of the environmental flows, the atmospheric instability, the air humidity, wind vertical shear, etc. The topography with different orientation, altitude, and shape exerts a different effect on the rainfall (Brian, 2004). This heavy rain happens to occur in the trumpet-like area of eastern Guangdong. The effects of topography on the heavy rainfall are not neglected. Especially before and after the formation of the vortex, a strong wind perturbation was passing through Yunwu Mountain area. The Yunwu Mountain may play a significant role in the extremely heavy rain in its surroundings.

The vertical circulation and latitude-altitude cross sections of θ_{se}, vorticity, and divergence along 113°E analyzed with NCEP at 2000 BT 21 May 2006 are shown in Figs.5a and b. It can be seen that a southerly flow below 900 hPa is lifted obviously before it arrives at the mountains near 25°N. The maximum upward velocity is around 23°N, while not in the maximum slope area, which is indicated by the low-level convergence in front of the mountain. It should be noted that the corresponding topography is the larger-scale Nanling Mountains. The upward velocity in the upslope of the mountains may be due to two factors—the synoptic-scale forcing and the topography dynamic lifting. As described above, a mesoscale vortex happens to be in the southwest of Guangdong Province, the location of which is indicated by strong positive relative vorticity in the upslope. Therefore, the synoptic scale forcing plays an important role. The WE-oriented Nanling Mountains mainly lift the flow. The moist F_r (Froude number) of the upstream flow at 950 hPa was about 1.594 (U=12 m s^{-1}, N_w=0.00502 s^{-1}, and h_m=1500 m), which indicates that the strong southerly flow mainly climbs over the mountain when the flow is close to it.

The vertical circulation and longitude-altitude cross sections of θ_{se}, vorticity and divergence along 22°N analyzed with NCEP at 2000 BT 21 May 2006 are shown in Figs.5c and d. It shows that a mesoscale vortex was located in the front of Dawu and Tianlu Mountains. A strong upward flow was in the east side of the mountains. The stream flow subsides in the downwind of the mountain after it flows over its ridge. An obvious convergence band is in the upstream side of the mountain in the low level and a column of strong positive vorticity is over the mountains and their eastern areas. The lifting by the mountains may play a certain role in the upward motion in the upslope of the mountains when viewed from the distribution of strong low level convergence and upward motion, that is, the forcing by the mesoscale vortex system and dynamic lifting by the mountains both lead to the strong upward motion, which triggers convection and brings heavy rain. Besides the trumpet-like topography surrounded by Yunwu, Jiulian, and Qingyun Mountains may have some effects on the heavy rain. It should be pointed out that the data analyzed here are in a low resolution and cannot reflect the real topography and are not enough to detailed mesoscale analysis. The activities of the mesoscale systems need to be further tested through numerical experiments.

3. Model introduction and numerical experimental design

With the non-hydrostatic Weather Research and Forecast model (WRF Version 2.1) developed by the NCEP and the National Center for Atmospheric Research (NCAR) of the United States, a numerical simulation and sensitivity experiments are carried out. The detailed notes of the WRF model are referred to the WRF website (http://www.mmm.ucar.edu/wrf/users/docs/userguide/contents.html). The results of simulation and comparison experiment by Sun et al. (2003) show that the WRF model has some ability to simulate rainfall processes with different properties in China. In case of model spin-up time, the model is integrated 36 h, with NCEP 1° × 1° longitude and latitude reanalysis data as model initial field at 2000 BT 20, to simulate the

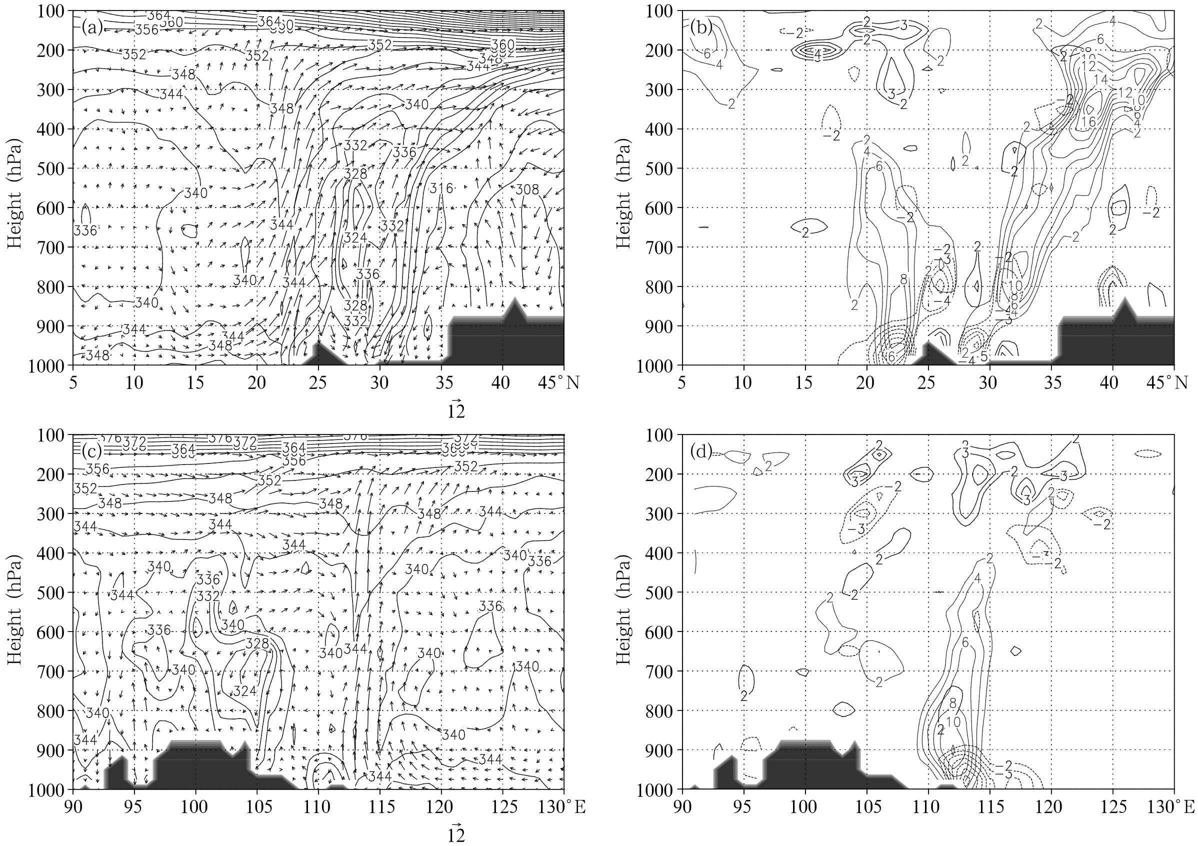

Fig.5. Latitude-height cross sections along 113°E/longitude-height cross sections along 22°N of (a/c) vertical circulation and θ_{se}, and (b/d) relative vorticity (10^{-5} s^{-1}) and divergence (10^{-5} s^{-1}) at 2000 BT 21 May 2006. The unit of u and v component of the vertical circulation in (a) and (c) is m s^{-1} and ω has been multiplied by 50 in Pa s^{-1}, the solid line in (b) and (d) is the relative vorticity greater than 2×10^{-5} s^{-1} and the dashed line is the divergence less than -2×10^{-5} s^{-1}, respectively.

heavy rain process in the period of 0800 BT 21 to 0800 BT 22, since there existed moderate to strong rainfall at 0800 BT 21 May 2006. A two-way nesting is adopted in the two model domains. The model center is at 25°N, 115°E. The outer domain's grid length is 45 km and the inner domain's is 15 km. A 31-level σ-coordination is set up in the vertical direction. The time step is 240 s. The physical schemes in the control run are the NCEP operational model microphysics (Eta scheme), new Kain-Fricth cumulus parameterization scheme, RRTM long wave scheme, Dudhia short wave scheme, Monin-Obukhov surface physics, 5-layer thermal dispersion scheme, and Yonsei University PBL physical scheme. The analysis mainly focused on the simulation results of the inner domain while the outer domain simulations are used in the verification of synoptic scale systems.

A series of experiments are designed to understand the effects of synoptic-scale trough on the northward propagating tropical system and the role of mesoscale topography and the land-sea contrast (Table 2). Sensitivity experiments are carried out: 1) to explore the effects of synoptic-scale trough on the northward tropical system with potential vorticity inversion technology to remove and deepen the north branch trough (denoted as NNT and DNT); 2) to reveal the role of the Yunwu Mountain and the trumpet-like topography of the Zhujiang Delta in the northward moving convective system triggering heavy rain with the Yunwu Mountain removed (the model topography is set to zero in (21°–23°N, 110°–113°E)) and Yunwu, Jiulian and Qingyun Mountains removed (the model topography is set to zero in (22°–23°N, 115°–118°E), (21°–23°N, 110°–113°E), and (23°–25°N, 113.8°–116°E)) simultaneously in the model; and 3) to understand the effects of land-sea contrast on the rainfall (the water body in (14°–30°N, 105°–120°E) is set to be land surface in the model).

Table 2. Names and schemes of different numerical simulations and sensitivity experiments

Experiment name	Initial field	Model topography
CTRL	No change	Model real topography
NNT	North branch trough deepened	Model real topography
DNT	North branch trough removed	Model real topography
NYM	No change	No Yunwu Mountain
NYJQM	No change	No Yunwu, Jiulian, and Qingyun Mountains
NSLC	No change	No land-sea contrast

4. Numerical simulation and experimental result analysis

4.1 The control run and its verification

The CTRL experiment simulates well the 24-h rainfall starting from 0800 BT 21 May 2006. Especially, the two rainfall centers are simulated very well (shaded area in Fig.1). One is in the east coast near Dongguan of Guangdong Province, the center of which is away about 50 km from the observation. The other one is near Zhuhai, the center of which is further southeast 100 km than the observed heavy rain center (Xinhui). But the model does not simulate well the frontal rainfall in the boundary area of Fujian and Jiangxi Provinces. The simulated rain band is much more north, which is related to the fact that the simulated moving velocity of southeastward north branch trough and shear line is less than the observation. Besides, the moderate to heavy rain in the coast of Fujian Province is not simulated and its cause is not clear. On the whole, the model reproduces well the strong heavy rain process in Guangdong Province. Furthermore, the 6 h rainfall is simulated rather well.

On the distribution of every 6-h simulated rainfall, the rainfall mass at 1400 BT 21 is basically close to the observation (Fig.6). Especially, the model simulates out the strong heavy rain center near Shangchuandao (135 mm), but the simulated rainfall is only about 80 mm and less to the observation. At 2000 BT 21, the simulated heavy rain center was a little northeast than and basically close to the observation. But the model does not simulate out the heavy rain center at Taishan (164 mm). At 0200 BT 22, the simulated rain mass moved to the boundary area of Fujian, Guangdong, and Jiangxi Provinces with the observed heavy rainfall near Guangzhou (93 mm). Another simulated rain mass was located in the southeast of Guangzhou (about 100 km away from the coast). An NE-SW oriented rain band occurred in the basin of the Changjiang River at 0800 BT 22 with the low level shear line translating south to the boundary area of Fujian and Jiangxi. But the simulated rain band is a little north than the observation. It is exciting that the model simulates out the heavy rain center near Zengcheng (111 mm) with rainfall intensity a little weaker. It can be seen that the model not only simulates well the 24-h accumulated rainfall, but also has some ability to simulate each 6-h rainfall well. Nonetheless the model does not catch every heavy rain in detail, which is the default of current model simulation. The same phenomenon occurred in the simulation of South China's heavy rain by Zhang et al. (2000), Sun et al. (2002), and Sun and Zhao (2002). This also reflects the current simulation ability of South China's heavy rain.

The model successfully simulates not only the distribution and evolution of rainfall, but also the large-scale circulation pattern and the structure of the temperature and humidity. Figure 7 shows the 12- and 24-h simulated height, temperature, and humidity fields at 500 hPa and wind field at 850 hPa. It is seen that the simulated north branch trough is located in the west of North China with temperature trough lagging it at 12-h model integration. The shear line is in the

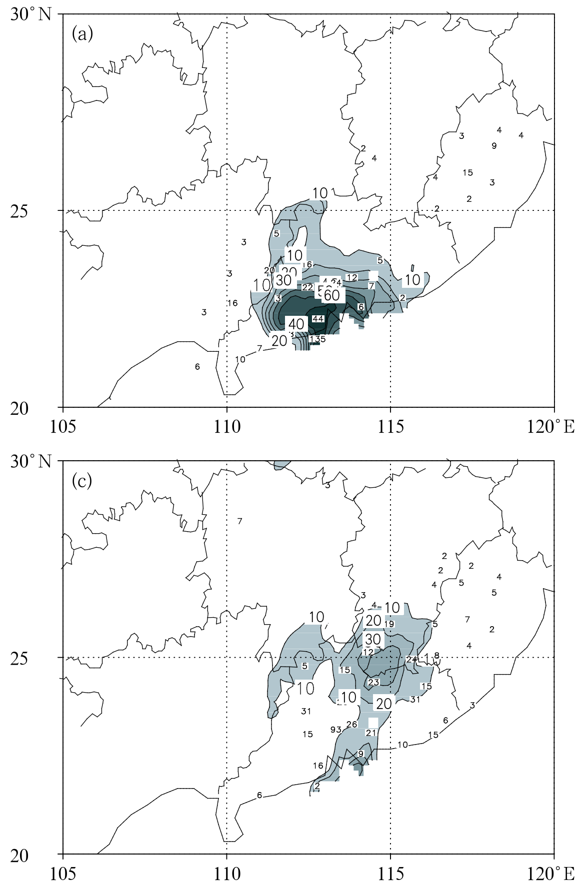

Fig.6. Simulated 6-h accumulative rainfall at 18 (a), 24 (b), 30 (c), and 36 h (d) in the CTRL experiment. The shaded area indicates simulated rainfall region, and small digital numbers are 6-h observed rainfalls in mm.

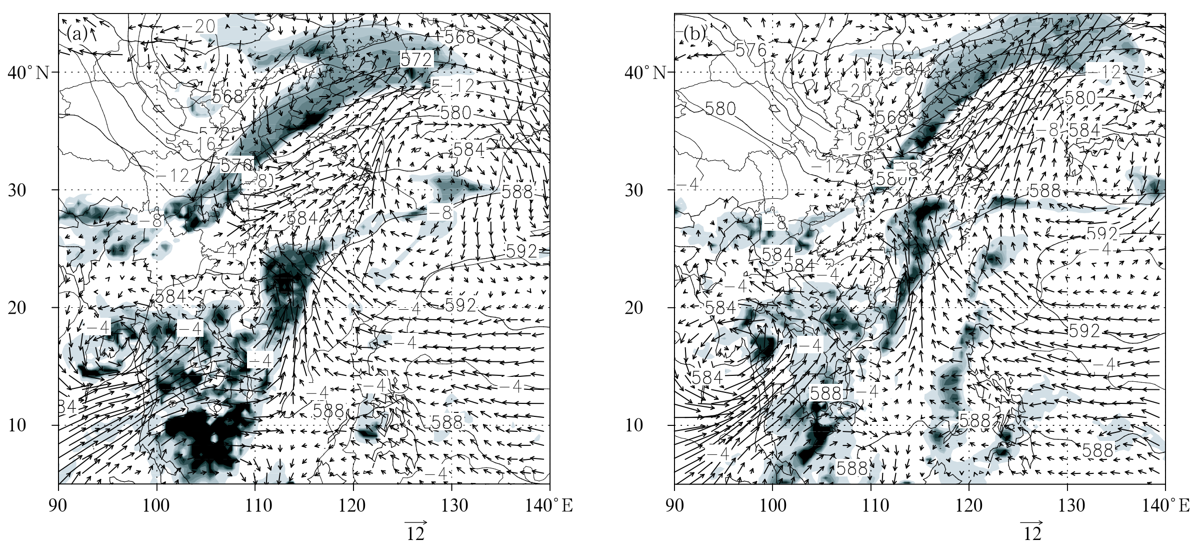

Fig.7. Simulated 500-hPa geopotential height (dagpm), temperature (°C), relative humidity (%), and 850-hPa wind fields (m s^{-1}) at 12 (a) and 24 h (b) in the CTRL experiment. The shaded area shows the relative humidity greater than 80%.

front of trough and the middle valleys of Changjiang River. All of these are close to the observation. The simulated south branch trough and subtropical high are also close to the observation. Besides, the north branch trough and low level shear line in mid-lower latitudes are well simulated after model integrating 24 h. The mesoscale vortex in the southwest of Guangdong, which is formed after model integrating 14 h, is simulated out and translates to the south of South China and disappears after model integration 31 h. The vortex maintains about 18 h. At the same time, the movement of the simulated 500-hPa relative humidity greater than 80% (shaded area) is basically near to the observed TBB cloud clusters. The combination of low-level shear line in front of the north branch trough with mesoscale vortex is well simulated out. Therefore, the control run not only simulates out the heavy rain, but also reproduces the large-scale circulation background, the structure of the atmospheric temperature, humidity and pressure, and their evolution processes. In the following, the difference of the sensitivity experiments between the control run is compared and analyzed to explore the main factors and mechanisms of the heavy rain with the control run results as a reference.

4.2 The role of the north branch trough

Chen et al. (1983) researched the effects of upper air trough on the generation of marine cyclone through hindering the large-scale trough propagating into the model domain with a sponge lateral boundary condition. Lapenta and Seaman (1992) tried to separate the upper level jet stream to explore its effects on the surface cyclone. Huo et al. (1999) and Milbrant and Yau (2001) analyzed the role of different upper air troughs in the surface cyclone formation and their relative importance through separating the upper air trough with the potential vorticity inversion (PVI) methodology. Essentially, the PVI method is to get the balanced mass and wind fields by use of any perturbed potential vorticity. It is of advantage to detach different weather systems and change the model initial field because no "noise" is generated and given to the model when the balanced perturbed field is added or subtracted. In the following, the Eterl PVI (EPVI) developed by Davis and Emannual (1991) and Davis (1992) is used to separate the north branch trough and explore its role in the mesoscale vortex formation and the effects of mesoscale vortex on the heavy rain under the condition of no southeast-moving shear line. The main steps of EPVI are firstly to calculate the 5-day average of every 6-h temperature, wind and height fields during the period of 19-23 May 2006 and the mean EPV, secondly obtain the perturbed temperature, wind and height fields and the perturbed EPV, thirdly compute the balanced mass and wind fields in the selected north branch trough area with PVI and deduce the perturbed temperature field and surface pressure, lastly subtract/add the balanced field from/to the model initial field and then obtain the north branch trough removed/deepened model initial field. It should be pointed out that only the perturbed fields below 400 hPa are subtracted or added in the initial field in order to investigate the impacts of low level troposphere systems.

On the panel of 500-hPa height field and 850-hPa wind field with the north branch trough removed from model initial field, the upper air trough in the east of Northwest China becomes flat with 850-hPa shear line still in the west of Henan and Hubei Provinces (Fig.8a). The wind velocities are changed obviously in the two sides of the shear line with south wind weakened in the south and north wind strengthened in the north. On the whole, the shear line is weakened. It can be seen that the upper air north branch trough is successfully removed after subtracting the perturbed mass and wind fields from the model initial field in the north branch trough area. The location of the trough is not changed and it is deepened obviously after adding the perturbed mass and wind fields to the model initial field (Fig.8b) and the location of the shear line at 850 hPa is not changed and the winds in its two sides are strengthened clearly.

The experiment NNT indicates that the simulated 24-h rainfall starting at 0800 BT 21 is changed very much after the north branch trough is removed. When comparing to the control run, the simulated rainfall intensity is stronger with its heavy rain center about 180 mm, and 40 mm more than experiment CTRL.

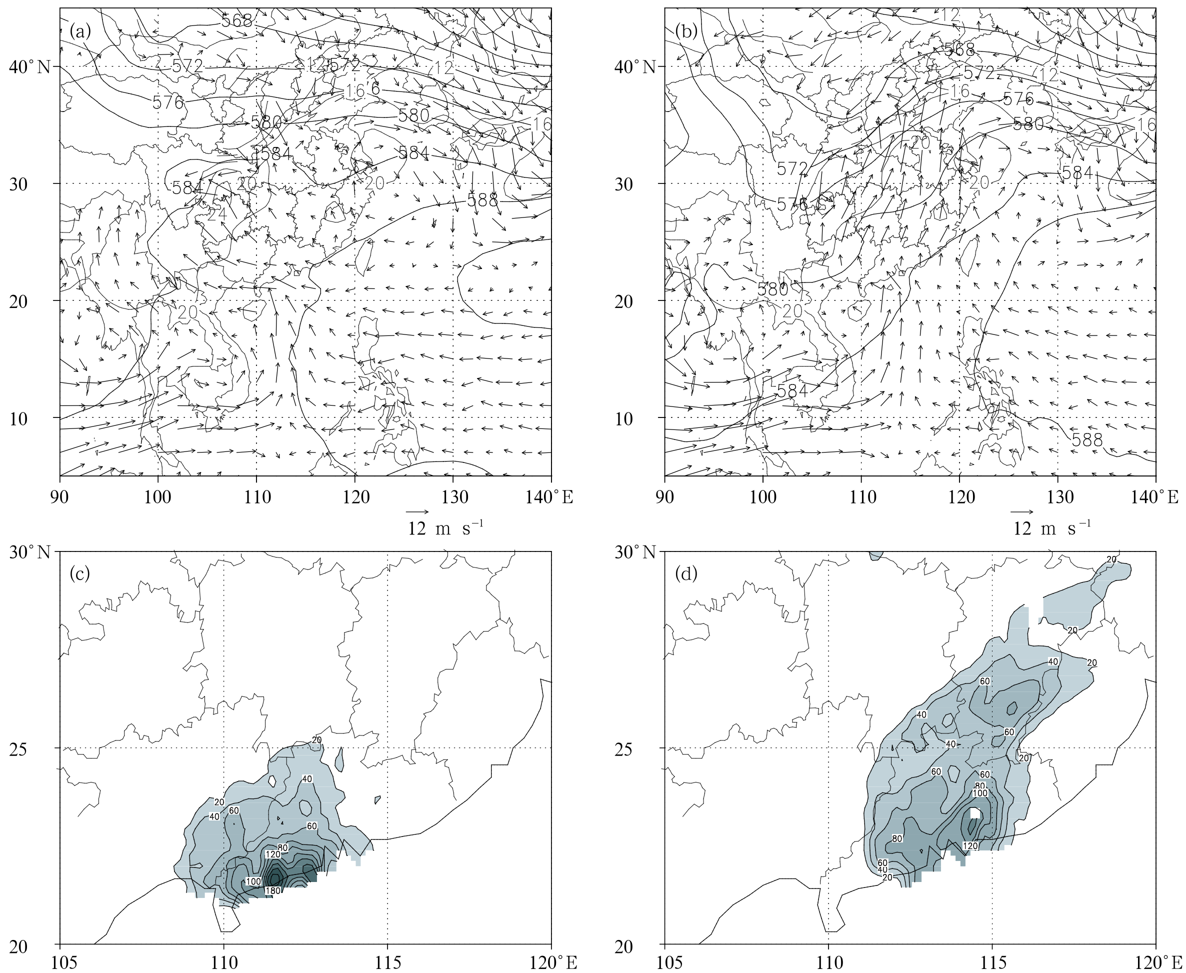

Fig.8. 500-hPa geopotential height (dagpm; a,b), 850-hPa wind fields (m s^{-1}; a,b), and simulated 24-h rainfall (mm; c,d) after the north branch trough has been artificially removed (a, c) and deepened (b, d).

But the heavy rain center is more south than the observation, moving to the Yangjiang surroundings in the south of Yunwu Mountain, with the rainfall from the north of Guangdong to the boundary area of Jiangxi and Fujian not simulated out. This indicates that the tropical cyclonic wind perturbation in the SCS does not translate northward and maintains in the coast of Guangdong with the shear line also not propagating to the south, which leads to intensify the simulated rainfall. The hourly wind field analysis of model output implies that the mesoscale vortex is simulated out after model integrating 14 hours, but it is formed near the Hainan Island. It is more south and west than the control run and does not move northward but strengthens and moves westward to the Beibu Gulf, maintaining over there till model integrating 36 hours. Its size is clearly increased, which may be related to the latent heating by enhanced vortex-made rainfall condensation release. The simulated rainfall in the Yangjiang surroundings to the south of Yunwu Mountain mainly results from the strong cyclonic wind perturbation in the northeast of the vortex. The vortex is over there for a long time and leads to that the simulated rainfall is more than the control run.

The simulated rainfall in experiment DNT is also changed significantly after the north branch trough is deepened, with heavy rain center in the Zhujiang Delta of Guangdong and the frontal rainfall in the boundary area of Fujian and Jiangxi both more east than the control run. But the rainfall intensity is not changed much (Fig.8d). In experiment DNT, the mesoscale vortex is formed in the southwest of Guangdong at model integrating 14 hours, which is the same as the control run. The difference is that the vortex moves northeastward and results in the simulated rainfall more east than that in the control run. At model integrating 26 hours, the middle-latitude shear line comes down to the south and merges with the vortex, 5 h earlier compared with the control run. This leads to the fact that the frontal rainfall in the boundary area of Fujian and Jiangxi is more east and south than the control run. It implies that the steering flow ahead of the trough is strengthened and the velocity of the southward moving shear line is increased after the north branch trough is deepened. It can be deduced that the south flow ahead of the trough has a steering role in the vortex's movement and results in the vortex not staying in the formation area but moving northward. The shear line ahead of the trough is pushed southward down to South China and affects the vortex's lifetime.

4.3 The impact of topography and land-sea contrast

The observation analysis shows that the complicated meso- and micro-scale topography in Guangdong and the land-sea contrast may exert some influences on the strong heavy rain formation in the Zhujiang Delta. But the spatial and temporal resolutions of the data used in diagnostic analysis may impact the accuracy of the mesoscale analysis. In the following, sensitivity experiments are carried out to investigate the effects of topography and land-sea contrast on the heavy rain induced by the northward translating tropical perturbation from the SCS. Because the horizontal resolution of the inner domain is 15 km, the model topography only describes the mesoscale topography, like Yunwu, Jiulian, and Qingyun Mountains in Guangdong, with microscale topography not described in the model. Two experiments are designed to see the role of Yunwu Mountains and Zhujiang Delta respectively according to the observation analysis.

On the panel of 24-h accumulated rainfall starting at 0800 BT 21 of experiment NYM, the maximum rainfall in the rain center is about 140 mm. The rainfall intensity is not changed, but the heavy rain center deviates 50 km to the downstream with another rain center in the upslope area of Qingyun Mountain. This indicates that the mesoscale Yunwu Mountain impacts the heavy rain area. The evolution of the low-level wind field and every 6-h rainfall are further analyzed to find out that the impacts of Yunwu Mountain on the rainfall are closely related to the vortex location and the prevailing wind direction: 1) In the formation stage of the vortex, strong east wind in its northeast part prevails in Yunwu Mountain area. The difference between the 6-h accumulated rainfall starting at model integrating 13 hours by the experiment NYM and the control run is negative in the east of Yunwu Mountain and positive in its west (Fig.9a), that is, the rainfall is decreased in its east and increased in its west. This implies that the dynamic lifting in front of the Yunwu Mountain does increase the upslope rainfall while the subsiding flow does decrease the lee side rainfall. 2) During the period of vortex center locating in the Yunwu Mountain area, the 6-h accumulated rainfall difference starting at model integrating 19 hours is positive in the northeast part of the vortex (Fig.9b), that is, the simulated rainfall is increased without Yunwu Mountain. On the other hand, the vortex is somewhat weakened by the Yunwu Mountain (the vortex weakening may be due to the friction of Yunwu Mountain) and leads to the fact that rainfall is weakened (but rainfall is intensified in some local area and its cause is not clear). 3) When the vortex moves to the northwest of the Yunwu Mountain, a southwest flow controls over there. The impacts of the Yunwu Mountain on the rainfall become indirect. The perturbed flow by the Yunwu Mountain may excite mountain waves to influence the downstream rainfall (the 6-h rainfall difference in Fig.9c is in a certain wave-like distribution). 4) When the shear line is pushed to South China, the vortex disappears and the southwest flow prevails over the Yunwu Mountain. The topography modifies the downstream rainfall mainly by exciting mountain waves (the 6-h rainfall difference in Fig.9d is obviously in a wave-like distribution).

There occurs an NE-oriented rain band from the

Zhujiang Delta to the boundary area of Fujian and Jiangxi on the panel of 24-h accumulated rainfall after Yunwu, Jiulian, and Qingyun mountains are removed simultaneously in the model topography (experiment NYJQM), that is, the rainfall is increased in the downstream of Zhujiang Delta. This indicates that the trumpet-like topography of Zhujiang Delta plays a certain "localization" role, that is, the large trumpet-like topography makes the heavy rain concentrate in the delta area and not propagate downstream. Sun and Zhao (2002) carried out a sensitivity numerical experiment for the June 1994 heavy rain in South China. Their results show that the trumpet-like topography does not increase obviously the heavy rain in the Zhujiang Delta. The experiment NYJQM also reveals that the trumpet-like topography does not increase the rainfall, but exerts an influence on the rainfall location. It should be pointed out that the interaction of topography disturbance and synoptic systems is very complicated and the transient changes of the atmospheric state may lead to a different topographic impact. As to numerical sensitivity experiments, there may exist a nonlinear interaction between the model topography perturbation and the atmosphere with model integration. This makes the topographic effects become more complicated.

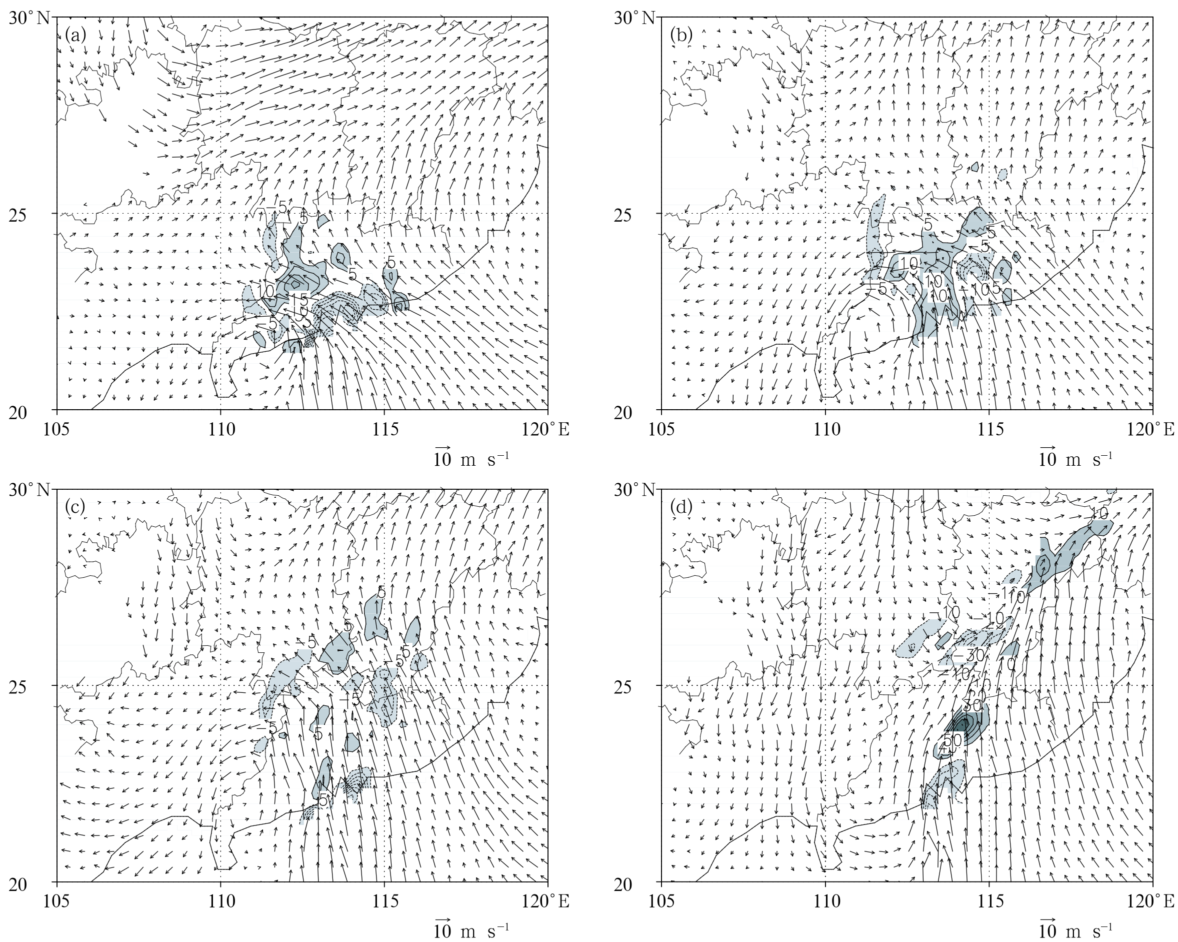

Fig.9. The 900-hPa wind fields at 14 (a), 19 (b), 27 (c), and 35 h (d) in the NYM experiment. The shaded area is differences of 6-h simulated accumulative rainfall between experiments NYM and CTRL at 18, 24, 30, and 36 h, respectively.

The simulated rainfall is changed dramatically without the land-sea contrast in experiment NSLC. Weakened is not only the strong rainfall along the coast of Guangdong, but also the frontal rainfall in the boundary area of Jiangxi and Fujian. The simulated rainfall is less than the control run, with a maximum rainfall only about 60 mm. It is found in the analysis of hourly low-level winds that the mesoscale vortex in the south of Yunwu Mountain is simulated out at model integrating 14 hours, with its maintaining time shorter than the control run. The vortex structure is not clear at model integrating 19 hours. The vortex evolutes into an “inverted trough”, which is open to the south, maintained near 31 h and combined with southward translating mid-latitude shear line. Figure 10 shows that the soundings of control run (Fig.10a) and experiment NSLC (Fig.10b) in heavy rain area (23°N, 113°E) at model integrating 19 hours. It is obvious that the moisture layer is deep in the control run, while the relative humidity above 400 hPa in experiment NSLC is low though its low-level moisture is high. It can be seen that the temperature, humidity, and pressure fields are changed in model integration after the land-sea contrast is changed. It is conjectured that the rainfall is largely affected by the change of land-sea contrast. The cause may be that, firstly, the moisture evaporation is decreased heavily, the moisture transported to the heavy rain area is therefore folded and the rainfall amount is directly affected after the model sea surface in the SCS is set as land. This suggests that the moisture transport from the SCS plays a significant role in the Guangdong heavy rain. Secondly, the disappearance of the land-sea contrast influences the formation of the local sea breeze circulation, weakens the local mesoscale circulation and leads to rainfall decreasing. Thirdly, the latent heat release is correspondingly decreased after the simulated rainfall reduced and therefore its positive feedback to the local circulation is cut down.

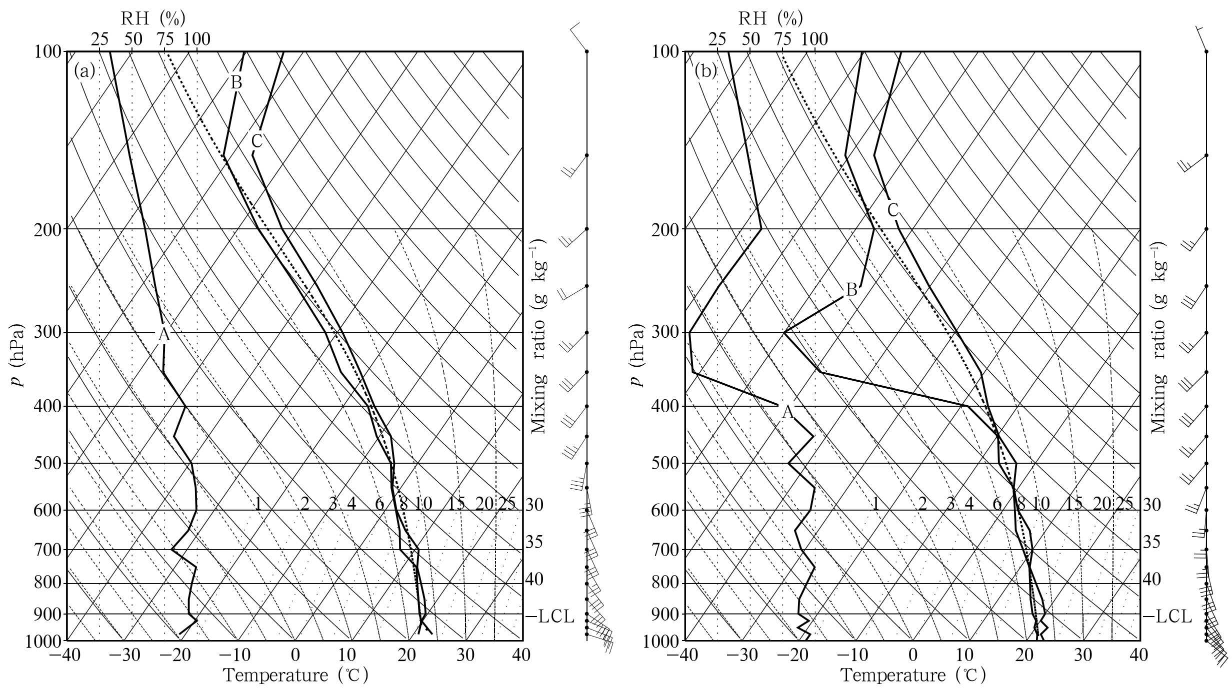

Fig.10. Simulated soundings at grid (23°N, 113°E) at the integrating 19 hours for (a) CTRL experiment and (b) NSLC experiment. Line A shows relative humidity, line B dew point temperature, and line C temperature, respectively.

5. Conclusions and discussions

With conventional observations, it is analyzed that the super heavy rain in the coast of Guangdong was triggered by a northward moving tropical disturbance. At the same time, sensitivity experiments about physical and dynamic factors affecting the heavy rain are carried out to explore the formation mechanism of the heavy rain. The results are as follows.

(1) With the cyclonic disturbance from the SCS fast shifting northward, there are two moving tropical convective systems landing in the coast of Guangdong. After the cyclonic perturbation fast landing the coast of Guangdong, a mesoscale vortex forms and brings about heavy rain there. A mid-latitude shear line is combined with the vortex after it shifs southeastward to South China. An MCS forms locally in Guangdong, whose formation may be related to the cold air intrusion in the rear of the shear line.

(2) Before the heavy rain, the air column water content is low and the lifting condensation level is higher, which is not conducive to the heavy rain formation. However the convective instable energy is somewhat accumulated. During the heavy rain, the atmosphere is in a favourable environment of high temperature and moisture, whose formation is associated with the moisture transport by southerly winds in the period of cyclonic wind disturbance migrating northward from the tropical SCS. The mesoscale vortex provides a lifting forcing for the convective initiation and heavy rain formation.

(3) The southwesterly flow in front of the trough plays a steering role for the vortex in the period of north branch trough (North China trough) translating southeastward, which makes the mesoscale vortex not stay locally but move to the north, with heavy rain mass translating with it. This means in some sense that it reduces the local 24-h maximum accumulated rainfall.

(4) The complicated mesoscale topography plays an important role in the heavy rain. The role of the mesoscale Yunwu Mountain in the heavy rain is determined by the vortex location and the prevailing wind direction. The trumpet-like topography of Zhujiang Delta exerts a "localization" influence on the strong heavy rain, that is, the topography tends to concentrate the heavy rainfall in the delta area and make it not propagate downstream. Besides, the special geography in Guangdong and the land-sea contrast also have some effects on the heavy rainfall. The short-range moisture transport from the SCS is the main cause for heavy rain formation.

Observed facts show that the MCS from the SCS are rapidly strengthened when it comes to the coastal area. At the same time, the numerical sensitivity experiments also prove the importance of land-sea contrast to the heavy rainfall. But it is not clear the mechanism for the rapid strengthening of the MCS in the coastal area. Furthermore, the interaction of the MCS and mesoscale vortex needs further research.

Due to the low spatial and temporal resolution of the data used in the diagnostic analyses, the mesoscale analysis is somewhat limited. It is the preliminary investigation on the synoptic background and mesoscale environment of heavy rain. It is necessary to carry out a detailed analysis of the heavy rain structure and evolution of this type of rain storms with intensive observational data. The meso- and micro-scale topography in Guangdong cannot be described by the 15-km numerical simulation. The high-resolution numerical modeling is needed to carry out further investigation. On the other side, here only a case study with numerical simulation is made of a heavy rain triggered by a northward propagating tropical cyclonic disturbance. The result is not of generality. Further study should be done to reveal the physical mechanism for this type of heavy rain formation and provide the relevant evidence for the heavy rain forecast and numerical model improvement.

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