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ANALYSIS OF MESOSCALE CONVECTIVE SYSTEMS ASSOCIATED WITH A WARM-SECTOR RAINSTORM EVENT OVER SOUTH CHINA

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Abstract: With multiple meteorological data, including precipitation from automatic weather stations, integrated satellite-based precipitation (CMORPH), brightness temperature (TBB), radar echoes and NCEP reanalysis, a rainstorm event, which occurred on May 26, 2007 over South China, is analyzed with the focus on the evolution characteristics of associated mesoscale-β convective systems (Mβcss). Results are shown as follows. (1) The rainstorm presents itself as a typical warm-sector event, for it occurs within a surface inverted trough and on the left side of a southwesterly low-level jet (LLJ), which shows no obvious features of baroclinicity. (2) The heavy rainfall event is directly related to at least three bodies of Mβcss with peak precipitation corresponding well to their mature stages. (3) The Mβcss manifest a backward propagation, which is marked with a new form of downstream convection different from the more usual type of forward propagation over South China, i.e., new convective systems mainly form at the rear part of older Mβcss. (4) Rainstorm-causing Mβcss form near the convergence region on the left side of an 850-hPa southwesterly LLJ, over which there are dominantly divergent air flows at 200 hPa. Different from the typical flow pattern of outward divergence off the east side of South Asia High, which is usually found to be over zones of heavy rains during the annually first rainy season of South China, this warm-sector heavy rain is below the divergence region formed between the easterly and southerly flows west of the South Asian High that is moving out to sea. (5) The LLJ transports abundant amount of warm and moist air to the heavy rainfall area, providing advantageous conditions for highly unstable energy to generate and store at middle and high levels, where corresponding low-level warm advection may be playing a more direct role in the development of Mβcss. As a triggering mechanism for organized convective systems, the effect of low-level warm advection deserves more of our attention. Based on the analysis of surface mesoscale airflow in the article, possible triggering mechanisms for Mβcss are also discussed.

Key words: mesoscale analysis; warm-sector rainstorm; South China rainstorm; Mesoscale β

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1 INTRODUCTION

Warm-sector rainstorms in South China ("warm-sector rainstorms" hereafter) are referred to as rainstorms that take place inside the warm sector south of a surface front in the region, or in the region from the Nanling Mountains to the north of the South China Sea where there are not any fronts or cold air or ridges of any transformed cold high pressures. An experiment on rainstorms during the annually first rainy season launched at the end of the 1970s supported the observational fact that heavy- to unusually-heavy- rainstorms are mainly caused in the warm sector in South China and changed the viewpoint that they mainly take place in fronts, which is held previously due to the lack of data[1]. Warm-sector rainstorms are marked by large intensity and concentrated precipitation; such typical convective nature can result in local flooding, landslides and mudslides, becoming one of the challenges in forecasting and one of the heated topics in rainstorm research in China. After years of study,

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there has been more knowledge about the warm-sector rainstorms and research achievements made so far have provided basis for more accurate forecasts of these events[2, 3]. Examining the governing systems, forecasters in South China usually categorize the warm-sector rainstorm in three types; it could be caused by (1) a return airflow, i.e., converging flow at the rear of a transformed cold high ridge or a warm and humid shear, (2) a strong Southwest Monsoon or a strong southwesterly jet stream, or (3) an upper-level pre-trough pattern in combination with a subtropical jet stream. Results achieved based on analysis and study of the three types of rainstorms for the accompanying weather situations and causations have now become important foundation for rainstorm forecasting[4].

The large rain rates and relatively concentrated precipitation shown in the warm-sector rainstorm is also attributed to terrain effect in some way, in addition to such environmental conditions as high temperatures and humidity and instability of the warm sector. As shown in a study, the centers of a number of rainstorms in South China are all related with favorable terrain[1]. On the other hand, warm-sector rainstorms spread over relatively small areas and often demonstrate lump-like distribution similar to the scale of convective cloud clusters, indicating that the formation of rainstorms are related with mesoscale convective systems and immediately caused by mesoscale-β convective system (Mβcss). In a general survey of the activities of mesoscale convective systems in China during the summers of 1993–1995, Ma et al.[5] discovered that there were as many as 585 incidents of Mβcss, more than twice that of Mαcss, though with shorter life cycles (only 5–6 h on average). It can then be concluded that Mβcss, such as mesoscale convective complex cells, is more important than Mαcss in triggering rainstorms in China. At present, research on Mβcss has become one of the essential subjects of rainstorms[6, 7]. As what people have already known, in addition to favorable large-scale environmental conditions, the formation of the Mβcss is more closely related to the triggering mechanism of terrain, boundary layer processes (such as the gravitational flow, mesoscale convergent lines, dewpoint fronts and land-sea breezes), and mesoscale gravitational waves[8-12].

How do Mβcss behave during rainstorms in South China? Hourly precipitation data from automatic weather stations in Guangdong province and satellite integrated precipitation data CMORPH (CPC MORPHing Technique) were used, in conjunction with the hourly TBB data at 0.05°×0.05° from the MTSAT satellite of Japan, Doppler data from Guangzhou and U.S. National Centers for Environmental Protection (NCEP) reanalysis, to study a warm-sector rainstorm over the Pearl River Delta and the area to the north during May 25–26, 2007. The aim of the research is to identify in detail the activity characteristics of mesoscale-β convective systems triggering the rainstorm and to broaden the knowledge about the process of warm-sector rainstorms through analysis of the environmental conditions associated with convective systems.

2 SUMMARY OF THE RAINSTORM

As shown in the surface weather map, the coastal region of South China was in the control of a frontal low pressure at 0800 Beijing Standard Time (BST) May 25, 2007. With the cold high behind the front moving out eastward to the sea, this region turned to be dominated by a southerly flow at the rear of the high, bringing right moisture conditions there. After 2000 BST of May 25 and with the eastward migration of the southern branch of a 500-hPa trough, convective systems began to develop on the north side of the delta and a mesoscale-β convective system became active at 0400 BST May 25 over Qingyuan, with the horizontal scale reaching the magnitude of mesoscale-β at its fullest development. Consequently, a rainstorm occurred in the northern side of the delta and central and northwestern Guangdong, unusually intense in some limited areas.

Figure 1 separately gives the distribution of 24-h accumulated rainfall amount from 2000 BST May 25 to 2000 BST May 26, obtained through merging CMORPH with automatic weather station (AWS) precipitation, and satellite cloud imagery superimposed with the surface map for 0800 BST May 26 (with the information for 1400 BST) for fully developed convective systems. As shown in Fig. 1a, local characteristics are obvious in the fallout area of the heavy rain, with a few areas of concentrated precipitation in central Guangdong at the northern tip of the Pearl River Delta and northwestern part of the province. Their 24-h accumulated rainfall all surpass 100 mm and the maximum rainfall center is more than 180 mm. The maximum amount of precipitation appeared in Qingyuan and the Huangpu and Huadu Districts of Guangzhou Municipality, where a record of 103.3 mm was measured at an AWS coded G1032 in Huangpu. Rainstorms directly result from mesoscale convective systems, which are shown by good corresponding relationship between the location of convective systems and precipitation areas. In Fig. 1, the convective cloud cluster is located within a surface inversed trough, which has developed in a convergent airflow at the rear of the ridge of a transformed cold high. Possessing the characteristics of a so-called “return airflow rainstorm”, the process is a typical warm-sector rainstorm with significant signature of convection. As the evolution of precipitation measured by an AWS can reveal the mesoscale features of such convective rainstorms, four north-south distributed AWSs, Qingyuan (113°32′E, 23°52′N), Conghua (113°43′E, 23°43′N), Huadu (113°16′E, 23°27′N), and Huangpu (113°27′E, 23°06′N), were selected in an area spanning 113°E to 114°E, and variations of hourly precipitation amount are given in Fig. 2. It shows that intense rainfall occurred from 0300 to 1400 BST on May 26; Qingyuan, the northernmost of these sites, had its peak rainfall at 0400 BST with the rain rate at 88.2 mm/h and a maximum 3-h accumulated amount at 130.2 mm; Conghua, which is 1 hour behind Qingyuan in the appearance of rain, had a precipitation peak of 56 mm/h, with the maximum 3-h accumulated amount at 90 mm; Huadu, located a little more southward and about five hours later, had a peak of 414 mm/h, with the maximum 3-h accumulated rainfall at 85.6 mm; the district of Huangpu, Guangzhou, located the most southward of all, had the latest precipitation peak (at 1300 BST) with an amount of 103.3 mm/h and a maximum 3-h accumulated precipitation of 159.3 mm.

All of these characteristics have shown that this warm-sector rainstorm was both intense and short-lived, with most of its precipitation concentrated within 3 hours and the rain area moving from north to south. Next, the behavior of mesoscale convective systems analysis will be made, which demonstrates how the rain area was affected by Mβcss convective systems that kept generating and dissipating during the north-to-south migration. Concentrated fall of the rainstorm and highly localized features are thought to be closely related with the activity of the Mβcss convective systems.

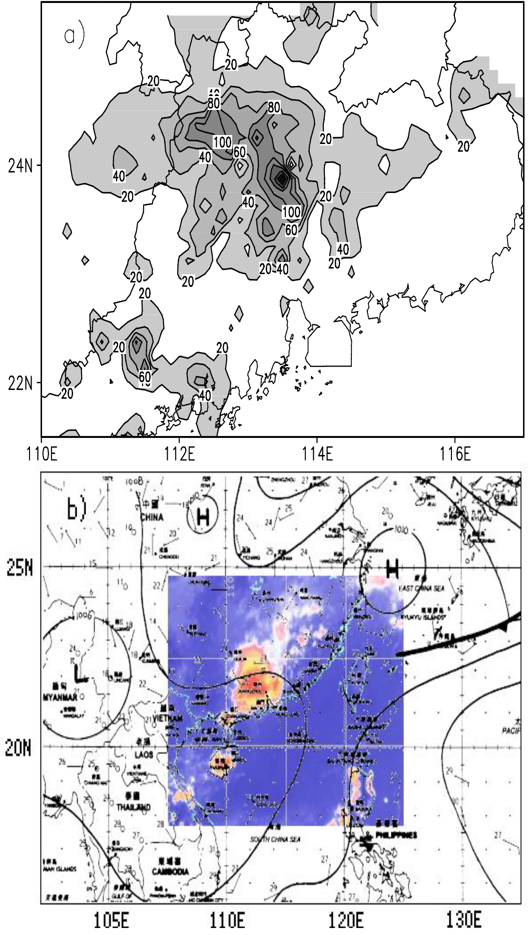


Fig. 1. 24-h accumulated rainfall from 2000 BST May 25 to 2000 BST May 26, 2007 (a, unit: mm); surface map for 0800 BST May 26 superimposed with satellite cloud imagery (b)

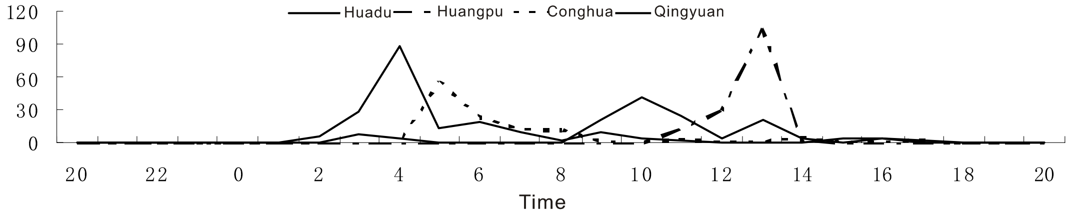
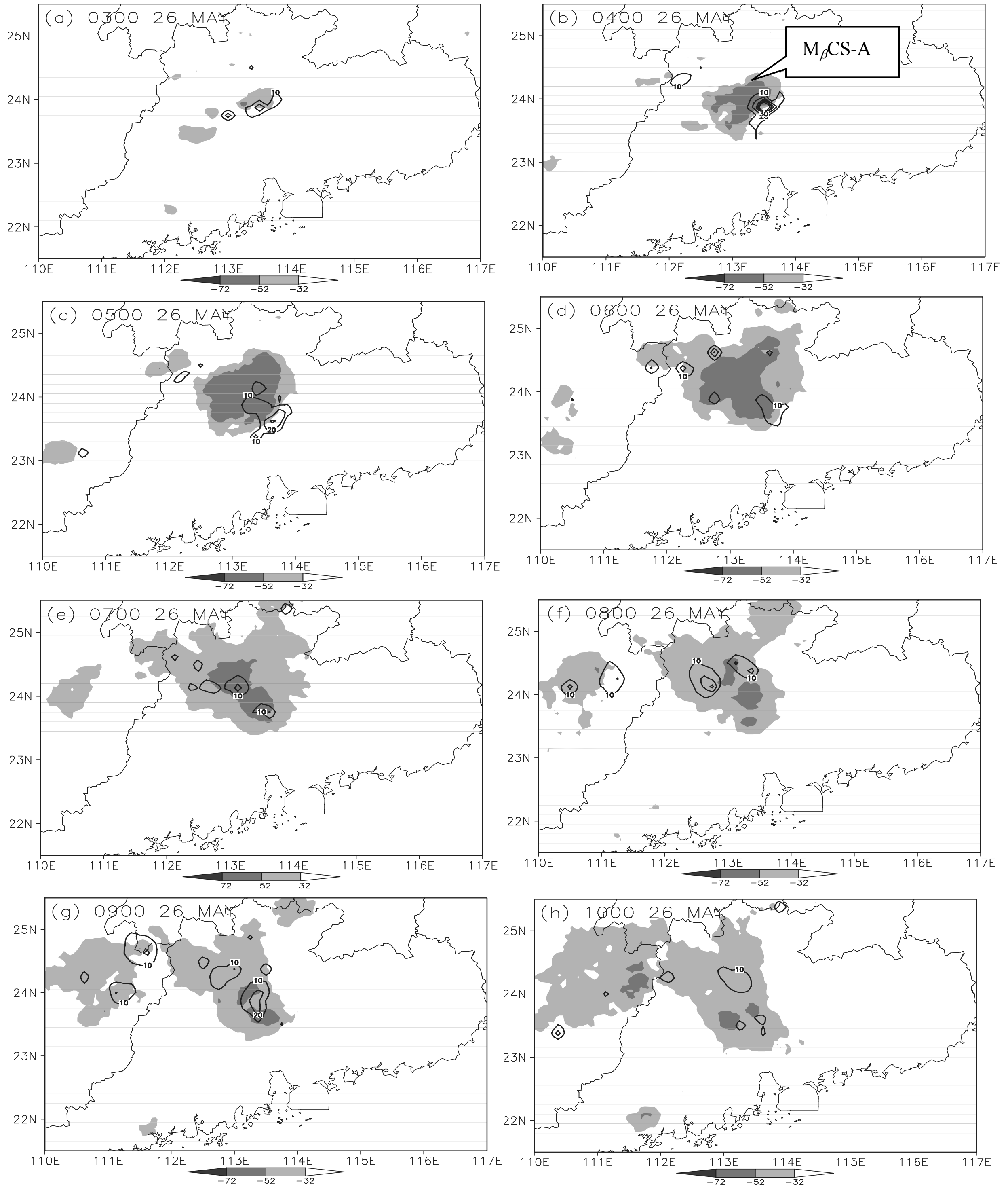


Fig. 2. Hourly evolution of rainfall (unit: mm) from the four AWSs from 2000 BST May 25 to 2000 BST May 26, 2007

3 EVOLUTION OF MESOSCALE-β SCALE CONVECTIVE SYSTEMS

3.1 *Analysis of TBB*

With the hourly available 0.05°×0.05° TBB data from the Japanese satellite of MTSAT, the Mβcss convective systems responsible for the warm-sector rainstorm was studied. Starting from 0300 BST May 26, the rainstorm-causing convective cloud clusters began to develop. An area of convective clouds, colder than -32°C and more than 50 km across, was spotted at Qingyuan on the TBB cloud imagery (Fig. 3a). A corresponding record of rain rates also goes beyond the 20 mm/h mark (indicated by the isolines therein). By 0400 BST, the cloud clusters had evolved into a mesoscale-β convective system with a diameter of about 200 km (denoted as Mβcs-A), with the main area of intense rain located in the southeastern part of the convective system and a rainfall of more than 80 mm at the center (Fig. 3b). The largest amount recorded at 0400 BST at the Qingyuan station showed that the rainstorm was caused by this very system. In the few hours that followed, the system kept evolving, with the central position stationary and the clouds gradually expanding to form an elliptic area, in which the part with temperature cooler than -52°C reached the maximum in size at 0500 and 0600 BST (Figs. 3c & 3d). Meanwhile, the area of intense rain was moving south along with the southward expansion of the convective system, which was reflected in the temporal evolution of precipitation at both Conghua and Huadu. The precipitation measured at these four sites showed that it was caused by this convective system Mβcs-A.



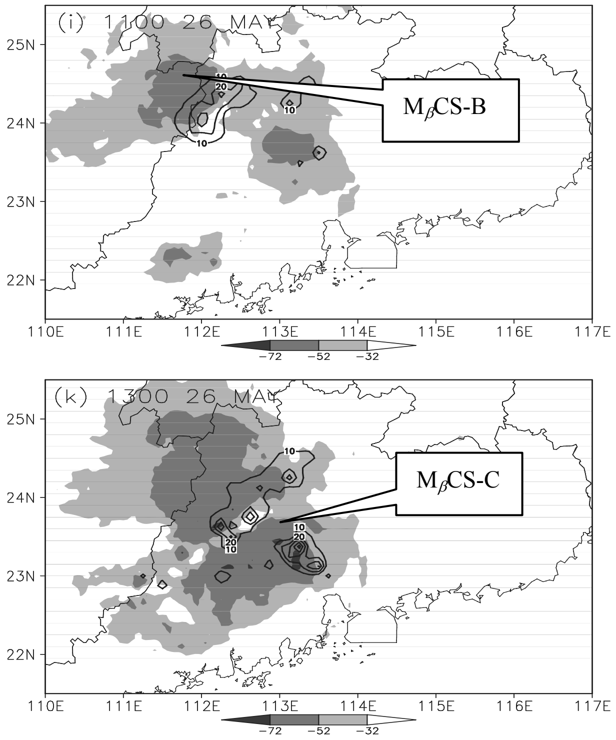


Fig. 3. Evolution of mesoscale-β convective systems from 0300 to 1400 BST May 26, 2007. Shades: areas with TBB -32°C; contours: corresponding 1-h accumulated rainfall (mm)

After 0800, Mβcs-A began to weaken in association with shrinking -52°C cloud coverage and a developing cloud cluster to the west inside Guangxi Zhuang Autonomous Region, which was moving east. By 1100 BST, the newly developed cloud cluster had migrated to the border between Guangxi and Guangdong, with the coverage gradually expanding to become another mesoscale-β convective system (denoted as Mβcs-B, as in Fig. 3i). Precipitation from this system also appeared on its front. It is noteworthy that new convective cloud clusters developed in the southwestern portion of the weakened Mβcs-A in Qingyuan. With the northward development of these cloud clusters and merging with what remained of Mβcs-A, yet another new system (denoted as Mβcs-C, as in Fig. 3k) had formed by 1300 BST and extended parts of the convective clouds had a cloud-top temperature below -52°C. Correspondingly, there was also an area of convective precipitation at the front edge of these clouds. A rain rate of 103.3 mm/h recorded at Huangpu was just caused by Mβcs-C. At 1400 BST, with further eastward advancement of Mβcs-B and its merge with Mβcs-C, these cloud clusters eventually evolved into a mesoscale-β convective regime with the -52°C cloud coverage exceeding 50 000 km^2, further strengthening the convection so that an area of ＜-72°C appeared at cloud top (Fig. 3l). At this point, however, the rain area corresponding to the former two mesoscale-α convective systems was still evident; the precipitation from Mβcs-B strengthened further and its location moved more to the southeast to be in the middle of the mesoscale-α convective system. Meanwhile, the precipitation brought by Mβcs-C to its east was decreasing rapidly. While in its strongest period of development, the mesoscale-α convective system lasted only for about one hour and soon began to weaken as the cloud area split and part of it decreased as it moved east. The cloud clusters to the west were weakening and dissipating where it had been, shrinking in both the area and intensity of precipitation. By 2000 BST, the process precipitation ended on the whole (Figure omitted).

As shown in the analysis above, this warm-sector rainstorm was caused by at least three convective systems on the mesoscale-β exerting consecutive influence over South China. At the point of its strongest development, these systems were about 200 km across horizontally and persisted for more than three hours, typical of convective precipitation. Following the definition that a rain area with 1-h precipitation amount ＞10 mm, life cycle ≥2 h, and spatial range as large as a few thousand km is classified as a mesoscale rain cluster, the authors found that there are a number of such clusters that mainly occurred from 0400 to 1400 BST on May 26 and corresponded to the mesoscale-β convective systems, leading directly to uneven distribution of the rainstorm. Being lump-shaped, most of the clusters corresponding to Mβcs-A occurred in central and northwestern Guangdong north of the Pearl River Delta, while those in association with Mβcs-B were in stripe shape and at the front of convective systems. Rain clusters for Mβcs-C had the largest rain rate and mainly affected Guangzhou and areas to its east.

It is noteworthy in previous studies that rainstorm cloud clusters active on stationary fronts usually develop to the east or in front of the old ones and display a type of forward propagation[13], while the mesoscale-β convective systems of the rainstorm of interest demonstrate a type of backward propagation that generate and dissipate continuously; new convective systems mainly take place at the rear of the formerly existing ones or upstream of the environmental flow field. As pointed out by authors' analysis coming forth in subsequent parts of this work, these backward-evolving convective systems not only depend on favorable environmental background for their formation and evolution, but also are possibly related with the outward flow of air from the rear portion of the formerly existent systems in the near-surface layer.

3.2 *Echoes of Doppler*

In another way, echo images from Doppler observations provide clearer indication of the convective nature of the warm-sector rainstorm. Following usual categorization methods, precipitation areas with associated radar echoes of <40 dBz are thought to be caused mainly by clouds mixed up with stratus and cumulus, while those corresponding to reflectivity rates ≥40 dBz are defined as precipitation of convective clouds. By examining the intensity of echoes of rain areas, general estimates can be made to judge whether the precipitation is convective or not. Fig. 4 gives the radar echoes and rainfall amount distribution of two representative points of measurement time. Fig. 4a presents the echoes of rain and associated distribution of 1-h precipitation amount at the 500-m altitude for 0400 BST May 26 when Mβcs-A affected Qingyuan. A center of intense rain was shown to be associated with echoes of ≥40 dBz. Fig. 4b is the radar echoes and associated 1-h rain amount, which clearly shows that in association with a stripe-shaped rain area caused by Mβcs-B, a strong echo area was similarly shaped with the intensity ＞40 dBz. These are sufficient evidences that the precipitation in question is convective. Similar to the nature of precipitation of these two systems, the strong rainfall affecting Guangzhou, caused by Mβcs-C, was also highly convective. Fig. 4b illustrates two obvious centers of rain over Guangzhou and the area nearby underneath a stripe-shaped rain belt, with the intensity of both surpassing 50 mm/h and the rain centers both corresponding to radar echoes of ≥40 dBz. Analysis also indicated that these convective system once reached altitudes of more than 10 km when fully developed (figure omitted), a sign that tells that the convective cells embedded in the convective cloud zones are the immediate drivers of the centers of intense rain.

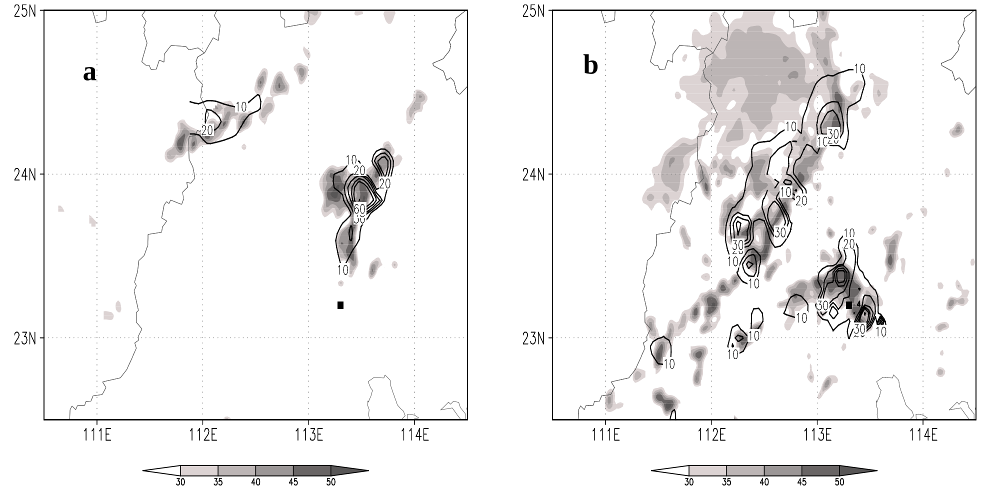


Fig. 4. Composite maps based on radar echoes and 1-h precipitation from AWSs for Guangzhou at 0400 BST (a) and 1300 BST, May 26

4 ENVIRONMENTAL CONDITIONS AND TRIGGERING MECHANISMS FOR MESOSCALE CONVECTIVE SYSTEMS

4.1 *Moisture conditions and accumulation of unstable energy*

The activity of low-level jet streams is closely related with rainstorms in South China, a fact that has been stressed and confirmed in many research results[15, 16]. Right before this rainstorm, a low-level cyclonic shear, formerly located in the north of South China, had moved east and disappeared, and a low-level jet stream began to appear at 850 hPa on the coast of South China and brought abundant warm and humid air to South China under the effect of increasing southwesterly airflows in the northwest of South China Sea. Based on 1.0°×1.0° NCEP reanalysis, Fig. 5 presents the distribution of wind field and divergence of moisture flux at 850 hPa for May 26, 2007. It shows that the low-level southwesterly jet stream were prevailing in Guangdong and southern Fujian and a center of moisture flux convergence was associated with an area of concentrated rainfall of the warm-sector rainstorm. The longitudinal vertical cross-section of moisture flux divergence for corresponding points of observation time also show that moisture flux converged over the rainstorm area from the surface to 500 hPa while a zone of maximum moisture convergence was mainly located at levels below 850 hPa (figure omitted), indicating that the establishment of low-level jet streams provide sufficient moisture for the generation of convective systems that give rise to rainstorms.

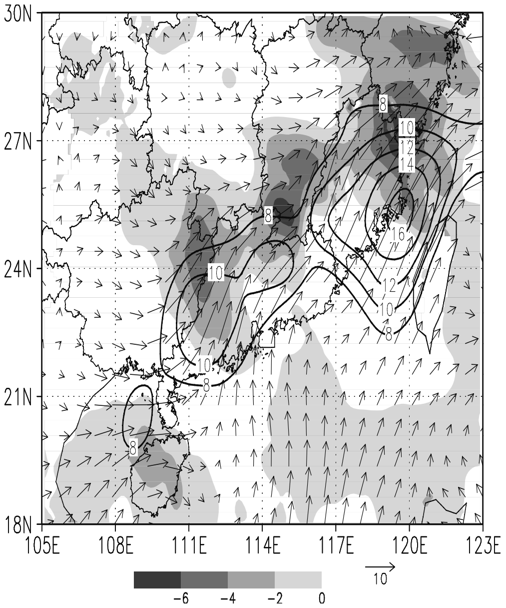


Fig. 5. Whole wind speed (unit: m/s) and divergence of moisture flux (unit: 10^{-7} g/(s•hPa•cm^2)) at 850 hPa for 0800 BST May 26

In addition to transferring moisture, low-level jet streams cause significant warming of the lower levels through advection of warm air to make low-level atmosphere more unstable. Fig. 6 gives the longitudinal vertical cross-section of the intensity of both pseudo-equivalent temperature and temperature advection at 113°E. It shows that there is a well-defined tongue in the warm and humid layers below 600 hPa near the area of rainstorm, in which a high-θ_{se} zone extends from its southern side to the rain area; θ_{se} near the surface is generally warmer than 350°K while being quite low between 600 and 500 hPa, forming a layer of intense convective instability. From the variation of convective instability over the Qingyuan site, for instance, the time from 2000 BST May 25 to 0800 BST May 26 was shown to have an increase of $\Delta\theta_{se(500-850\,\mathrm{hPa})}$ from -8 K to -10 K. It is probable that the temperature advection contributes to the formation of this convectively unstable stratification. The shades in Fig. 6 denote some zones of positive temperature advection. They show that strong warm advection exists above the rainstorm area below the level of 800 hPa with the center having a maximum of more than 6×10^{-5} K/s. Such robust relationships between strong warm advection and rainstorm areas also suggest a possible important role played by low-level warm advection in the initiation and evolution of rainstorm-inflicting convective systems. In their study on the formation and development of strong convective systems over the Americas, Maddox et al.[17] pointed out that it may help in forecasting the outbreak of organized, intense convective systems if the forecaster shifts his attention from the analysis of the differences in 500-hPa vorticity advection to the analysis and observation of low-level warm advection, when large-scale background conditions are favorable. It is necessary to take warm advection more as one of the triggering mechanisms of convection development.

Besides, the distribution and variation of convective available geopotential energy (CAPE) are also a good indicator of the formation and development of rainstorms, as it is a thermodynamic variable closely related with the development of deep convection. Examining the distribution of CAPE values determined by calculating the NCEP reanalysis for 0800 BST May 26, the authors learned that a high-value area of CAPE extended from the northwest of South China Sea all the way to Guangdong and southeastern Fujian, with the value of CAPE generally higher than 1 000 J/kg for Guangzhou and Qingyuan, which was obviously related with warm and humid unstable air being transferred by the low-level jet stream. Analysis of the temporal evolution of the CAPE values also indicated that convective systems mainly develop in areas with the significant growth of CAPE values. For the time from 0800 BST May 25 to 0800 BST May 26, CAPE generally grew to more than 300 J/kg in central Guangdong and tended to concentrate in some particular areas. It was right over these fast-growing CAPE areas that convection took place, which shows that it is just a good indicator of where rainstorms are going to fall.

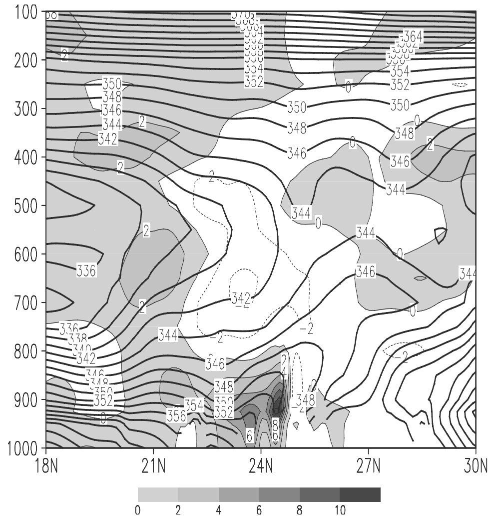


Fig. 6. 113°E vertical cross sections of moisture flux divergence and temperature advection for 0800 BST May 26. The shades are for warm advection in the unit of 10^{-5} K/s.

4.2 *Favorable allocation of high- and low-level flow fields*

As shown in previous statistics and analyses[4], most of Guangdong province is usually located underneath a northwesterly airflow to the northeast or northeast-to-east of the South Asian high, which is active mostly over northern Indo-china Peninsula and adjacent areas. As a result, at upper levels above 200 hPa, westerly airflows usually prevail in the south of the middle and lower reaches of Yangtze River and northerly airflows usually dominate in the Hainan Island, making divergent northwesterly airflows a common pattern over Guangdong, which helps “suck” in airflows for the evolution of rainstorms in South China. However, the rainstorm of interest is much different from this typical allocation of upper-level flow fields. As shown in the NCEP 1.0°×1.0° reanalysis, the 200-hPa center of the South Asian high was over the ocean east of Taiwan Island, and most of the South China region was within a divergent area formed between an easterly and a southerly, which were to the southwest-west of the center of anti-cyclonic upper-tropospheric circulation. In other words, it has consistent effect; the upper-level divergent flows happened to be superimposed on low-level converging flows and an intense ascending flow forming consequently is conducive to up-lifting conditions for the evolution of the rainstorm. As shown in Fig. 7b, the central and southern Guangdong was located to the left of an 850-hPa southwesterly jet and an area of intense convergence, resulting from wind-speed shear, was just below a strong upper-level diverging flow at 200 hPa. These are the conditions favorable for the generation of the rainstorm of interest. Of course, whether or not such allocation of upper- and lower-level flow fields can be representative needs to be studied with more cases for verification.

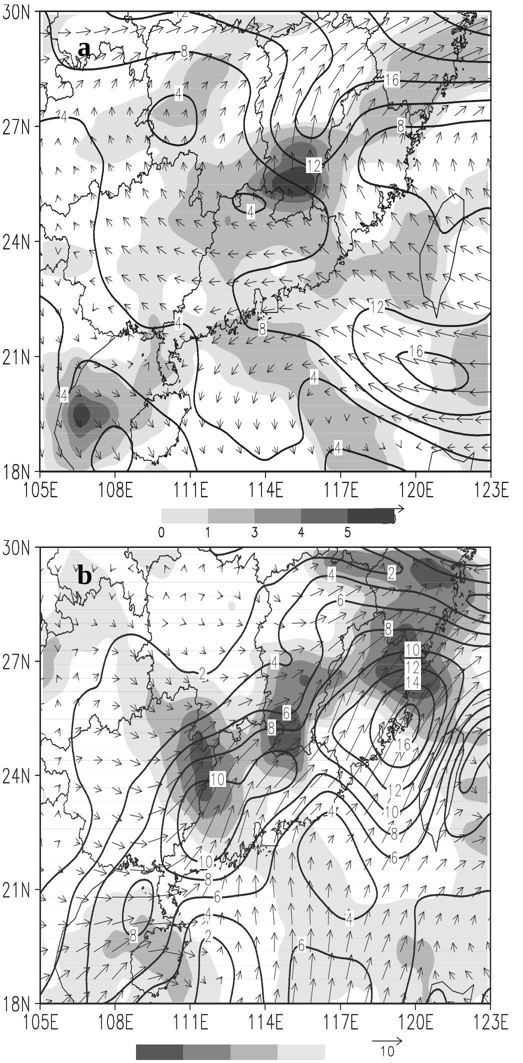


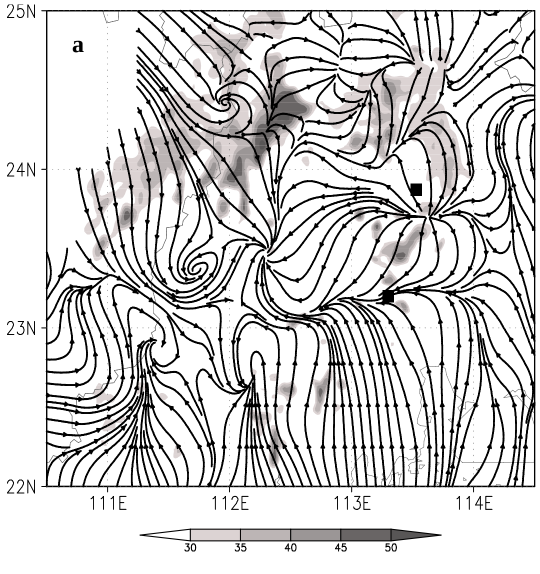
Fig. 7. Wind field and divergence field for 200 hPa (a) and 850 hPa (b) at 0800 BST May 26. (Unit: 10^{-5} s^{-1})

4.3 *Triggering mechanisms for mesoscale convective systems*

Under favorable large-scale conditions, it is still a great challenge to forecast the mesoscale-β convective systems that cause rainstorms. In addition to the contribution of low-level warm advection to the formation and development of organized convective systems, as aforementioned in earlier sections, this work especially focuses on probing into the developing mechanism of mesoscale-β convective systems responsible for rainstorms that keep generating and dissipating. What effect did the matured Mβcs-A have on the newly developed convective systems upstream in Guangxi? Why were there new systems to its southwest after it began to weaken from 1000 BST May 26? Analysis was done on the wind field from mesoscale surface AWSs to have better understanding of the mechanism of continuous generation and decline of the mesoscale-β

convective systems.

Having simple quality control on the wind field data by mesoscale surface AWSs, this work used the Barnes objective analysis method (cf. Zhang et al.[18]) to interpolate it on a grid mesh with a resolution of about 25 km. It was found that factors triggering the development of these Mβcss may be greatly associated with the mesoscale convergence at low levels, in addition to favorable large-scale environmental conditions. Especially, the development of new convective systems may be related with the outflow caused by old convective systems in the near-surface layer. Fig. 8a, which gives the surface flow field and Doppler echoes for 1100 BST May 26, shows significant outflow in the surface flow field over what corresponded to the matured Mβcs-A. Flows coming out to the north and east joined the flow going out from the zone of intense convective echoes to form a well-defined belt of convergence. It could be considered one of the important reasons for Mβcs-B to sustain and move eastward. It is also noted that the northerly flow moving southward from Mβcs-A joined with the southerly flow to the south to form a well-defined east-west mesoscale convergence line. It was under the triggering effect of this line that Mβcs-C got developed. Fig. 8b further gives the surface flow field and radar echoes for 1200 BST May 26, which clearly shows that the area of intense echoes over Guangzhou was the result of the convergence line and the southward flow to the south. It is then estimated that the surface mesoscale convergence could be a more immediate trigger in the sustained development of the convective system.



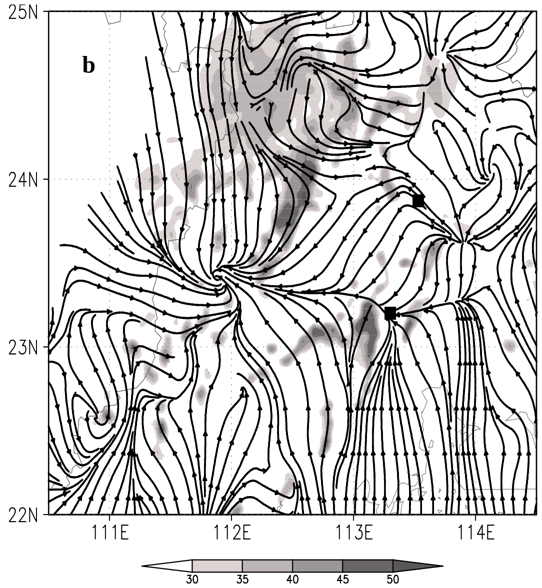


Fig. 8. Surface flow field and radar echo in Guangzhou as analyzed with AWS data for 1030 BST (a) and 1200 BST (b) May 26 (at the altitude of 500 m)

5 CONCLUSIONS AND DISCUSSIONS

Affected directly by a mesoscale-β convective system (Mβcss) that kept generating and dissipating, a rainstorm occurred over central and northwestern Guangdong at the northern tip of the Pearl River Delta on May 26, 2007. Data from AWSs, satellite-integrated CMORPH, TBB, radar echoes and NCEP reanalysis were used to study the characteristics of mesoscale-β convective systems that were responsible for this rainstorm. Besides, analysis was done of the favorable conditions for the activity of the systems. Conclusions were drawn as follows.

(1) Formed within a surface inversed trough and to the left of a southwesterly low-level jet, this rainstorm was poorly boraclinic; instead, it was a typical warm-sector rainstorm.

(2) The rainstorm was directly associated with at least three Mβcss that kept generating and dissipating; the time for precipitation peaks over different hyetal areas corresponded well with the prime stages of individual Mβcss.

(3) Differing from the more usual type of evolution—forward propagation, the Mβcss evolved in backward propagation, i.e., newly developed convective systems mainly formed at the rear portion of the old Mβcss.

(4) The rainstorm-triggering mesoscale-β convective system formed in a convergence zone to the left of the 850-hPa southwesterly low-level jet, with well-defined converging flows at the upper level of 200 hPa. Being different from the typical pattern for the annually first raining season of South China in which the hyetal of rainstorms are

allocated with outgoing diverging flows off the eastern side of the South Asian high, the warm-sector rainstorm in question was located below an area of divergence consisting of easterly and southerly flows to the west of the ocean-heading South Asian high.

(5) Low-level jet streams not only transport abundant amount of water vapor to where the rainstorms are and help store highly unstable energy at the middle and lower levels, their corresponding warm air also exert direct effects on the formation of convective system themselves. As one of the triggering mechanisms for organized convective systems, the role of warm advection is worth paying attention to.

Setting off from the viewpoint of surface mesoscale flow field, this work also makes meaningful analysis of possible triggering mechanisms for the formation and development of warm-sector rainstorms. It is argued that the interactions between low-level outflows triggered by Mβcss and local flow fields are playing an important role in the generation and development of Mβcss, especially the formation of new convective systems, in addition to favorable large-scale environmental conditions. It might result from the effects of gravity waves or gravity inertial waves, as the gravity waves excited during the rainstorm can move both forward and backward and trigger new convection during these processes and dispersion. Whether these sustained mesoscale-β convective systems display forward or backward propagation may depend on the different allocation of the environmental field and the non-linear interactions with the gravity wave. Besides, it is necessary to shift the focus of research more on the representativeness of the upper and lower levels of divergence fields of the warm-sector rainstorm disclosed in this work.

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