Characteristics of a mesoscale convective system in a warm zone that created an extreme, short rainstorm in Southern China in May 2016

Z Y Huang¹, W Chen²,³ and M Xu¹

¹Institute of Heavy Rain, Wuhan, CMA, 430205, China
²Wuhan Meteorological Bureau, 430000, China

E-mail: chenweiy2008@163.com

Abstract. An extremely intense rainstorm occurred on 20 May 2016. It had been the heaviest rainfall event recorded in Xinyi, Guangdong Province, China, since 1960. The black body temperature (TBB) output of FY-2B satellite images, weather radar, and NCEP/NCAR reanalysis data were used to investigate the characteristics of a mesoscale convective system (MCS) associated with the rainstorm. Heavy rainstorms formed under the influence of an eastward migration of a low trough at 500 hPa, typical of warm area heavy rain. In front of the 500 hPa trough, there was strong coupling of high and low jet streams, high convective effective bit energy, strong middle and low water vapor convergence and high ground dew point temperature, creating a favorable environment for the formation and development of MCSs. The convective region of the linear convective cloud developed into an organized MCS, and Xinyi’s heavy rainfall occurred during the MCS lifecycle from formation to maturity to extinction. Five MCSs, with radar echo intensities of 40-55 dBz, created a ‘train effect’, which was the main driver of the heavy rainstorm. The strong echoes observed above 40 dBz were below 0°C, and the strongest echo center was near 2 km. The convective precipitation system had a low mass center and high precipitation efficiency. The echo top (with intensity ≥ 10 dBz) was as high as 19 km, and there was a deep ice phase growth belt above -10°C, which contributed to the heavy rainfall, which peaked at 132.8 mm in one hour.

1. Introduction
MacGorman et al [1] proposed that mesoscale convective systems (MCSs) are a type of storm which interacts with the environment and changes it. Many studies [2-9] have shown MCSs to be important weather systems that cause extreme rainstorms. For example, Schumacher et al [2] found that from 1999 to 2001, about 65.6% of the 116 extreme storms in the eastern United States were caused by MCSs. Some scholars in Europe and the United States have done much research on the organization, environmental characteristics and development mechanisms of MCSs in the mid-latitudes of Europe and North America. MCSs differ according to different life stages of cloud organization. By using the Oklahoma storm test data, Leohrer et al [3] divided MCSs into four classes: linear, posterior nascent, unorganized and cross-convective zones. Schinasser et al [4], Parker et al [5], Houze et al [6], Jirak et al [7], Rigo et al [8] and Maddox [9] carried out similar studies, but their classifications of MCS were not exactly the same. In recent years, with ongoing research, there is a new understanding of the occurrence and development mechanisms of MCSs. For example, Maddox believes that MCSs are generated in the vicinity of weak surface fronts and have obvious southerly low-level jet regions of
warm air transport. Maddox [9] believes that MCSs generate in areas with near-ground weak fronts which have obvious southerly low-level jet transport of warm moist air. Cotton et al [10] argued that MCSs are formed in the 200 hPa anticyclonic side of weaker westerly jets. Laing et al [11] and Bluestein et al [12] think that MCSs are formed in areas with high convective effective potential energy and low vertical wind shear. Parker et al [13] believes that MCSs occur in environments with minimum available convective potential energy and the lowest level of atmospheric stratification stability. Thorpe et al [14], Hane et al [15], Fovell et al [16] and Lin et al [17] believe that the new monomer in the MCS is caused by the convergence of the fronts. Shu Y et al [18] believes that mesoscale eddies are prone to occur in the middle warmer zone of stratified precipitation systems, and that the mesoscale eddies affect the development and movement of MCSs. Raymond et al [19] thinks that MCSs maintain their longevity through quasi-equilibrium vertical movement and the wet convection non-adiabatic effect of the interaction.

Some Chinese scholars [20-22] believe that South China rainstorms have clear characteristics of MCSs. Jian-Hu et al [20] believes that MCSs directly result from heavy rain, and that the local trumpet-shaped topography is very conducive to the triggering and maintenance of MCSs. By studying the characteristics of MCS activity during rainstorms in Southern China’s warm sector, Zhang et al [21] proposed that storms are directly related to MCS activity, and that the peak precipitation appears occur in the corresponding period of MCS development. Qin et al [22] provided evidence that MCSs directly affect heavy rain systems in Southern China’s warm sector by numerical simulation. Zhi S L et al [23] studied the mesoscale characteristics of heavy rainfall occurring at the edges of subtropical highs, and found that the surface mesoscale convergence line was an important factor leading to the development of MCSs.

Because Southern China is located in a low-latitude tropical region affected by the East Asian monsoon and tropical systems, we asked: What are the characteristics of the organization, structure and environment of MCSs in this region? Are these features exactly the same as in the mid-latitudes? The extreme rainfall event of 20 May 2016 was the heaviest rainfall that had occurred in Xinyi, Guangdong Province, China, since 1958. Direct observations, TBB of FY-2B satellite cloud images, Doppler radar echoes and NCEP/NCAR reanalysis data were used to study the characteristics of the organization, structure and environment of MCSs, in order to provide reference for related research.

In this study, Section 2 introduces the data and research methods used in this paper. Section 3 describes in detail the characteristics of storm evolution, and the morphological, structural and environmental characteristics of MCSs. Section 4 discusses the MCS environmental field characteristics and the reasons for the low centroid aspect of the convective system. Section 5 provides the conclusions.

2. Data and methods
The NCEP (National Center for Environmental Prediction) reanalysis data were used to analyze the circulation and weather systems and calculate the water vapor flux divergence, vertical velocity, KI index and CAPE values. The horizontal resolution of the data was 0.5° × 0.5°. The time resolution was 6 hours.

The FengYun-2G geostationary satellite’s visible weather data had a resolution of 1.25 km. Infrared and water vapor data had a resolution of 5 km, and one image was provided per hour. HUI The study of Wen et al [24] demonstrated that FY-2G images give good performance and can meet the needs of business operations and practical applications. The TBB data from the FengYun-2G geostationary meteorological satellite were used to analyze and characterize the height of cloud tops and the degree of convective development.

The South China radar network includes 17 Doppler weather radars in the range of 105-122° E and 20-30° N. The radar echo data used in the study are from the China Meteorological Administration's Atmospheric Survey Center and were quality controlled.

3. Results
3.1. Characteristics of heavy rain evolution

Figure 1(a) shows the 24-hour precipitation on 20 May 2016. The strongest rainstorm center was located in Xinyi City (22°21'10" N, 110°57'04" E) in Guangdong Province, and had 463 mm of rainfall in 24 hours. Figure 1(b) shows the hourly rainfall in Xinyi. Precipitation began at 00:00 on the 20th and had mostly ended by 09:00. The majority of precipitation occurred between 01:00-08:00, and the 1 h maximum rain intensity occurred at 03:00 with 132.8 mm. From 02:00 to 08:00 there was a 6-hour cumulative rainfall of 429.5 mm, breaking the local 6-hour precipitation record. It can be seen that this heavy rainfall event in Xinyi had the characteristics of concentrated precipitation and strong intensity.

![Figure 1. The distribution of 24-hour precipitation (mm) on 20 May 2016. (a) Multi-space distribution of precipitation. The black triangle represents Xinyi and (b) 00:00 to 12:00 hourly rainfall (mm), 20 May 2016, Xinyi.](image)

Figure 2 shows the evolution of rainfall over 10 mm in South China from May 19 to 20, 2016. At 23:00 on the 19th (figure 2(a)), there were two 10-15 mm/h mesoscale rain masses (B and C) to the south of mesoscale rain belt A. At 00:00 on the 20th (figure 2(c)), the mesoscale rain masses B and C merged into mesoscale rain mass D, with the maximum rain intensity being ≥ 30 mm for one hour. At 02:00 (figure 2(d)), the rain intensity of the northern part of the A-rain cluster weakened, and the rain intensity of the southern part was maintained and turned to the east-west direction. At 03:00 (figure 2(e)), the rain mass remained only in the southern section and formed an east-west rain band with rain mass D. Its maximum rain intensity was ≥ 30 mm in 1 h. At 04:00 (figure 2(f)), rain mass A and rain group D merged and created a 1-hour maximum rainfall intensity ≥ 30 mm of the mesoscale rain group E, Xinyi rainstorm to maintain. From 05:00 onwards, rain group E gradually weakened and split.
At 09:00, rain group E disappeared, which should represent the end of the precipitation.

Figure 2. The evolution of rainfall (mm) over 10 mm in South China from May 19 to 20, 2016 at the following times: (a) 23:00 on the 19th; (b) 00:00 on the 20th; (c) 01:00 on the 20th; (d) 02:00 on the 20th; (e) 03:00 on the 20th; (f) 08:00 on the 20th; (g) 05:00 on the 20th; (h) 06:00 on the 20th; (i) 07:00 on the 20th; (j) 08:00 on the 20th; and (k) 09:00 on the 20th.

In summary, the Xinyi heavy rainfall event can be divided into three stages: 1) from 01:00-02:00 was the initial stage of heavy rainfall caused by the merger of two mesoscale rain groups; (2) from 03:00-04:00 was the stage of development and maintenance of the storm. At this stage there was also a mesoscale rain mass merger; (3) from 05:00-09:00 the storm weakened and eventually stopped. The
mesoscale rain mass gradually weakened, split, and disappeared. Precipitation at Xinyi then gradually weakened and stopped.

3.2. Storm evolution characteristics

Maddox [25] proposed identifying mesoscale convective complexes (MCCs) according to the range and shape of the regions identified by black body temperature (TBB) at -32°C and -52°C. Augustine and Howard [26] and Jirak et al [27] proposed the use of -52°C TBB to identify the MCS. Sun et al [28] considered MCSs to be cloud-containing convective nuclei which extend about 100 km in one direction to form a general precipitation area, and may be organized in a linear or quasi-circular form.
Figure 3 shows the TBB image of the FengYun-2G geostationary meteorological satellite in South China from May 19 to 20, 2016. At 19, 23 (figure 3(a)), there was a mesoscale quasi-circular MCC in the southern coastal area of South China, and its northeastern side had a linear MCC with a TBB ≤ -52°C in the northeast direction stretching over 500 km. At 20:00 (figure 3(b)), the TBB ≤ -52°C area in the linear MCC was reduced to an ellipse, and a region of TBB ≤ 72°C developed, which indicates that the MCC was in development. For the next 3 hours (figures 3(c)-3(e)), the TBB ≤ -72°C area in the linear MCC increased, indicating that the linear MCC was mature. From 20:04 (figure 3(f)), the radial radius of the TBB ≤ -52°C region in the linear MCC increased and the structure became loose, which indicates that the MCC was in the weakening stage. From 05:00 (figures 3(f)-3(h)), the linear convective cloud gradually split as it moved eastward, indicating a significant decrease in convection. In summary, the heavy rain in Xinyi occurred in a linear MCC convection area moving eastward.

3.3. Morphological characteristics of MCS on radar echo

Schumacher et al [2] defined MCSs according to radar reflectivity. They result in an area with a radar reflectivity factor ≥ 40 dBZ stretching over 10 km and lasting for 3 h. Figure 4 shows the unusual South China radar net reflectivity factor (0.5° elevation angle) on 20 May 2016. At 00:06 on the 20th (figure 4(a)), there were strong echoes of ≥ 40 dBZ in the transition zone between the two eastward-moving band echoes, and the mesoscale rain mass precipitating 10-15 mm/h on the ground corresponds to it (B and C in figures 2(a) and 2(b)). According to the classification of MCSs by Leohrer et al [3], the echoes of ≥ 40 dBZ intensity in the northern and southern bands are linear MCSs, and the echoes of ≥ 40 dBZ intensity in the transition zone are new MCS monomers. At 00:06 on the 20th (figure 4(b)), the new MCS monomer in the transition zone affected Xinyi and the rainstorm began. From 03:00 to 04:30 (figures 4(c) and 4(d)), MCSs in the northern branch and transition zone merged into one linear MCS. In these latitudinal linear MCSs, there were more than 50-55 dBZ monomeric units moving eastward, and the storms intensified. As the zonal linear MCSs moved southward, Xinyi was at the northern edge of the banded echoes at 06:30 (figure 4(e)) and precipitation weakened.
3.4. Structural characteristics of MCS
Figure 5(a) is a radial section of radar echo reflectance factor intensity over Xinyi on May 20, 2016. From 00:00 to 09:00, there were 5 areas of MCS with echo intensities ≥40 dBz affecting Xinyi. These five MCSs mainly migrated towards the northeast. It can be seen that the heavy rainfall echoes continuously flowed from Xinyi to produce a "train effect", which is the main factor leading to the heavy rainfall. From the vertical section of the radar echo reflectance factor over Xinyi (figure 5(b)), it can be seen that the five MCSs affect the time of the letter should be about 01:00 to 02:00, 03:00 to 04:00, 04:00 to 06:00, 06:00 to 08:00, and 08:00 to 09:00. For ease of description, MCSs 1, 2, 3, 4, and 5 are defined in order of occurrence. The echo height of MCSs 1 and 3 above 40 dBz are below the -10°C layer height, and the other 3 MCSs are all below -0°C. The average echo height of these 5 MCSs exceeding 40 dBz is about 2-3 km. It can be seen that the convective precipitation system has a low center of mass and high precipitation efficiency during the heavy rainfall. In addition, the echo tops of these five MCSs are above the -20°C layer height, and the echo top of the second MCS reaches 19 km. There is a deep ice growth zone above -10°C, which is conducive to the formation of a large
number of ice crystals or cryolite particles, and ice crystals attaching to larger ice crystals. These phenomena form large raindrops, resulting in heavy instantaneous rainfall. This is also one of the biggest drivers of the heavy rainfall (132.8 mm) at 03:00. In terms of duration, the lifespans of the five MCSs were more than 1 h, and the lifespans of MCSs 1 and 3 were close to 2 h. It can be seen that the formation and development of MCSs in the mesoscale convective cloud cluster are the main causes of the formation of this heavy rainstorm.

![Figure 5](image)

**Figure 5.** (a) Radar echo reflectivity factor (dBz) over Xinyi, radial profile, May 20, 2016 and (b) Radar echo reflectivity factor (dBz) over Xinyi, vertical profile, May 20, 2016.

3.5. Environmental field characteristics of MCS

3.5.1. Circulation Background

At 20:00 on 20 May 2016 (figure 6(a)), the 100 hPa south-pressure high-pressure main body was located in the east-west direction at about 30°N. The 1668 dagpm line extended eastward to about 120°E and the ridge line occurred at around 23°N. The 200 hPa south branch westerly jet stream was located at about 20°N, and Xinyi was located at the right side of the entrance area of the high-level jet.
stream. The high pressure ridge in the Ural and Sakhalin areas extended northward to 60°N. There was a deep trough of low pressure between Lake Baikal and Lake Balkh, and a low pressure cut-off in the northern part of Xinjiang. The 500 hPa Eurasian mid- and high-latitude atmospheric circulation was a stable formation of ‘two ridges and one trough’. At 850 hPa and 925 hPa (figures 6(c) and 6(e)), there was a low vortex in the eastern part of Guangxi, which corresponded to the 500 hPa low trough. There were significant divergences to the south and east of the 850 hPa vortex. There was a southwest jet of 18-20 m/s at the south side of the 925 hPa low vortex, and Xinyi was to the southeast of the 850 hPa and 925 hPa vortices. On the surface weather map (figure 6(b)), there is a latitudinal warm trough from the Yunnan-Guizhou Plateau to the coastal area of Zhejiang. The dew point front is at 22-24°N, Xinyi is at the bottom of the ground warm trough and on the ground dew point front. At 06:00, the 500 hPa trough slowly moved eastward to Xinyi (Figure omitted), and the 850 hPa and 925 hPa vortices (figures 6(d) and 6(f)) moved eastward to the east of Guangxi. At 12:00 (Figure omitted), the 500 hPa low trough moved to eastern Guangdong. Xinyi switched to the north after the slot by the flow control, the end of precipitation. It can be seen that heavy rain occurred at the right side of the entrance area of the 100 hPa high-level jet center near the 200 hPa south Asian high ridgeline. The 850 hPa and 925 hPa southwest low-level jet was to the left and the low vortex center to the east. The main impact system was a 500 hPa low latitude region of the westerly trough.
Figure 6. Eurasian atmospheric circulation situation map, May 20, 2016. 100 hPa South Asia high pressure (blue solid line, dagpm), 200 hPa rapid flow (red vector arrow, m/s) and 500 hPa height field (black solid line, dagpm) at 00:00; 1000 hPa height field (black solid line, dagpm) and Td (blue solid line, °C) at 00:00; 850 hPa height field (blue solid line, dagpm), wind (wind pole, a pole represents 4 m/s) and divergence (shadow, 10-5m-1) at 00:00; 850 hPa height field (blue solid line, dagpm), wind (wind pole, a pole represents 4 m/s) and divergence (shadow, 10-5m-1) at 06:00; 925hPa height field (black solid line, dagpm), wind (wind pole, a pole represents 8 m/s) at 00:00; 925 hPa height field (black solid line, dagpm), wind (wind pole, a pole represents 8 m/s) at 06:00.
3.6. Environmental fields

Figure 7(a) is a time-series plot of divergence and vertical velocity from May 19 to 21 above Xinyi. At 00:00 on the 20th, the subsurface movement below 600 hPa was weak at Xinyi, and at 600 hPa the upper atmosphere above was relatively stable. At 06:00, there was a sudden change in the vertical motion of the atmosphere, and the whole 1000-250 hPa layer shifted into ascending motion. There were ascending motion centers at 350 hPa and 750 hPa. From the vertical distribution of divergence, it can be seen that the ascending motion center of the 350 hPa layer corresponds to the divergent center near 200 hPa, and the ascending motion center of 750 hPa layer corresponds to the convergent center near the 850 hPa layer. Figure 7(b) shows the vertical evolution of horizontal wind over Xinyi. At 00:00 on the 20th, the whole layer over Xinyi was dominated by westerly winds and the wind speed in the 1000-850 hPa layer was very small. At 06:00, there was a sudden change in the level of wind over Xinyi. In the 925-250 hPa layer, the horizontal wind direction changed from westerly to southwesterly, indicating that the development of warm and wet air was relatively strong. In terms of wind speed, there was a jet stream generated in the 925-700 hPa and 400-300 hPa layers. It can be seen that the rising motion center of the 350 hPa layer was caused by the radiation of the high-level jet, and the rising motion center of the 750 hPa layer was due to the convergence of the low-level jet.

Figure 7. (a) Spatial dispersion (blue line, 10-5m-1) and vertical velocity (black line, 10-1 pa/s) over Xinyi, May 19-20, 2016 and (b) Figure 7b: The vertical distribution of wind (wind pole, a pole represents 12 m/s) over Xinyi, May 19-20, 2016.
3.7. A su

Figure 8 shows the water vapor flux divergence at 850 and 925 hPa on 20 May 2016. At 00:00 (figure 8(a)), there was a relatively strong water vapor convergence zone on the left of the 925 hPa ultra-low-level jet, and Xinyi is on the right side of this convergence zone. At 06:00 (figure 8(b)), the strong water vapor convergence zone shifted to the east with the 925 hPa ultra-low-level jet, and Xinyi was at the center of the strong water vapor convergence zone. At 12:00 (figure omitted), the strong water vapor convergence zone moved to the east of Guangdong, and the precipitation over Xinyi finished. At 00:00 (figure 8(c)) there was an 850 hPa strong water vapor convergence zone and for 925 hPa it was basically the same. At 06:00 (figure 8(d)), the 850 hPa strong water vapor convergence zone was located at the border of Guangxi and Guangdong, and Xinyi was at the edge of strong water vapor convergence center. At 12:00 (figure omitted), the 850 hPa strong water vapor convergence zone moved to the northeast of Guangdong and Xinyi into a weak water vapor divergence area. It can be seen that the 850 hPa low-level jet and 925 hPa ultra-low-level jet were the main transporters of water vapor during the formation of this torrential rain.

![Figure 8](image_url)

*Figure 8.* The 850 and 925 hPa water vapor flux divergences (shadow, 10^-7 g·cm\(^{-2}\)·(hPa·s\(^{-1}\)) and wind vector (wind pole, a pole represents 20 m/s); (a) 850 hPa at 00; (b) 850 hPa at 06:00; (c) 900 hPa at 00:00; and (d) 900 hPa at 06:00, May 20, 2016.
From May 20, the vertical distribution of theta se (θse) point of view. At 00:00 (figure omitted), the low energy region was located in the atmosphere below 600 hPa north of 25°N, and to the south of 25°N occurred the high energy region. At 06:00 (figure 9(a)), although the low-lying low-energy zone south of pressure, but was still located to the north of 25°N. The area to the south of 25°N still had the high energy areas, and Xinyi was in a strong updraft area of the high energy zone. At 00:00 on May 20, the Xinyi KI index was about 38°C, and the CAPE value was about 1200 J/kg, indicating that at this time the letter should be in the atmosphere above the unstable state. At 06:00 (figure 9(b)), the KI index of the atmosphere above Xinyi increased to 40°C and the CAPE value was maintained at 1200 J/kg, indicating that the atmosphere was unstable. At 12:00, the KI index dropped below 32°C and the CAPE was about 200 J/kg. Thus, the heavy rainfall at Xinyi was caused by a very unstable atmosphere which produced warm, heavy rain.

Figure 9. (a) 06:00 θse radial section of the figure (shadow, K), (b) 06:00 KI index (line, °C) and CAPE (shadow, J/kg), May 20, 2016.
4. Conclusion

The extreme short-term rainstorm on 20 May 2016 was the heaviest rainfall recorded in Xinyi, Guangdong Province, China, since 1958. In this study, the evolution of mesoscale rain mass characteristics were analyzed by hourly precipitation observation data, FY-2B satellite images and South China radar puzzle data were used to analyze the evolution and structural features of MCS. Additionally, NCEP reanalysis data were used to analyze the background and environmental characteristics of MCS.

From the meteorological point of view, the heavy rainstorms were formed under the influence of the eastward migration of a low trough at 500 hPa, characteristic of heavy rain in a warm area. The 850 hPa low vortex, 925 hPa warm shear line and ground low pressure inverted trough convergence provided a good dynamic uplift condition for the occurrence of heavy rain. The strong coupling of high and low jets caused the vertical ascending motion to develop strongly. The 850 hPa and 925 hPa low-level southwesterly winds provided favorable conditions for the occurrence of heavy rain.

From the ground mesoscale rain group activity point of view, the heavy rainfall event can be divided into three stages: (1) From 01-02 the initial stage of heavy rain occurred, caused by the merger of two mesoscale rain groups. (2) From 03-04 was the stage of the development and maintenance of the storm. This stage also experienced a mesoscale rain mass from the merger. (3) From 05-09, the storm weakened due to the gradual weakening of the mesoscale rain mass, which split and disappear. Precipitation at Xinyi then gradually weakened and stopped.

Satellite TBB images show that the convective region of the linear convective cloud developed into an organized MCC at the left side of the low level jet and at the front of the low vortex in the lower troposphere. Xinyi's heavy rainfall occurred during the life cycle of the MCC, from formation to maturity to extinction.

From the evolution of the radar echo reflectivity factor, a total of five MCSs were affected during the heavy rain. The first MCS formed in the transition region of the two linear MCSs. The other four formed in the linear MCSs in the northern MCS, and the MCS in the transition region. The 5 MCSs with radar echoes of 50-55 dBz had a long-term effect, resulting in a ‘train effect’, which was the main cause of heavy rain.

The strong echoes above 40 dBz were below -10°C or 0°C, and the strongest echo center was near 2 km. The convective precipitation system had a low mass center and high precipitation efficiency. At 03:00, the echo top with intensity ≥ 10 dBz was as high as 19 km, and there was a deep ice phase growth belt above -10°C. This is conducive to the formation of large ice crystals, or ice particles and ice crystals, resulting in heavy instantaneous rain strength. This is one of the reasons why 132.8 mm of rainfall was observed at 03:00.

Before the 500 hPa low trough, the high and low jet coupling was strong, the convective effective bit energy was large, the middle and low water vapor convergence was strong and there was a high ground dew point temperature, creating a favorable environment for the formation and development of this heavy rain MCS.

Conflict of Interests

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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