

A Review of Research on Warm-Sector Heavy Rainfall in China

Jianhua SUN^{1,2}, Yuanchun ZHANG¹, Ruixin LIU³, Shenming FU¹, and Fuyou TIAN⁴

¹Key Laboratory of Cloud-Precipitation Physics and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

²Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China

³Beijing Municipal Weather Forecast Center, Beijing 100089, China

⁴National Meteorological Center, China Meteorological Administration, Beijing 100081, China

(Received 11 April 2019; revised 22 June 2019; accepted 22 July 2019)

ABSTRACT

Warm-sector heavy rainfall (WSHR) events in China have been investigated for many years. Studies have investigated the synoptic weather conditions during WSHR formation, the categories and general features, the triggering mechanism, and structural features of mesoscale convective systems during these rainfall events. The main results of WSHR studies in recent years are summarized in this paper. However, WSHR caused by micro- to mesoscale systems often occurs abruptly and locally, making both numerical model predictions and objective forecasts difficult. Further research is needed in three areas: (1) The mechanisms controlling WSHR events need to be understood to clarify the specific effects of various factors and indicate the influences of these factors under different synoptic background circulations. This would enable an understanding of the mechanisms of formation, maintenance, and organization of the convections in WSHR events. (2) In addition to South China, WSHR events also occur during the concentrated summer precipitation in the Yangtze River–Huaihe River Valley and North China. A high spatial and temporal resolution dataset should be used to analyze the distribution and environmental conditions, and to further compare the differences and similarities of the triggering and maintenance mechanisms of WSHR events in different regions. (3) More studies of the mechanisms are required, as well as improvements to the model initial conditions and physical processes based on multi-source observations, especially the description of the triggering process and the microphysical parameterization. This will improve the numerical prediction of WSHR events.

Key words: warm-sector heavy rainfall, synoptic weather conditions, triggering mechanism, South China

Citation: Sun, J. H., Y. C. Zhang, R. X. Liu, S. M. Fu, and F. Y. Tian, 2019: A review of research on warm-sector heavy rainfall in China. *Adv. Atmos. Sci.*, **36**(12), 1299–1307, <https://doi.org/10.1007/s00376-019-9021-1>.

Article Highlights:

- Recent progress in warm-sector heavy rainfall (WSHR) research in China is reviewed.
- Future avenues of research on WSHR that advance our understanding of its formation mechanisms and prediction are proposed.

1. Introduction

China suffers heavy rainfall frequently, with the pre-rainy season rainfall in South China being the strongest of the three heavy rain belts (Tao, 1980). The rainfall during the pre-rainy season contributes 40%–60% of the annual total precipitation in South China, with heavy rainfall accounting for ~50% of the total in the same period. Warm-sector heavy rainfall (WSHR) is a special type of heavy rainfall in

South China (Huang et al., 1986), and is defined as heavy rainfall that occurs in the warm sector, about 200–300 km from the surface front, or in the convergence zones between southwesterly and southeasterly flow, or even in southwesterlies without wind shear, but that is not influenced by tropical systems such as typhoons. According to this definition, it is clear that WSHR is not directly affected by cold fronts or cold air. In recent years, with new observations, it was found that WSHR events also occur in other regions besides South China (Chen et al., 2012b, 2016b, 2018; Sun et al., 2013; Jiang et al., 2017). WSHR features strong and concentrated precipitation, with a smaller coverage than frontal

* Corresponding author: Jianhua SUN
Email: sjh@mail.iap.ac.cn

heavy rainfall but with a sudden occurrence (Lin et al., 2006; Chen et al., 2018), which often causes serious floods. The predictability of WSHR is lower than other types of heavy rainfall mainly caused by synoptic weather systems. For example, deterministic operational numerical weather prediction (NWP) models failed to forecast the sudden local warm-sector torrential rainfall at Guangzhou on 7 May 2017, which caused more than 20 000 casualties and economic losses of 177 million RMB (Wu et al., 2018b). This heavy rainfall event created widespread concern throughout society.

Early studies of WSHR focused on South China, with the definition developed according to the situation in that region. In recent years, WSHR events in other regions, such as southern China (25°–35°N, east of 110°E) and North China have been studied. A heavy rainfall event occurred in North China on 21 July 2012, which included warm-sector and frontal precipitation (Chen et al., 2012a; Zhong et al., 2015). As WSHR ahead of the cold front had not been predicted in numerical models, the total precipitation of this extreme torrential rainfall was much weaker than the actual rainfall (Chen et al., 2012a; Sun et al., 2012).

WSHR events often cause severe flooding, huge economic losses, and many casualties, but the operational prediction of these events is difficult and often inaccurate. It is therefore of great operational significance to further study WSHR events. To encourage more scientists to study this problem, the existing research and the challenges presented by WSHR are summarized in this paper. The definition, synoptic weather patterns, and trigger mechanisms of WSHR in South China are summarized in section 2. WSHR events in other regions of China (southern China and North China) are discussed in section 3. In section 4, a discussion of WSHR events and conclusions are provided.

2. WSHR events in South China

South China is located across low latitudes and is influenced by the weather systems of both tropical and midlatitude regions. There are two rainy periods in South China, the pre-rainy season in May and June, and the second rainy season in July, August, and September. Observations have shown that heavy rainfall events in South China frequently occur in the warm sector of a front, in addition to the rain belts located in or behind the front (Ninomiya and Akiyama, 1971; Tao, 1980; Ninomiya et al., 1988; Xue, 1999; Zhou, 2000; Zhou et al., 2003; He et al., 2016). The prediction of WSHR in South China is difficult because the formation mechanism is not clearly understood. Several experiments have been conducted since the 1980s to observe heavy rainfall in South China, such as the Taiwan Area Mesoscale Experiment in 1987 (Kuo and Chen, 1990), the Heavy Rainfall Experiment during the pre-rainy season in 1987 (Zhou et al., 2003), the South China Sea Monsoon Experiment in 1998 (Ding et al., 2006), the South China Heavy Rainfall Experiment in 2008–09 (Zhang et al., 2011), the Southwest Monsoon Experiment, and the Terrain-influenced Mon-

soon Rainfall Experiment in 2008 (Jou et al., 2011). These experiments have led to a better understanding of the large-scale characteristics and structural features of heavy rainfall systems. To better understand the triggering mechanisms and organization of mesoscale convective systems (MCSs) in South China, the 2013–15 Southern China Monsoon Rainfall Experiment (SCMREX), as a Research & Development Project of the WMO's World Weather Research Program, was conducted by the China Meteorological Administration (Luo et al., 2017). Moreover, SCMREX (2013–21) is still ongoing; more results will be published in the future. Based on observations from these experiments, our understanding of the mesoscale systems in southern China monsoon heavy rainfall have been improved. Some studies also focused on WSHR events and obtained some new understanding related to the environmental conditions, triggering mechanism and effects of low-level jets (LLJs) and terrain.

2.1. Definition and objective identification of WSHR

Atkinson and Smithson (1972) found that precipitation was mainly located near warm fronts and in the warm sector within a certain distance of a warm front in England and Wales, but no specific definition of warm-sector rainfall was proposed. The high frequency of WSHR events in South China has the following features (Lin et al., 2006): (1) severe rainfall occurs under the background environmental conditions of high temperature, high humidity, and strong instability; (2) the rainfall is concentrated over several hours; (3) the rainfall has a smaller coverage than frontal heavy rainfall, with horizontal scales from dozens to hundreds of kilometers. Some previous studies have defined WSHR (Tao, 1980; Huang et al., 1986; Lin et al., 2006), but there are no objective criteria for identifying WSHR events.

Liu et al. (2019) studied a 34-year dataset of heavy rainfall in South China and quantitatively defined the criteria for WSHR events: (1) No frontal systems appear in vertical cross sections, the rainfall areas are influenced by a southerly wind in the middle and lower troposphere, and the distance to the surface northerly wind is more than 200 km. (2) When frontal systems occur in the vertical cross sections, the distance between the precipitation and front is more than 200 km. According to these criteria, 177 WSHR events were identified objectively, which occurred from April to September during 1982 to 2015 (Fig. 1), which accounted for 16.86% of the selected severe heavy rainfall events. Most WSHR events occurred in the pre-rainy season (April to June), and the peak appeared in June, which was consistent with the results of previous studies (Huang et al., 1986; Ding et al., 2011; Chen et al., 2012a). It was also found that most of the WSHR events in April to June occurred in Guangdong Province, while events in July to September mainly occurred in Guangxi Province (Liu et al., 2019). There were fewer WSHR events in inland locations than in the eastern coastal areas (Fig. 2a). Four main WSHR precipitation areas were identified (Fig. 2a): the coastal area in Guangxi (centered on Qinzhou); the mountainous area in northern Guangdong (centered on Longmen); the coastal region in

southern Guangdong (centered on Yangjiang and Enping); and the coastal area in eastern Guangdong (centered on Shanwei). In Guangxi Province, the frequency of WSHR events was lower and the precipitation was weaker in inland areas compared to the coast regions (Fig. 2b), with precipitation be-

ing stronger in individual coastal stations than in inland stations. In the inland regions, the precipitation in Guangdong was stronger than that in Guangxi, and the rainfall in coastal regions of Guangdong was the heaviest among the four main WSHR areas.

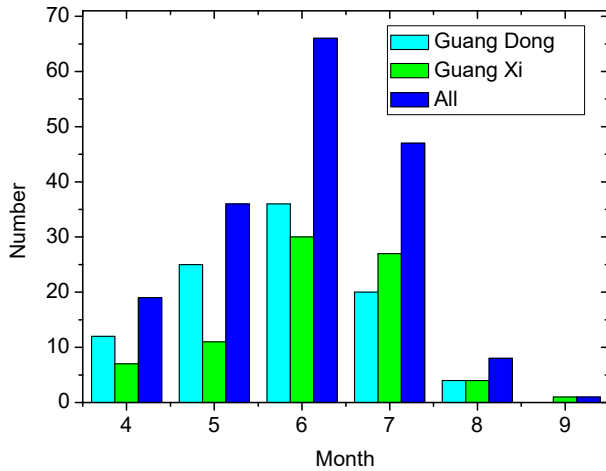


Fig. 1. Monthly variation of WSHR events from 1982 to 2015. The cyan, green, and blue columns show the number of WSHR events in Guangdong Province, Guangxi Autonomous Region, and all regions, respectively.

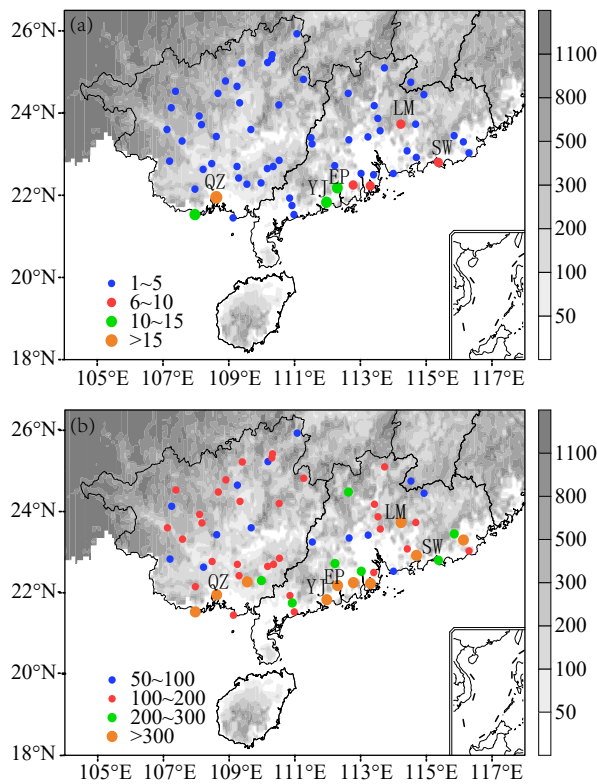


Fig. 2. The locations of selected WSHR stations in South China from 1982 to 2015, and (a) the frequency of occurrence and (b) maximum precipitation (units: mm). “QZ” “YJ”, “EP”, “LM”, and “SW” represent Qinzhou, Yangjiang, Enping, Longmen, and Shanwei stations, respectively. [Reprinted from (Liu et al., 2019)]

2.2. Synoptic weather patterns

For operational forecasting in China, the forecaster often determines an occurrence of WSHR according to the synoptic weather situation, as most WSHR cannot be predicted successfully by numerical models. Therefore, many studies have focused on the weather systems and environmental conditions that produce WSHR in South China (Huang et al., 1986; Lin et al, 2006; Miao et al., 2018; Zheng et al., 2018). Huang et al. (1986) summarized heavy rainfall in four types of weather systems: warm wind shear line, the LLJ along coastlines, the prefrontal LLJ, and cold fronts or quasi-stationary fronts. Forecasters in South China have categorized the synoptic weather systems influencing WSHR events into three types (Lin et al., 2006): backflow heavy rainfall caused by converging flows or warm and wet wind shear behind a transformed cold high pressure system; heavy rainfall caused by a strong southwestern monsoon surge or southwestern LLJ, and heavy rainfall produced by the upper-level trough and subtropical LLJ. The backflow WSHR was not included in the categories proposed by He et al. (2016). Based on previous research and numerous case studies, Liu et al. (2019) divided the synoptic patterns of heavy rainfall into four types: wind shear, low vortex, southern wind, and backflow. The wind shear and low vortex types of heavy rainfall were mainly concentrated in June and July (Fig. 3), while the frequency of southern wind type heavy rainfall was similar from April to July and the backflow type occurred in April to the middle of May (Fig. 3). It was also found that different types of WSHR could influence the weather in different regions of South China. The low vor-

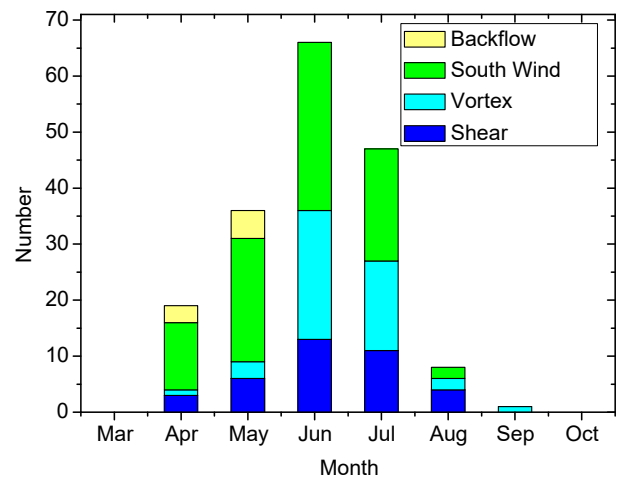


Fig. 3. Monthly variation of four types of WSHR events in South China. The blue column is the shear line type; the cyan column is the low vortex type; the green column is the south wind type; the yellow column is the backflow type. [Reprinted from (Liu et al., 2019)]

tex type of heavy rainfall mainly occurred along the coastline of Guangxi Province, while the backflow heavy rainfall often occurred in the coastal regions of the Pearl River Delta in Guangdong Province during the spring.

Under the control of the above-mentioned weather systems, synoptic circulations are favorable for the occurrence of convective systems, such as large amounts of convective available potential energy (CAPE, greater than 800 J kg^{-1}), abundant water vapor, and thick convective unstable layers. Among the key environmental parameters of the four types of WSHR, CAPE in the low vortex type is the strongest, but is the weakest in the backflow type (Liu, 2018). It is possible that all the backflow type events occurred in spring, with strong baroclinity, and the dynamic forcing played a more important role than thermal forcing. However, for the 0–3 km vertical wind shear, the warm wind shear line type was the strongest.

2.3. MCSs and trigger mechanisms for WSHR

Generally, WSHR is produced by MCSs related to certain weather systems and environmental conditions. The triggering of WSHR events in South China shows different features in different situations (Zhao et al., 2007; Luo et al., 2017; Du and Chen, 2018). Since the relevant triggering mechanism locally is far from the obvious synoptic forcing and/or cold air, rainfall forecasting has been a challenge and has attracted wide attention (Chen et al., 2014, 2015; Wang et al., 2014; Wu and Luo, 2016; Du and Chen, 2018). The triggering mechanisms are the key scientific uncertainty associated with MCSs. Generally, there are two kinds of triggering mechanism: (1) the inhomogeneous underlying surface layer, such as the wave or lifting effect triggered by topography and/or land–sea contrast (Xu et al., 2012; Chen et al., 2014, 2015, 2016a), and (2) the atmospheric perturbation instability (Wilson and Schreiber, 1986; Weckwerth and Wakimoto, 1992; Ding and Shen, 1998; Moncrieff and Liu, 1999), density current (Houston, 2017), and the gravity wave (Liu et al., 2012; Xu et al., 2013).

The terrain in South China is high in the north and low in the south, and features various mountain ranges, hills, and a convoluted coastline. The terrain blocking, lifting, and abundance of water vapor near the oceans complicates the triggering mechanism of WSHR events in South China. The specific mechanisms are still unclear, and it is difficult for NWP models to forecast these heavy rainfall events. Huang et al. (1986) proved that WSHR generally occurs under a southerly wind in the low troposphere. When the mountain direction is perpendicular to the low-level southerly wind, the lifted warm and wet air can cause severe convective storms or strengthen the precipitation. According to the statistical results, the WSHR in South China occurred more frequently in coastal areas than in inland areas (Liu et al., 2019). Some studies have indicated that the topography and land–sea contrast affected the triggering mechanism associated with WSHR near the coastal region (Chen et al., 2014, 2015; Du and Chen, 2018). An observational analysis of surface station, satellite, and radar datasets demonstrated that

the diurnal variation of the rainfall in the eastern coastal areas is very significant (Yu et al., 2007; Chen et al., 2009, 2013a, 2014, 2015; Jiang et al., 2017; Zheng et al., 2019), and the diurnal variation of deep convection and rainfall is related to the circulation of land–sea breezes (Zheng and Chen, 2013; Chen et al., 2015, 2016a). The interaction between convergence of land–sea breezes and topography near coastal areas enhances the intensity of precipitation (Chen et al., 2016a). Additionally, a relatively high topography and the trumpet-shaped topography in inland South China could also induce WSHR and enhance the total precipitation (Sun and Zhao, 2002a, b; Xia et al., 2006, Xia and Zhao, 2009; Tu et al., 2017; Liu et al., 2019). These previous studies suggest that topography and land–sea contrast are important factors impacting the intensity and distribution of WSHR events in South China.

Besides the influences of topography and land–sea contrast, the MCSs that produce WSHR events are mostly associated with the mesoscale convergence line and the LLJ, and other disturbances in the boundary layer (Lin et al., 2006). It has been suggested that warm-sector convection could be triggered by the low-level convergence associated with boundary layer processes and thin layers of cold air intruding into the boundary layer in South China (Sun and Zhao, 2002a, b; Xia et al., 2006). Heavy rainfall in South China is often accompanied by an LLJ or boundary layer jet (BLJ) (Chen and Yu, 1988; Chen et al., 2005, 2006; Tu et al., 2014). An LLJ or BLJ was also found to be significant in the generation of heavy rainfall (Tao and Chen, 1987; Zhang et al., 2000; Du and Chen, 2018, 2019; Du and Rotunno, 2018; Xue et al., 2018). Du and Chen (2018, 2019) found that the WSHR is associated with the southerly BLJ occurring over the northern region of the South China Sea. Moreover, the synoptic system-related LLJ and a BLJ, and their coupling, have key effects on triggering mechanisms, while the BLJ colliding with terrain may enhance coastal convergence for amplifying triggering mechanisms (Du and Chen, 2018, 2019). Moreover, the cold pool, the mesoscale outflow boundaries or cold dome, due to the precipitation, has been shown to have a strong effect on triggering convection (Wang et al., 2014; Wu and Luo, 2016; Tu et al., 2017; Liu et al., 2018). Especially, the mesoscale outflow boundaries over South China present weak surface outflows with little movement, which is crucial to the generation of long-lasting extreme rainfall events (Liu et al., 2018). Some observational analyses and numerical simulations have been conducted on these MCSs, and the three-dimensional structure of convective systems and their evolution has been revealed (Zhang et al., 2000; Sun and Zhao, 2002a, b; Xia et al., 2006; Zhao et al., 2007). As WSHR events are usually not directly affected by synoptic forcings and/or cold air, accurate prediction in numerical models is a big challenge (Chen and Xu, 2011; Zhang et al., 2016; Huang and Luo, 2017; Wu et al., 2018a). The predictability of MCSs is also an important scientific topic within the field of mesoscale meteorology, with NWP models used to investigate the predictability of MCSs (Anthes et al., 1985; Cintineo and Stensrud, 2013). Chen and Xu (2011)

found that the forecasting error and dispersion of WSHR events in South China was larger than that for heavy rainfall in the Yangtze River–Huaihe Valley, which led to large uncertainties in simulation results. In terms of error growth and ensemble forecasts, the numerical predictability of heavy rainfall in South China is lower than this in the Yangtze River–Huaihe Valley. The errors associated with water vapor transport and the humidity of the initial field have large impacts on the predictability of convective systems and its rainfall. Liu et al. (2005) indicated that the heating and water vapor transport from the convective systems in the South China Sea could influence synoptic circulation and the evolution of convection in South China. Many studies have proved that the humidity error is the largest uncertainty in the initial conditions and has a large impact on convection over South China (Wu et al., 2013, 2018a; Zhang et al., 2016; Lu et al., 2018). Lu et al. (2018) indicated that convective systems in the South China Sea play an important role in the convection and precipitation over the coastal areas of South China. Zhang et al. (2016) found that the assimilation of wind profile data significantly improved the short-range prediction of WSHR in southern China in terms of both intensity and location because of the improved representation of wind and moisture at lower levels in the analyses. Bao et al. (2017) demonstrated that assimilating the radial velocity of operational weather radar near the South China coast in both deterministic and probabilistic experiments generally improves the prediction of heavy-rain-producing MCSs.

3. WSHR in other areas of China

Many long-term research and forecasting results have been applied in the operational forecasting of WSHR events in South China. The understanding among forecasters is very limited for these WSHR events in other regions of China. Thus, the forecasting of WSHR events in these regions is difficult in operational forecasting (Chen et al., 2018). Fortunately, there are still some studies for WSHR events in southern areas of China and North China. Here, a brief summary of these studies is given.

Some studies have focused on WSHR events over southern areas of China in addition to the South China region (Chen et al., 2016b; Jiang et al., 2017; Wu et al., 2018; Wang et al., 2018). Some heavy rainfall south of the Yangtze River has been observed in the warm sector, about 100–300 km from the surface cold front or warm wind shear line at 850 hPa, and at the edge of the western Pacific subtropical high (WPSH) (Chen et al., 2016b; Jiang et al., 2017). The WSHR events in the regions south of the Yangtze River and the middle and lower reaches of the Yangtze River have the synoptic patterns of the warm wind shear line, pre-cold front, and edge of the WPSH. It has also been reported that the severe precipitation maxima in these WSHR events are dispersed and occur on the mountains, borders of mountains and plains, and borders between lakes (Ji-

ang et al., 2017). Torrential rainfall occurs frequently in the mountainous areas in western Hunan Province, and can cause extreme flooding events. The WSHR maxima over the middle and lower regions of the Yangtze River Valley occur in the Dabie Mountains and the hilly areas in southern Anhui Province. These rainfall events occur in an environment of low-level high humidity, inhomogeneous local heating differences on the underlying surfaces, and the accumulation of large unstable energy in the upper dry and lower wet air (Jiang et al., 2017). Although it is difficult to forecast WSHR events, according to the mesoscale analysis technology from the National Meteorological Center of the China Meteorological Administration (Zhang et al., 2012), some events could be successfully predicted.

WSHR events can also occur in North China, such as the extreme heavy rainfall on 21 July 2012 that caused many casualties and considerable economic losses. This extreme heavy rainfall included warm-sector and frontal precipitation. Due to the lack of understanding of WSHR, forecasts of their occurrence are inaccurate and the forecast intensity is typically less than the actual precipitation record (Chen et al., 2012b, 2013b). After the rainfall event on 21 July 2012, multi-scale weather systems, convections, and predictability were studied (Sun et al., 2013; Zhang et al., 2013; Meng et al., 2019), but the triggering mechanisms of the convection required for WSHR ahead of cold fronts in North China are still not fully understood. Some WSHR events in North China have been studied, and it has been suggested that the conditional symmetric instability might be responsible for the formation of parallel-type warm sector rain bands (Xu and Wang, 1989; Wang et al., 1990). However, there is still uncertainty regarding the temporal and spatial characteristics, triggering, and maintenance mechanisms of WSHR events in North China.

4. Conclusion and discussion

Systematic studies of WSHR events in South China have been conducted for several decades, including investigations of the formation of synoptic weather conditions, the categories and composite features, the triggering mechanisms, and structural features of MCSs during the rainfall events. A few studies have focused on WSHR events in other regions of China. Because of the strong intensity, locality, and their micro-mesoscale features, both NWP and subjective forecasts are difficult. Further scientific studies need to be undertaken.

(1) The environmental conditions, topography, land–sea contrast, BLJ and SLJ could impact the triggering and development of WSHR events. A WSHR can be affected by more than two of these factors. The interaction of these factors is very complicated. For example, the land–sea breezes that occur due to the heating differences in the coastal areas of South China, together with the trumpet-shaped and hilly topography of the Pearl River Delta, play important roles in the intensity of heavy rainfall events. Addi-

tionally, large urban agglomerations could influence the local thermal circulations. Because of the complex mechanisms of the WSHR in South China, the specific effects of the above-mentioned factors and their impacts under different synoptic background circulations need to be investigated and explored. Thus, the mechanisms of triggering, maintenance, and organization of the convections in WSHR can be better understood and used to improve forecasts.

(2) Most studies of WSHR in China have focused on South China. To better understand the concentrated summer precipitation in the Yangtze River–Huaihe Valley and North China, with its complicated terrain, a high spatial and temporal resolution dataset should be collected and used to analyze the distribution and environmental conditions of WSHR events. This would enable the differences and similarities of the triggering and maintenance mechanisms of WSHR events to be evaluated in different regions.

(3) Current NWP models have a limited ability to predict WSHR events. To improve the prediction of WSHR events, there is a need to better understand their mechanisms based on high spatial and temporal resolution observations. There is also a need to improve the initial conditions and physical processes of numerical models, especially the description of the triggering process and the microphysical parameterizations.

Acknowledgments. This research was supported by the National Natural Science Foundation of China (Grant No. 41675045), National Key R&D Program of China (Grant No. 2018YFC1507200), and the Jiangxi Key Basic Research and Development Project of China (Grant No. 20171BBG70005).

REFERENCES

- Anthes, R. A., Y. H. Kuo, D. P. Baumhefner, R. M. Errico, and T. W. Bettge, 1985: Predictability of mesoscale atmospheric motions. *Advances in Geophysics*, **28**, 159–202, [https://doi.org/10.1016/S0065-2687\(08\)60188-0](https://doi.org/10.1016/S0065-2687(08)60188-0).
- Atkinson, B. W., and P. A. Smithson, 1972: An investigation into meso-scale precipitation distributions in a warm sector depression. *Quart. J. Roy. Meteor. Soc.*, **98**, 353–368, <https://doi.org/10.1002/qj.49709841608>.
- Bao, X. H., Y. L. Luo, J. X. Sun, Z. Y. Meng, and J. Yue, 2017: Assimilating Doppler radar observations with an ensemble Kalman filter for convection-permitting prediction of convective development in a heavy rainfall event during the pre-summer rainy season of South China. *Science China Earth Sciences*, **60**, 1866–1885, <https://doi.org/10.1007/s11430-017-9076-9>.
- Chen, G. T.-J., and C. C. Yu, 1988: Study of low-level jet and extremely heavy rainfall over northern Taiwan in the Mei-Yu season. *Mon. Wea. Rev.*, **116**, 884–891, [https://doi.org/10.1175/1520-0493\(1988\)116<0884:SOLLJA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1988)116<0884:SOLLJA>2.0.CO;2).
- Chen, G. T.-J., C.-C. Wang, and D. T.-W. Lin, 2005: Characteristics of low-level jets over northern Taiwan in Mei-Yu season and their relationship to heavy rain events. *Mon. Wea. Rev.*, **133**, 20–43, <https://doi.org/10.1175/MWR-2813.1>.
- Chen, G. T.-J., C.-C. Wang, and L.-F. Lin, 2006: A diagnostic study of a retreating Mei-Yu front and the accompanying low-level jet formation and intensification. *Mon. Wea. Rev.*, **134**, 874–896, <https://doi.org/10.1175/MWR3099.1>.
- Chen, G. X., W. M. Sha, and T. Iwasaki, 2009: Diurnal variation of precipitation over southeastern China: Spatial distribution and its seasonality. *J. Geophys. Res. Atmos.*, **114**, D13103, <https://doi.org/10.1029/2008JD011103>.
- Chen, G. X., W. M. Sha, M. Sawada, and T. Iwasaki, 2013a: Influence of summer monsoon diurnal cycle on moisture transport and precipitation over eastern China. *J. Geophys. Res. Atmos.*, **118**, 3163–3177, <https://doi.org/10.1002/jgrd.50337>.
- Chen, M. Q., and H. M. Xu, 2011: Comparison of the model predictability between a front rainstorm in Yangtze-Huaihe river basin and a warm-area rainstorm in South China. *Journal of Nanjing University of Information Science and Technology: Natural Science Edition*, **3**, 118–127, <https://doi.org/10.3969/j.issn.1674-7070.2011.02.002>. (in Chinese)
- Chen, M. X., Y. C. Wang, X. Xiao, and F. Gao, 2013b: Initiation and propagation mechanism for the Beijing extreme heavy rainstorm clusters on 21 July 2012. *Acta Meteorologica Sinica*, **71**, 569–592, <https://doi.org/10.11676/qxxb2013.053>. (in Chinese)
- Chen, X. C., K. Zhao, and M. Xue, 2014: Spatial and temporal characteristics of warm season convection over Pearl River Delta region, China, based on 3 years of operational radar data. *J. Geophys. Res. Atmos.*, **119**, 12 447–12 465, <https://doi.org/10.1002/2014JD021965>.
- Chen, X. C., K. Zhao, M. Xue, B. W. Zhou, X. X. Huang, and W. X. Xu, 2015: Radar-observed diurnal cycle and propagation of convection over the Pearl River Delta during Mei-Yu season. *J. Geophys. Res. Atmos.*, **120**, 12 557–12 575, <https://doi.org/10.1002/2015JD023872>.
- Chen, X. C., F. Q. Zhang, and K. Zhao, 2016a: Diurnal variations of the land-sea breeze and its related precipitation over South China. *J. Atmos. Sci.*, **73**, 4793–4815, <https://doi.org/10.1175/JAS-D-16-0106.1>.
- Chen, X. X., Z. Y. Ding, C. H. Liu, Y. Chang, and C. L. Zhu, 2012a: Statistic analysis on the formation system of warm-sector heavy rainfall in May and June from 2000–2009. *Journal of Tropical Meteorology*, **28**, 707–718, <https://doi.org/10.3969/j.issn.1004-4965.2012.05.010>. (in Chinese)
- Chen, Y., J. Sun, J. Xu, S. N. Yang, Z. P. Zong, T. Chen, C. Fang, and J. Sheng, 2012b: Analysis and thinking on the extremes of the 21 July 2012 torrential rain in Beijing Part I: Observation and Thinking. *Meteorological Monthly*, **38**, 1255–1266, <https://doi.org/10.7519/j.issn.1000-0526.2012.10.012>. (in Chinese)
- Chen, Y., Y. Chen, T. Chen, and H. He, 2016b: Characteristics analysis of warm-sector rainstorms over the middle-lower reaches of the Yangtze River. *Meteorological Monthly*, **42**, 724–731, <https://doi.org/10.7519/j.issn.1000-0526.2016.06.008>. (in Chinese)
- Chen, Y., W. Q. Lü, C. Yu, S. Q. Li, S. N. Yang, W. J. Zhu, J. Xu, and Y. Gong, 2018: Analysis of a forecast failure case of warm sector torrential rainfall in North China. *Meteorological Monthly*, **44**, 15–25, <https://doi.org/10.7519/j.issn.1000-0526.2018.01.002>. (in Chinese)
- Cintineo, R. M., and D. J. Stensrud, 2013: On the predictability of supercell thunderstorm evolution. *J. Atmos. Sci.*, **70**, 1993–2011, <https://doi.org/10.1175/JAS-D-12-0166.1>.
- Ding, Y. H., and X. Y. Shen, 1998: Symmetric instability in nonconservative systems Part I: Forcing effect of weak viscosity. *Scientia Atmospherica Sinica*, **22**, 145–155, <https://doi.org/>

- 10.3878/j.issn.1006-9895.1998.02.03. (in Chinese)
- Ding, Y. H., and Coauthors, 2006: South China Sea Monsoon Experiment (SCSMEX) and the East Asian Monsoon. *Acta Meteorologica Sinica*, **20**, 159–190.
- Ding, Z. Y., C. H. Liu, and X. Y. Shen, 2011: Statistical analysis of the relationship among warm sector heavy rainfall, upper and lower tropospheric jet stream and South Asia high in May and June from 2005 to 2008. *Journal of Tropical Meteorology*, **27**, 307–316, <https://doi.org/10.3969/j.issn.1004-4965.2011.03.003>. (in Chinese)
- Du, Y., and G. X. Chen, 2018: Heavy rainfall associated with double low-level jets over southern China. Part I: Ensemble-based analysis. *Mon. Wea. Rev.*, **146**, 3827–3844, <https://doi.org/10.1175/MWR-D-18-0101.1>.
- Du, Y., and R. Rotunno, 2018: Diurnal cycle of rainfall and winds near the south coast of China. *J. Atmos. Sci.*, **75**, 2065–2082, <https://doi.org/10.1175/JAS-D-17-0397.1>.
- Du, Y., and G. X. Chen, 2019: Heavy rainfall associated with double low-level jets over southern China. Part II: Convection initiation. *Mon. Wea. Rev.*, **147**, 543–565, <https://doi.org/10.1175/MWR-D-18-0102.1>.
- He, L. F., T. Chen, and Q. Kong, 2016: A review of studies on pre-frontal torrential rain in South China. *Journal of Applied Meteorological Science*, **27**, 559–569, <https://doi.org/10.11898/1001-7313.20160505>. (in Chinese)
- Houston, A. L., 2017: The possible role of density current dynamics in the generation of low-level vertical vorticity in supercells. *J. Atmos. Sci.*, **74**, 3191–3208, <https://doi.org/10.1175/JAS-D-16-0227.1>.
- Huang, L., and Y. L. Luo, 2017: Evaluation of quantitative precipitation forecasts by TIGGE ensembles for south China during the presummer rainy season. *J. Geophys. Res. Atmos.*, **122**, 8494–8516, <https://doi.org/10.1002/2017JD026512>.
- Huang, S. S., and Coauthors, 1986: *Rainstorms During Pre-Rainy Season in South China*. Guangdong Science and Technology Press, 58 pp. (in Chinese)
- Jiang, Z. N., D.-L. Zhang, R. D. Xia, and T. T. Qian, 2017: Diurnal variations of presummer rainfall over southern China. *J. Climate*, **30**, 755–773, <https://doi.org/10.1175/JCLI-D-15-0666.1>.
- Jou, B. J.-D., W.-C. Lee, and R. H. Johnson, 2011: An overview of SoWMEX/TiMREX. *The Global Monsoon System: Research and Forecast*, 2nd ed., C.-P. Chang, Ed., World Scientific, 303–318.
- Kuo, Y.-H., and G. T.-J. Chen, 1990: The Taiwan area meso-scale experiment (TAMEX): An overview. *Bull. Amer. Meteor. Soc.*, **71**, 488–503, [https://doi.org/10.1175/1520-0477\(1990\)071<0488:TTAMEA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1990)071<0488:TTAMEA>2.0.CO;2).
- Lin, L. X., Y. R. Feng, and Z. Huang, 2006: *Technical Guidance on Weather Forecasting in Guangdong Province*. China Meteorological Press, Beijing, 143–152. (in Chinese)
- Liu, L., Z. Y. Ding, Y. Chang, and M. Q. Chen, 2012: Application of parameterization of orographic gravity wave drag in WRF model to mechanism analysis of a heavy rain in warm sector over South China. *Meteorological Science and Technology*, **40**, 232–240, <https://doi.org/10.3969/j.issn.1671-6345.2012.02.017>. (in Chinese)
- Liu, R. X., 2018: The statistical characteristics and mechanism of warm-sector rainfall events over South China. PhD dissertation, University of Chinese Academy of Sciences, 122 pp.
- Liu, R. X., J. H. Sun, and B. F. Chen, 2019: Selection and classification of warm-sector heavy rainfall events over South China. *Chinese Journal of Atmospheric Sciences*, **43**, 119–130, <https://doi.org/10.3878/j.issn.1006-9895.1803.17245>. (in Chinese)
- Liu, X., Y. L. Luo, Z. Y. Guan, and D.-L. Zhang, 2018: An extreme rainfall event in coastal South China during SCMREX-2014: Formation and roles of rainband and echo trainings. *J. Geophys. Res. Atmos.*, **123**, 9256–9278, <https://doi.org/10.1029/2018JD028418>.
- Liu, Y. J., Y. H. Ding, and N. Zhao, 2005: A study on the meso-scale convective systems during summer monsoon onset over the South China Sea in 1998: I analysis of large-scale fields for occurrence and development of meso-scale convective systems. *Acta Meteorologica Sinica*, **63**, 431–442, <https://doi.org/10.11676/qxxb2005.043>. (in Chinese)
- Lu, R., J. H. Sun, and S. M. Fu, 2018: Influence of offshore initial moisture field and convection on the development of coastal convection in a heavy rainfall event over South China during the pre-summer rainy season. *Chinese Journal of Atmospheric Sciences*, **42**, 1–15, <https://doi.org/10.3878/j.issn.1006-9895.1705.16261>. (in Chinese)
- Luo, Y. L., and Coauthors, 2017: The Southern China monsoon rainfall experiment (SCMREX). *Bull. Amer. Meteor. Soc.*, **98**, 999–1013, <https://doi.org/10.1175/BAMS-D-15-00235.1>.
- Meng, Z. Y., X. J. Tang, J. Yue, L. Q. Bai, and L. Huang, 2019: Impact of EnKF surface and rawinsonde data assimilation on the simulation of the extremely heavy rainfall in Beijing on July 21, 2012. *Acta Scientiarum Naturalium Universitatis Pekinensis*, **55**, 237–245, <https://doi.org/10.13209/j.0479-8023.2019.004>. (in Chinese)
- Miao, C. S., Y. Y. Yang, J. H. Wang, and P. Li, 2018: A comparative study on characteristics and thermo-dynamic development mechanisms of two types of warm-sector heavy rainfall along the South China coast. *Journal of Tropical Meteorology*, **24**, 494–507, <https://doi.org/10.16555/j.1006-8775.2018.04.008>.
- Moncrieff, M. W., and C. H. Liu, 1999: Convection initiation by density currents: Role of convergence, shear, and dynamical organization. *Mon. Wea. Rev.*, **127**, 2455–2464, [https://doi.org/10.1175/1520-0493\(1999\)127<2455:CIBDCR>2.0.CO;2](https://doi.org/10.1175/1520-0493(1999)127<2455:CIBDCR>2.0.CO;2).
- Ninomiya, K., and T. Akiyama, 1971: The development of the medium-scale disturbance in the Baiu front. *J. Meteor. Soc. Japan*, **49A**, 663–677, https://doi.org/10.2151/jmsj1965.49A.0_663.
- Ninomiya, K., T. Akiyama, and M. Ikawa, 1988: Evolution and fine structure of a long-lived meso- α -scale convective system in Baiu frontal zone. Part I: Evolution and meso- β -scale characteristics. *J. Meteor. Soc. Japan*, **66**, 331–350, https://doi.org/10.2151/jmsj1965.66.2_331.
- Sun, J., Y. Chen, S. N. Yang, K. Dai, T. Chen, R. Yao, and J. Xu, 2012: Analysis and thinking on the extremes of the 21 July 2012 torrential rain in Beijing Part II: Preliminary causation analysis and thinking. *Meteorological Monthly*, **38**, 1267–1277, <https://doi.org/10.7519/j.issn.1000-0526.2012.10.013>. (in Chinese)
- Sun, J. H., and S. X. Zhao, 2002a: A study of mesoscale convective systems and its environmental fields during the June 1994 record heavy rainfall of South China Part I: A numerical simulation study of Meso- β convective system inducing heavy rainfall. *Chinese Journal of Atmospheric Sciences*, **26**,

- 541–557, <https://doi.org/10.3878/j.issn.1006-9895.2002.04.11>. (in Chinese)
- Sun, J. H., and S. X. Zhao, 2002b: A study of mesoscale convective systems and its environmental fields during the June 1994 record heavy rainfall in South China Part II: Effect of physical processes, initial environmental fields and topography on Meso- β convective system. *Chinese Journal of Atmospheric Sciences*, **26**, 633–646, <https://doi.org/10.3878/j.issn.1006-9895.2002.05.05>. (in Chinese)
- Sun, J. H., S. X. Zhao, S. M. Fu, H. J. Wang, and L. L. Zheng, 2013: Multi-scale characteristics of record heavy rainfall over Beijing area on July 21, 2012. *Chinese Journal of Atmospheric Sciences*, **37**, 705–718, <https://doi.org/10.3878/j.issn.1006-9895.2013.12202>. (in Chinese)
- Tao, S. Y., 1980: *Rainstorms in China*. Science Press, Beijing, 45–46. (in Chinese)
- Tao, S. Y., and L. X. Chen, 1987: A review of recent research on the East Asian summer monsoon in China. *Monsoon Meteorology*, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 60–92.
- Tu, C.-C., Y.-L. Chen, C.-S. Chen, P. L. Lin, and P. H. Lin, 2014: A comparison of two heavy rainfall events during the Terrain-Influenced Monsoon Rainfall Experiment (TiMREX) 2008. *Mon. Wea. Rev.*, **142**, 2436–2463, <https://doi.org/10.1175/MWR-D-13-00293.1>.
- Tu, C.-C., Y.-L. Chen, S.-Y. Chen, Y.-H. Kuo, and P.-L. Lin, 2017: Impacts of including rain-evaporative cooling in the initial conditions on the prediction of a coastal heavy rainfall event during TiMREX. *Mon. Wea. Rev.*, **145**, 253–277, <https://doi.org/10.1175/MWR-D-16-0224.1>.
- Wang, H., Y. L. Luo, and B. J.-D. Jou, 2014: Initiation, maintenance, and properties of convection in an extreme rainfall event during SCMREX: Observational analysis. *J. Geophys. Res. Atmos.*, **119**, 13 206–13 232, <https://doi.org/10.1002/2014JD022339>.
- Wang, L. Y., Y. Chen, T. G. Xiao, S. Q. Li, and L. Ge, 2018: Statistical analysis of warm-sector rainstorm characteristics over the Southern of Middle and lower reaches of the Yangtze River in summer. *Meteorological Monthly*, **44**, 771–780, <https://doi.org/10.7519/j.issn.1000-0526.2018.06.005>. (in Chinese)
- Wang, P. Y., Z. X. Xu, and Z. T. Pan, 1990: A case study of warm sector rainbands in North China. *Adv. Atmos. Sci.*, **7**, 354–365, <https://doi.org/10.1007/BF03179767>.
- Weckwerth, T. M., and R. M. Wakimoto, 1992: The initiation and organization of convective cells atop a cold-air outflow boundary. *Mon. Wea. Rev.*, **120**, 2169–2187, [https://doi.org/10.1175/1520-0493\(1992\)120<2169:TIAOOC>2.0.CO;2](https://doi.org/10.1175/1520-0493(1992)120<2169:TIAOOC>2.0.CO;2).
- Wilson, J. W., and W. E. Schreiber, 1986: Initiation of convective storms at radar-observed boundary-layer convergence lines. *Mon. Wea. Rev.*, **114**, 2516–2536, [https://doi.org/10.1175/1520-0493\(1986\)114<2516:IOCSAR>2.0.CO;2](https://doi.org/10.1175/1520-0493(1986)114<2516:IOCSAR>2.0.CO;2).
- Wu, D. C., Z. Y. Meng, and D. C. Yan, 2013: The predictability of a squall line in South China on 23 April 2007. *Adv. Atmos. Sci.*, **30**, 485–502, <https://doi.org/10.1007/s00376-012-2076-x>.
- Wu, M. W., and Y. L. Luo, 2016: Mesoscale observational analysis of lifting mechanism of a warm-sector convective system producing the maximal daily precipitation in China mainland during pre-summer rainy season of 2015. *Journal of Meteorological Research*, **30**, 719–736, <https://doi.org/10.1007/s13351-016-6089-8>.
- Wu, Y. L., W. G. Meng, D. H. Chen, W. S. Lin, and L. J. Zhu, 2018a: A study of the impact of initial conditions on the predictability of a warm-sector torrential rain over South China. *Acta Meteorologica Sinica*, **76**, 323–342, <https://doi.org/10.11676/qxxb2018.001>. (in Chinese)
- Wu, Z. F., J. J. Cai, L. X. Lin, S. Hu, H. L. Zhang, and K. H. Wei, 2018b: Analysis of mesoscale systems and predictability of the torrential rain process in Guangzhou on 7 May 2017. *Meteorological Monthly*, **44**, 485–499, <https://doi.org/10.7519/j.issn.1000-0526.2018.04.002>. (in Chinese)
- Xia, R. D., and S. X. Zhao, 2009: Diagnosis and modeling of meso- β -scale systems of heavy rainfall in warm sector ahead of front in South China (middle part of Guangdong Province) in June 2005. *Chinese Journal of Atmospheric Sciences*, **33**, 468–488, <https://doi.org/10.3878/j.issn.1006-9895.2009.03.06>. (in Chinese)
- Xia, R. D., S. X. Zhao, and J. H. Sun, 2006: A study of circumstances of Meso- β -scale systems of strong heavy rainfall in warm sector ahead of fronts in South China. *Chinese Journal of Atmospheric Sciences*, **30**, 988–1008, <https://doi.org/10.3878/j.issn.1006-9895.2006.05.26>. (in Chinese)
- Xu, W. X., E. J. Zipser, Y.-L. Chen, C. T. Liu, Y. C. Liou, W. C. Lee, and B. J.-D. Jou, 2012: An orography-associated extreme rainfall event during TiMREX: Initiation, storm evolution, and maintenance. *Mon. Wea. Rev.*, **140**, 2555–2574, <https://doi.org/10.1175/MWR-D-11-00208.1>.
- Xu, Y., J.-H. Yan, Q. Q. Wang, and J.-B. Dong, 2013: A low-level gravity wave triggering mechanism for rainstorm of warm zone in South China. *Plateau Meteorology*, **32**, 1050–1061, <https://doi.org/10.7522/j.issn.1000-0534.2012.00100>. (in Chinese)
- Xu, Z. X., and P. Y. Wang, 1989: Mesoscale rainbands ahead of cold fronts in North China and their dynamical mechanisms. *Acta Meteorologica Sinica*, **3**, 516–525.
- Xue, J. S., 1999: *Study of Heavy Rainfall in the Summer of South China in 1994*. China Meteorological Press, 185 pp. (in Chinese)
- Xue, M., X. Luo, K. F. Zhu, Z. Q. Sun, and J. F. Fei, 2018: The controlling role of boundary layer inertial oscillations in Mei-yu frontal precipitation and its diurnal cycles over China. *J. Geophys. Res. Atmos.*, **123**, 5090–5115, <https://doi.org/10.1029/2018JD028368>.
- Yu, R. C., T. J. Zhou, A. Y. Xiong, Y. J. Zhu, and J. M. Li, 2007: Diurnal variations of summer precipitation over contiguous China. *Geophys. Res. Lett.*, **34**, L01704, <https://doi.org/10.1029/2006GL028129>.
- Zhang, D., Y. H. Lin, P. Zhao, X. D. Yu, S. Q. Wang, H. W. Kang, and Y. H. Ding, 2013: The Beijing extreme rainfall of 21 July 2012: “Right results” but for wrong reasons. *Geophys. Res. Lett.*, **40**, 1426–1431, <https://doi.org/10.1002/grl.50304>.
- Zhang, Q. H., K.-H. Lau, H. Q. Wang, and S. J. Chen, 2000: Numerical simulation on mesoscale convective system along Mei-Yu front in southern China. *Chinese Science Bulletin*, **45**, 2093–2096, <https://doi.org/10.1007/BF03183534>.
- Zhang, R. H., Y. Q. Ni, L. P. Liu, Y. L. Luo, and Y. H. Wang, 2011: South China heavy rainfall experiments (SCHeREX). *J. Meteor. Soc. Japan*, **89A**, 153–166, <https://doi.org/10.2151/jmsj.2011-A10>.
- Zhang, X. B., Y. L. Luo, Q. L. Wan, W. Y. Ding, and J. X. Sun, 2016: Impact of assimilating wind profiling radar observations on convection-permitting quantitative precipitation fore-

- casts during SCMREX. *Wea. Forecasting*, **31**, 1271–1292, <https://doi.org/10.1175/WAF-D-15-0156.1>.
- Zhang, X. L., Y. Chen, and T. Zhang, 2012: Meso-scale convective weather analysis and severe convective weather forecasting. *Acta Meteorologica Sinica*, **70**, 642–654. (in Chinese)
- Zhao, S. X., N. F. Bei, and J. H. Sun, 2007: Mesoscale analysis of a heavy rainfall event over Hong Kong during a pre-rainy season in South China. *Adv. Atmos. Sci.*, **24**, 555–572, <https://doi.org/10.1007/s00376-007-0555-2>.
- Zheng, T. F., X. Yu, J. Huang, Q. L. Wan, and X. T. Liu, 2018: An observational analysis of a torrential rainstorm in the warm sector of South China coastal areas. *Journal of Tropical Meteorology*, **24**, 481–493, <https://doi.org/10.16555/j.1006-8775.2018.04.007>.
- Zheng, Y. G., and J. Chen, 2013: A climatology of deep convection over South China and the adjacent waters during summer. *Journal of Tropical Meteorology*, **19**, 1–15, <https://doi.org/10.16555/j.1006-8775.2013.01.002>.
- Zheng, Y. G., Y. D. Gong, J. Chen, and F. Y. Tian, 2019: Warm-season diurnal variations of total, stratiform, convective, and extreme hourly precipitation over central and eastern China. *Adv. Atmos. Sci.*, **36**, 143–159, <https://doi.org/10.1007/s00376-018-7307-3>.
- Zhong, L. Z., R. Mu, D. L. Zhang, P. Zhao, Z. Q. Zhang, and N. Wang, 2015: An observational analysis of warm-sector rainfall characteristics associated with the 21 July 2012 Beijing extreme rainfall event. *J. Geophys. Res. Atmos.*, **120**, 3274–3291, <https://doi.org/10.1002/2014JD022686>.
- Zhou, X. J., 2000: *Study of Experiment of Heavy Rainfall Across the Taiwan Strait and its Neighbors*. China Meteorological Press, 370 pp. (in Chinese)
- Zhou, X. J., J. S. Xue, Z. Y. Tao, S. X. Zhao, Q. J. Yi, and B. X. Su, 2003: *Study of Experiment of Heavy Rainfall Experiment in South China in 1998*. China Meteorological Press, 218 pp. (in Chinese)