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Citation: Luo, Y. L., J. S. Sun, Y. Li, et al., 2020: Science and prediction of heavy rainfall over China: Research progress since the reform and opening–up of new China. *J. Meteor. Res.*, **34**(3), 427–459, doi: 10.1007/s13351-020-0006-x

View online: http://jmr.cmsjournal.net/article/doi/10.1007/s13351-020-0006-x

Science and Prediction of Heavy Rainfall over China: Research Progress since the Reform and Opening-Up of New China

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(Received January 13, 2020; in final form May 22, 2020)

ABSTRACT

This paper reviews the major progress on development of the science and prediction of heavy rainfall over China since the beginning of the reform and opening-up of new China (roughly between 1980 and 2019). The progress of research on the physical mechanisms of heavy rainfall over China is summarized from three perspectives: 1) the relevant synoptic weather systems, 2) heavy rainfall in major sub-regions of China, and 3) heavy rainfall induced by typhoons. The development and application of forecasting techniques for heavy rainfall are summarized in terms of numerical weather prediction techniques and objective forecasting methods. Greatly aided by the rapid progress in meteorological observing technology and substantial improvement in electronic computing, studies of heavy rainfall in China have advanced to investigating the evolution of heavy-rain-producing storms and observational analysis of the cloud microphysical features. A deeper and more systematic understanding of the synoptic systems of importance to the production of heavy rainfall has also been developed. Operational forecast of heavy rainfall in China has changed from subjective weather event forecasts to a combination of both subjective and objective quantitative precipitation forecasts, and is now advancing toward probabilistic quantitative precipitation forecasts with the provision of forecast uncertainty information.

Key words: heavy rainfall, reform and opening-up of new China, physical mechanisms, forecasting techniques

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Supported by the National Key Research and Development Program of China (2018YFC1507400) and National Natural Science Foundation of China (41775050).

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1. Introduction

Heavy rainfall frequently occurs over China as a result of the influence of the East Asian summer monsoon (EASM) and the country's complex terrain (Tao et al., 1979; Tao S. Y., 1980). Global climate change (IPCC, 2013) and rapid urbanization over the last 30 years have led to more severe flooding from heavy rainfall events and urban waterlogging, making disaster prevention and mitigation more challenging (Qin et al., 2015). Heavy rainfall events in China are therefore an important area of research in the atmospheric sciences.

Heavy rainfall events in China have distinct regional and seasonal characteristics. The main area of heavy rainfall advances from south to north with the annual northward march of the EASM, influencing, in turn, South China, the Yangtze–Huai River basin (YHRB), North China, and Northeast China. A particular area of heavy rainfall forms in Southwest China, specifically over the Sichuan basin, as a result of the influence of the complex terrain on the eastern margin of the Tibetan Plateau (TP) (Fig. 1). Typhoon-induced heavy rainfall is also one of the main types of heavy rainfall in China due to the vicinity of the Pacific Ocean. Low-level jets (LLJs), subtropical high-pressure systems, fronts, and tropical cyclones all exert profound influences on the production of heavy rainfall over China. Other important weather systems governing rainstorms in China include the cold vortex affecting northeastern China; and the low vortex affecting Southwest China, which forms as a result of the unique topography of the TP.

This paper reviews the important progress and major achievements in the science and prediction of heavy rainfall over China since the reform and opening-up of the country from the 1980s to the present day. It aims to supplement the recent summary of the history and achievements of theoretical studies on heavy rainfall in China from 1930 to 2010 (Ding, 2019). Section 2 summarizes the results of research on the main synoptic weather systems influencing the production of heavy rainfall in China. Section 3 considers research on heavy rainfall events in major sub-regions of China (i.e., South China, the YHRB, North China, Northeast China, and Southwest China) and the heavy rainfall induced by typhoons. Section 4 describes the history and frontiers in numerical weather prediction (NWP) and objective forecasting methods for heavy rainfall in China. Section 5 provides concluding remarks, including the future research directions that need to be strengthened.

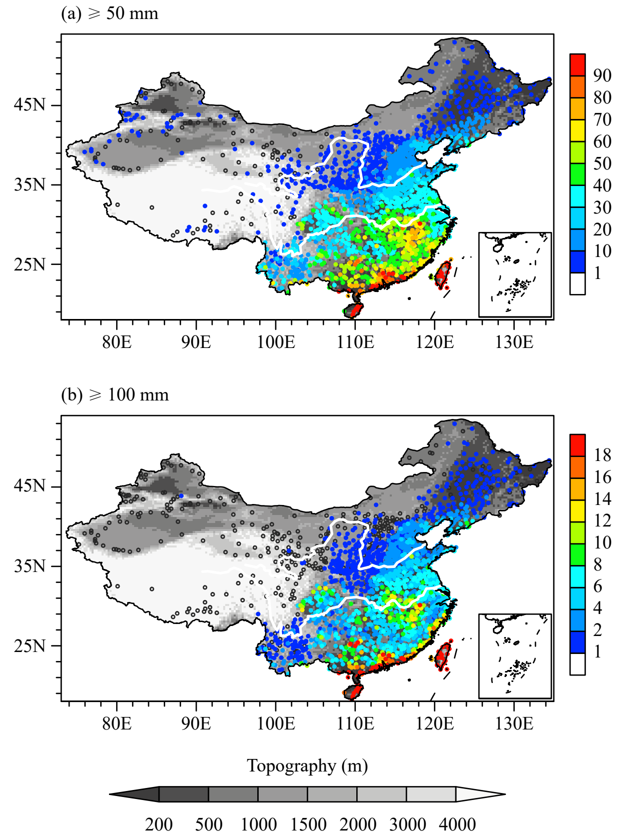


Fig. 1. Occurrence frequency (color dots; day decade^{-1}) of (a) heavy rainfall (⩾ 50 mm day^{-1}) and (b) extreme rainfall (⩾ 100 mm day^{-1}) events over mainland China and Hainan Island during 1980–2018 and over Taiwan Island during 1993–2015. The total numbers of stations over mainland China, Hainan Island, and Taiwan Island are 1897, 10, and 23, respectively. All the stations have yearly valid data ratios of > 80% during all the individual years of the analysis periods.

2. Studies of the physical mechanisms of heavy rainfall over China

2.1 *Understanding of the main synoptic weather systems*

LLJs, fronts, the western Pacific subtropical high (WPSH), and the weather systems induced by the TP all exert profound influences on the formation of rainstorms in China. This section briefly summarizes the studies carried out by Chinese researchers on these four types of weather system and their relationships with heavy rainfall in China. Given the strong regional features of the Northeast China Cold Vortex (NECV) and the Southwest China Low Vortex (SWLV), research progress on these two types of weather system is introduced in Section 2.2—that is, in the subsections describing studies on heavy rainfall over Northeast and Southwest China, respectively.

2.1.1 *LLJs*

LLJs are usually defined as horizontal wind speed maxima in the lower troposphere or boundary layer (Stensrud,1996). Based on their attributes and mechanisms of formation, LLJs are classified into two types: the LLJs related to the synoptic system (SLLJs) and the boundary layer jets (BLJs) (Chen et al., 1994; Du et al., 2012, 2014; Liu et al., 2014). SLLJs have wind speeds that peak in the lower to mid troposphere (about 1–4 km height). They are mainly driven by the development and movement of synoptic or mesoscale systems (Uccellini and Johnson 1979; Uccellini, 1980; Yuan, 1981; Gao and Sun, 1984) and changes in the pressure gradient as a result of the release of latent heat (Huang, 1981; Uccellini et al., 1987; Chen and Yu, 1988; Ding, 2005). By contrast, BLJs have maximum wind speeds in the boundary layer and are typically explained by the inertial oscillation of ageostrophic winds (Blackadar, 1957) or baroclinicity associated with the terrain (Holton, 1967), or a combination of the two (Du and Rotunno, 2014; Du et al., 2015; Shapiro et al., 2016). The formation of BLJs may also be associated with the transport of momentum by waves or thermodynamic processes (He and Wu, 1989), narrow tube-like winds induced by gaps in the terrain (Chen G. C. et al., 2006), and the strengthening of southwesterly monsoonal flows (Zhao et al., 2003).

Many previous studies have considered the physical mechanisms by which SLLJs are closely linked to heavy rainfall in China. SLLJs increase the moist static energy by transporting warm moist air from the tropical oceans, which produces convergence and enhances the vertical wind shear at the terminus of the SLLJ. This leads to the development of instability in gravity waves (Sun and Zhai, 1980) or an increase in the moist potential vorticity (Zhai et al., 1999), which are favorable dynamic and thermodynamic conditions for the production of heavy rainfall (Zhu, 1975; Tao and Chen, 1987; Chen et al., 1998). The release of the latent heat generated in heavy rainfall events can lower the surface pressure and increase upper-level divergence, resulting in stronger vertical secondary circulations and acceleration of the SLLJs, which also favors the production of heavy rainfall. This positive feedback could play a key part in the development of heavy rainfall events (Chou et al., 1990; Qian et al., 2004; Zhao, 2012).

Recent studies have shown that BLJs are closely related to heavy rainfall over the YHRB during the night and in the early morning (Luo and Chen, 2015). The coupling of BLJs and SLLJs favors the initiation of coastal convection in warm-sector heavy rainfall events over South China through boundary layer convergence and lower- to mid-level divergence (Du and Chen, 2019a; Li et al., 2020; Shen Y. A. et al., 2020) (Fig. 2).

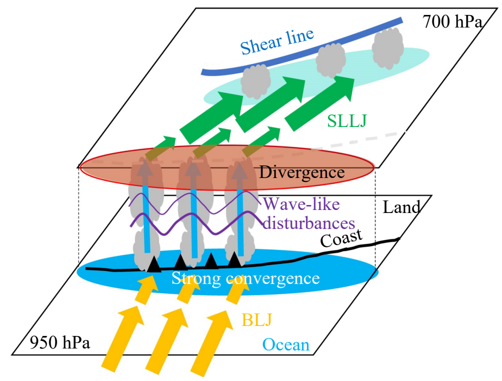


Fig. 2. Schematic diagram showing the relationship between the production of warm-sector heavy rainfall near the coast of South China and low-level jets (LLJs). At 950 hPa, convergence occurs near the coast at the exit point of the marine boundary layer jet (BLJ). At 700 hPa, a synoptic-scale low-level jet (SLLJ) moves southward along with the front, causing divergence near the coast at the entrance point of the SLLJ. The coupling configuration between boundary layer convergence and mid–lower tropospheric divergence near the coast collectively produces mesoscale lifting, which favors the initiation of convection. Adapted from Du and Chen (2019a).

These two types of LLJ distinctly influence the distribution and type of rainfall in South China (Du and Chen, 2018, 2019b). Numerous studies have also documented that BLJs are an important factor controlling the diurnal variations of rainfall over many regions of China (Chen X. C. et al., 2017; Pan and Chen, 2019; Zeng et al., 2019; Zhang and Meng, 2019).

2.1.2 *Fronts*

Synoptic fronts, hereafter referred to simply as fronts, are usually defined as the interface or transition zone between two air masses with distinct properties. Fronts are formed over mainland China (to the east of the TP) during the warm season as a transition zone between the warm moist air transported by the EASM and the relatively dry and cold air mass to the north. The uplift of warm humid air on the front is an important dynamic mechanism for the production of heavy rainfall in China. The structure of the warm season fronts varies greatly with latitude. Fronts associated with rainstorms in North China generally show an extratropical frontal structure with a strong horizontal temperature or potential temperature gradient and a large contrast in humidity across the frontal area.

The well-known Meiyu front (Hsieh, 1956) is characterized by a subtropical frontal structure. The western portion of the Meiyu front is an intersection between a tropical air mass and a denatured polar air mass over the YHRB and features clear horizontal shear of the southwesterly and southeasterly winds and a large humidity gradient, but only a small temperature gradient (Ninomiya, 1984; Cui et al., 2005; Zheng et al., 2007; Yang S. et al., 2014; Yang et al., 2015). The frontal system often presents a quasi-stationary state during the pre-summer rainy season of southern China because the cold air mass weakens in intensity when it reaches southern China (Lin et al., 2009; Xu et al., 2009). The temperature gradient across such a front tends to be smaller than that associated with the subtropical front over central eastern China (Chen et al., 2007; Luo et al., 2013).

2.1.3 *WPSH*

The WPSH is one of the most important components of the EASM circulation system. Classical theory holds that the north–south gradient of net solar radiation and the magnitude of the earth's rotational velocity collectively determine the mean meridional circulation of the atmosphere. In the Hadley circulation, warmer and lighter moist air rises in the equatorial region and cooler and heavier air sinks in the subtropical region, thus forming the subtropical high belt (Peixot and Oort, 1992). The warm Rossby wave generated by the release of latent heat by the EASM acts on the westerly airflow, causing a sinking motion and maintaining the WPSH (Hoskins, 1996). Chinese researchers have considered the effect of spatially non-uniform heating on the formation and variation of the subtropical high based on the complete-form vertical vorticity tendency equation (Liu et al., 1999a, b; Wu et al., 1999, 2002). Under the complex effects of the atmospheric circulation, sea surface temperature, sea ice cover, and other factors (Tao and Zhu, 1964; Li and Luo, 1988; Ren et al., 2013; Chen and Zhai, 2015; Qian and Shi, 2017), the WPSH presents a seasonal north–south advance and retreat (Ye and Zhu, 1958; Ye et al., 1958; Ye et al., 2014), quasi-biweekly oscillations, low-frequency oscillations with a 30–50-day period, and interannual variations (Lu, 2001; Lu and Dong, 2001; Zhou et al., 2009; Li T. et al., 2017). These activities and variations significantly affect the amount of warm season precipitation and the location of the main rainbelt in China (Tao et al., 1963; Huang, 1978; Wu et al., 2002; Ding and Chan, 2005; Zhou et al., 2009; Yang J. et al., 2014; Wu and Wang, 2015; Lin et al., 2016; Guan et al., 2019).

2.1.4 *Synoptic systems induced by the TP*

The dynamic and thermal effects of the TP can change the atmospheric circulation and weather systems over the surrounding areas and influence heavy rainfall over China (Ye et al., 1977; Tao and Ding, 1981; Wu, 1984). If the intensity of diabatic heating over the TP is sufficiently strong, a zonally distributed low zone of low potential vorticity is formed in the upper troposphere above the heating source of the TP; the high potential vorticity center to the east of the low potential vorticity zone (i.e., an anticyclone) first moves southward into the easterly winds and then moves westward. As a result, a strong meridional gradient is formed in the potential vorticity of the upper troposphere (Liu Y. M. et al., 2007), which leads to instability in the anticyclone in the upper troposphere over the TP. This is the physical reason why the meridional position of the South Asian high has a quasi-biweekly oscillation, which affects the environmental conditions under which rainstorms develop over the YHRB (Wu et al., 2008; Fig. 3).

A positive anomaly in the surface sensible heat over the TP tends to strengthen the cyclonic circulation in the mid troposphere through the adjustment of thermal winds. Thus, a large-scale dynamic background in which advection of the potential vorticity increases with height forms, which favors the development of ascending motion. The southwesterly LLJ on the southeast side of the cyclone is strengthened, enhancing the transport of water vapor and increasing precipitation in Southeast China (Li et al., 2014; Shi and Wen, 2015; Wan et al., 2017; Ma et al., 2020). During the eastward movement of a vortex originating over the TP, the associated vertical gradient of diabatic heating produces a positive potential vorticity anomaly in the lower layer and strengthens the lower-level cyclonic vorticity, leading to an increase in the vertical extension of the vortex. The horizontal gradient of diabatic heating produces a positive (negative) potential vorticity on the right- (left-) hand side of the vertical shear of the horizontal wind. The generation of positive potential vorticity on the right-hand side of the vertical shear of the horizontal wind not only intensifies the local vertical vorticity, but also affects the direction of movement of the vortex and, as a consequence, the heavy rain-

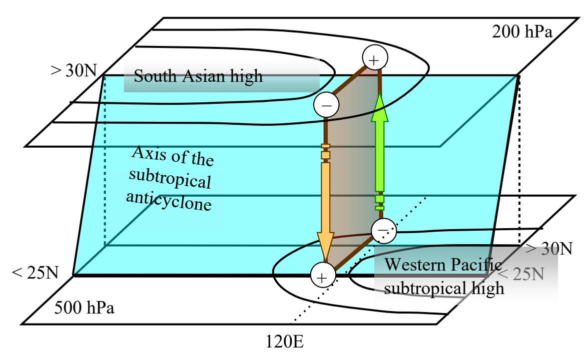


Fig. 3. Schematic diagram showing a synoptic situation of the upper-level South Asian high coupled with the lower-level western Pacific subtropical high (WPSH) associated with persistent heavy rainfall over the Yangtze and Huai River basins in summer. Adapted from Wu et al. (2008).

fall events in eastern China. Therefore, a new concept of the development of a generalized slantwise vorticity has been introduced (Wu et al., 2013; Zheng et al., 2013).

2.2 *Heavy rainfall in the major sub-regions of China*

2.2.1 *Heavy rainfall over South China*

South China mainly refers to the area south of about 26°N and east of the TP. The rainy season in South China is from April to early October (Ramage, 1952). Long-term statistics show that the hourly and daily intensity of rainfall and the number of days recording rainfall > 50 and 100 mm day^{-1} in this region are almost the highest in the whole of China (Zheng et al., 2016; Fig. 1). Extreme hourly rainfall in South China can reach 100 or even 200 mm, and the accumulated rainfall can reach 400–500 mm in 10 h (e.g., Wang et al., 2014; Wu and Luo, 2016), easily leading to flood disasters. The main rainy season in South China can be divided into two stages—namely, the earlier and later rainy seasons, with mid to late June as the dividing point (Yuan F. et al., 2010). This is consistent with the sub-seasonal march of the EASM circulation and rainfall (Tao and Chen, 1987; Ding, 1994; Ding and Chan, 2005).

Since the reform and opening-up of China from the 1980s, there have been four large research projects with field observation experiments during the earlier rainy season (April–June) in South China: the first scientific project from 1977 to 1981 (Huang, 1986); the Heavy Rainfall Experiment on both sides of the Taiwan Strait and adjacent areas in 1998 (HUAMEX; Zhou et al., 2003); the South China Heavy Rain Experiment in 2008–2009 (SCHeREX; Zhang et al., 2011; Ni et al., 2013); and the South China Monsoon Rainfall Experiment in 2013–2021 (SCMREX; Luo et al., 2017). These field observation campaigns have gradually promoted research on the multi-scale mechanisms of heavy rainfall events during the earlier rainy season in southern China, the development of radar and satellite observing technologies and data applications, and the development of NWP technology (Luo, 2017).

Research in the past 10 years has advanced to investigating the initiation of convection and mechanisms of evolution of heavy rainfall (Luo et al., 2020). In particular, the multi-scale processes of the triggering and evolution of "warm-sector heavy rainfall in South China" proposed in the 1980s (Huang, 1986) have been explored based on high spatiotemporal resolution observations. The cloud microphysical features of heavy rainfall have been studied through observational analyses. Researchers have found that the characteristics of diurnal variation of rainfall are significantly different between the western and eastern parts of South China and among the coastal and inland regions and the northern mountains of eastern South China. The underlying physical processes of the diurnal variation of rainfall have been shown to be related to the collective effects of the southwest monsoonal airflow, fronts, the thermal contrast between the sea and land, and the topography (Chen X. C. et al., 2014, 2016, 2017; Jiang et al., 2017; Chen G. et al., 2018; Du and Rotunno, 2018).

In the 1980s and 1990s, Chinese researchers showed that the frequency and intensity of heavy rainfall events during the earlier rainy season of South China are closely related to the time of onset and the intensity of the South China Sea (SCS) monsoon (Ding, 1994). The worst flood over South China in the 20th century occurred in mid June 1994 and caused huge economic losses and a considerable death toll (Zhao and Wang, 2009). This event was mainly due to the unusually strong SCS summer monsoon (Wu et al., 2003) and the distribution of the monsoon trough or subtropical high. The configuration of these synoptic-scale systems favored the transport of warm humid air from the SCS toward South China by the strong low-level monsoonal airflow (Xue, 1999). Topographic effects promoted the development of mesoscale convective clouds (Sun and Zhao, 2000). Chen and Luo (2018) showed that the water vapor transport channel to South China changes significantly after the onset of the SCS summer monsoon in mid to late May. The transport of water vapor from the Bay of Bengal and Indian Ocean increases significantly, whereas that transported from the Pacific Ocean decreases. At the same time, the convective available potential energy and water vapor in South China both increase significantly. Regional extreme rainfall events in South China mainly occur after the onset of the SCS monsoon (Huang et al., 2018). The daily-averaged occurrence frequency of extreme hourly rainfall (⩾ 60 mm h^{-1}) observed by the dense network of automatic weather stations increases by about 40% after the onset of the monsoon. Before and after the onset of the monsoon, the weak gradient (i.e., warm-sector) and surface front types of extreme hourly rainfall dominate. In addition, the occurrence frequencies of surface front, low-level vortex, and shear-line types of extreme hourly rainfall are higher in western than in eastern South China, but the weak gradient type shows the opposite pattern (Li, 2019; Luo et al., 2020; Fig. 4).

Recent studies have brought new insights into the physical mechanisms of heavy rainfall in South China on a range of scales from interannual and synoptic to daily and sub-daily. The interannual variability of heavy rainfall during the earlier rainy season in South China is sig-

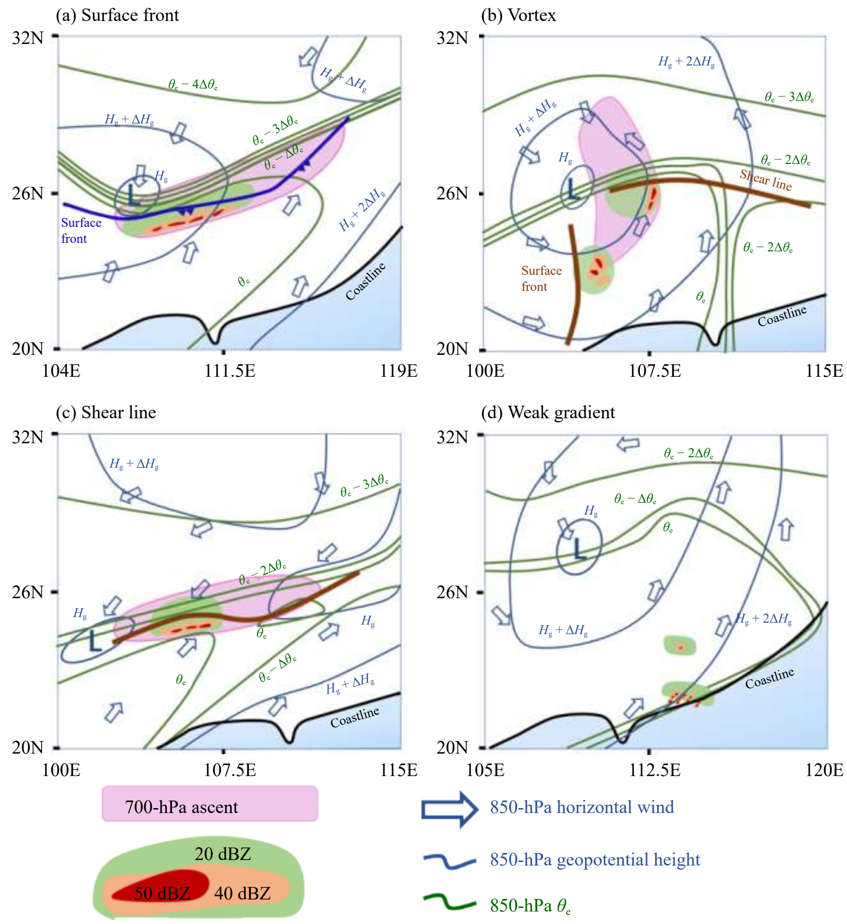


Fig. 4. Schematic diagrams of the environmental conditions in the mid and lower troposphere during the four types of extreme hourly rainfall events (60 mm h^{-1}) over South China during the pre-summer rainy season: (a) surface front type; (b) low-level vortex type; (c) low-level shear line type; and (d) weak gradient (i.e., warm-sector) type. The light-blue and green contours represent the geopotential height (H_g) and equivalent potential temperature (θ_e) at 850 hPa, respectively. The letter L denotes the synoptic-scale low-pressure center. The light-blue arrows denote the 850-hPa horizontal winds. The thick bright-blue line with double triangles in (a) represents the surface front. The thick brown lines in (b) and (c) denote shear lines at 850 hPa. The purple shading indicates areas where the 700-hPa ascent is maximized. The green, orange, and red shadings represent radar reflectivities of roughly 20, 40, and 50 dBZ, respectively. The light-blue shading south of the coastline (denoted by thick black line) indicates the South China Sea. From Luo et al. (2020).

nificantly affected by the sea surface temperatures of the tropical Pacific and Indian oceans. The stimulated Matsuno–Gill-type Rossby wave and the warm atmospheric Kelvin wave lead to anomalous southwesterly winds in the lower troposphere over the northern SCS (Gu et al., 2018; Yuan et al., 2019). The synoptic-scale disturbances (3–8 days) of cyclonic and front–trough circulation are closely related to regional extreme rainfall events during the earlier rainy season in South China (Huang, et al., 2018). The formation and enhancement of these synoptic-scale disturbances could be contributed by the surface sensible heating of the TP (Li et al., 2014; Wan et al., 2017) and are also related to the blocking and deflecting effects of the TP on westerly winds (Wu and Chen, 1985; Kuo et al., 1986; Chang et al., 1998). Dual rainbelts often co-occur over northern and southern South China on daily and sub-daily timescales. The rainbelt located on the north side of South China is closely related to large-scale dynamic uplift by the subtropical weather systems (the low vortex and associated front or shear line). The western extension and eastern retreat of the western North Pacific subtropical high, the quasi-stationary and eastward movement of the subtropical weather systems, and the enhancement of the southwest monsoon airflow play important roles in transporting warm moist air toward western and eastern South China, and roughly determine the location of heavy rainfall over inland South China (Li et al., 2020). The rainbelt located on the south side of South China, with a smaller horizontal scale but higher intensity, often occurs in a warm sector over inland or coastal regions. The warm-sector heavy rainfall in the northern mountains of South China are mainly caused by terrain uplift and near-ground air instability in the afternoon induced by heating via solar radiation (Jiang et al., 2017), whereas the Pearl River Delta urban agglomeration has become a center of high-frequency extreme short-term rainfall events because of the combined effect of urban heat islands, sea breezes, and the terrain (Wu et al., 2019; Yin et al., 2020).

A recent study proposed a new concept of the coupling effect of double LLJs on the initiation of convection in warm-sector heavy rainfall events in the coastal areas of South China during the earlier rainy season. The deceleration of the southerly jet in the northern boundary layer above the SCS causes convergence and uplift of the atmosphere near the coast, while the jet in the lower to mid troposphere causes divergence near the coast; and the vertical coupling effect of the double LLJs is an important factor in the initiation of convection in warm coastal areas (Du and Chen, 2018, 2019a; Fig. 2). Statistical analysis supports the importance of the southerly winds in the northern boundary layer over the SCS. The boundary layer airflow in the northern SCS does not always reach the intensity of a jet stream, but it can cause heavy precipitation or even extreme local heavy rainfall via deceleration near the coastline and convergence-induced weak uplift (Wang et al., 2014; Li et al., 2020). This is because the warm humid air near the ground has such a low convection inhibition energy that convection can be initiated by the combined effect of land–sea frictional differences, the coastal terrain, and cold pools left by previous convection (Wang et al., 2014; Wu and Luo, 2016). The mesoscale convective system (MCS) that produces extreme rainfall events over the coast is maintained when the near-surface cold pool produced by convection in the humid atmosphere is weak, leading to the formation of a stable and quasi-stationary mesoscale outflow boundary on its leading edge. The unstable warm humid air at the mesoscale outflow boundary is continuously uplifted, triggering convection to form an organized mode of multiple convective belts almost in parallel with each other (Wang et al., 2014; Fig. 5). The rapid splitting and rebuilding process of a leading bow-shaped convective belt inside the MCS contributes to the formation of this organized structure of multiple convective belts (Liu X. et al., 2018).

There has been less research on heavy rainfall in the later rainy season in South China (July–September) than on heavy rainfall events in the earlier rainy season. The influencing systems in the later rainy season are mainly monsoonal troughs and lows (Huang et al., 2005; Jiang et al., 2007; Meng et al., 2014), in addition to tropical cyclones (Meng and Wang, 2016a, b). One of the key factors

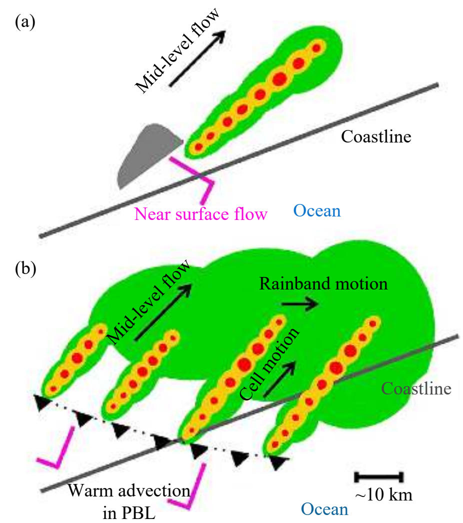


Fig. 5. Schematic diagrams of the back-building, echo-training, and rainband training associated with an extreme-rain-producing mesoscale convective system during (a) early development and (b) mature stages. Shading in red, orange, and green represents radar reflectivity values of 50, 35, and 20 dBZ at 3 km above mean sea level, respectively. The gray symbol near the southwestern edge of the linear-shaped mesoscale convective system in (a) represents a mountain. The thick gray line represents the coastline. From Wang et al. (2014).

in the occurrence of persistent rainfall is the intraseasonal oscillation of the SCS summer monsoon (Hong and Ren, 2013; Chen G. J. et al., 2014; Li and Zhou, 2015; Li C. H. et al., 2017).

Recent studies have revealed some features of the microphysical processes of heavy rainfall in South China using the latest remote sensing observations, such as satellite-borne precipitation radar and ground-based dual-polarization radar. For example, the record-breaking extreme rainfall event in Guangzhou on 7 July 2017 (Huang et al., 2019) was mainly caused by active warm rain processes (Luo et al., 2020). The statistical analysis of strong MCSs using Tropical Rainfall Measuring Mission (TRMM) satellite observations (Luo et al., 2013) and a case study of strong squall lines using ground-based radar observations (Wu et al., 2018) both found graupel and hail generated by the relatively active riming processes in the strongest convective core. The distribution of the size of raindrops changed from analogous to oceanic convection, then to between continental and oceanic convection, during the evolution of a squall line passing over eastern South China (Wang et al., 2019).

2.2.2 *Heavy rainfall over the YHRB*

Along with the northward march of the WPSH in mid to late June to early July, the southwesterly monsoonal flow and northwesterly cold airflow converge over the YHRB, leading to the formation of the Meiyu front. As a consequence, the main rainy area is located over the mid and lower reaches of the Yangtze River. This rainy season is named the Meiyu season (Ding, 1993; Tao et al., 2001; Zhao et al., 2004). From the 1990s to the beginning of the 21st century, Chinese researchers systematically studied the disastrous persistent heavy rainfall over the Yangtze River basin in 1991 and 1998 (Ding, 1993; Lu et al., 1994; Lu and Ding, 1997; Tao et al., 2001; Zhao et al., 2004).

Ding (1993) comprehensively documented the rainfall and water conditions of the 1991 flood, the physical causes of the rainstorms, the forecast service and evaluation, as well as the causes of the disaster and the prevention countermeasures. Tao et al. (2001) summarized the disaster and precipitation of the 1998 flood, the characteristics of the large-scale atmospheric circulation, the mechanism of the abnormal change in the WPSH, the activities of synoptic-scale systems, and the evolution of meso-β-scale convective systems during the Meiyu season. In 1998 and 1999, China and Japan successfully carried out the HUBEX study in the Huai River basin (Fujiyoshi et al., 2006). The three-dimensional mesoscale structure of clouds and precipitation in the Meiyu front system were observed by digital weather radar and Doppler radar for the first time. HUBEX was also the first time a joint experiment of hydrology and meteorology had been carried out in the East Asian semi-humid monsoon region, which laid a solid foundation for further observational experiments of heavy rainfall in China. During the first two decades of the 21st century, studies on heavy rainfall and severe convective weather were developed further by a few National Key Research and Development Projects (Ni and Zhou, 2006; Tan and Zhao, 2013; Xue, 2016), resulting in deeper insights into the mechanisms of multi-scale interactions leading to the production of heavy rainfall over the YHRB.

Chinese researchers first noted the importance of the upper-level jet to Meiyu front heavy rainfall in the 1980s. The development of Meiyu front heavy rainfall is supported by divergence on the right-hand side of the entrance area of the upper-level jet to the north of the Meiyu front at about 40°N, which favors the formation of a southwesterly LLJ (Si, 1989). Subsequent studies have revealed physical processes involving multiple weather systems that lead to extensive and persistent heavy rainfall in the YHRB (e.g., Sampe and Xie, 2010; Fig. 6). The mid-tropospheric westerly jet transports warm air to central eastern China and Japan along the eastern edge of the TP, which induces adiabatic ascending motion along the jet stream. The southerly LLJ located between the North Pacific subtropical high and the continental warm low-pressure system transports water vapor toward the ascending regions to maintain convective instability there. The westerly jet also stimulates midlatitude synoptic disturbances, which move eastward and enhance upward motion and instability.

In recent years, temporal-separation energy budget equations have been used to investigate persistent heavy

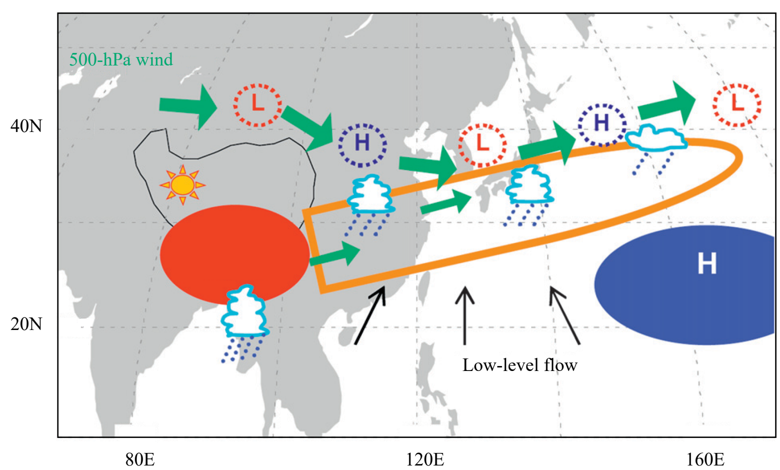


Fig. 6. Schematic diagram showing the factors that bring Meiyu/Baiu rainfall to East Asia in early summer. Mid-tropospheric winds (thin green arrows) advect warm air from the warm region over the south flank of the TP (red oval; the thin black curve is the 3000-m contour of topography) associated with the heated surface of the plateau and monsoon convection to the south. Warm advection over central China and Japan (orange) induces ascending motion along the jet stream. This ascent favors convection (the clouds in orange area) in the presence of convective instability sustained by the low-level southerly transport of moisture (black arrows) between a heat low over the continent and an oceanic high over the North Pacific (blue oval with letter H). The northern jet stream (thick green arrows) steers transient weather disturbances from midlatitudes (blue and red dotted circles with H and L) eastward, increasing the probability of intense ascent and instability. The location of the atmospheric components in this diagram varies. From Sampe and Xie (2010).

rainfall events over the YHRB from the viewpoint of energy transport, conversion, and cascades (Fu et al., 2016a, 2018). Sub-synoptic eddy flows (which directly induce heavy rainfall) sustain their kinetic energy in the lower and upper troposphere through the downscale energy cascade of kinetic energy. By contrast, an upscale energy cascade is dominant in the mid troposphere, suggesting strong feedback from the eddy flows. The large-scale background circulations of sub-synoptic eddy flows maintain their kinetic energy through baroclinic energy conversion and horizontal transport. The mesoscale vortices relevant to persistent heavy rainfall develop or are maintained when the vortices gain energy from the background circulation, which allows the associated heavy rainfall to continue. By contrast, when the energy supply from the background circulation is cut off, the vortices dissipate rapidly and the associated heavy rainfall ends (Fu et al., 2015, 2016b; Zhang et al., 2017).

Since the start of the 21st century, meteorological scientists have strengthened their studies on the relationship between vortices and heavy rainfall in the YHRB. When the upstream vortex moves eastward along the Meiyu front under the guidance of a low trough at high altitudes, the southwesterly flows in the southeastern quadrant of the vortex are intensified, the kinetic energy and water vapor transported into the Meiyu front are increased, and the vertical wind shear along the Meiyu front is also increased. All these mechanisms favor the development of convection and the production of heavy rainfall along the Meiyu front (Zhao and Fu, 2007; Fu et al., 2011a, b). The vortices, especially long-lived vortices, along the lower reaches of Yangtze River (including Dabie mountain) (Fu et al., 2013, 2016c) and the mesoscale convective vortices (MCVs) also make a major contribution to heavy rainfall in the YHRB (Shi et al., 1996; Gao and Xu, 2001; Sun et al., 2004; Zhang et al., 2004; Zhang Y. C. et al., 2013).

Great progress has been made in the study of the diurnal variation of precipitation in the past 10–20 years, especially heavy rainfall during the night and early morning over the YHRB. The diurnal variation of Meiyu precipitation over the YHRB region has a double peak structure, with peaks from the night to early morning and in the afternoon (Yu et al., 2007; Zhou et al., 2008; Chen H. M. et al., 2010; Yuan W. H. et al., 2010; Luo et al., 2013). The mountain–plain solenoids (MPSs) over the stepped topography contribute to the generation of nocturnal heavy rainfall in the YHRB. The upward motion of the nocturnal MPS between the eastern edge of the TP and the Sichuan basin intensifies the SWLV. The northeastward-extending disturbance of the SWLV, combined with the updraft of the MPS over the eastern part of the second-step terrain, triggers a local vortex and convection on the leeside of the second-step terrain (Zhang et al., 2014a, b). As the coupled vortex and convection move eastward along the Meiyu front, they experience stages of decoupling, recoupling, and occlusion (Zhang et al., 2018; Fig. 7). The convection and lower-level vor-

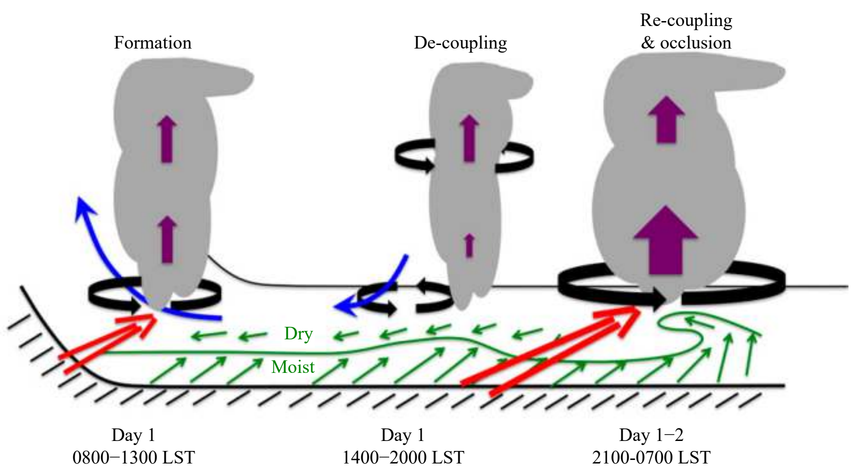


Fig. 7. Schematic diagram of the eastward progression and diurnal evolution of convection and MCVs east of the second-step terrain, i.e., over the Yangtze–Huai River basin (YHRB) of China. Left-hand panel: the formation stage in the early morning of day 1 (stage 1). Middle panel: the afternoon decoupling stage as deep convection is displaced from the center of the vortex and the vortex tilts eastward with height (stage 2). Right-hand panel: convection reintensifies near the center of the vortex during the following evening, the low-level jet intensifies and the vortex strengthens, ultimately reaching an occluded configuration (stages 3 and 4). Features include the low-level jet (red arrows), the mountain–plain solenoid (blue arrows), mesoscale updraft (purple arrows), vortex horizontal circulation (black arrows), the earth's surface (black line), the region of convection (gray shading), the boundary of the Meiyu front (green line), and the surface winds (green arrows). LST: Local Standard Time. Adapted from Zhang et al. (2018).

tex weaken and decouple as a result of the subsiding branch of the daytime MPS over the MCV center in the lower troposphere. The updraft branch of the nocturnal MPS circulation and the enhanced nocturnal LLJ favor new convection on the southeastern side of the MCV. Diabatic heating from the condensation of water vapor at low levels produces a strong potential vorticity maximum in the lower troposphere, which induces recoupling and occlusion of the vortex and convection. The new MCV evolves into a sub-synoptic cyclone with signs of occlusion, causing heavy rainfall in the YHRB (Sun and Zhang, 2012; Zhang et al., 2018).

In addition to the MPS, the surface mesoscale cold pool generated by previous convection in front of the Meiyu front in the afternoon to early evening and the enhanced boundary layer airflow at night can collectively trigger nocturnal convection (Luo and Chen, 2015). The main reason for the enhancement of the nocturnal BLJ is the inertial oscillation of the ageostrophic wind in the boundary layer (Xue et al., 2018). The nocturnal initiation of convection may also be related to a mesoscale line of convergence above the stable boundary layer. The formation of the line of convergence may be the result of the increased horizontal pressure gradient and the enhanced southerly winds, which is caused by the eastward-moving mesoscale vortex and the simultaneous enhancement of the WPSH (He et al., 2018). Recent observational analyses suggest that the strong effects of the urban agglomeration in the Yangtze River Delta is related to the increase in the occurrence frequency of short-term heavy rainfall events over the region, under the influence of both typhoon and non-typhoon systems (Jiang et al., 2020).

Using the high spatiotemporal resolution (at the minute and kilometer scale) data collected by an operational radar network that was developed in the YHRB around 2008, it was found that the type of MCS that produces extreme rainfall ahead of the Meiyu front has a structure of "echo training of convective cells–band training of the rainbands" (Luo et al., 2014). The echo-training results in a west–east or southwest–northeast convective band from the back-building of convection, while band-training means that several such convective bands are arranged in a quasi-parallel pattern and move southeastward as a whole. The superposition of the convective train effects on two different scales and directions of movement leads to extreme rainfall. A modeling study further showed the coupling of cloud microphysical and dynamic processes within the MCS, which affects the intensity and fine-scale distribution of precipitation (Luo et al., 2010). Subsequent studies on extreme precipitation in the warm sector of coastal South China also found similar structural features of MCSs (Wang et al., 2014; Wu and Luo, 2016; Liu X. et al., 2018).

In recent years, with the gradual application of raindrop disdrometers and dual-polarization radar, observational analyses have been conducted of the microphysical features of precipitation in the YHRB. The results show that the size distribution of raindrops in summer convective precipitation in the YHRB is by average close to that of oceanic convection (Wen et al., 2016). However, during the evolution of a squall line over the YHRB, the size distribution of raindrops changed from close to oceanic convection to continental convection, and the warm cloud processes played a dominant part in producing surface rainfall (Wen et al., 2017).

2.2.3 *Heavy rainfall over North China*

The rainy season in North China begins after the presummer (April–June) rainy season of South China and the following Meiyu season of the YHRB. In the 1960s and 1970s, Chinese researchers noted that the evolutionary features and physical processes associated with rainstorms in North China differed from those in the southern regions. The regional characteristics of heavy rainfall over North China have been revealed more clearly and quantitatively in the last decade by using high spatiotemporal resolution data from surface automatic weather stations and radar observing systems.

The occurrence frequency of heavy rainfall in North China is lower than that in South China and the YHRB (Fig. 1), but the production of rainfall is often accompanied by strong convection, with a high intensity of short duration precipitation (Zhang and Zhai, 2011; Chen J. et al., 2013; Luo et al., 2016). The effects of the south–north oriented Taihang Mountains on the southeasterly and easterly LLJs and the west–east oriented Yan Mountains on the southwesterly LLJs favor heavy rainfall on the North China Plain near the mountains (Sun, 2005; Xia and Zhang, 2019; Fig. 8). The local atmospheric circulation around the Beijing–Tianjin area becomes more complex as a result of the sea–land circulation, mountain–valley winds, and the atmospheric circulation induced by the urban areas, which tend to produce local centers of small-scale heavy and intense rainfall (Sun J. S. et al., 2006; Jiang and Liu, 2007; Sun and Yang, 2008; Yin et al., 2011; Li Z. et al., 2015).

Numerous studies since the 1970s have suggested that the interaction between the synoptic systems in mid and lower latitudes is an important feature of heavy rainfall events in North China. Specifically, the southward devel-

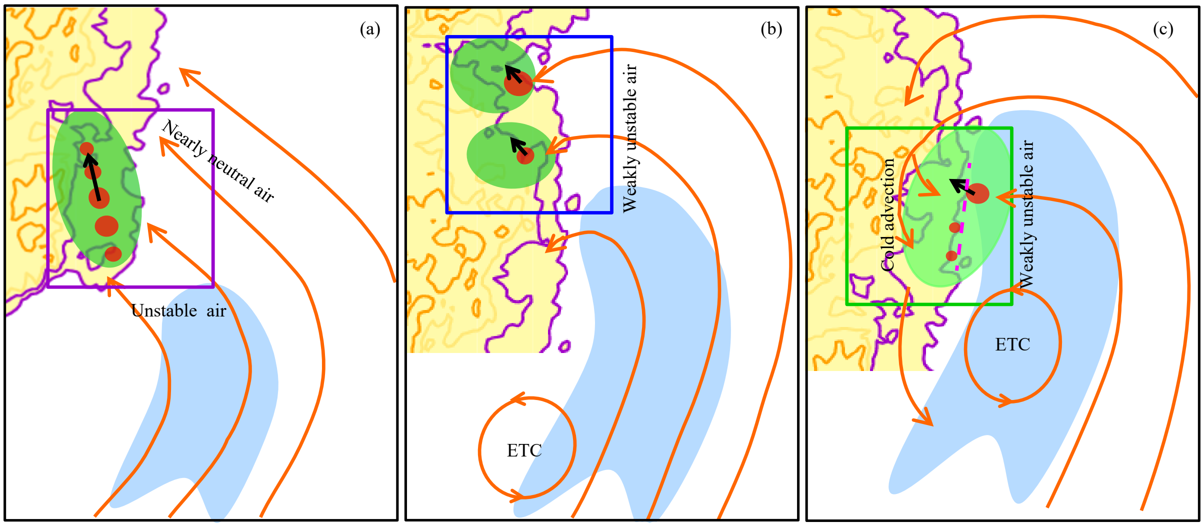


Fig. 8. Schematic diagrams showing the factors responsible for an extreme rainfall event over the (a) southern (denoted by the purple box), (b) northern (blue box), and (c) middle (green box) portions of the eastern foothills of Mt. Taihang associated with an extratropical cyclone (ETC). The orange lines with arrows indicate the low-level flows with an indication of the warm and moist tongues. The green and red shadings represent the 30- and 45-dBZ radar reflectivity at 3-km altitude, respectively. The black arrows indicate the direction of movement of extreme rain-producing convective cores. The purple curves represent terrain elevations of 200 and 600 m, and the light and dark yellow curves represent terrain elevations of 1000 and 1400 m, respectively. The magenta dashed line in (c) denotes a convergence line of low-level flows. Adapted from Xia and Zhang (2019).

opment of the TP trough strengthens the southwesterly LLJ in front of the trough and forms a large-scale transportation belt for warm wet air, which transports water vapor and heat from the Bay of Bengal to North China (Liu et al., 1979; Sun and Zhao, 1980; Tao Z. Y., 1980). The southwesterly LLJ on the western side of the WPSH is a major carrier of water vapor from the SCS to North China. The WPSH affects the movement of the westerly trough and the low vortex, and therefore the duration of heavy rainfall events over North China (Liu H. Z. et al., 2007; Yang et al., 2016). The direct interaction between typhoons that make landfall and westerly synoptic systems is more likely to cause extremely heavy rainfall over North China (Sun et al., 2005; Xu et al., 2014), such as the disastrous "75.8" and "96.8" extreme rainfall events (Faculty of Meteorology, Department of Geophysics, Peking University, 1977; Jiang et al., 1981; Jiang and Xiang, 1998; Sun J. H. et al., 2006).

The important part played by mesoscale weather systems in heavy rainfall events over North China was noticed in as early as the 1960s (You, 1965; Cai and Zhou, 1982). Mesoscale weather systems have become an active area of research in studies of heavy rainfall over North China in recent decades and have been shown to be related to the rapid urbanization in the Beijing–Tianjin–Hebei area since the early 1990s. The extension of Beijing city toward the western hills and that of Tianjin city toward the east coast result in more complex interactions among the terrain circulation, the urban heat island (UHI) circulation, and the land–sea circulation under a variety of synoptic situations, which could favor the formation of the mesoscale vortex, shear line, and convergence line (Sun J. S. et al., 2006; Zhong et al., 2015; Li et al., 2017a, b).

Vertical mixing is more effective when Beijing city is controlled by a strong UHI effect and the boundary layer deepens over the urban area (Miao et al., 2011). With weak ambient winds, the horizontal gradient of the potential temperature strengthens the vertical wind shear and induces horizontal wind convergence in a relatively deep boundary layer over the urban area (Sun J. S. et al., 2006). Such dynamic processes favor the triggering or intensifying of convective systems, and therefore the maximum precipitation is produced over the most urbanized area (Dou et al., 2015).

Some of the physical mechanisms of the meso-β-scale systems producing heavy rainfall under the collective influence of the UHI effect, the terrain slope, and convectively generated cool pool have been revealed by using the disturbed momentum equations with the mesoscale Boussinesq approximation (Sun and Yang, 2008). Under a background of low-level easterly winds, horizontal wind convergence tends to be generated in front of the western hills. The strong UHI effect can intensify the vertical wind shear of the low-level winds in front of the mountains and enhance the easterly BLJ. Once heavy rainfall has been produced along the windward slope, the cold outflow at the earth's surface enhances convergence and uplift in front of the mountains. The horizontal temperature gradient is further strengthened as a result of the cold pool and the UHI effect; as a consequence, the easterly BLJ is further intensified. Such positive feedbacks may play an important part in the formation of meso-β-scale systems producing heavy rain in front of the western hills. In addition, the UHI effect of the Beijing–Tianjin urban agglomeration increases the temperature contrast between the land and sea, which may enhance the sea breeze front (Zhang Y.-Z. et al., 2013). When the sea breeze front approaches a head-on thunderstorm in the afternoon, the storm may be strengthened and produce intense local rainfall (Dong et al., 2011, 2013; He et al., 2011).

In addition to the mesoscale weather systems driven by the complex surface, mesoscale systems derived from the interactions among the synoptic systems or feedback from heavy rainfall could also have an important role in producing heavy rainfall over North China. For example, if geopotential instability and dynamic shear instability both exist in front of an upper-level trough during its baroclinic development stage, a mesoscale low may appear ahead of the surface cold front and produce heavy rainfall (Tian and Zeng, 1982; Yang and Gao, 2006; Yang et al., 2007). When an abnormal positive potential vorticity overlaps with the frontal zone in the mid and lower troposphere, a vortex tends to develop and rapidly stretch downward, leading to the formation of a new cyclone ahead of the front (Lei et al., 2017). A new mesoscale vortex and mesoscale LLJ can be induced by the release of strong latent heat and the surface cool pool effect generated by intense convective rainfall (Zhao et al., 2011; Lei et al., 2017).

An extreme rainfall event that resulted in deaths took place in Beijing on 21 July 2012, with the most intense rainfall produced in a warm moist environment with weak synoptic forcing (Sun et al., 2012). Several studies have been carried out to understand the initiation and development of warm-sector heavy rainfall over North China (Sun et al., 2013; Zhang D.-L. et al., 2013; Li J. et al., 2015; Liu et al., 2015; Zhong et al., 2015; Meng et al., 2019; Lei et al., 2020). These studies have confirmed that topographic lifting (Chen M. X. et al., 2013; Sun et al., 2013; Lei et al., 2020) and mesoscale convergence lines or vortices (Zhong et al., 2015; Meng et al., 2019) are important mechanisms for the initiation of convection. Other studies have revealed the dynamic processes associated with the conditional symmetry instability (Wang et al., 1990; Liu et al., 2015), inertial instability (Sun et al., 2012), and the interaction between LLJs and convective storms (Chen M. X. et al., 2013; Lei et al., 2020) during the development and maintenance stages of warm-sector heavy rainfall events over North China.

2.2.4 *Heavy rainfall over Northeast China*

Northeast China consists of Heilongjiang, Jilin, and Liaoning provinces, with the Greater Xing'an Mountains in the west, Changbai Mountain in the east, the Xiao Xing'an Mountains in the north, and the Northeast Plain in the center. The occurrence frequency of heavy rainfall over Northeast China is much lower than that over southern regions and North China (with an average of < 20 day decade^{-1}, or even < 10 day decade^{-1} in northern Northeast China; Fig. 1).

Heavy precipitation over Northeast China is concentrated in July–August—that is, the strongest stage of the EASM. Under the control of the East Asian trough, warm moist air from lower latitudes can advance northward, providing the necessary water vapor for the production of heavy rainfall over Northeast China. A number of books were published by Chinese researchers in the 20th century, such as *Heavy Rainfall in Northeast China* (Zheng et al., 1992) and *Study on Rainstorms in Heilongjiang Province* (Bai and Jin, 1992), summarizing the climatological characteristics, large-scale background circulation and synoptic systems, and the macroscale environmental conditions of rainstorms in Northeast China.

The NECV refers to the large-scale vortex that often influences Northeast China during the warm season. The NECV is defined by Chinese researchers as a low-pressure system collocating with a cold center or an outstanding cold trough, with a closed contour line at 500 hPa within the region (35°–60°N, 115°–145°E) and with a life span of at least 3 days (Sun et al., 1994). The NECV prevails from May to August (Sun et al., 1994; Xie and Bueh, 2012). Most NECVs have a lifetime of less than a week and a horizontal scale of 500–1000 km (Hu et al., 2010; Fu and Sun, 2012). The vortices usually form in the eastern portion of Lake Baikal and dissipate on the western coast of the North Pacific Ocean. The NECV tends to occur more frequently in the northern part of the Northeast China Plain. The area of maximum occurrence frequency expands to continental China in summer and shifts to the western coast of the North Pacific Ocean in winter (Hu et al., 2010). The positive vorticity generated on the north side of the midlatitude jet in summer, the topographic dynamics from the eastern and western sides of the Northeast China Plain, and the thermal wind vorticity advection all contribute to the formation of the

NECV (Zheng et al., 1992).

The NECV could induce extremely heavy rainfall when combined with northward-moving tropical systems (Zhao et al., 1980). In summer 1998, heavy rainfall occurred frequently in Northeast China, which resulted in severe floods in the Songhua River and Nen River basins. The main reason was that the cross-equatorial airflow in Somalia was abnormally strong, the strong southerly jet in eastern China transported water vapor to Northeast China, and the abundant water vapor from lower latitudes entered the NECV's circulation (Sun et al., 1998; Li et al., 2000; Zhao and Sun, 2007). The configuration of the NECV, the East Asian blocking high, and the WPSH with their correct intensities and locations provides a favorable large-scale background circulation supporting the continuous development of rainstorms over the Songhua River and Neng River basins (Sun et al., 2002). Under the influence of the NECV, the invasion of dry and cold air greatly enhances the instability and promotes the development of vertical air motion, which is a feature of the production of heavy rainfall over Northeast China (Wang et al., 2007; Wang and Yang, 2010; Zhong et al., 2011; Gao et al., 2018). Heavy rainfall over Northeast China can also be produced under the influence of cyclones and shear lines.

2.2.5 *Heavy rainfall over Southwest China*

Southwest China consists of Yunnan, Guizhou, Sichuan provinces, and Chongqing and Tibet. It comprises different types of landforms, such as plateaus, mountains, plains, and basins. The distribution of heavy rainfall is very uneven over this region (Tao S. Y., 1980; Yang et al., 2019a). The occurrence frequency of heavy rainfall (> 50 mm day^{-1}), especially extreme rainfall (> 100 mm day^{-1}), is higher over the Sichuan basin than in other areas of Southwest China, followed by southwestern Yunnan and southern Guizhou (Fig. 1). The frequency of heavy rainfall over the Sichuan basin is higher in the west than in the east. Heavy rainfall occurs on < 1 day decade^{-1} at most stations over the TP and even the maximum over the southeastern TP is < 10 day decade^{-1}. Heavy rainfall over Southwest China mainly occurs during summer months (June–August).

Chinese researchers have studied the causes of rainstorms in Southwest China from the effects of multi-scale weather systems and the complex topography. The influences of the South Asian monsoon, the EASM, the WPSH, the South Asia high, and the blocking high and trough in mid–high latitudes of East Asia on the large-scale circulation associated with the production of heavy rainfall over Southwest China have been revealed (e.g., Ye and Li, 2016). Many studies have focused on the most important system responsible for rainfall production over Southwest China—that is, the SWLV—and have gained considerable insights about the mechanisms of SWLV's formation and movement. Some studies have shown that tropical cyclones can enhance the SWLV and increase rainfall over Southwest China by increasing the transport and convergence of water vapor in the lower troposphere (Chen et al., 2004).

In as early as the 1950s, Chinese researchers found that SWLV is a key weather system producing heavy rain over Southwest China (Ye and Gu, 1955; Hsieh, 1956). The early studies revealed the structural features of the SWLV. These include a cyclonic circulation or closed contours at the 700- or 750-hPa isobaric surface with a horizontal scale of 300–500 km. The cyclonic circulation generally appears at 700 hPa in the initial stage of the SWLV, with an area of high pressure or a high-pressure ridge in the 500–300-hPa layer (Tao S. Y., 1980). A strongly developing SWLV is a deep, warm, and humid low-pressure system in its mature stage, with positive vorticity extending up to about 100 hPa and an asymmetrical distribution of momentum, stratification, and vertical motion in the vortex. In its weakening stage, the SWLV is a shallow baroclinic system with a cold structure in the lower troposphere (Luo, 1977, 1992; Ye and Gao, 1979).

There are three major originating regions of the SWLV: Jiulong and Xiaojin counties over the western Sichuan plateau, and the Sichuan–Chongqing basin. The classic theory assumes that the formation of the SWLV is associated with the warming-induced decrease in pressure caused by the southerly airflow transporting warm air along the southeastern side of the TP. This southerly airflow also produces cyclonic shear under the influence of terrain's friction and then converges with the northerly airflow with an anticyclonic shear on the northeastern side of the TP (Ye and Gao, 1979; Luo, 1992; He, 2012; Wang and Tan, 2014). Studies in the 21st century have further advanced our understanding of the mechanisms for the initiation and development of the SWLV. The development of the SWLV could also be related to perturbations in the potential vorticity at the upper level, the development of inclined vorticity, non-equilibrium forcing, and the decrease in air pressure and increase in cyclonic perturbation induced by convection over the TP (Huang and Xiao, 1989; Chen et al., 2004; Liu and Li, 2008; Li Y. Q. et al., 2010; Fu et al., 2019). The movement of the SWLV is largely determined by the airflow at mid and upper levels. During its eastward movement, the interaction of the SWLV and other weather systems such as LLJs, may produce heavy rainfall in the mid and lower reaches of the Yangtze River, South China, and even Northeast China.

As a result of the unique geographical environment of the Sichuan basin, the diurnal variation of heavy rainfall over the basin is characterized by a single peak between midnight and the early morning, which is significantly different from most other sub-regions of China, where an afternoon peak is observed (Yin et al., 2009; Yuan et al., 2012; Luo et al., 2016). This diurnal cycle of rainfall over the Sichuan basin is thought to be associated with the diurnal variation in the regional circulation caused by differential heating between the basin and the TP (Bao et al., 2011; Jin et al., 2012), in addition to the eastward- and northeastward-moving convective systems that initiate over eastern Tibetan and the Yunnan–Guizhou plateaus, respectively, and enter the Sichuan basin around midnight (Wang et al, 2004). Another mechanism proposed to explain the diurnal variation of rainfall over the Sichuan basin emphasizes the key part played by inertial oscillations of boundary layer ageostrophic winds in the airflows from the southeastern side of the basin (Zhang Y. H. et al., 2019; Fig. 9).

2.3 *Heavy rainfall induced by tropical cyclones*

Rainstorms in coastal areas of China are significantly affected by tropical cyclones (typhoons). The most disastrous flooding events in China are often caused by extremely heavy rainfall associated with landfalling tropical cyclones (LTCs). Indeed, the top six largest 24-h rainfall accumulations in China are all closely associated with LTCs. The top five 24-h rainfall accumulations were observed over Taiwan Island and the sixth (1062 mm within 24 h) was observed at Linzhuang, Henan Province in August 1975. This event was produced by Typhoon Nina (1975) and caused severe flooding and a death toll of > 26,000. This famous event is referred to as the “75.8” Henan extreme rainfall event (Tao S. Y., 1980; Chen L. S. et al., 2010).

Rainfall associated with an LTC can be categorized into six parts: rain in the tropical cyclone core region; rain in the spiral rainband; rain produced by meso- and small-scale systems; unstable rain; peripheral rain; and tropical cyclone remote rain (Fig. 10a; Chen L. S. et al., 2010). The precipitation in the tropical cyclone core region has clear convective characteristics and the rain rate is positively related to the intensity of the tropical cyclone (Feng, 2019). Spiral rain is scattered convective precipitation embedded in the regions of broad stratiform precipitation and does not have a statistically significant relationship with the intensity of the tropical cyclone (Hence and Houze, 2012; Yu et al., 2017). Tropical cyclone rainstorms can also be found in the peripheral systems. For example, about 40% of landfalling typhoons are associated with pre-tropical cyclone squall lines, which occur on average about 600 km from the center of the tropical cyclone in its front-right quadrant (Meng and Zhang, 2012). About 14.7% of tropical cyclones induce remote rainfall > 1000 km away, mainly in the areas around Bohai and at the junction of Sichuan and Shanxi provinces (Cong et al., 2012).

The physical mechanisms of tropical cyclone rainstorms have attracted much attention from Chinese researchers. Systematic studies have been carried out on the “75.8” Henan extreme rainfall event and have ad-

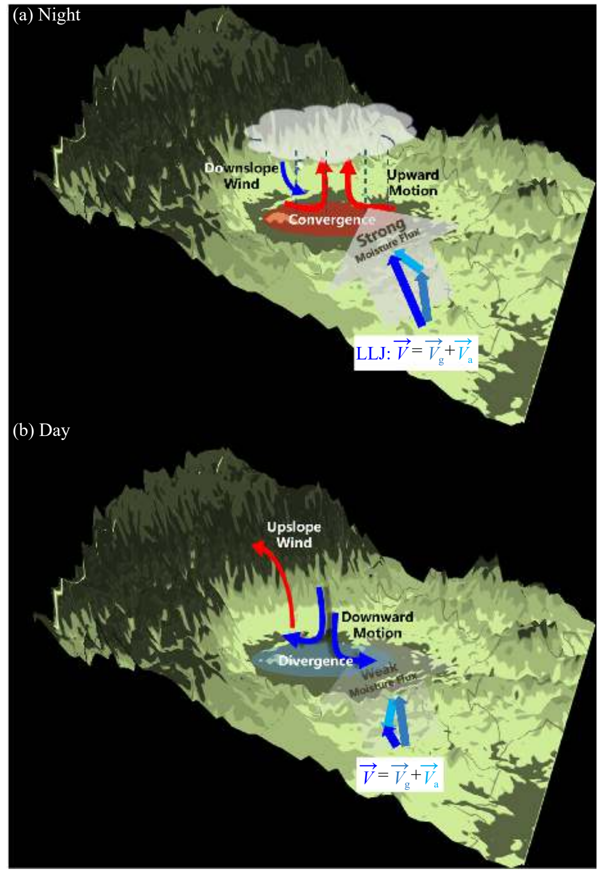


Fig. 9. Schematic diagrams showing the diurnal variations of precipitation (including the peak nighttime precipitation) over the Sichuan basin. The wind over the eastern Yunnan–Guizhou Plateau, including the daily mean quasi-geostrophic wind $\boldsymbol{V}_g$ (dark blue vector), the total wind $\boldsymbol{V}$ (the mid-blue vector), and the perturbation ageostrophic wind $\boldsymbol{V}_a$ (light blue vector) (a) at the time of peak precipitation shortly after midnight and (b) during the daytime precipitation minimum. The wide light gray arrow indicates the flux of moisture into the Sichuan basin. Updrafts, downdrafts, and the upslope and downslope flows are represented by the red and blue curved arrows, respectively. Strong net low-level convergence within the Sichuan basin forces precipitation at night, whereas low-level divergence dissipates and suppresses daytime precipitation. From Zhang Y. H. et al. (2019).

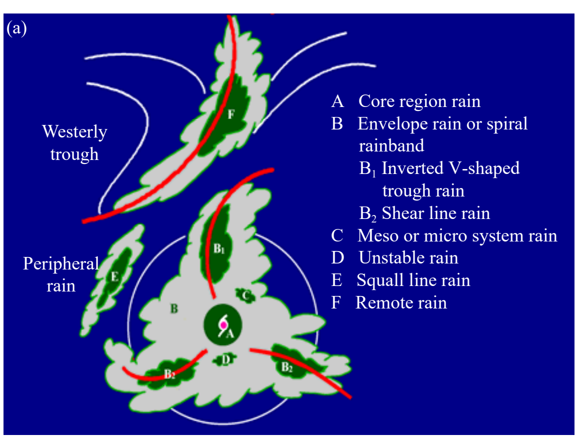
vanced the research on rainstorms and hydrometeorology in China (Ding, 2015). These studies have shown that the three-dimensional circulation of the weather system producing extreme rain during the "75.8" event is generally consistent with the typical features of the circulation of a tropical cyclone (Fig.10b; Ding et al., 1978). An LLJ transported a huge amount of water vapor and contributed to the formation and maintenance of an unstable stratification, which was rebuilt after the unstable energy was released. The mesoscale wind shear and topography provided favorable conditions for the initiation of intense convection in the larger-scale system.

Recent studies on tropical cyclone rainstorms have focused on the internal structure of the tropical cyclone, the underlying surface forcing, the large-scale atmospheric circulation, and their interactions (Chen and Xu, 2017). These studies indicate that the interaction between typhoons and the westerly circulation system could influence the intensity and distribution of the rainfall induced by tropical cyclones (Tao et al., 1994; Lei and Chen, 2001). Atmospheric instability may be increased when midlatitude cold air meets the warm and humid air carried by a typhoon, leading to an increase in precipitation (Ding et al., 2001; He et al., 2009). However, a large amount of too cold air may destroy the structure of the tropical cyclone too soon and decrease the amount of precipitation (Bian et al., 2005; Yao et al., 2019). Tropical cyclones often undergo an extratropical transition in such interaction processes, with a remarkable transformation in their dynamic and thermodynamic structure (Zhong et al., 2008) and changes in the location of heavy rainfall (Zhu et al., 2005).

Recent studies suggested that the interactions between typhoons and westerly circulation systems could also produce remote rainstorms a long distance away from the center of the typhoon (Chen L. S. et al., 2017). The role of a typhoon in generating remote rainstorms is not only to transport heat and water vapor to the rainstorm area (Wang Y. Q. et al., 2009; Cong et al., 2016), but also to act as a strong source of disturbance to disperse energy to midlatitudes and trigger severe convection (Xu et al., 2004; Lu et al., 2007). Under certain conditions, the long-distance propagation of the gravity-inertia wave induced by a typhoon could be a dynamic mechanism for generating remote rainstorms (Li et al., 2007).

Interactions between typhoons and monsoonal flows may sustain and enhance precipitation—for example, the remnant of Typhoon Bilis (2006) induced and maintained continuous heavy rainfall over a large area in southern and eastern China after its landfall, as a result of the transport of water vapor by monsoon surges (Wang et al., 2010; Cheng et al., 2012). Studies have shown that the phenomenon of vortex mutual spin, attraction, and merger resulting from the interactions between two typhoons (Wang and Zhu, 1992; Wu et al., 2011) and the transport of water vapor and energy between two typhoons may strengthen precipitation in one of the typhoons (Xu et al., 2011, 2013).

Many studies have investigated the influence of the underlying surface on typhoon precipitation over China. The dynamic and thermal heterogeneity of the underlying surface often lead to the apparently asymmetrical distribution of rainfall associated with LTCs (Yu et al., 2010; Wei and Li, 2013). The interaction between the circulation of an LTC and the coastal terrain can enhance the potential instability and induce heavier rainfall in coastal areas of eastern China (Liang et al., 2002). The windward and leeward effects of the coastal topography



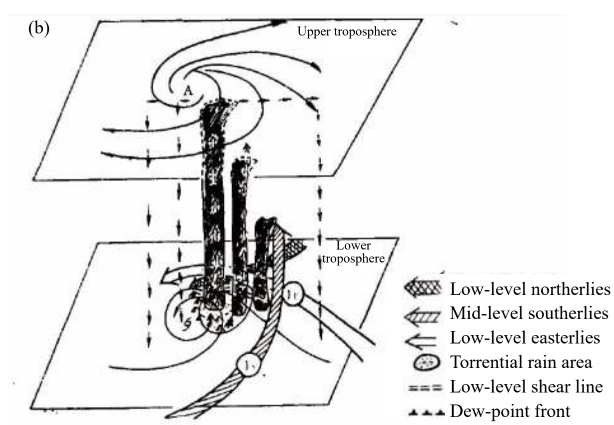


Fig. 10. (a) Schematic diagram showing the classification of landfalling typhoon rainfall. Adapted from Chen L. S. et al. (2010). (b) Schematic diagram showing the three-dimensional structure of airflow associated with the generation and development of the "75.8" extreme rainfall event in Henan Province, China. Adapted from Ding et al. (1978).

can cause spatial differences in the amount of rainfall produced by a tropical cyclone (Ji et al., 2007).

Mountains over inland areas may also increase the amount of typhoon rainfall (Dong et al., 2010). The most prominent effect of terrain on typhoon rainfall is probably that induced by the topography over Taiwan Island (Chen J. et al., 2017). The mountains of Taiwan Island often intensify convection in the circulation of a typhoon (Chen J. et al., 2017). The location of extreme hourly precipitation on Taiwan Island is roughly determined by the position of the typhoon center relative to the central mountain range of Taiwan Island (Wu et al., 2017). The highest daily precipitation (1748.5 mm within 24 h) was produced by Typhoon Herb (1996) over the Ali Mountain on Taiwan Island (Chen L. S. et al., 2010).

If a tropical cyclone stagnates over water bodies such as lakes, large reservoirs, and rivers after landfall, or on nearly saturated wetlands formed by its own rainfall, it could produce an even larger amount of rainfall (Li and Chen, 2007; Zhang S. J. et al., 2012; Mai et al., 2017). Numerical experiments indicate that when Typhoon Nina (1975) stagnated over a nearly saturated soil land formed as a result of its heavy downpour, the strong underlying latent heat flux may have helped maintain and enhance the precipitation in the disastrous "75.8" flooding event (Li and Chen, 2007). Recent studies have highlighted the influence of urban surfaces on tropical cyclone precipitation in China (Yin and Liang, 2010; Yue et al., 2019). For example, the rough surface of cities in the Pearl River Delta led to a decrease in the ground wind velocity of Typhoon Nida (2016) and strengthened the convective-scale circulation and unstable energy, resulting in an increase in precipitation over the urban area (Yang et al., 2018).

Recent studies have gained deeper insights on the influence of small-scale or mesoscale convective systems on typhoon rainfall. The convective outburst in the inner core of a typhoon can cause a sudden increase in the intensity of the typhoon and an increase in eyewall precipitation (Chen and Zhang, 2013; Yang et al., 2019b). Intense convection in the outlying area of a typhoon can also produce heavy precipitation during its landfall (Chen L. S. et al., 2017). Mesoscale shear lines or small vortices in the remnant of an LTC can enhance local precipitation after it has made landfall (Li Y. et al., 2010). Supercells may cause tornados in the northeast or right quadrant of the typhoon's forward direction and produce local heavy precipitation (Li et al., 2016; Bai et al., 2017).

The microphysical processes in tropical cyclones have also attracted the attention of Chinese researchers. A number of studies suggested a significant role of ice phase processes in producing tropical cyclone heavy rainfall (Wang D. H. et al., 2009; Hua and Liu, 2011; Ren and Cui, 2014). However, a numerical study by Tao et al. (2011) indicated that ice phase microphysical processes only played a minor part in the flood-inducing extreme rainfall produced by Typhoon Morakot (2009). Dual-polarization radar observations in eastern China were used to analyze the spectral distribution of raindrops in Typhoon Matmo (2014). The typhoon showed typical characteristics of oceanic convection, and the warm rain microphysical processes were dominant (Wang et al., 2016). The microphysical processes in tropical cyclone rainstorms still require further investigations.

3. Development and application of heavy rain forecasting techniques

The prediction of heavy rainfall has always been one of the most difficult challenges in operational weather forecasting worldwide (Ebert et al., 2003). From 2007 to 2019, the threat score of the 24-h lead-time heavy rainfall forecast made by the National Meteorological Center (NMC), China Meteorological Administration (CMA) increased at a rate of about 2.9% (Bi et al., 2016; Fig. 11). This improvement was largely due to the advances in NWP techniques. This section summarizes the history of development of NWP in China, including studies on the predictability of rainfall and ensemble forecast methods, and then describes the trends in the development and application of objective methods for forecasting heavy rain at major operational centers in China and elsewhere.

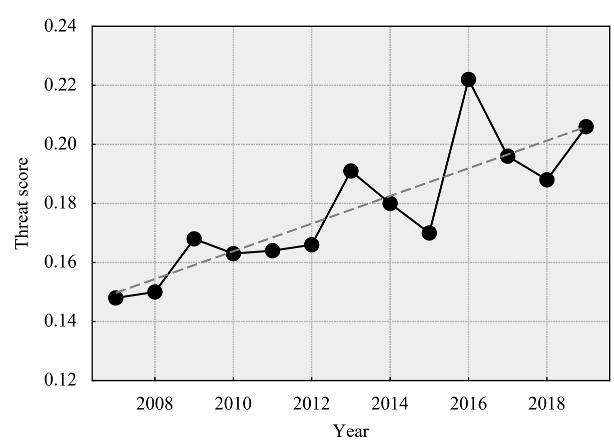


Fig. 11. The threat score of the 24-h forecast of heavy rainfall (⩾ 50 mm day^{-1}) at the National Meteorological Center (NMC), China Meteorological Administration (CMA) from 2007 to 2019. The threat score for 2019 is from January to September.

3.1 *Development of NWP in China*

China is one of the earliest countries to carry out NWP studies, with relevant research beginning in the middle of the 20th century. Over the following 30 years, the achievements in the adaptation theory of atmospheric motion (Ye et al., 1952; Yeh, 1957; Ye and Li, 1964) guided and promoted the development of NWP. Specifically, a semi-implicit difference scheme was proposed (Zeng, 1963a) and real weather prediction was made for the first time worldwide by using the primitive equations describing the atmospheric motion (Zeng, 1963b). This is an important contribution to the basic mathematical and physical problems in the development of NWP models (Zeng, 1979a, b).

Since the reform and opening-up of China in the 1980s, new progress has been made in the research and operational applications of NWP. For example, a computationally stable difference scheme with total energy conservation was proposed to calculate the implicit advection terms (Zeng and Ji, 1981), and an easily solvable explicit square-conservation scheme (Wang and Ji, 1990) was also proposed. In the 21st century, China has independently developed a new generation of multi-scale data assimilation and NWP system: the Global/Regional Assimilation and PrEdiction System (GRAPES) (Chen et al., 2008; Xue and Chen, 2008).

After more than 10 years of effort to make constant improvements and technological upgrades, integrated operational determination and ensemble NWP systems have been developed, including a 3–10 km resolution regional model and a 25–50 km resolution global model. Innovative achievements have been made in the non-static, fully compressible dynamic framework, four-dimensional variational assimilation, the cloud–precipitation physics scheme, a high-precision numerical algorithm, and satellite and radar data assimilation technology (Shen X. S. et al., 2020). These have continuously and steadily improved the research and operational capability of NWP in China, providing important scientific and technological support to the accurate prediction of daily weather and early warning of rainstorms and other disastrous weather events. The Chinese Academy of Meteorological Sciences is developing a global, high-resolution, multi-scale weather–climate integrated model system to meet the needs of weather prediction, climate prediction, and climate research. At present, a dynamic framework based on an unstructured icosahedron grid has been built up, which is capable of flexible static/non-static switching and the horizontal stretching of model grids (Zhang Y. et al., 2019).

With the continuous increase in the horizontal resolution of the NWP models, spatial verification methods suitable for high-resolution NWP products have been developed in the past 10 years (Ebert and Gallus, 2009; Gilleland et al., 2010; Dorninger et al., 2018) and have been widely used in major operational centers worldwide. Faced by the difficulties in prediction, such as the sub-daily scale evolution of precipitation (Yu et al., 2014) and the evolution of heavy precipitation in complex terrain areas, China is carrying out a systematic evaluation of high-resolution NWP products (Yu et al., 2019). In 2019, CMA established the operational evaluation metrics for NWP models based on the hourly features of precipitation. The developers of NWP technology have started to analyze the physical mechanisms of simulated rainstorms with the NWP outputs to more deeply understand how the updated methods of, for example, data assimilation, improve the prediction of convection and heavy rainfall (e.g., Zhang X. B. et al., 2016; Bao et al., 2017).

The forecast lead time of the atmosphere is limited by its intrinsic stochasticity (Lorenz, 1963, 1969; Chou, 2002), and thus has an upper bound. The forecast has no skill beyond that upper bound. This is an intrinsic property of the atmosphere and is referred to as the "intrinsic predictability of atmosphere." By repeatedly reducing the initial errors in numerical experiments, Bei and Zhang (2007) showed that the Meiyu frontal heavy rainfall has a predictability limit. Sun and Zhang (2016) showed that the intrinsic predictability of MCSs is limited by the rapid upscale growth of the forecast error as a result of moist convection. The errors in the forecast model and the initial and boundary conditions cannot be fully removed, and therefore the practical forecast ability cannot reach the upper bound of the intrinsic predictability. The upper bound of the practical forecast skill is referred to as the "practical predictability of atmosphere." Zhang F. Q. et al. (2019) showed that, at present, the practical predictability limit of midlatitude weather is around 10 days; reducing the initial error by an order of magnitude might extend the deterministic forecast lead time of midlatitude weather by up to 5 days.

Chinese researchers have carried out considerable studies to investigate the impacts of initial errors and model uncertainties on rainstorm forecasts (Mu et al., 2004). The results show that rainstorm forecasts are sensitive to the initial uncertainties (Luo and Zhang, 2010; Zhou and Cui, 2015) and the uncertainties in physical parameterization schemes (e.g., the land surface, cloud microphysics, and cumulus convection) (Chen J. et al., 2003, 2006; Luo and Chen, 2015). The degree of sensitivity is closely related to the dynamic processes that lead to the generation of rainstorms (Li Y. Y. et al., 2010; Luo and Chen, 2015; Huang and Luo, 2017).

Ensemble forecasting is a new type of numerical prediction used to quantitatively estimate the uncertainty in the forecasting of heavy rain (Chen et al., 2002). The generation of ensemble members is primarily realized by initial condition perturbation and model perturbation methods (Chen and Xue, 2009; Du and Li, 2014). Chinese researchers have successively developed the different-physical-mode initial condition perturbation method (Chen et al., 2005a), the multi-scale initial condition perturbation method (Zhang et al., 2015), the blending initial condition perturbation method (Zhuang et al., 2017), the orthogonal conditional non-linear optimal perturbation (Duan et al., 2019), and other ensemble forecasting methods that represent the uncertainty of initial condition. They have also used multiple physical parameterization schemes for ensemble forecasting (Chen et al., 2005b) and have added stochastic physical perturbations to the initial condition perturbations (Li J. et al., 2015; Xu et al., 2019; Zhang Y., 2019). Multiple initial conditions, multi-physical processes, and multiple models have been combined to carry out super-ensemble forecasting, which has significantly improved the forecast timeliness of some heavy rainfall events (Duan et al., 2012; Wu et al., 2012). Convection-allowing high-resolution ensemble prediction (with horizontal grid size of 1–4 km) has become the mainstream of NWP development around the world (Clark et al., 2018). Chinese researchers have built an experimental regional convection-allowing ensemble prediction system (Zhang, 2018) and preliminarily reported the characteristics of interactions between perturbations from different sources and their influence on the prediction of torrential rain over South China during early summer (May–June) (Zhang, 2019).

3.2 *Objective methods for forecasting heavy rain*

The ensemble prediction system (Deng et al., 2010; Wang et al., 2018) and convection-permitting NWP system (Xu et al., 2017) provide massive outputs and forecast information. To meet the needs of operational weather forecasting, objective heavy rain forecasting methods are required to rapidly and efficiently post-process the huge amount of NWP outputs (Tang et al., 2018). The objective heavy rain forecasting methods at the major operational centers worldwide can be summarized into the following five categories.

(1) Cluster analysis, data synthesis, and visualization techniques have been developed to rapidly extract information that can be used effectively. A few examples are given here. An objective and quantitative tool for the classification and forecasting of atmospheric circulation has been developed (Neal et al., 2016) and can be used to make probabilistic forecasts of different circulation patterns by classifying weather circulations from dozens of ensemble members. The characteristics of processes producing heavy rain can then be obtained by analyzing similar historical cases. Certain techniques have been developed to obtain synthetic satellite imagery of the atmosphere from the outputs of NWP (Bikos et al., 2012). Conventional cloud image interpretation techniques can then be used to give a rapid understanding of the large-scale environmental conditions relevant to the development of convective systems. Data visualization techniques are used to assist in the inspection and correction procedures used to forecast heavy rain (Liao et al., 2015) so that the forecast results can be clearly and effectively communicated to the end users (Rautenhaus et al., 2018).

(2) Synoptic diagnostic and analysis techniques have been developed to help forecasters understand the dynamics of the torrential rainfall events (Tao and Zheng, 2012; Zhou et al., 2013, 2014). For example, a quasi-geotropic diagnostic analysis tool (Thaler and Nutter, 2009) has been developed to help forecasters understand the dynamics of weather systems at different scales. Potential vorticity theory (Hoskins et al., 1985; Mansfield, 1996) has been used to analyze synoptic-scale systems such as fronts (Zadra et al., 2002; Chen Y. S. et al., 2003; Wernli and Sprenger, 2007) and the interactions among weather systems at various scales (Brennan et al., 2008; Joos and Wernli, 2012). Ensemble sensitivity analysis and inter-group standard deviation diagnosis methods have been used to analyze the source and evolution of forecast errors in extreme rainfall events (Dai et al., 2018a).

(3) Objective bias-correction integration methods have been developed to obtain the most likely or optimum forecasts (Dai et al., 2018b). For example, the frequency-matching technique has been used to improve the distribution of the frequency of rainfall from NWP (Zhu and Luo, 2015) and the averaging method based on a Bayesian model has been used to calibrate probabilistic forecasts of extreme rainfall (Chen C. P. et al., 2010; Han et al., 2013; Zhang Y. T. et al., 2016). The two-step analog statistical correction method based on the re-forecasting model (Hamill et al., 2006) and the multi-model information integrating technique (Novak et al., 2014; Gilbert et al., 2015; Hamill et al., 2017) have also been used.

(4) Extreme weather forecasting methods have been developed. This is one of the newest development trends,

both in China and abroad (Lalaurette, 2003; Lamberson et al., 2016). The Numerical Prediction Center, CMA has developed extreme precipitation forecasting technology based on the CMA's global ensemble forecasting system (Liu L. et al., 2013, 2018). In operational forecasting, Extreme Forecast Index composite products are generated through an ensemble prediction system toolbox, effectively helping forecasters and users to gain early warning of extreme or severe weather events.

(5) Probabilistic forecasting techniques have been developed to communicate the uncertain information in forecasting to the end users. The ensemble forecast output statistical method (Bentzien and Friederichs, 2012) and the Bayesian model averaging method (Sloughter et al., 2007) have become the benchmarks for probabilistic precipitation forecasts. The probabilistic forecasting method based on "face-to-face" analysis has also been rapidly developed (Johnson and Wang, 2012; Schwartz and Sobash, 2017).

The operational forecast centers in China and elsewhere are actively developing subjective and objective integrated forecasting technologies and platforms to help forecasters comprehensively utilize the massive amount of forecasting data based on understanding of the weather and model evaluation. For example, the US Weather Prediction Center developed the WPC MASTER BLENDER system (Petersen et al., 2014). Using this system, forecasters can rapidly select models, give them corresponding weights based on the inspection and evaluation results, and then make a precipitation forecast. The NMC of China has designed and developed a quantitative precipitation forecast platform that integrates both subjective and objective forecasts. Forecasters can integrate multi-source precipitation forecasts, adjust and revise precipitation forecasting, conduct gridded analysis, and produce service products (Tang et al., 2018).

4. Concluding remarks

Since the start of the reform and opening-up of new China at the end of the 1970s, Chinese researchers have made continuous and substantial progress in understanding multi-scale physical processes and developing forecast techniques for heavy rainfall events, greatly aided by the rapid progress in meteorological monitoring technology and substantial improvement in operational observing systems, as well as significant improvements in electronic computing capabilities.

Studies of heavy rainfall events over the major sub-regions of China and heavy rainfall induced by typhoons have advanced to investigating the evolution of convective storms producing heavy rain. Some important mesoscale phenomena and processes have been revealed. Evidence has been provided about the impact of urbanization on the intensity and distribution of rainfall around the major urban agglomerations in eastern China. Observational analysis of cloud microphysical features has recently been conducted. A deeper and more systematic understanding of the synoptic systems of importance to the production of heavy rainfall over China has also been developed. Along with advances in the understanding the physical mechanisms and predictability of heavy rainfall events, NWP technology has been continuously developed. Operational forecasts of heavy rainfall in China has changed from subjective weather event forecasts to subjective and objective combined quantitative precipitation forecasts and are now advancing toward probabilistic quantitative precipitation forecasts with the provision of forecast uncertainty information.

The following areas are suggested for future studies on the science and prediction of heavy rainfall in China.

(1) Studies of the evolution and associated physical mechanisms of extreme rainfall events in various climate zones and geographical regions of China to advance our understanding of the independent impacts and interactive effects of synoptic forcing, mesoscale processes, cloud microphysics, aerosols, and complex surfaces (such as urban areas and mountains).

(2) Studies of the long-term changes in extreme rainfall accumulations at a range of temporal scales (monthly, daily, and sub-daily) in past, present, and future climates and the causes of the independent and coupled roles of climate change, variations in the large-scale circulation, the dynamic and thermodynamic effects of urbanization, and anthropogenic emissions of aerosols.

(3) Studies of the features of disasters induced by heavy rainfall, including compound disasters collectively caused by the simultaneous or successive occurrence of heavy rainfall and other disastrous weather, such as high-speed winds and high temperatures; and studies of their impacts on human society and natural physical systems.

(4) Development of methods that can effectively assimilate new data such as those collected by phased array radar systems, aiming to establish ensemble forecast systems with a resolution of kilometers or even sub-kilometers; and use of high-resolution in situ and remotely sensed observations to further improve the model physics schemes and improve ensemble generation methods.

(5) Collective use of high-resolution in situ and remote sensing observational datasets, high-resolution en-

semble NWP models, and artificial intelligence technology to develop advanced warning systems for heavy precipitation and short-term probability prediction methods; and development of warning and forecasting methods for heavy precipitation that are accurate on the block scale in densely populated large cities.

Acknowledgments. We would like to thank the three anonymous reviewers for their helpful comments.

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Tech & Copy Editor: Lan YI