VOLUME 34 ADVANCES IN METEOROLOGICAL RESEARCH AND OPERATION SINCE THE FOUNDING OF THE PEOPLE'S REPUBLIC OF CHINA AUGUST 2020

Progress in Severe Convective Weather Forecasting in China since the 1950s

Xiaoling ZHANG[1], Jianhua SUN[2,3], Yongguang ZHENG[1], Yuanchun ZHANG[2], Ruoyun MA[2,3], Xinlin YANG[2], Kanghui ZHOU[1], and Xuqing HAN[1]

1 *National Meteorological Center*, *China Meteorological Administration*, *Beijing* 100081
2 *Key Laboratory of Cloud–Precipitation Physics and Severe Storms*, *Institute of Atmospheric Physics*, *Chinese Academy of Sciences*, *Beijing* 100029
3 *University of Chinese Academy of Sciences*, *Beijing* 100049

(Received September 10, 2019; in final form June 27, 2020)

ABSTRACT

Located in the Asian monsoon region, China frequently experiences severe convective weather (SCW), such as short-duration heavy rainfall (SDHR), thunderstorm high winds, hails, and occasional tornadoes. Progress in SCW forecasting in China is closely related to the construction and development of meteorological observation networks, especially weather radar and meteorological satellite networks. In the late 1950s, some county-level meteorological bureaus began to conduct empirical hail forecasting based on observations of clouds and surface meteorological variables. It took over half a century to develop a modern comprehensive operational monitoring and warning system for SCW forecast nationwide since the setup of the first weather radar in 1959. The operational SCW forecasting, including real-time monitoring, warnings valid for tens of minutes, watches valid for several hours, and outlooks covering lead times of up to three days, was established in 2009. Operational monitoring and forecasting of thunderstorms, SDHR, thunderstorm high winds, and hails have been carried out. The performance of operational SCW forecasting will be continually improved in the future with the development of convection-resolving numerical models (CRNMs), the upgrade of weather radar networks, the launch of new-generation meteorological satellites, better understanding of meso-γ and microscale SCW systems, and further application of artificial intelligence technology and CRNM predictions.

Key words: severe convective weather (SCW), forecasting, radar, meteorological satellite, artificial intelligence, convection-permitting numerical model (CRNM)

Citation: Zhang, X. L., J. H. Sun, Y. G. Zheng, 2020: Progress in severe convective weather forecasting in China since the 1950s. *J. Meteor. Res.*, **34**(4), 1–21, doi: 10.1007/s13351-020-9146-2.

1. Introduction

Located in the East Asian monsoon region, China is prone to mesoscale convective systems (MCSs) that not only bring heavy rainfall (Tao, 1980), but also produce severe convective weather (SCW), such as thunderstorm high winds, hails (Zhang et al., 2008; Yang et al., 2017), and tornadoes (Fan and Yu, 2015; Chen et al., 2018). In the operational meteorological forecasting in China, SCW refers to short-duration heavy rainfall (SDHR) with hourly precipitation of no less than 20 mm, thunderstorm high winds exceeding Beaufort scale 8 or 17 m s^{-1}, hails with a diameter of no less than 5 mm, or any tornado. This paper follows these criteria to define SCW. SCW usually develops rapidly and locally, and has great destructive power and high impacts. SCW forecasting remains a great challenge due to its small spatial and temporal scales and high nonlinearity.

SCW events occur mainly over eastern China in the afternoon during the period of April–September. SDHR is an SCW type with the highest occurrence frequency and the most wide spread in China (Fig. 1a; Chen et al., 2013). Thunderstorm high winds mostly occur in North China and Guangdong Province (Fig. 1b; Yang et al., 2017), whereas hails occur more frequently in mountains and plateaus, with the highest frequency located in the

Sponsored by the National Key Research and Development Program of China (2017YFC1502003 and 2018YFC1507504), National Natural Science Foundation of China (41675045 and 41375051), and Strategic Research Projects on Medium- and Long-Term Development of Chinese Engineering Science and Technology (2019-ZCQ-06).

central Qinghai–Tibetan Plateau (Fig.1c, Zhang et al., 2008; Xie et al., 2010; Li X. F. et al., 2018). The occurrence probability of tornadoes in China is extremely low, with an annual frequency less than 1/10 of that in the US, and the relevant climatological statistics demonstrate that tornadoes, especially significant ones, appear mainly over the eastern plains of China (Fig.1d; Chen et al., 2018; Meng et al., 2018), and are usually associated with cold vortices, Meiyu fronts, and landfalling typhoons (Wei and Zhao, 1995; Fan and Yu, 2015; Yao et al., 2015; Wang et al., 2015; Chen et al., 2018).

The first meteorological observation station in China, the Xujiahui Observatory, was established in Shanghai in 1898 (Wen, 2004). In the 1930s, operational meteorological observations and forecasting were gradually standardized, and weather information began to be broadcast by radios. A few meteorologists made the first attempt to analyze the characteristics of SCW using sparse surface observations (Lu, 1938a; Wu, 1938), and the interactions between cold and warm air masses were used to explain the occurrence of squall lines and thunderstorms (Lu, 1935a, b, c, 1938b). The schematic diagram of a squall line, shown in Fig. 2, was presented by Lu (1938b).

As in other countries, the progress in operational weather forecasting in China depends on the development of scientific understanding and forecasting technology. Scientific and technological studies based on meteorological observations have played a significant role in the progress of SCW forecasting. Yu and Zheng (2020) recently reviewed the advances in severe convection research in China during the past several decades, and showed that an in-depth understanding of convection triggering, along with environmental conditions, organizational storm structures/modes, and maintenance mechanisms of SCW, has been attained. However, few effective meteorological observation stations were established and little progress was made in weather forecasting and research in China before 1950 due to the severe disruption brought about by military conflicts. After the founding of the China Meteorological Administration (CMA)

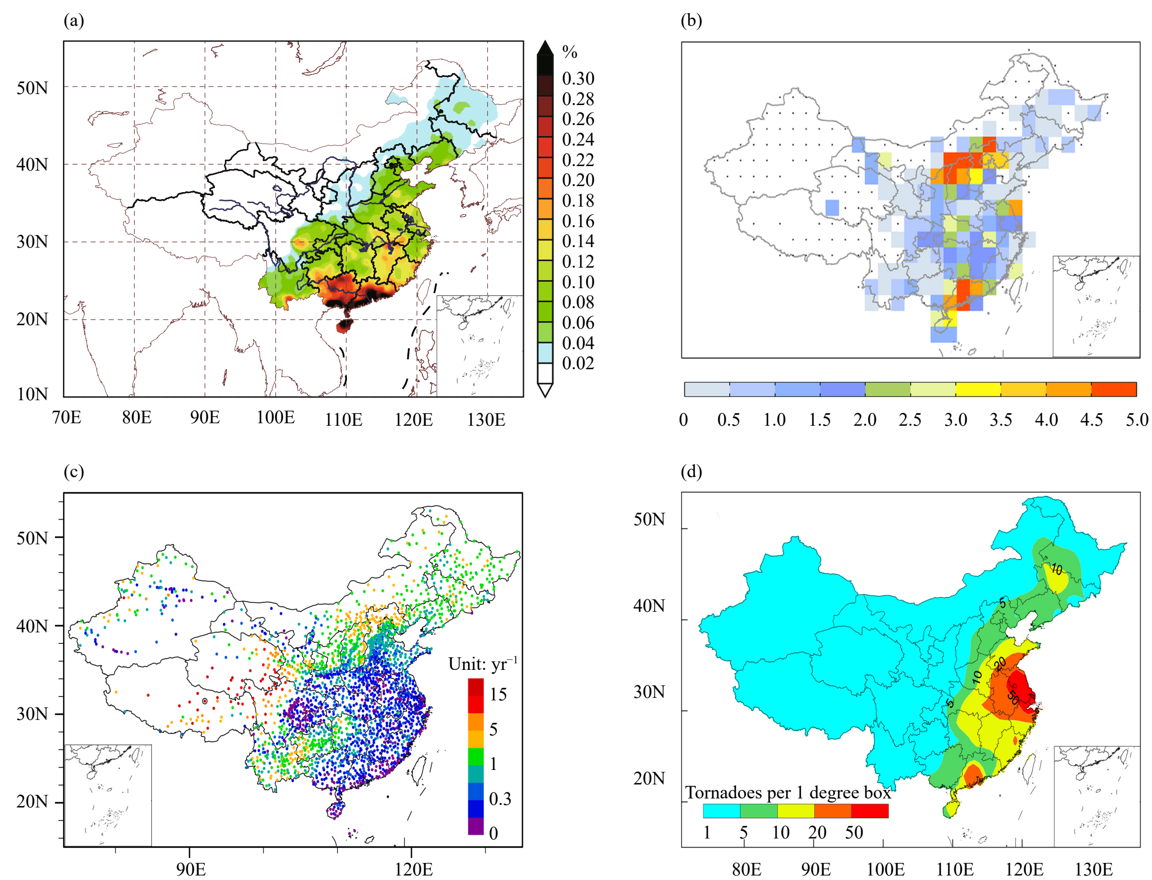


Fig. 1. Climatology of various types of SCW over China. (a) Occurrence frequency (%) of SDHR events with hourly rainfall of no less than 20 mm during April–September [adapted from Chen et al. (2013)]; (b) spatial distribution of thunderstorm strong winds after normalization during 2010–2014 (unit: events per station per unit time) [adapted from Yang et al. (2017)]; (c) distribution of annual mean hail frequency from 1980 to 2015 [adapted from Li X. F. et al., (2018)]; and (d) occurrence frequency of tornadoes, interpolated to 1° (longitude) × 1° (latitude) grids using an inverse square distance method [adapted from Chen et al. (2018)].

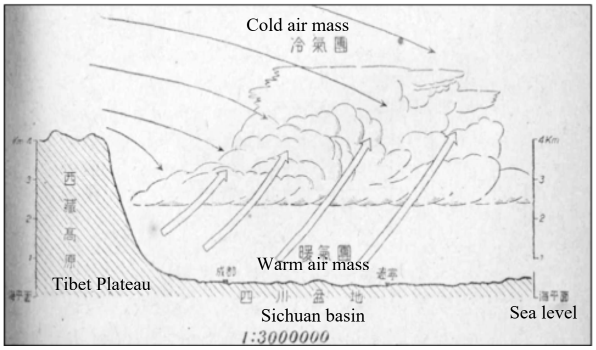


Fig. 2. Schematic diagram of the squall line that occurred over the Sichuan basin on 20 April 1938 [adapted from Lu (1938b)].

and the National Meteorological Center (NMC) in 1950, weather forecasting and research developed quickly along with the establishment of various meteorological observation networks.

In the late 1950s, some county-level meteorological bureaus started to conduct very short-range SCW forecasting and nowcasting based on the experience of the forecasters and surface weather observations, mainly for the purpose of guiding artificial hail suppression. These forecasts provided important supplements to the operational weather forecasts of the NMC and the corresponding provincial meteorological bureaus. After 1970, a large number of weather radars were deployed, and experiments for very short-range forecasting of SCW based on radar echo mosaics were carried out in the 1980s. With further understanding of the environmental conditions of SCW, the potential of SCW forecasting based on sounding analysis was developed in the 1980s and 1990s. In the 21st century, with the deployment of China's new generation Doppler weather radars (CINRAD), the launch of the Fengyun (FY) series of meteorological satellites since 1998, the construction of the China lightning detection network, and the implementation of huge number of automatic weather stations since 2000, SCW research has been greatly advanced from synoptic-scale background study to meso-β or even meso-γ-scale mechanism study. Based on scientific understanding of SCW and relevant advanced technologies, various techniques and methods for the application of radar data, satellite data, and numerical weather prediction (NWP) model outputs have been developed rapidly, and operational SCW services entered a rapid development era characterized by nationwide standardized monitoring, warning, and forecasting of SCW.

In this paper, we review the progress in SCW forecasting in China since the 1950s. Three stages are broadly

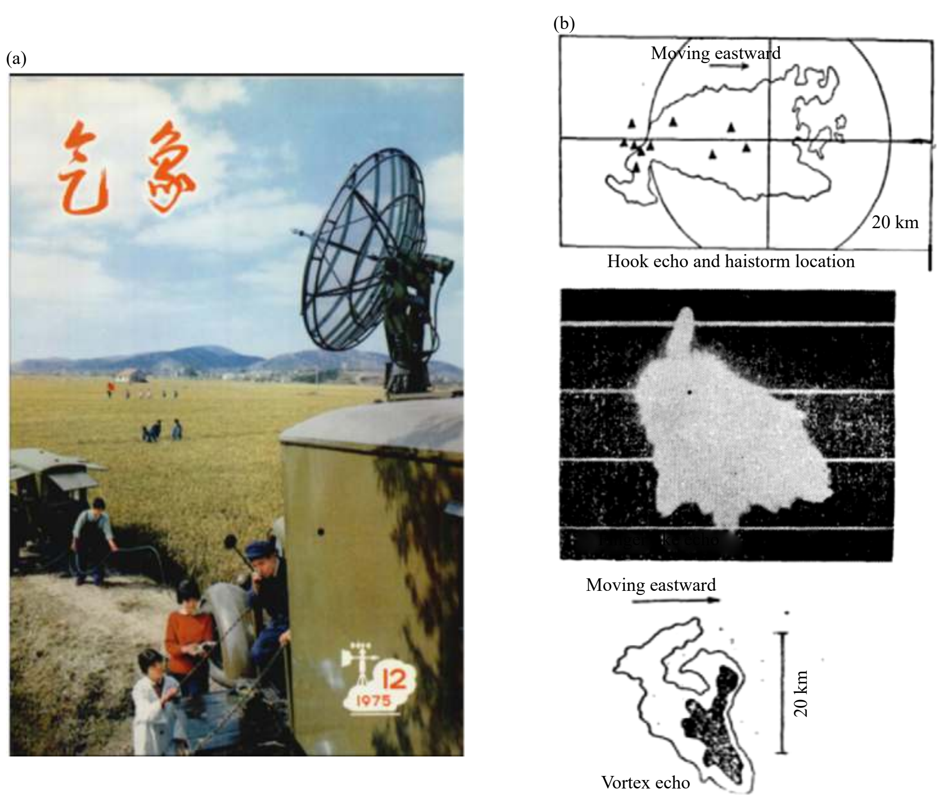


Fig. 3. (a) The 3-cm weather radar developed in China and (b) radar echoes of three types of hailstorms detected by the model 711 conventional weather radar. (a) is adapted from the cover of *Meteorological Monthly* published in December 1975 and (b) is adapted from Lei (1976a).

identified and described in Sections 2–4. In Stage I, the county-level meteorological bureaus provided supplementary forecasting for hails from the late 1950s to the 1970s; in Stage II, the province-level bureaus conducted very short-range SCW forecasting experiments in the 1980s and 1990s; in Stage III, operational SCW forecasting is conducted nationwide since the beginning of the 21st century. The factors that have substantially contributed to the advancement of SCW forecasting in China in each stage, e.g., the development of enhanced forecasting technologies and scientific understanding of SCW-produced MCSs and environmental conditions favorable for their development based on observations, are highlighted and reviewed. In Section 5, we highlight future directions in SCW forecasting, including the application of convection-resolving numerical models (CRNMs) for SCW forecasting. Section 6 presents a brief summary.

2. Stage I: Supplementary forecasting by the county-level bureaus from the late 1950s to the 1970s

2.1 *Status of SCW forecasting*

Subjective map analysis was the major method for operational weather forecasting in the 1950s. It was effective to forecast synoptic-scale processes such as cold waves and typhoons by combining analysis of weather charts with forecasters' experience (Wen, 2004). However, severe hailstorms, which can cause crop failure and subsequent starvation in affected areas, had become one of the most disastrous types of severe weather back then. How to use limited surface observations to correctly forecast hail and provide guidance for hail suppression had become one of the most urgent concerns in many local meteorological bureaus. In 1957, Zhenxiong County in Yunnan Province suffered from several severe hail disasters, which prompted the Zhenxiong County Meteorological Bureau to conduct very short-range hail forecasting by observing sky conditions and changes in cloud features. Compared with the forecast solely based on synoptic analysis, the forecast using this method was more effective to provide guidance for local hail suppression during a very short period (Yunnan Meteorological Bureau, 1978). The method was then applied nationwide in 1958. As a result, the forecasts by county meteorological bureaus effectively supplemented large-scale weather forecasts issued by the national and provincial meteorological bureaus (Chinese Academy of Meteorological Sciences, 1959). This forecasting approach under the specific historical conditions in China was called county-level bureaus supplementary forecasting (CBSF), and it continued to be used until the 1970s.

Based on changes in local surface meteorological variables and knowledge obtained from historical data and forecasters' experience, the CBSF actually employed some simple mathematical statistical methods to obtain forecasting rules. In the operational forecasting, county bureaus summarized/reported the characteristics of local weather as local weather forecasting indices based on weather situations (Tao, 1977). However, it was impossible for forecasters to predict convective weather tens of kilometers away in several hours solely based on surface meteorological variables and cloud variations. Furthermore, the CBSF for SCW focused mainly on hails, which would occur in a very short-range period, for the purpose to provide guidance for artificial hail suppression. A discussion on 14 issues pertinent to improvement of the CBSF in 1977–1978 was published in *Meteorological Monthly*. In the next 20 years, more hail forecasting techniques were gradually added to the CBSF method (Lei, 1976b). Despite its viability, the CBSF method was not applied to forecast SDHR events or downbursts (or thunderstorm high winds) at that time for the simple reason that the disasters produced by such events did not yet receive enough attention.

To further understand mesoscale weather systems and increase the forecast lead time for the CBSF, the first severe mesoscale weather observation and prediction experiment in the Yangtze River Delta region was launched in 1963–1964 by the CMA, the Institute of Atmospheric Physics of Chinese Academy of Sciences, and several universities. The aviation danger reports, radar echo images, and surface intensive observations obtained during this experiment were used for a comprehensive mesoscale analysis (Zhang, 1979). In the 1960s, Chinese researchers started to pay attention to mesoscale systems and statistical characteristics of the environmental conditions favorable for the development of SCW (Wang, 1965; You, 1965a, b). They found that the triggering and development of convection are closely related to large-scale circulation and mesoscale thermal and dynamic conditions. These results were employed to develop the 12-h thunderstorm potential forecast techniques (Wang, 1964; Xu and Wang, 1965). In addition, the relationship between the intensity of SCW and environmental conditions has also been investigated. For example, Zhao and Xue (1963) summarized the simple rules for predicting hail diameter according to updrafts and vertical distribution of moisture in cumulus clouds based on the growth mechanism of hail. The forecasting experiments and studies of SCW in the early 1960s effectively promoted the improvement of operational forecasting at that time, which mainly relied on surface and cloud observations. Unfortunately, few of the studies and forecasting experiments took place in the subsequent 10 years because of the Great Cultural Revolution during 1966–1976.

2.2 *Technologies and scientific understanding beneficial to operational forecasting*

The meteorological observation stations were deployed with a distance of about 150 km in plains and about 100 km in mountainous regions between individual stations, and a total of 1377 stations had been set up in China by 1956. The conventional observations collected at these stations were the basis for performing nationwide CBSF in China. However, it was difficult to capture the three-dimensional structure and rapid evolution of SCW systems solely based on such observations. With the widespread deployment of weather radars in China as well as the broadcasting of the meteorological satellites data by the United States in the 1970s, the use of radar echoes and satellite-based images to reveal SCW characteristics made up for the deficiency of the CBSF that relied on the analysis of surface weather observations alone in the 1950s and 1960s.

By the 1950s, weather radars had been developed in many countries, and the first weather radar in China was established in Shanghai in June 1959, after a damaging thunderstorm high-wind event with a maximum wind speed of 25.5 m s^{-1} occurred in the Yangtze River estuary on 11 April 1959. The event resulted in 399 deaths and 1212 people missing, as well as 148 sunken, 1342 seriously damaged, and 132 missing fishing vessels. Yet an effective nationwide radar network was not established until the early 1970s. In the mid-to-late 1970s, the models 711, 713 and 714 weather radars were widely deployed in China. These weather radars, which processed analog signals, were mainly used for typhoon warning in the coastal areas of eastern China and for studying the structure and evolution of SCW and heavy rainfall systems. Based on radar echoes, the structure and formation mechanisms of hailstorms or tornado events were revealed, and identification methods and techniques for very short-range hail forecasting were developed (Lei, 1976a; Chen, 1979; Ge, 1979, 1980; Lin, 1979). For instance, radar echoes of three types of hailstorms, i.e., hook echoes, finger-like echoes, and vortex echoes, detected by the model 711 conventional weather radar were identified (Fig. 3; Lei 1976a).

In 1972, direct broadcasting of cloud image data from the NOAA-2 satellite launched by the USA became available. The data were received and applied in China by meteorologists shortly afterwards (Zhou, 1977; Tao et al, 1979; Fang and Qin, 2006; Fang et al., 2006). By identifying the major characteristics of cloud images related to SCW, the methods and techniques for analyzing and forecasting SCW were developed in the 1970s (Tao, 1977; Zhu, 1977; Ding, 1978; Li, 1978; Zhao, 1978). Ding (1978) demonstrated that satellite data could be used to improve mesoscale analysis and predict the timing, location, and intensity of convection. He revealed that the prediction based on the evolution of the cloud systems of severe weather shown in the satellite cloud images was sometimes approximately 2 h earlier than that using radar observations. Figure 4 shows a team of meteorologists analyzing cloud patterns obtained from satellite images, along with the conceptual models of SCW in China, in the 1970s.

Mesoscale meteorology developed rapidly worldwide in the 1960s and 1970s. In China, research on the relationship between radar echo characteristics and SCW started in the 1960s (Ge, 1966). Although the application technologies and scientific studies using radar and satellite data had started and developed in the 1970s, radar and satellite observations were not used in operational SCW forecasting until the 1980s. Studies of SCW warning techniques using radar data developed gradually in China after 1975 (Institute of Gansu Meteorological Bureau, 1975; Radar Team of Anhui Meteorological Observatory, 1975; Lei, 1976a, b). Mesoscale analysis techniques, such as the time–space transformation analysis using surface observations developed by Fujita in the 1950s (Fujita, 1955, 1960), composite radar echo analysis techniques, and the MCS analysis methods using satellite cloud images, were also introduced into China in the 1970s (Ke, 1976).

3. Stage II: Very short-range forecasting experiments conducted by provincial bureaus in the 1980s and 1990s

3.1 *Status of SCW forecasting*

In the 1980s, the CMA upgraded its weather radars to use digital rather than analogue signals. This made it possible to share radar data in real time. An experiment network consisting of 12 weather radars in eastern China was implemented by the CMA in 1980–1982. Echo data from each radar were sent to the Shanghai Meteorological Bureau every 30 min; the manual mosaicking was then completed within 1.5 h, and the mosaic was finally released to relevant meteorological bureaus. Experiment results suggested that the radar echo mosaics could signi-

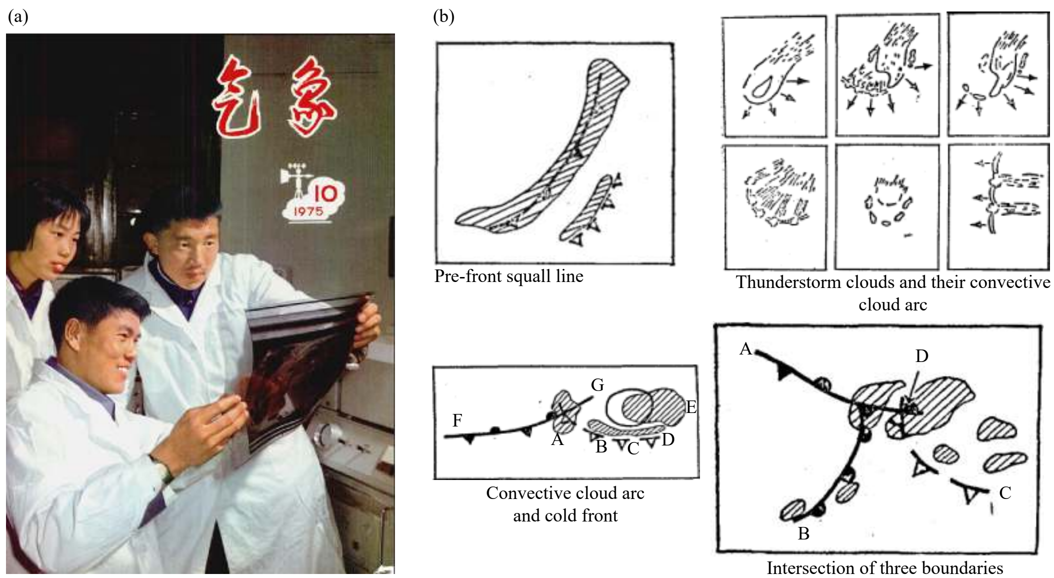


Fig. 4. (a) Meteorologists analyzing satellite images and (b) schematics of the conceptual models of SCW cloud patterns [adapted from Ding (1978)].

ficantly improve very short-range (2–6 h) forecasting of SCW. In 1983, the eastern China radar network was put into operation, and very short-range operational forecasting and nowcasting (0–2 h) were carried out at the corresponding local meteorological bureaus (Lu and Liu, 1983). Encouraged by the results of the forecasting experiment in eastern China, many other local meteorological bureaus developed very short-range forecasting and nowcasting techniques for SCW during the mid-to-late 1980s and the 1990s (Wang and Ding, 1994; Ji et al., 1996), and operational SCW forecasting was also conducted in several provinces. For example, Guangdong Meteorological Bureau has been conducting the regular 0–6-h thunderstorm high winds forecasting and even 6–12-h SCW outlook since 1985 for the purpose to reduce the risk of shipping disasters caused by strong winds in the Pearl River.

Apart from the above-mentioned experiments carried out by the meteorological bureaus, many very short-range forecasting and nowcasting experiments were also conducted in the 1980s by research institutes and universities in China in collaboration with the meteorological bureaus (Zhang, 1982, 1991; Tang, 1990). In the rainy seasons of 1979–1981, the nowcasting of severe convective weather and joint defense experiment were carried out in Hunan Province with the participation of both scientists and forecasters. This experiment was the first to comprehensively analyze weather systems from large scale to meso and microscale and to perform SCW prediction by integrating information from satellite remote sensing and radar data and intense surface observations (Zhang, 1982). Under the leading efforts of the Air Force Meteorological Institute in 1980 (Zhang et al., 1986), the procedures for very short-range SCW forecasting were then developed based on weather radar data collected during the eastern China mesoscale weather experiment. During the "Monitoring and Nowcasting of Hazardous Weather" experiment managed by the Chinese Academy of Meteorological Sciences (CAMS) in 1986–1990, an experimental base for producing surface and remote sensing observations was also established in the Beijing–Tianjin–Hebei region. In this experiment, a mesoscale weather monitoring and nowcasting system that could accomplish collection and analysis of radar data, mesoscale automatic weather station data, and other observations within one hour, and provide support for 0–3-h objective prediction was successfully developed into experimental operation at the Beijing Meteorological Bureau. The techniques for rapid collection and comprehensive analysis of multiple types of data were then incorporated into similar experiments in other provincial bureaus such as Fujian, Guangdong, Shanghai, Hubei, and Anhui (Zhou, 2006).

In the 1990s, empirical forecasting and NWP model prediction were developed simultaneously, and they were used in operational settings independently. The empirical forecasting of SDHR, hails, and thunderstorm high winds based on comprehensive subjective and statistical analyses of pre-convection synoptic situations, radar echo characteristics, and climatological characteristics of SCW, was gradually established at many local meteorological bureaus (Wang, 1996). At the same time, efforts were made by the Shanghai Meteorological Bureau to develop a routine operation for very short range forecasting of SCW by utilizing mesoscale NWP model prediction results (Yao and Huang, 2000).

3.2 *Technologies and scientific understanding beneficial to operational forecasting*

An extremely heavy rainfall event struck the upper reaches of the Huaihe River in the south of Henan Province during 5–7 August 1975, bringing a catastrophic flooding that killed tens of thousands of people. Since then, many field experiments have been conducted with the focus on MCSs and their prediction techniques (Tao et al., 1979; Tao and Ding, 1981; Writing Group of "Pre-Rainy Season Heavy Rainfall in South China," 1986). At the same time, the CMA built up four mesoscale experimental bases in the Pearl River Delta, the Yangtze River Delta, the middle reaches of the Yangtze River basin, and the Beijing–Tianjin–Hebei region. In the 1990s, several provincial mesoscale meteorological bases were also set up in Fujian, Beijing, Shanghai, and Shenzhen. Based on these field observations and scientific experiments, the environmental conditions of SCW were widely investigated in the 1980s (Ding et al., 1982; Xu, 1982; Yang, 1983; Zou and Tao, 1984; Yu et al, 1985; Cai et al., 1988). The formation and development of the synoptic circulation, the thermal and dynamic conditions of the SCW, as well as the influence of low-level jets and the underlying surface on SCW were better understood. Prediction methods associated with the use of numerical models were also developed.

In the late 1970s, an energy analysis method was proposed for severe weather analysis and prediction. It used sounding data to examine vertical instability, and surface observations were incorporated to analyze energy fronts (mesoscale fronts) (Lei et al., 1978; Lei, 1980). Potential SCW occurrence was estimated by examining the vertical profiles of the dry air, wet air, and saturated wet air, and analyzing the atmospheric instability based on the air-parcel lifting theory with radiosonde data analysis. The simple and effective tool for forecasting and analyzing the potential for SCW, called the three-line chart by Chinese forecasters, was very popular in many local meteorological bureaus in the 1980s and 1990s. Tao (1980) and Ding et al. (1981) outlined the favorable conditions and synoptic-scale situations for SCW, and Ding et al. (1981) further showed the differences in these conditions between heavy rain processes and SCW events. Ding et al. (1982) proposed four types of synoptic circulations that are favorable for the occurrence of squall lines: rear of trough, front of trough, rear of high pressure, and inverted trough (inverted typhoon trough or easterly waves). He also revealed the important features of SCW in sounding plots, such as a low-level temperature inversion, and a moisture profile characterized by wetter lower layers and dryer upper layers—which are still used in short-range forecasting of SCW in China. Chen (1984) analyzed the environmental conditions for large hails in the Beijing–Tianjin area and found that the cold vortex is the main synoptic system favorable for the occurrence of hail in this area.

During this period, radar data were more extensively used to explore the major characteristics and identification methods associated with hailstorms and heavy rainfalls (Ge, 1979; Yang and Guo, 1981). The studies on radar echo characteristics of hailstorms progressed from case analyses to statistical investigations of a number of cases (Yang et al, 1980). The major characteristics of radar echoes of supercells and hailstorms were presented, such as bounded weak echo regions and hook echoes (e.g., Yang et al., 1980; Wang and Xu, 1983, 1985). Based on research findings in the 1970s, the Chinese journal *Meteorological Monthly* published 12 papers on meteorological applications of radars in the early 1980s. These findings are helpful for forecasters to better understand the features of SCW (Ge, 1982).

NWP models developed rapidly in the 1980s and 1990s (Benjamin et al., 2018). Based on NWP model outputs, the method of ingredients-based forecasting that can diagnose environmental conditions favorable for SCW became widely used in SCW forecasting (Doswell III et al., 1996; Brooks et al., 2019). Under the international trend, the NWP outputs were also applied to very short-range prediction of SCW in China in the late 1980s. The favorable dynamic and thermal conditions of convection diagnosed from numerical model outputs and the movement and intensity of the MCSs obtained from the satellite cloud images and radar echoes were sorted out as prediction factors, and the equations governing the SCW short-range prediction and for estimating the potential for SCW were established as well (Xu et al., 1988; Zhang, 1991).

4. Stage 3: Nationwide operational forecasting in the 21st century

4.1 *Status of SCW forecasting*

Since 2000, a series of monographs on SCW forecasting have been published in China (Yu et al., 2006; Zhang, 2011; Xu, 2012; Sun et al., 2014; Zhang X. L. et al., 2019). Advances in the principles and operational application of weather radar (Yu et al., 2006), knowledge of the climatological characteristics and formation mechanisms of SCW, and the basic principles and analysis methods for short-range forecasting and nowcasting of SCW (Zhang, 2011; Xu, 2012; Sun et al., 2014) were revealed. This greatly improved forecasters' understanding of convective initiation, convection intensity, and convective weather types. Based on the improved understanding and operational experiments developed over past several decades, operational forecasting of SCW has been conducted nationwide since 2009, when the Severe Weather Prediction Center (SWPC) of the NMC was established. The SWPC has been serving as the national center for SCW forecasting since its establishment. Monitoring and warning of thunderstorms, SDHR, thunderstorm high winds, and hails are achieved, and their potential forecasting can be issued up to three days in advance (Zheng et al., 2015; Zhang et al., 2018). The establishment of the nationwide operational forecasting system for SCW demonstrates that the SCW forecasting in China has entered a new era.

4.1.1 *SCW monitoring*

Since its establishment in 2009, the SWPC has developed a comprehensive operational system to monitor SCW and provide analysis products to forecasters based on data from radars, satellites, and conventional and unconventional surface observation stations. Quality control techniques are applied to automatic weather station data, and extraction techniques and statistical analysis are applied to SCW prediction. Other techniques implemented by the SWPC include the Cartesian Tracking Radar Echoes by Correlation (CTREC), the Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN), the deep convective cloud identification technology, the MCS identification and tracking technology, and the lightning density monitoring technology, etc. (Zheng Y. G. et al., 2013).

4.1.2 *Nowcasting and warning of SCW*

In 2004, the CMA incorporated warnings of thunderstorm high winds [Beaufort scale 7 (blue), 9 (yellow), 11 (orange), and 12 (red)] and warnings of hails into its warning system for sudden hazardous meteorological events, and further standardized its operational warning (China Meteorological Administration, 2004). This marks the official beginning of operational warning for SCW in China. In 2007, lightning warning signals were also added into the warning system (China Meteorological Administration, 2007). In 2013, the NMC began to issue nationwide warning for SCW that can be valid up to 24 h. However, the responsibility for issuing SCW warning to the public in China is mainly taken by local meteorological bureaus in different counties and cities. Figure 5 shows the statistics of valid lead time for the red warning signals of lightning and hails issued by local meteorological bureaus in China from 2013 to 2019. Although there are no warning signals for thunderstorm high winds and SDHR in China, the evaluation result of the red warning signals of lightning and hails, which are likely to cause disasters over the following two hours, can roughly indicate the ability of SCW warning. Generally, the lead time of SCW warning is less than 1 h, and the average lead time of hail warning is less than 20 min. However, the assessment results since 2013 show that the SCW warning ability has been gradually improved in recent years. For instance, the lead time of red warning signals of hail in 2013 was less than 5 min, and it has been extended to more than 15 min since 2016.

The SWPC started an experiment in 2015 to investigate issues related to SCW watch that is valid for no more than 6 h. This experiment led to quasi-operational forecasting of SCW in 2018. The SCW watches are issued on a need basis to indicate regions that have conditions favorable for SCW. The SWPC typically issues these watches only when a nationwide SCW warning valid for one day has already been issued, or when a disastrous threat related to severe local convection is highlighted. These SCW watches provide updated information on SCW locations and the risk categories of extreme SCW events, including SDHR with hourly precipitation larger than 50 or 80 mm, wind gusts with speed exceeding the Beaufort scale 10 or 12, hails with diameters of over 20 or 50 mm, or any tornado that is expected to occur. Figure 6 illustrates an SCW watch issued by the SWPC during a squall-line process that occurred in Jiangxi

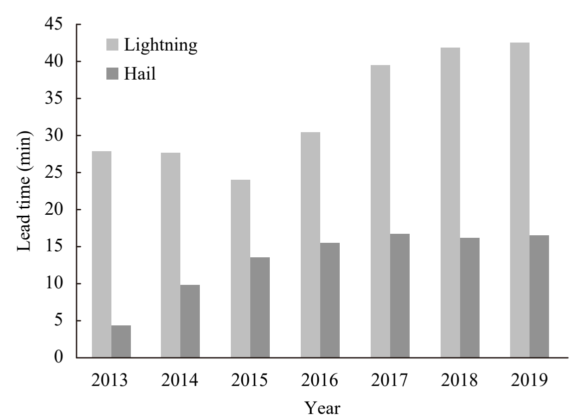


Fig. 5. The lead time of the red warning signals of lightning and hail issued by local meteorological bureaus in China from 2013 to 2019. Information of lead time of the red warning signals of lightning and hail issued by the CMA since 2013 is available at http://10.1.64.154/FIMS/WEB/ybyc/ybjy.html.

Province on 4 March 2018.

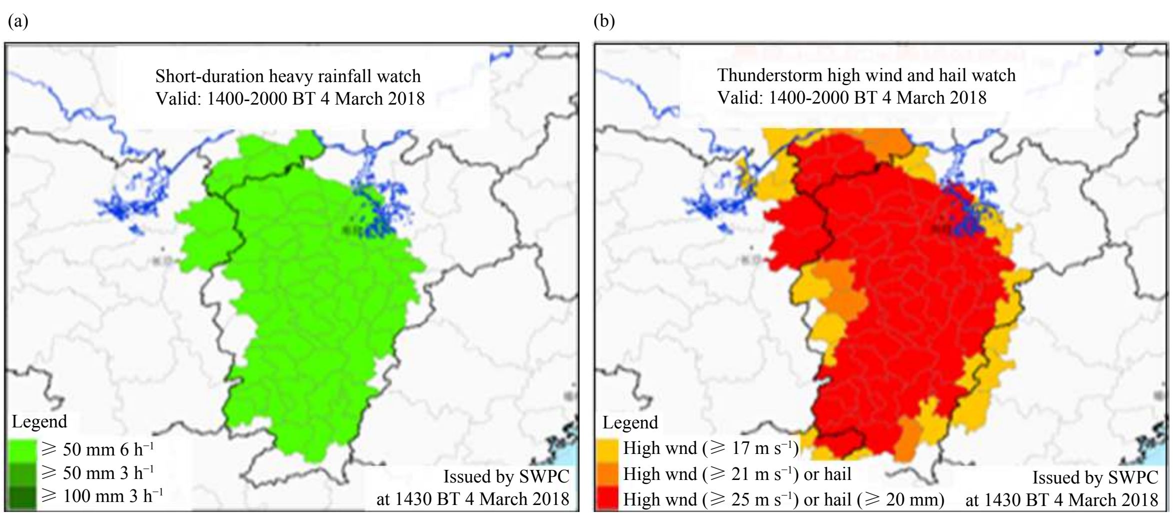
Due to the occurrence of several violent tornadoes over the past several years, the CMA launched experiments for operational monitoring and warning of tornadoes and extreme wind gusts. For example, an experiment for tornado and extreme wind-gust monitoring and warning was jointly conducted by the SWPC and provincial meteorological bureaus of Jiangsu, Anhui, Hubei, Zhejiang, and Guangdong in 2017. In 2018, tornado warnings triggered by a landfalling typhoon were issued by the Tornado Research Center in Foshan, Guangdong Province (Li C. L. et al., 2018), which represented a rather bold prediction. Nevertheless, due to the extremely rare occurrence of tornado in China, as well as insufficient operational observation systems and monitoring technologies for microscale convective weather such as tornadoes, intense downbursts, and extreme wind gusts, it is difficult to implement nowcasting and warning of the microscale convective weather events over an area as vast as China.

4.1.3 *Short-range forecasting of SCW*

Doswell et al. (1996) proposed an ingredients-based method for SCW forecasting based on the fact that deep moist convection can only develop under the support of conditional instability, sufficient water vapor, and uplifting conditions. A predictive method for potential SCW that combines the above convection conditions with vertical wind shear has gradually become the main method for short-range forecasting of SCW in China (Zhang X. L. et al., 2010, 2012). Accordingly, an objective method for classified SCW forecasting was derived from the "ingredients-based method" by Tian et al. (2015) at the SWPC.

The ingredients-based method benefits from scientific understanding of the environmental conditions required for the development of SCW, yet it is limited by the insufficient understanding of SCW mechanisms at present. Therefore, artificial intelligence (AI) technologies such as deep learning have also been applied for classified SCW forecasting at the SWPC (Zhou et al., 2019). Combining the ingredient-based method and deep learning method, an outlook valid for three days currently represents the optimal SCW operational forecast.

In 2009, the SWPC began to issue deterministic and probabilistic forecasts of classified SCW events (thunderstorms, hails, thunderstorm high winds, and SDHR) one day in advance for the period from April to September. The forecast is issued 3 times per day at 0600, 1100, and 1800 BT, while two- and three-day deterministic forecasts are issued once per day at 1800 BT. Figure 7 presents an example of the 0800–2000 BT SCW probabilistic and deterministic forecasts for thunderstorms,



(c) Categorical prediction for extreme SCW events

SCW type	SDHR (⩾ 50 mm h^{-1})	SDHR (⩾ 80 mm h^{-1})	Thunderstorm high wind (⩾ 25 m s^{-1})	Thunderstorm high wind or tornado (⩾ 32 m s^{-1})	Hail (⩾ 20 m s^{-1})	Hail (⩾ 50 mm)
Risk	Moderate	Marginal	Enhanced	Moderate	Enhanced	Slight

Fig. 6. Locations and risk categories in an SCW watch of (a) SDHR, (b) thunderstorm high winds and hails, and (c) risk probabilistic prediction of extreme SCW event for the period 1400–2000 Beijing Time (BT), issued at 1430 BT on 4 March 2018.

hails, thunderstorm high winds, and SDHR issued at 0600 BT 21 September 2017.

Figure 8 presents the threat score (TS) for short-range forecasts of four types of SCW issued by the SWPC during 2010–2018. The SCW short-range forecasting ability has improved remarkably during this 10-yr period, especially for thunderstorms and SDHR. The improvement in the prediction is mainly attributed to the better prediction ability for the SCW associated with well-organized severe MCSs, such as squall lines. A good example is the SCW caused by squall lines that occurred in southern China on 4 March 2018 (Fig. 9). The intense squall lines swept across the regions south of the Yangtze River, bringing widespread SDHR, thunderstorm high winds, and hails from the afternoon to the next morning. The terminal of the Nanchang Airport in Jiangxi Province was damaged by the gust wind that exceeded 30 m s^{-1} at 1530 BT on 4 March. Based on real-time monitoring and

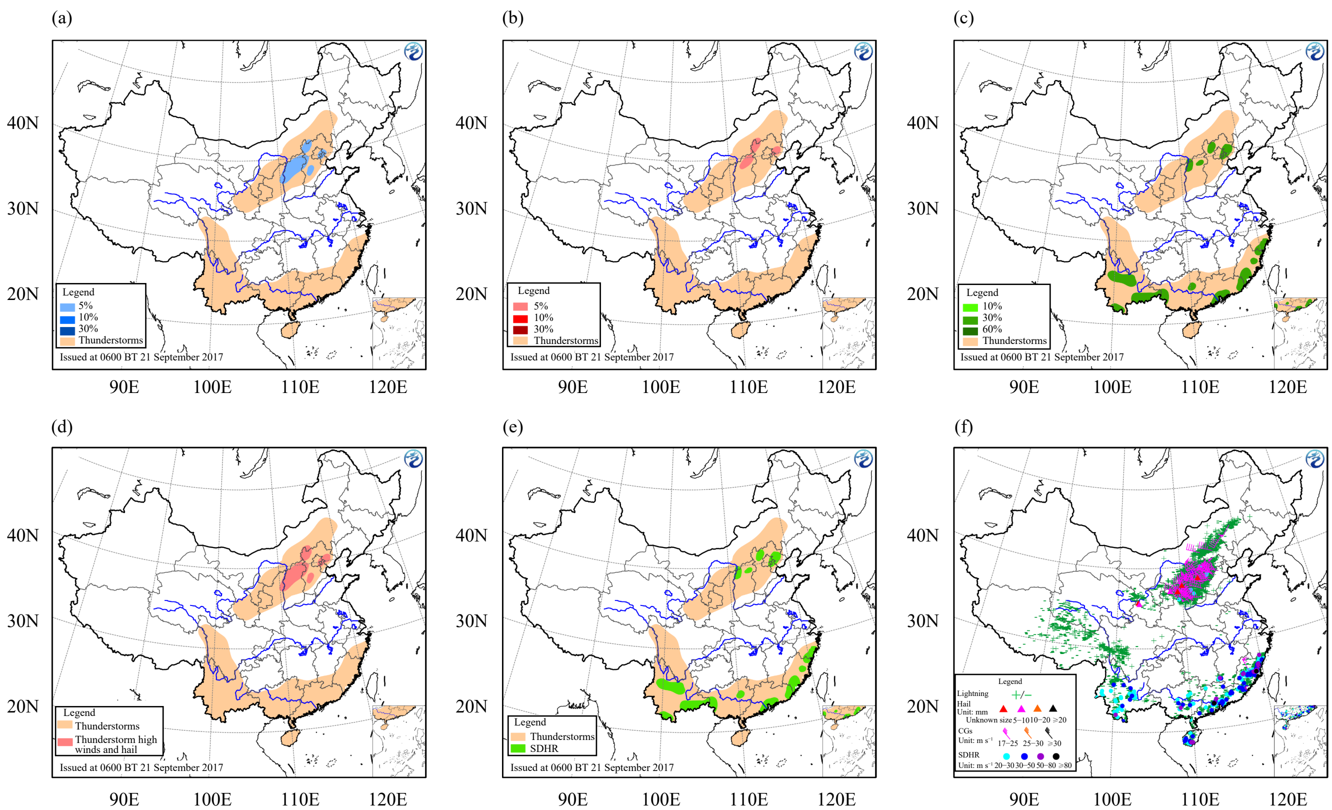


Fig. 7. Probabilistic forecasts of (a) thunderstorm high winds, (b) hails, and (c) SDHR; and deterministic forecasts of (d) location of thunderstorm high winds and hails and (e) location of SDHR in China for 0800–2000 BT 21 September 2017, issued at 0600 BT on the same day. (f) Observed SCW events during 0800–2000 BT 21 September 2017. CGs in the legend of (f) denote convective wind gusts.

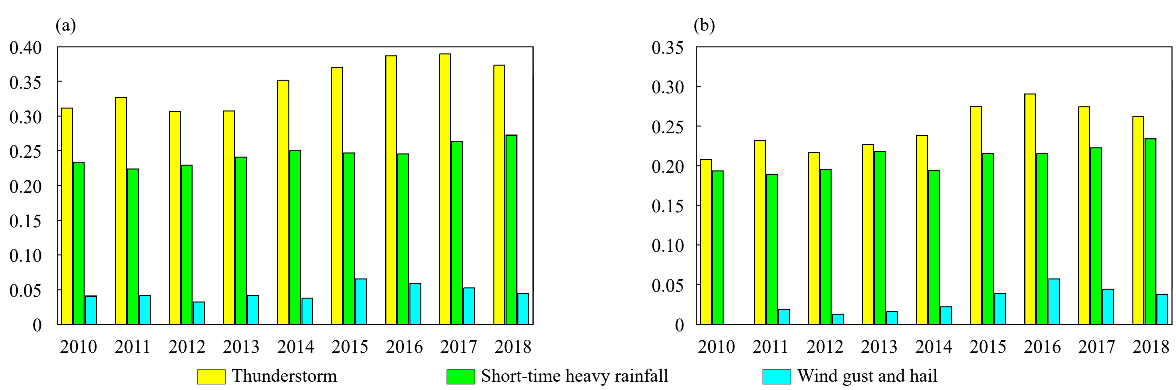


Fig. 8. Annual threat scores for (a) 12-h and (b) 24-h forecasts of thunderstorms, SDHR, thunderstorm high winds, and hails during the period of 2010–2018 at the SWPC of the NMC.

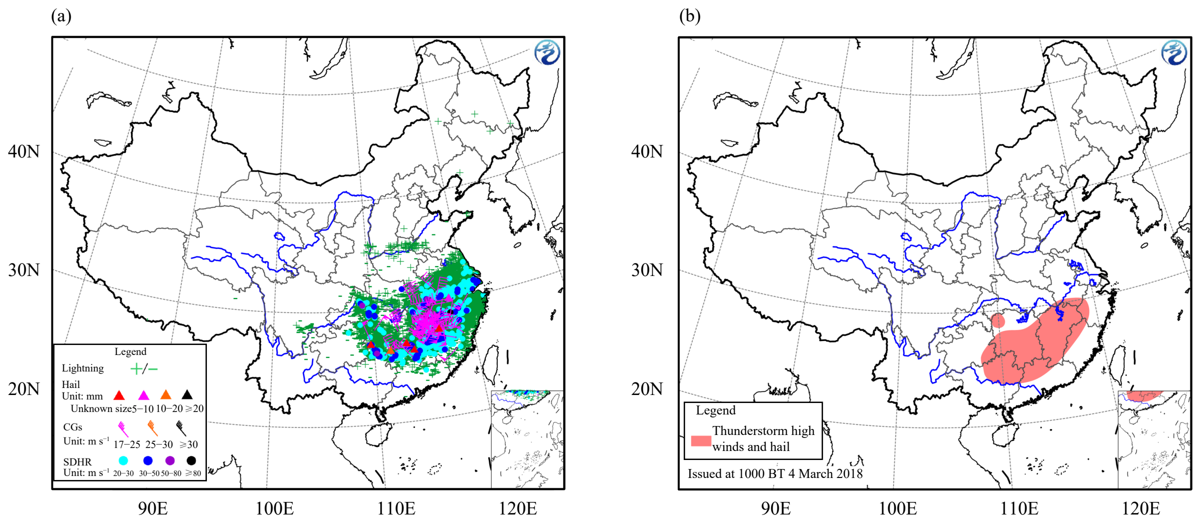


Fig. 9. (a) Observed SCW events during 1400 BT 4–1400 BT 5 March 2018 and (b) the yellow-level warning for thunderstorm high winds and hails issued by the SWPC at 1000 BT 4 March 2018. CGs in the legend of (a) denote convective wind gusts.

analysis of the developments of the MCSs and their environmental conditions with multiple types of observations and NWP outputs, the SWPC issued a 24-h SCW yellow-level warning at 1000 BT on 4 March (Fig. 9b) and a 6-h SCW watch at 1400 BT on 4 March of high risk of thunderstorm high winds that may exceed Beaufort scale 10 (25 m s^{-1}) and of hails with a diameter of no less than 20 mm at county-size resolution (Fig. 6), which served as a guidance for local meteorological bureaus to issue warning signals of lightning, thunderstorm high winds, hails, and rainstorms.

On the whole, the forecasting performance of thunderstorm high winds and hails is much poorer than those of thunderstorms and SDHR (Fig. 8). The SWPC and local meteorological bureaus still have relatively low prediction skill to forecast the sudden occurrence of SCW caused by local small-scale convective systems, such as the extreme heavy rainfall event caused by a meso-γ-scale convective system in Guangzhou city on 7 May 2017 with maximum 4-h accumulated precipitation of more than 400 mm.

4.2 *Technologies and scientific understanding beneficial to operational forecasting*

Doppler radar observations have become important for SCW forecasting and nowcasting. For instance, they have been used in nationwide SCW operational forecasting to identify storm rotations (i.e., mesocyclones or meso-vortices), which are important for detecting and estimating convective gusts and tornadoes. The success of the USA WSR-88D radar network, along with the extremely catastrophic Yangtze River flooding event in 1998, promoted the construction of the CINRAD network in China (Xu, 2003). CINRAD, an observation network consisting of 216 Doppler weather radars in S (10 cm) and C (5 cm) bands was constructed by the CMA starting in 1998. By 2018, an observational system consisting of 214 Doppler radars, 8 operational Fengyun meteorological satellites, and more than 57,000 automatic weather stations had been established (Fig. 10).

The quality control of the CINRAD data (Liu and Ge, 2006; Liu et al., 2006), the three-dimensional mosaicking technology (Xiao and Liu, 2006; Xiao et al., 2008), the wind field retrieval technology (Liu et al., 2005), and the nowcasting of SCW based on echo tracking (Zhang et al., 2006) have been developed rapidly. These technologies have provided valuable support to the current operational SCW nowcasting.

Current nowcasting of SCW depends mainly on radar echo-based extrapolation forecasting technology (Chen et al., 2007; Liang et al., 2010; Cao et al., 2015), such as SCIT (Storm Cell Identification and Tracking), TITAN,

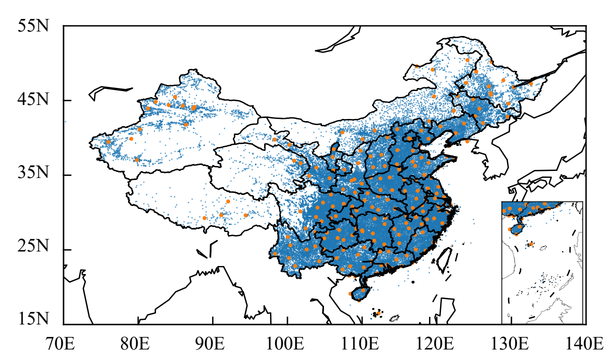


Fig. 10. Surface automatic weather stations (blue dots) and radar stations (red dots) in China.

and CTREC techniques. This technology has been widely used in the nowcasting systems such as Severe Weather Automatic Nowcasting (SWAN), which is developed collaboratively by the NMC and provincial meteorological bureaus (Han and Wo, 2018), Short-range Warnings of Intense Rainstorm of Localized Systems (SWIRL) and SWIRL-II at the Hong Kong Observatory (Li et al., 2014), and Beijing Auto-Nowcasting (BJ-ANC) system for convective storms (Chen M. X. et al., 2010), which was used during the 2008 Beijing Olympic Games. These nowcasting systems were mainly used for automatic tracking of the movement of radar echoes and for the 0–2 h quantitative precipitation forecast (QPF). By monitoring multiple parameters in real time (such as radar echoes and vertical liquid water content), these forecasting systems can identify and automatically issue quantitative information, e.g., hail index, short-range QPF, etc., and qualitative information on possible occurrences of mesocyclones, tornado vortex signatures (TVSs), and so on. Specifically, for example, under the support of the Severe Weather Alert and Track Comprehensive (SWATCH) nowcasting system, the forecasters of the Jiangsu Meteorological Bureau issued several warnings for tornado events.

A significant tornado event struck Funing County, Jiangsu Province during 1414–1530 BT 23 June 2016 (Fig. 11). The forecasters at the Jiangsu Meteorological Bureau identified an embryonic tornado using SWATCH and subsequently guided the Funing County Meteorological Office to issue an urgent tornado warning to the public at 1439 BT (Fig. 11a; Wang X. H. et al., 2018).

With the deployment of the CINRAD, many statistical studies can be conducted with a focus on the convection organization categories and their evolution based on Doppler weather radar observation data. Meng et al. (2012, 2013) analyzed the climatology of the squall lines preceding landfalling tropical cyclones and the midlatitude squall lines in eastern China, and compared their features with the squall lines in the USA. Zheng L. L. et al., (2013) explored the radar organizational modes of SCW

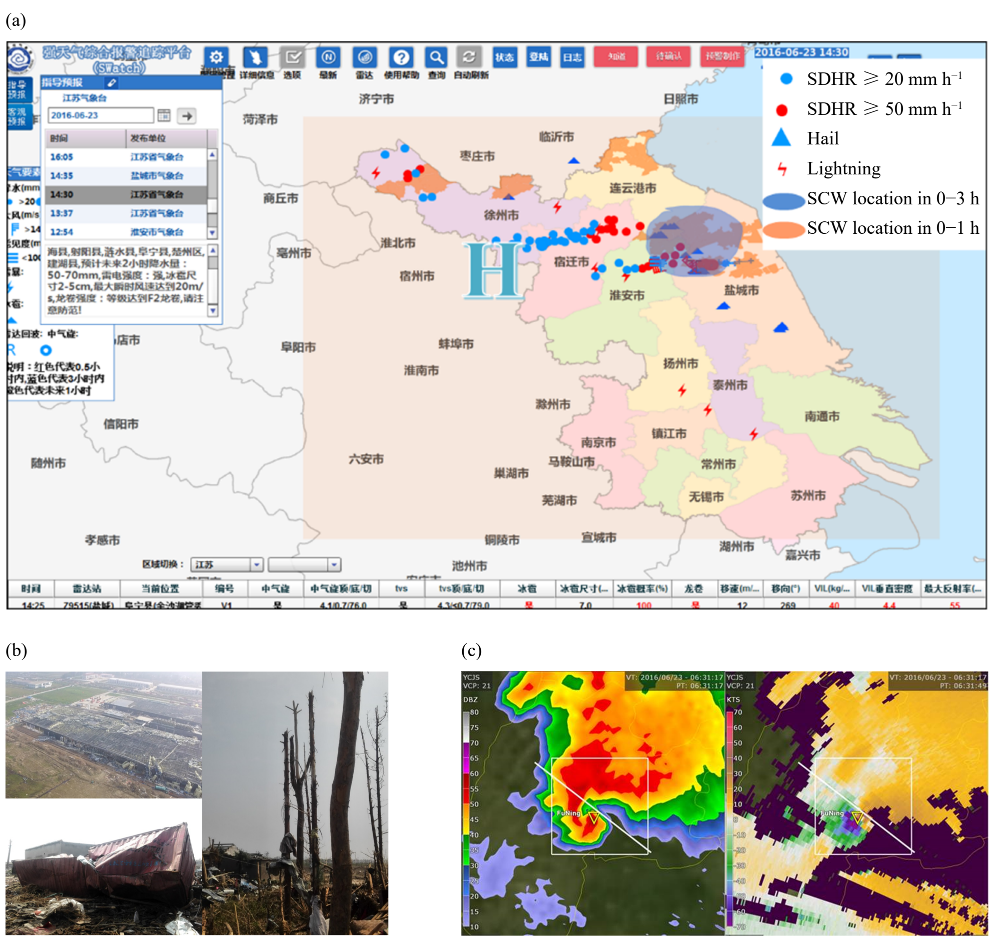


Fig. 11. (a) Screenshot of the user interface of the SWATCH platform at 1430 BT 23 June 2016 [adapted from Wang X. H. et al., 2018], (b) photos of the damages brought by the tornado in Funing county [adapted from Zheng et al. (2016b)], and (c) Yanchen radar reflectivity (left panel, unit: dBZ) and radial velocity (right panel, unit: kts h^{-1}, 1 kts $h^{-1} \approx 0.5$ m s^{-1}) at 0.5° elevation [adapted from Zhang X. L. et al. (2016)].

in the Yangtze–Huai River valley. Some studies found that the triggering conditions and different organizational modes of convection are related to environmental stratification, water vapor saturation level, and vertical wind shear (Meng et al., 2013; Zheng L. L. et al., 2013; Yang and Sun, 2018). Compared with the squall lines in the USA (Bluestein and Jain 1985; Parker and Johnson 2000; Schumacher and Johnson, 2005), the squall lines in eastern China occur in more humid atmospheric environments with weaker vertical wind shears (Meng et al., 2013; Zheng L. L. et al., 2013); however, convection can still appear in dry environments and under strong vertical wind shears (Zheng L. L. et al., 2013; Yang and Sun, 2018). These findings could improve the accuracy of forecasts of SCW induced by squall lines.

In the 1980s, Maddox (1980, 1983) and Maddox et al. (1981) used satellite data to study the life cycle of thunderstorms and proposed criteria for Mesoscale Convective Complexes (MCCs) and MCSs. As SCW in China has been related to the development of deep convective systems (Zheng and Chen, 2013; Zheng et al., 2016a; b), numerous studies of MCCs and MCSs have been carried out by Chinese researchers since the launch of the FY geostationary meteorological satellites (Jiang and Fang, 2002; Fang and Qin, 2006; Fei et al., 2008; Zheng et al., 2008; Yang et al., 2011; Zheng, 2011; Li and Fang, 2012; Qin and Fang, 2014; Yang and Sun, 2018). Research on the identification of convective initiation, the tracking of convection, and the SCW nowcasting technology by comprehensively using the satellite data and other observation data has also been carried out in recent years (Cao et al., 2013; Liu and Jiang, 2013; Qin and Fang, 2014; Ai et al, 2016; Liu et al., 2019).

The progress of the SCW forecasting is closely related to forecasters' understanding of the rules that determine the occurrence and development of SCW. The improved understanding is driven by several catastrophic heavy rainfall and SCW events caused by intense MCSs that attracted extensive public attention. Since the occurrence of the torrential rainfall in Zhumadian City, Henan Province, in August 1975 (called the "75.8" torrential rainfall event), Chinese researchers have paid more attention to large-scale circulation conditions and related mesoscale convection that can produce heavy rainfall (Tao, 1980; Zhou et al., 1984, 1988; Ding, 2015). Figure 12 is adapted from Ding (2015). It shows an meso-α-scale conceptual model of the "75.8" typhoon rainstorm. In another example, Meng and Zhang (2012) found that squall lines preceding tropical cyclones occur most frequently in the transition zone between the typhoon and the subtropical high (Fig. 12b). The major flooding in the Yangtze River valley in 1998 promoted more studies on meso-α- and meso-β-scale systems (Ni and Zhou, 2006). The sinking of the "Oriental Star" cruise ship in 2015 (Zheng et al., 2016a) and the EF4 Tornado in Funing County in 2016 (Zhang X. L. et al., 2016; Zheng et al., 2016b) accelerated the SCW research in China to advance from meso-α- and meso-β-scale to meso-γ-scale systems (Xue, 2016). Based on damage surveys and radar observation analyses, the generation, development, and damage characteristics of tornadoes and downbursts have been studied in recent years (Meng and Yao, 2014; Meng et al., 2016; Bai et al., 2017;Yao et al., 2019). Bai et al. (2017) carried out a comprehensive damage survey and radar analysis of the EF3 tornado caused by Typhoon Mujigae in Foshan, Guangdong Province on 4 October 2015. They revealed the damage distribution and near-surface wind features of the tornado. The three-dimensional structure of a meso-γ-scale tornado was simulated by Yao et al. (2019; Fig. 12c).

Since 2000, non-hydrostatic regional NWP models have enabled the high-resolution simulation of convective storms, due to the progress in data assimilation techniques for radar, satellite, and other fine-spatiotemporal-resolution data (Benjamin et al., 2018). By rapidly updating the predictions, CRNMs could improve the predictive ability of the diurnal cycle and propagation of convective systems. CRNMs have been applied to SCW forecasting at the Storm Prediction Center (SPC) of the USA since 2010 (Clark et al., 2012, 2013). Application of the CRNMs is also important in establishing national and local severe weather warning system in China. In 2019, the mesoscale NWP version of the Global and Regional Assimilation and PrEdiction System (GRAPES-Meso) developed by the Numerical Weather Prediction Center of CMA, which has a horizontal resolution of 3 km and covers the whole China, was implemented for operational forecasting. In the next section, we will highlight some applications of the predictions of CRNMs, such as the 3-km resolution GRAPES-Meso, in SCW forecasting in China.

5. Recent highlights and future work

With the continuous research on SCW and the gradual improvement of China's meteorological observation networks over the past 70 years, understanding of SCW from the synoptic-scale environmental conditions to meso-α- and meso-β-scale mechanisms has gradually deepened in China. In recent years, this understanding has also been extended to meso-γ-scale convective systems. Operational SCW warnings valid for tens of

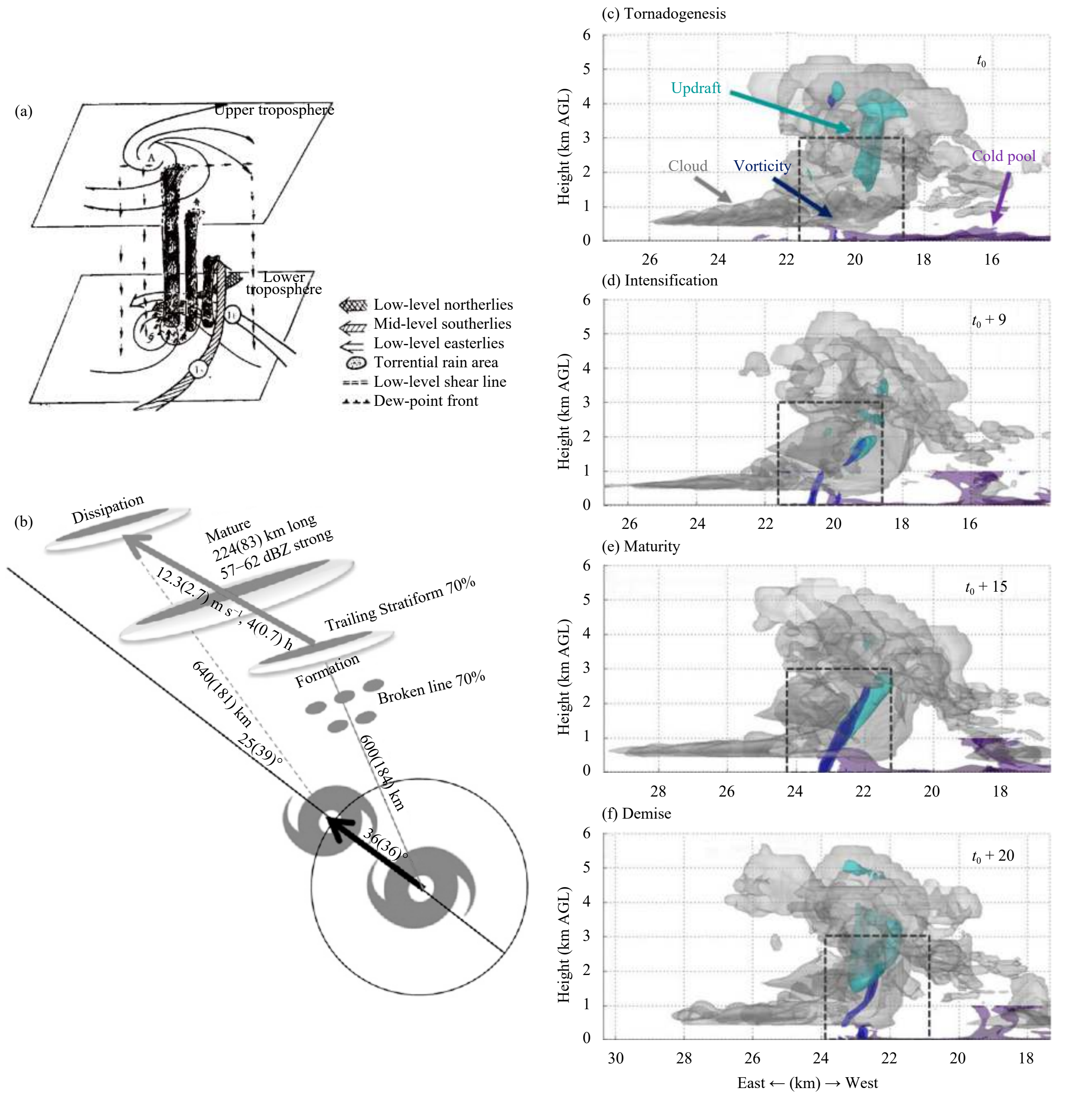


Fig. 12. (a) Three-dimensional weather system model explaining the generation and development of the "75.8" torrential rainfall event induced by a tropical cyclone [adapted from Ding (2015)]. (b) Schematic diagram of pre-tropical cyclone squall lines [adapted from Meng and Zhang (2012)]. (c) Three-dimensional demonstration of the simulated tornado and cumulonimbus clouds in the Beijing tornado event on 21 July 2012 [adapted from Yao et al. (2019)].

minutes and SCW outlooks valid for three days have been developed, and they are gradually becoming more precise and accurate. However, the ability of the operational SCW forecast system for the prediction of thunderstorm high winds and hails remains slow (Fig. 8), and very short-range forecasting (2–6 h) of SCW is still in the development stage. The ability to monitor and issue warnings for meso-γ-scale SCW events such as tornadoes is also limited. It will be a challenging issue to fully overcome these forecast shortcomings over the next 10 years, but it is expected that the performance of the SCW forecast system can be improved through the application of new monitoring technologies, CRNM forecasts, and AI technologies.

5.1 *New monitoring and warning technologies for SCW*

At present, the CINRAD network, which provides 6-min-interval and 9-level scanning data, is much limited in its applicability. The operational application of WSR-88D dual polarization radars in the USA shows that radar network has great potential to improve hail and tornado observations, quantitative precipitation estimation (QPE), and warnings of SCW (Zhang G. F. et al., 2019). At present, the application of dual-polarization Doppler radars in China is still in its initial stages. Since 2013, the operational Doppler radars in Guangdong, Shanghai, and Anhui provinces have been upgraded to dual-polarization Doppler radars (Zhao et al., 2019). The CMA plans to complete the construction of the radar network and upgrade all the operational radars to dual-polarization Doppler radars by 2025. Studies by Chinese researchers have shown that dual-polarization radar can better detect heavy precipitation and hails generated by MCSs (Zhang J. et al., 2010; Guo and Guo, 2016; Liu L. P. et al., 2016; Wu et al., 2018; Yang et al., 2019; Zhao et al., 2019). Various approaches like quality control of observational data (Xiao et al., 2012; Du et al., 2013), precipitation particle phase recognition (Hu et al., 2015), and QPE and QPF (Zhao et al., 2019) are gradually incorporated into the operational forecast system. The X-band phased array weather radar experiment in China showed that the 1-min-interval data are very helpful for further understanding the evolution of meso-γ- and microscale convective systems. Therefore, the deployment of X-band phased array weather radars in a few large cities with high-frequency occurrences of convection will enhance the SCW warning capability at these cities in the future (Liu L. P. et al., 2016).

The new generation geostationary meteorological *FY-4A* satellite launched by China in 2016 has infrared hyperspectral vertical detection and lightning imaging observation capabilities, which represents a milestone in the monitoring and warning of SCW (Zhang P. et al., 2016). The finest horizontal resolution of the *FY-4A* visible image is 0.5 km, and the time intervals of full disk images and regional images are 15 and 3–5 min, respectively (Lu et al., 2017). This dataset will greatly enhance the monitoring capabilities of meso- and microscale SCW systems.

5.2 *Development and application of convection-resolving numerical models (CRNMs)*

Predictions of rapid-refresh CRNMs with data assimilation have become important for extending the forecast lead time of SCW warnings during the last 10 years (Clark and Coniglio, 2014; Wheatley et al., 2015; Gallo et al., 2016). By developing the GRAPES_Meso model and localizing the Weather Research and Forecasting (WRF) model, China has also developed several CRNMs with rapid-refresh assimilation capability (Fan et al., 2009; Chen Z. T. et al., 2010; Chen M. X. et al., 2011; Xu et al., 2013; Liu L. et al., 2016; Huang et al., 2017).

Integrating radar echo extrapolation technology with CRNM predictions is the principal method for extending the very short-range forecasting to over 2 h (Wilson et al., 1998; Wolfson et al., 2008; Yu et al., 2012). In China, technologies for 6-h precipitation prediction have been developed, which are based on a combination of radar extrapolation and outputs of rapid-refresh CPNMs with data assimilation (Cheng et al., 2013; Chu et al., 2017). Great efforts have also been made to improve the four-dimensional variational Doppler radar analysis system (VDRAS) to make it suitable for real-time rapid-refresh application. A nowcasting system that combines high-spatiotemporal-resolution radar data with CRNM outputs has been developed and preliminarily applied over the Beijing–Tianjin–Hebei region (Chen et al., 2016; Liu L. et al., 2016).

Although CRNMs, to a certain extent, can simulate and forecast MCSs, they are certainly unable to accurately predict SCW events in China (Zheng et al., 2015). Therefore, new prediction methods for tornadoes, hails, and thunderstorm high winds need to be developed based on the combination of CRNM predictions with information of dynamical characteristics, cloud physical processes, and environmental parameters obtained from statistical studies that can more accurately describe the triggering and evolution of MCSs (Clark et al., 2012, 2013; Clark and Coniglio, 2012; Jirak, 2014; Gallo et al., 2016). The key to enhance the capability of very short-range SCW forecasting over the next few years is to develop technologies that can interpret the results of rapid-refresh CRNMs with data assimilation.

5.3 *Artificial Intelligence (AI) technology in SCW forecasting*

Deep learning techniques, such as convolutional neural network (CNN), have been used in nowcasting of radar echoes and quantitative precipitation (Klein et al., 2015; Shi et al., 2015). In 2017, researchers at Tsinghua University proposed the recurrent neural networks for predictive learning model for radar echo prediction. Prediction experiments have shown that it is much better than other popular prediction models used worldwide (Wang Y. B. et al., 2017, 2018). As mentioned above, Zhou et al. (2019) applied a deep CNN to successfully implement a probabilistic forecasting model of classified SCW, which has provided an important operational guidance for SCW forecasting at the SWPC.

In the future, novel methods such as the application of AI technology to the forecasting and nowcasting of SCW by mining information on the occurrence and development of severe convection from multi-source observations and CRNM outputs should be further improved and developed to significantly improve the SCW prediction capability.

6. Concluding remarks

Forecasting of SCW except hails was seldom conducted in China before 1970. SCW forecasting experiments began in the 1970s with the deployment of a conventional weather radar network. Following the deployment of the CINRAD network, research on and forecasting of SCW events have been developed rapidly from 1998 onwards. Since 2009, operational forecasting of classified SCW, including real-time monitoring, warnings valid for tens of minutes, watches valid for several hours, and outlooks valid for three days, has been established. The performance of the operational forecast system of classified SCW events in China has been improved gradually. However, the ability for monitoring, warning, and predicting microscale convective weather events such as tornadoes remains extremely poor. The way to improve the operational forecasting is to upgrade the CINRAD network and to develop advanced nowcasting technologies and rapid-refresh fine-resolution (ensemble) CRNMs that can more effectively assimilate high-spatiotemporal-resolution observations.

SCW nowcasting in China currently relies mainly on the extrapolation of radar echoes, which is insufficient for comprehensively applying multi-source observational data and for understanding physical mechanisms. Furthermore, it is difficult to produce accurate forecasts with lead times of more than 1 h. Convective-initiation prediction techniques haven't been effectively developed yet, and the application of outputs of rapid-refresh CRNMs with data assimilation is still preliminary. With the upgrade of the dual-polarization CINRAD network, the application of data from FY-4 satellites and other new remote sensing instruments, the improvements in the rapid-refresh assimilation and CRNMs, and the application of AI technology, a more effective and seamless operational monitoring, warning, and forecasting system for SCW will be developed over the coming years.

Acknowledgments. We would like to thank the anonymous reviewers and the Editor for their constructive comments, which have helped improve the manuscript. We would also like to thank Yanan Meng and Cui Liu for working on the list of references.

REFERENCES

Ai, Y. F., W. B. Li, Z. Y. Meng, et al., 2016: Life cycle characteristics of MCSs in middle east China tracked by geostationary satellite and precipitation estimates. *Mon. Wea. Rev.*, **144**, 2517–2530, doi: 10.1175/MWR-D-15-0197.1.

Bai, L. Q., Z. Y. Meng, L. Huang, et al., 2017: An integrated damage, visual, and radar analysis of the 2015 Foshan, Guangdong, EF3 tornado in China produced by the landfalling typhoon Mujigae (2015). *Bull. Amer. Meteor. Soc.*, **98**, 2619–2640, doi: 10.1175/BAMS-D-16-0015.1.

Benjamin, S. G., J. M. Brown, G. Brunet, et al., 2018: 100 years of progress in forecasting and NWP applications. *Meteor. Monogr.*, **59**, 13.1–13.67, doi: 10.1175/AMSMONOGRAPHS-D-18-0020.1.

Bluestein, H. B., and M. H. Jain, 1985: Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring. *J. Atmos. Sci.*, **42**, 1711–1732, doi: 10.1175/1520-0469(1985)042<1711:FOMLOP>2.0.CO;2.

Brooks, H. E., C. A. Doswell, X. L. Zhang, et al., 2019: A century of progress in severe convective storm research and forecasting. *Meteor. Monogr.*, **59**, 18.1–18.41, doi: 10.1175/AMS-MONOGRAPHS-D-18-0026.1.

Cai, Z. Y., H. Z. Li, and H. A. Li, 1988: Structure and evolution of squall line systems in North China. *Scientia Atmos. Sinica*, **12**, 191–199, doi: 10.3878/j.issn.1006-9895.1988.02.11. (in Chinese)

Cao, C. Y., Y. Z. Chen, D. H. Liu, et al., 2015: The optical flow method and its application to nowcasting. *Acta Meteor. Sinica*, **73**, 471–480, doi: 10.11676/qxxb2015.034. (in Chinese)

Cao, Z.-Q., Q.-N. Huang, and S.-R. Zhao, 2013: Using satellite data to analyze the initiation and evolution of deep convective clouds. *Atmos. Ocean. Sci. Lett.*, **6**, 445–450, doi: 10.3878/j.issn.1674-2834.13.0007.

Chen, J. Q., 1984: Analysis of strong hail environment field in Beijing–Tianjin area. *Acta Meteor. Sinica*, **42**, 375–381, doi: 10.11676/qxxb1984.044. (in Chinese)

Chen, J., Y. G. Zheng, X. L. Zhang, et al., 2013: Distribution and diurnal variation of warm-season short-duration heavy rainfall in relation to the MCSs in China. *Acta Meteor. Sinica*, **27**, 868–888, doi: 10.1007/s13351-013-0605-x.

Chen, J. Y., X. H. Cai, H. Y. Wang, et al., 2018: Tornado climatology of China. *Int. J. Climatol.*, **38**, 2478–2489, doi: 10.1002/joc.5369.

Chen, L. D., 1979: Investigation of the structure and formation mechanism of arc-shaped radar echo related with hail cloud. *Meteor. Mon.*, **5**, 6–11, doi: 10.7519/j.issn.1000-0526.1979.06.003. (in Chinese)

Chen, M. X., Y. C. Wang, and X. D. Yu, 2007: Improvement and application test of TREC algorithm for convective storm nowcast. *J. Appl. Meteor. Sci.*, **18**, 690–701, doi: 10.3969/j.issn.1001-7313.2007.05.014. (in Chinese)

Chen, M. X., F. Gao, R. Kong, et al., 2010: Introduction of autonowcasting system for convective storm and its performance in Beijing Olympics meteorological service. *J. Appl. Meteor. Sci.*, **21**, 395–404, doi: 10.3969/j.issn.1001-7313.2010.04.002. (in Chinese)

Chen, M. X., S. Y. Fan, Z. F. Zheng, et al., 2011: The performance of the proximity sounding based on the BJ-RUC system and its preliminary implementation in the convective potential forecast. *Acta Meteor. Sinica*, **69**, 181–194, doi: 10.11676/qxxb2011.016. (in Chinese)

Chen, M. X., F. Gao, J. Z. Sun, et al., 2016: An analysis system using rapid-updating 4-D variational radar data assimilation based on VDRAS. *J. Appl. Meteor. Sci.*, **27**, 257–272, doi: 10.11898/1001-7313.20160301. (in Chinese)

Chen, Z.-T., Y.-Y. Huang, Q.-L. Wan, et al., 2010: Rapid updating cycle assimilation and forecasting system and its experiments and analysis in flood seasons. *J. Trop. Meteor.*, **26**, 49–54, doi: 10.3969/j.issn.1004-4965.2010.01.007. (in Chinese)

Cheng, C. L., M. X. Chen, J. J. Wang, et al., 2013: Short-term quantitative precipitation forecast experiments based on blending of nowcasting with numerical weather prediction. *Acta Meteor. Sinica*, **71**, 397–415, doi: 10.11676/qxxb2013.041. (in Chinese)

China Meteorological Administration, 2004: Tentative Measures for Issuing Warnings of Abrupt Weather Disasters. Administrative Order No. 206. Available at http://www.cma.gov.cn/2011zwxx/2011zflfg/2011zgfxwj/201110/t20111027_134927.html. Accessed on 6 August 2020. (in Chinese)

China Meteorological Administration, 2007: Meteorological Disaster Warning Information Delivery and Communication Measures. Administrative Order No. 16. Available at http://www.gov.cn/zhengce/2007-06/28/content_2602977.htm. Accessed on 6 August 2020. (in Chinese)

Chinese Academy of Meteorological Sciences, China Meteorological Administration, 1959: Supplementary forecasting in weather stations—A new method of weather forecasting. *Acta Meteor. Sinica*, **30**, 64–71, doi: 10.11676/qxxb1959.010. (in Chinese)

Chu, H., L. Chen, J. H. Dai, et al., 2017: Aspects on seamless weather forecast technologies for Shanghai city. *Adv. Meteor. Sci. Technol.*, **7**, 59–66, doi: 10.3969/j.issn.2095-1973.2017.06.007. (in Chinese)

Clark, A. J., and M. C. Coniglio, 2014: Lessons learned from 10 years of evaluating convection-allowing models in the HWT. End of 2014 Warn-on-Forecast and High-Impact Weather Workshop, Norman, OK, USA. [Available online at https://www.nssl.noaa.gov/projects/wof/documents/workshop2014/].

Clark, A. J., S. J. Weiss, J. S. Kain, et al., 2012: An overview of the 2010 hazardous weather testbed experimental forecast program spring experiment. *Bull. Amer. Meteor. Soc.*, **93**, 55–74, doi: 10.1175/bams-d-11-00040.1.

Clark, A. J., J. D. Gao, P. T. Marsh, et al., 2013: Tornado path-length forecasts from 2010 to 2011 using ensemble updraft helicity. *Wea. Forecasting*, **28**, 387–407, doi: 10.1175/waf-d-12-00038.1.

Ding, Y. H., 1978: Analysis and forecasting of severe convective weather. *Meteor. Mon.*, **4**, 15–17, doi: 10.7519/j.issn.1000-0526.1978.05.007. (in Chinese)

Ding, Y. H., 2015: On the study of the unprecedented heavy rainfall in Henan Province during 4–8 August 1975: Review and assessment. *Acta Meteor. Sinica*, **73**, 411–424, doi: 10.11676/qxxb2015.067. (in Chinese)

Ding, Y.-H., M.-L. Zhang, H.-Z. Li, et al., 1981: A comparative study on the occurrence conditions of heavy rainfall and severe convective weather. *Scientia Atmos. Sinica*, **5**, 388–397, doi: 10.3878/j.issn.1006-9895.1981.04.05. (in Chinese)

Ding, Y.-H., H.-Z. Li, M.-L. Zhang, et al., 1982: A study on the genesis conditions of squall-line in China. *Scientia Atmos. Sinica*, **6**, 18–27, doi: 10.3878/j.issn.1006-9895.1982.01.03. (in Chinese)

Doswell III, C. A., H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–581, doi: 10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2.

Du, M. Y., L. P. Liu, Z. Q. Hu, et al., 2013: An analysis of dual-linear polarimetric Doppler radar data quality. *Acta Meteor. Sinica*, **71**, 146–158, doi: 10.11676/qxxb2013.01. (in Chinese)

Fan, S.-Y., M. Chen, J.-Q. Zhong, et al., 2009: Performance tests and evaluations of Beijing local high-resolution rapid update cycle system. *Torr. Rain Disas.*, **28**, 119–125, doi: 10.3969/j.issn.1004-9045.2009.02.004. (in Chinese)

Fan, W. J., and X. D. Yu, 2015: Characteristics of spatial–temporal distribution of tornadoes in China. *Meteor. Mon.*, **41**, 793–805, doi: 10.7519/j.issn.1000-0526.2015.07.001. (in Chinese)

Fang, Z. Y., and D. Y. Qin, 2006: A review of satellite observed heavy rainfall cloud clusters. *J. Appl. Meteor. Sci.*, **17**, 583–593, doi: 10.3969/j.issn.1001-7313.2006.05.008. (in Chinese)

Fang, Z. Y., J. M. Xu, and. F. S. Zhao, 2006: Review and development on the studies of Chinese meteorological satellite and satellite meteorology. *Acta Meteor. Sinica*, **20**, 259–274.

Fei, Z. P., Y. G. Zheng, Y. Zhang, et al., 2008: MCS census and modification of MCS definition based on geostationary satellite infrared imagery. *J. Appl. Meteor. Sci.*, **19**, 82–90, doi: 10.3969/j.issn.1001-7313.2008.01.011. (in Chinese)

Fujita, T., 1955: Results of detailed synoptic studies of squall lines. *Tellus*, **7**, 405–436, doi: 10.3402/tellusa.v7i4.8920.

Fujita, T. T., 1960: A Detailed Analysis of the Fargo Tornadoes of June 20, 1957. U.S. Wea. Bur. Res. Paper 42, U. S. Wea. Bur. Res., Washington, 67 pp.

Gallo, B. T., A. J. Clark, and S. R. Dembek, 2016: Forecasting tornadoes using convection-permitting ensembles. *Wea. Forecasting*, **31**, 273–295, doi: 10.1175/WAF-D-15-0134.1.

Ge, R. S., 1966: Radar features analysis of hailstorm events in Beijing in 1964. *Acta Meteor. Sinica*, **36**, 213–222, doi: 10.11676/qxxb1966.027. (in Chinese)

Ge, R. S., 1979: A tornado process in Beijing. *Meteor. Mon.*, **5**, 33–34, doi: 10.7519/j.issn.1000-0526.1979.11.014. (in Chinese)

Ge, R. S., 1980: Radar echo characteristics of hailstorm cloud and its identification method. *Meteor. Mon.*, **6**, 19–20, doi: 10.7519/j.issn.1000-0526.1980.05.008. (in Chinese)

Ge, R. S., 1982: Lesson one—Weather radar. *Meteor. Mon.*, **8**, 33–35, doi: 10.7519/j.issn.1000-0526.1982.05.017. (in Chinese)

Guo, X. K., and X. L. Guo, 2016: Preliminary application of product from dual polarization radar in Qingyuan. *Guangdong Meteor.*, **38**, 45–48, doi: 10.3969/j.issn.1007-6190.2016.05.011. (in Chinese)

Han, F., and W. F. Wo, 2018: Design and implementation of SWAN2.0 platform. *J. Appl. Meteor. Sci.*, **29**, 25–34, doi: 10.11898/1001-7313.20180103. (in Chinese)

Hu, Z. Q., L. P. Liu, L. L. Wu, et al., 2015: A comparison of de-noising methods for differential phase shift and associated rainfall estimation. *J. Meteor. Res.*, **29**, 315–327, doi: 10.1007/s13351-015-4062-6.

Huang, L. P., D. H. Chen, L. T. Deng, et al., 2017: Main technical improvements of GRAPES_Meso V4.0 and verification. *J. Appl. Meteor. Sci.*, **28**, 25–37, doi: 10.11898/1001-7313.20170103. (in Chinese)

Institute of Gansu Meteorological Bureau, 1975: Radar echo characteristics of hail cloud. *Meteor. Mon.*, **1**, 11–12, doi: 10.7519/j.issn.1000-0526.1975.07.006. (in Chinese)

Ji, Y. H., X. Z. Wu, B. Zhou, et al., 1996: Severe convective weather monitoring and nowcasting system. *Meteor. Mon.*, **22**, 20–23. (in Chinese)

Jiang, J. X., and M. Z. Fan, 2002: Convective clouds and mesoscale convective systems over the Tibetan Plateau in summer. *Chinese J. Atmos. Sci.*, **26**, 263–270, doi: 10.3878/j.issn.1006-9895.2002.02.12. (in Chinese)

Jirak, I., 2014: SPC ensemble applications: Current status and future plans. Proc. Sixth NCEP Ensemble User Workshop, College Park, MD, USA. Available at https://www.emc.ncep.noaa.gov/gmb/ens/WkShopOct13/program/pdf/S2-01-Jirak_SPC.pdf. Accessed on 6 August 2020.

Ke, F., 1976: Meso- and micro-scale weather systems (II). *Meteor. Mon.*, **2**, 38–40, doi: 10.7519/j.issn.1000-0526.1976.09.026. (in Chinese)

Klein, B., L. Wolf, and Y. Afek, 2015: A dynamic convolutional layer for short-range weather prediction. Proc. 2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), IEEE, Boston, 4840–4848, doi: 10.1109/CVPR.2015.7299117.

Lei, X., 1976a: Detection of hail cloud using weather radars. *Meteor. Mon.*, **2**, 24–25, doi: 10.7519/j.issn.1000-0526.1976.07.019. (in Chinese)

Lei, X., 1976b: Short-range forecasting of hail. *Meteor. Mon.*, **2**, 27–28, doi: 10.7519/j.issn.1000-0526.1976.05.022. (in Chinese)

Lei, Y. S., 1980: Some aspects of severe convective storms. *Scientia Atmos. Sinica*, **4**, 94–102, doi: 10.3878/j.issn.1006-9895.1980.01.12. (in Chinese)

Lei, Y. S., B. J. Wu, and Z. H. Wu, 1978: A method for analyzing and forecasting the local severe storms in summer using the theory of instability energy. *Scientia Atmos. Sinica*, **2**, 297–306, doi: 10.3878/j.issn.1006-9895.1978.04.04. (in Chinese)

Li, C. L., K. L. Cai, X. X. Huang, et al., 2018: Characteristics and warning of Foshan tornado on the periphery of typhoon No. 1822. *Guangdong Meteor.*, **40**, 41–44. (in Chinese)

Li, J., and Z. Y. Fang, 2012: The development of satellite meteorology—Challenges and opportunities. *Meteor. Mon.*, **38**, 129–146. (in Chinese)

Li, P.-W., W.-K. Wong, P. Cheung, et al., 2014: An overview of nowcasting development, applications, and services in the Hong Kong Observatory. *J. Meteor. Res.*, **28**, 859–876, doi: 10.1007/s13351-014-4048-9.

Li, X. F., Q. H. Zhang, T. Zou, et al., 2018: Climatology of hail frequency and size in China, 1980–2015. *J. Appl. Meteor. Climatol.*, **57**, 875–887, doi: 10.1175/JAMC-D-17-0208.1.

Li, Y. L., 1978: (VI) Analysis of weather systems over the Tibetan Plateau based on satellite cloud images. *Meteor. Mon.*, **4**, 10–12, doi: 10.7519/j.issn.1000-0526.1978.04.005. (in Chinese)

Liang, Q. Q., Y. R. Feng, W. J. Deng, et al., 2010: A composite approach of radar echo extrapolation based on TREC vectors in combination with model-predicted winds. *Adv. Atmos. Sci.*, **27**, 1119–1130, doi: 10.1007/s00376-009-9093-4.

Lin, Y. H., 1979: An analysis of the heavy rainstorm of "May 1977" using radar echo and mesoscale systems. *Acta Scient. Natural. Univ. Sun-yat.*, **18**, 123–130. (in Chinese)

Liu, J., and J. Y. Jiang, 2013: Using FY-2C high temporal resolution regional scan data to monitor strong convective cloud. *Chinese J. Atmos. Sci.*, **37**, 873–880, doi: 10.3878/j.issn.1006-9895.2012.12062. (in Chinese)

Liu, L., M. X. Chen, and Y. C. Wang, 2016: Numerical nowcasting experiments for the simulation of a mesoscale convective system using a cloud model and radar data assimilation with 4DVar. *Acta Meteor. Sinica*, **74**, 213–228, doi: 10.11676/qxxb2016.021. (in Chinese)

Liu, L. P., and R. S. Ge, 2006: An overview on radar meteorology research in Chinese Academy of Meteorological Sciences for a half century. *J. Appl. Meteor. Sci.*, **17**, 682–689, doi: 10.3969/j.issn.1001-7313.2006.06.006. (in Chinese)

Liu, L.-P., Y.-Q. Mo, X.-S. Sha, et al., 2005: Radar data processing and a variational algorithm for 3-dimensional wind field retrieval by C-Band Bistatic Radar Network. *Chinese J. Atmos. Sci.*, **29**, 986–996, doi: 10.3878/j.issn.1006-9895.2005.06.14. (in Chinese)

Liu, L.-P., J.-W. Cao, Y.-Q. Mo, et al., 2006: Advanced radar technology and application on observation of disaster weathers. *J. Trop. Meteor.*, **22**, 1–9, doi: 10.3969/j.issn.1004-4965.2006.01.001. (in Chinese)

Liu, L. P., Z. Q. Hu, and C. Wu, 2016: Development and application of dual linear polarization radar and phased-array radar. *Adv. Meteor. Sci. Technol.*, **6**, 28–33. (in Chinese)

Liu, Z. J., M. Min, J. Li, et al., 2019: Local severe storm tracking and warning in pre-convection stage from the new generation geostationary weather satellite measurements. *Remote Sens.*, **11**, 383, doi: 10.3390/rs11040383.

Lu, F., X. H. Zhang, H. Liu, et al., 2017: FY-4 geostationary meteorological satellite imaging characteristics and its application prospects. *J. Mar. Meteor.*, **37**, 1–12, doi: 10.19513/j.cnki.issn2096-3599.2017.02.001. (in Chinese)

Lu, J. L., and F. W. Liu, 1983: Establishing weather joint radar network and short-term weather forecasting. *Meteor. Mon.*, **9**, 13–14, doi: 10.7519/j.issn.1000-0526.1983.06.004. (in Chinese)

Lu, W., 1935a: The movement of cold and warm airflows and a squall line on 10 June 1931. *Acta Meteor. Sinica*, **11**, 10–23, doi: 10.11676/qxxb1935.003. (in Chinese)

Lu, W., 1935b: The convective storm over the Yangtze River valley on 23 June 1935. *Acta Meteor. Sinica*, **11**, 167–178, doi: 10.11676/qxxb1935.024. (in Chinese)

Lu, W., 1935c: The cold current and squall line in the early May of 1935. *Acta Meteor. Sinica*, **11**, 217–228, doi: 10.11676/qxxb1935.032. (in Chinese)

Lu, W., 1938a: The distribution of the number of thunderstorms in eastern China. *Acta Meteor. Sinica*, 146–151, doi: 10.11676/qxxb1938.017. (in Chinese)

Lu, W., 1938b: The spring thunderstorms of the Sichuan basin. *Acta Meteor. Sinica*, 219–226, doi: 10.11676/qxxb1938.022. (in Chinese)

Maddox, R. A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374–1387, doi: 10.1175/1520-0477(1980)061<1374:MCC>2.0.CO;2.

Maddox, R. A., 1983: Large-scale meteorological conditions associated with midlatitude, mesoscale convective complexes. *Mon. Wea. Rev.*, **111**, 1475–1493, doi: 10.1175/1520-0493(1983)111<1475:LSMCAW>2.0.CO;2.

Maddox, R. A., D. J. Perkey, and J. M. Fritsch, 1981: Evolution of upper tropospheric features during the development of a mesoscale convective complex. *J. Atmos. Sci.*, **38**, 1664–1674, doi: 1175/1520-0469(1981)038<1664:EOUTFD>2.0.CO;2.

Meng, Z. Y., and Y. J. Zhang, 2012: On the squall lines preceding landfalling tropical cyclones in China. *Mon. Wea. Rev.*, **140**, 445–470, doi: 10.1175/MWR-D-10-05080.1.

Meng, Z. Y., and D. Yao, 2014: Damage survey, radar, and envir-

onment analyses on the first-ever documented tornado in Beijing during the heavy rainfall event of 21 July 2012. *Wea. Forecasting*, **29**, 702–724, doi: 10.1175/WAF-D-13-00052.1.
Meng, Z. Y., D. C. Yao, and Y. J. Zhang, 2013: General features of squall lines in east China. *Mon. Wea. Rev.*, **141**, 1629–1647, doi: 10.1175/mwr-d-12-00208.1.
Meng, Z. Y., D. Yao, L. Q. Bai, et al., 2016: Wind estimation around the shipwreck of the "Oriental Star" based on field damage survey and radar observations. *Sci. Bull.*, **61**, 330–337, doi: 10.1007/s11434-016-1005-2.
Meng, Z. Y., L. Q. Bai, M. R. Zhang, et al., 2018: The deadliest tornado (EF4) in the past 40 years in China. *Wea. Forecasting*, **33**, 693–713, doi: 10.1175/WAF-D-17-0085.1.
Ni, Y.-Q., and X.-J. Zhou, 2006: Main scientific issues and achievements of State 973 Project on study for formation mechanism and prediction theories of severe weather disasters in China. *Adv. Earth Sci.*, **21**, 881–894, doi: 10.3321/j.issn:1001-8166.2006.09.001. (in Chinese)
Parker, M. D., and R. H. Johnson, 2000: Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev.*, **128**, 3413–3436, doi: 10.1175/1520-0493(2001)129<3413:OMOMMC>2.0.CO;2.
Qin, D. Y., and Z. Y. Fang., 2014: Research progress of geostationary satellite-based convective initiation. *Meteor. Mon.*, **40**, 7–17, doi: 10.7519/j.issn.1000-0526.2014.01.002. (in Chinese)
Radar Team of Anhui Meteorological Observatory, 1975: Radar analysis of the 6.17 convective storm. *Meteor. Mon.*, **1**, 14–15, doi: 10.7519/j.issn.1000-0526.1975.05.009. (in Chinese)
Schumacher, R. S., and R. H. Johnson, 2005: Organization and environmental properties of extreme-rain-producing mesoscale convective systems. *Mon. Wea. Rev.*, **133**, 961–976, doi: 10.1175/mwr2899.1.
Shi, X. J., Z. R. Chen, H. Wang, et al., 2015: Convolutional LSTM network: A machine learning approach for precipitation nowcasting. Proc. Advances in Neural Information Processing Systems, Montreal, Quebec, 802–810. Available at https://arxiv.org/abs/1506.04214v2. Accessed on 5 August 2020.
Sun, J. S., J. H. Dai, L. F. He, et al., 2014: *Basic Principles and Technical Methods of Severe Convective Weather Prediction*. China Meteorological Press, Beijing, 282 pp. (in Chinese)
Tang, X. Z., 1990: A review of the nowcasting over the world. *Quart. J. Appl. Meteor.*, **1**, 93–99. (in Chinese)
Tao, S. Y., 1977: The current status of weather forecasting technology. *Meteor. Mon.*, **3**, 26–29, doi: 10.7519/j.issn.1000-0526.1977.01.022. (in Chinese)
Tao, S. Y., 1980: Heavy Rainfalls in China. Science Press, Beijing, 225 pp. (in Chinese)
Tao, S.-Y., and Y.-H. Ding, 1981: Observational evidence of the influence of the Qinghai-Xizang (Tibet) Plateau on the occurrence of heavy rain and severe convective storms in China. *Bull. Amer. Meteor. Soc.*, **62**, 23–30, doi: 10.1175/1520-0477(1981)062<0023:OEOTIO>2.0.CO;2.
Tao, S.-Y., Z.-Y. Fang., Y.-L. Li, et al., 1979: The application of the meteorological satellite data to weather analysis and forecating in China. *Scientia Atmos. Sinica*, **3**, 239–246, doi: 10.3878/j.issn.1006-9895.1979.03.06. (in Chinese)
Tian, F. Y., Y. G. Zheng, T. Zhang, et al., 2015: Sensitivity analysis of short-duration heavy rainfall related diagnostic parameters with point-area verification. *J. Appl. Meteor. Sci.*, **26**, 385–396, doi: 10.11898/1001-7313.20150401. (in Chinese)
Wang, A. S., and N. Z. Xu, 1983: Structure of severe hailstorm and its hail shooting. *Scientia Atmos. Sinica*, **7**, 95–101, doi: 10.3878/j.issn.1006-9895.1983.01.11. (in Chinese)
Wang, A. S., and N. Z. Xu, 1985: The studies of strong cell hailstorms. *Scientia Atmos. Sinica*, **9**, 260–267, doi: 10.3878/j.issn.1006-9895.1985.03.06. (in Chinese)
Wang, D. Z., 1965: Relationship between thunderstorm activity and convergence zone in spring warm area of Fujian Province. *Acta Meteor. Sinica*, **37**, 316–327, doi: 10.11676/qxxb1965.035. (in Chinese)
Wang, L., 1996: Comments on the short-term forecast of severe convective weather by radar echo at Jiangxi Meteorological Observatory in 1995. *Jiangxi Meteor. Sci. Technol.*, **(3)**, 40–42. (in Chinese)
Wang, P. L., 1964: A mean unstable energy index for convective forecasting. *Acta Meteor. Sinica*, **34**, 209–303, doi: 10.11676/qxxb1964.031. (in Chinese)
Wang, X. F., and Y. H. Ding, 1994: Study on method of short-range forecast of severe convective weather in Beijing area. *Scientia Atmos. Sinica*, **18**, 173–183, doi: 10.3878/j.issn.1006-9895.1994.02.05. (in Chinese)
Wang, X. H., Y. Y. Zheng, M. J. Pu, et al., 2018: Design of the comprehensive severe weather alert and track platform and its application in tornado warning. *Adv. Meteor. Sci. Technol.*, **8**, 61–69. (in Chinese)
Wang, X. M., X. D. Yu, and X. G. Zhou, 2015: Study of northeast China tornadoes: The environmental characteristics. *Acta Meteor. Sinica*, **73**, 425–441, doi: 10.11676/qxxb2015.031. (in Chinese)
Wang, Y. B., M. S. Long, J. M. Wang, et al., 2017: PredRNN: Recurrent neural networks for predictive learning using spatiotemporal LSTMs. Proc. Advances in Neural Information Processing Systems, Long Beach, California, USA, 879–888. Available at https://www.semanticscholar.org/paper/PredRNN%3A-Recurrent-Neural-Networks-for-Predictive-Wang-Long/566d9637c465e4dfc1c1695ecc7155adbb54f45c. Accessed on 5 August 2020.
Wang Y. B., Z. F. Gao, M. S. Long, et al., 2018: PredRNN++: Towards a resolution of the deep-in-time dilemma in spatiotemporal predictive learning. Proc. 35th International Conference on Machine Learning, PMLR, Stockholm, 5110–5119, Available at https://arxiv.org/pdf/1804.06300v2.pdf. Accessed on 6 August 2020.
Wei, W. X., and Y. M. Zhao, 1995: The characteristics of tornadoes in China. *Meteor. Mon.*, **21**, 36–40. (in Chinese)
Wen, K. G., 2004: *Chinese Meteorological History*. China Meteorological Press, Beijing, 902 pp. (in Chinese)
Wheatley, D. M., K. H. Knopfmeier, T. A. Jones, et al., 2015: Storm-scale data assimilation and ensemble forecasting with the NSSL experimental warn-on-forecast system. Part I: Radar data experiments. *Wea. Forecasting*, **30**, 1795–1817, doi: 10.1175/WAF-D-15-0043.1.
Wilson, J. W., N. A. Crook, C. K. Mueller, et al., 1998: Nowcasting thunderstorms: A status report. *Bull. Amer. Meteor. Soc.*, **79**, 2079–2100, doi: 10.1175/1520-0477(1998)079<2079:NTASR>2.0.CO;2.
Wolfson, M. M., W. J. Dupree, R. M. Rasmussen, et al., 2008: Consolidated storm prediction for aviation (CoSPA). Proc. 2008 Integrated Communications, Navigation and Surveil-

lance Conference, IEEE, Bethesda, doi: 10.1109/ICNSURV.2008.4559190.

Writing Group of "Pre-rainy Season Heavy Rainfall in South China," 1986: *The Heavy Rainfall in South China Pre-Rainy Season*. Guangdong Science and Technology Press, Guangzhou, 230 pp. (in Chinese)

Wu, C., L. P. Liu, M. Wei, et al., 2018: Statistics-based optimization of the polarimetric radar hydrometeor classification algorithm and its application for a squall line in South China. *Adv. Atmos. Sci.*, **35**, 296–316, doi: 10.1007/s00376-017-6241-0.

Wu, S. Z., 1938: The thunderstorms of China. *Acta Meteor. Sinica*, 131–145, doi: 10.11676/qxxb1938.016. (in Chinese)

Xiao, Y. J., and L. P. Liu, 2006: Study of methods for interpolating data from weather radar network to 3-D grid and mosaic. *Acta Meteor. Sinica*, **64**, 647–657, doi: 10.11676/qxxb2006.063. (in Chinese)

Xiao, Y. J., L. P. Liu, and Y. Shi, 2008: Study of methods for three-dimensional multiple-radar reflectivity mosaics. *Acta Meteor. Sinica*, **22**, 351–361.

Xiao, Y. J., B. Wang, X. H. Chen, et al., 2012: Differential phase data quality control of mobile X-band dual-polarimetric Doppler weather radar. *Plateau Meteor.*, **31**, 223–230, doi: 10.1007/s11783-011-0280-z. (in Chinese)

Xie, B. G., Q. H. Zhang, and Y. Q. Wang, 2010: Observed characteristics of hail size in four regions in China during 1980–2005. *J. Climate*, **23**, 4973–4982, doi: 10.1175/2010JCLI3600.1.

Xu, H. B., 2012: *The Physics of Severe Convective Storms and Its Application*. China Meteorological Press, Beijing, 340 pp. (in Chinese)

Xu, X. F., 2003: Construction, techniques and application of new generation Doppler weather radar network in China. *Eng. Sci.*, **5**, 7–14, doi: 10.3969/j.issn.1009-1742.2003.06.002. (in Chinese)

Xu, X. N., 1982: Analysis of a cold front heavy rain over North China in summer. *Scientia Atmos. Sinica*, **6**, 71–76, doi: 10.3878/j.issn.1006-9895.1982.01.10. (in Chinese)

Xu, Y. M., X. C. Tang, and W. M., Xia, 1988: An objective method for discrimination and short-term forecast of severe storms by using of weather radar. *Scientia Atmos. Sinica*, **12**, 434–438, doi: 10.3878/j.issn.1006-9895.1988.04.14. (in Chinese)

Xu, Z. F., M. Hao, L. J. Zhu, et al., 2013: On the research and development of GRAPES_RAFS. *Meteor. Mon.*, **39**, 466–477, doi: 10.7519/j.issn.1000-0526.2013.04.009. (in Chinese)

Xu, Z. X., and M. Y. Wang, 1965: Analysis of the weather process of the eastward moving troughs in the south branch of westerlies over the cushion of cold air in South China in spring. *Acta Meteor. Sinica*, **37**, 117–125, doi: 10.11676/qxxb1965.014.

Xue, M., 2016: Preface to the special issue on the "Observation, Prediction and Analysis of Severe Convection of China" (OPACC) national "973" project. *Adv. Atmos. Sci.*, **33**, 1099–1101, doi: 10.1007/s00376-016-0002-3.

Yang, G. X., 1983: *Meso- and Micro-Scale Weather Meteorology*. China Meteorological Press, Beijing, 231 pp. (in Chinese)

Yang, J., J. M. Xu, and C. H. Dong, 2011: 40th anniversary of Fengyun meteorological satellites: Evolution in view of the international development. *Adv. Meteor. Sci. Technol.*, **1**, 6–13, 24. (in Chinese)

Yang, P.-C., and Y.-F. Guo, 1981: A preliminary analysis of hailstorm echo systems of the squall line type. *Scientia Atmos. Sinica*, **5**, 85–91, doi: 10.3878/j.issn.1006-9895.1981.01.10. (in Chinese)

Yang, P.-C., Y.-F. Guo, J.-L. Liu, et al., 1980: The classification of hailstorm systems in North China and the characteristics of the cells in the hailstorms. *Scientia Atmos. Sinica*, **4**, 236–244, doi: 10.3878/j.issn.1006-9895.1980.03.05. (in Chinese)

Yang, X. L., and J. H. Sun, 2018: Organizational modes of severe wind-producing convective systems over North China. *Adv. Atmos. Sci.*, **35**, 540–549, doi: 10.1007/s00376-017-7114-2.

Yang, X. L., J. H. Sun, and Y. G. Zheng, 2017: A 5-yr climatology of severe convective wind events over China. *Wea. Forecasting*, **32**, 1289–1299, doi: 10.1175/WAF-D-16-0101.1.

Yang, Z. L., K. Zhao, K. Xu, et al., 2019: Microphysical characteristics of extreme convective precipitation over the Yangtze–Huaihe River basin during the Meiyu season based on polarimetric radar data. *Acta Meteor. Sinica*, **77**, 58–72, doi: 10.11676/qxxb2018.040. (in Chinese)

Yao, D., Z. Y. Meng, and M. Xue, 2019: Genesis, maintenance and demise of a simulated tornado and the evolution of its preceding Descending Reflectivity Core (DRC). *Atmosphere*, **10**, 236, doi: 10.3390/atmos10050236.

Yao, Y. Q., X. D. Yu, Y. J. Zhang, et al., 2015: Climate analysis of tornadoes in China. *J. Meteor. Res.*, **29**, 359–369, doi: 10.1007/s13351-015-4983-0.

Yao, Z. Q., and Y. Huang, 2000: The working flow of short-term forecast for severe convection in Shanghai. *Meteor. Mon.*, **26**, 15–18, 23, doi: 10.3969/j.issn.1000-0526.2000.09.004. (in Chinese)

You, J. Y., 1965a: Structure characteristics of the warm shear lines in North China. *Acta Meteor. Sinica*, **37**, 107–110, doi: 10.11676/qxxb1965.011. (in Chinese)

You, J. Y., 1965b: Mesoscale systems in heavy rainfall belt. *Acta Meteor. Sinica*, **37**, 293–304, doi: 10.11676/qxxb1965.033. (in Chinese)

Yu, X. D., and Y. G. Zheng, 2020: Advances in severe convection research and operation in China. *J. Meteor. Res.*, **34**, 189–217, doi: 10.1007/s13351-020-9875-2.

Yu, X. D., X. G. Zhou, and X. M. Wang, 2012: The advances in the nowcasting techniques on thunderstorms and severe convection. *Acta Meteor. Sinica*, **70**, 311–337, doi: 10.11676/qxxb2012.030. (in Chinese)

Yu, X. D., X. P. Yao, T. N. Xiong, et al., 2006: *Doppler Weather Radar Principle and Business Applications*. China Meteorological Press, Beijing, 11–12. (in Chinese)

Yu, Z. X., R. G. Wu, G. Q. Zhai, et al., 1985: The relationship between the boundary layer convergence and occurrence of hail weather in Zhejiang. *Scientia Atmos. Sinica*, **9**, 268–275, doi: 10.3878/j.issn.1006-9895.1985.03.07. (in Chinese)

Yunnan Meteorological Bureau, 1978: Great achievements in Zhenxiong weather station: A first-time weather forecasting at a county station. *Meteor. Mon.*, **4**, 1–2, doi: 10.7519/j.issn.1000-0526.1978.10.001. (in Chinese)

Zhang, B. C., G. X. Yang, Z. Y. Zhang, et al., 1986: Summary of mesoscale weather experiment in East China. *Meteor. Mon.*, **12**, 2–5. (in Chinese)

Zhang, C. X., Q. H. Zhang, and Y. Q. Wang, 2008: Climatology of hail in China: 1961–2005. *J. Appl. Meteor. Climatol.*, **47**,

795–804, doi: 10.1175/2007JAMC1603.1.
Zhang, G. C., 2011: *Severe Convective Weather Analysis and Forecast*. China Meteorological Press, Beijing, 337 pp. (in Chinese)
Zhang, G. F., V. N. Mahale, B. J. Putnam, et al., 2019: Current status and future challenges of weather radar polarimetry: Bridging the gap between radar meteorology/hydrology/engineering and numerical weather prediction. *Adv. Atmos. Sci.*, **36**, 571–588, doi: 10.1007/s00376-019-8172-4.
Zhang, J., M. Tian, K. Y. Zhu, et al., 2010: Analysis on the products and echo of dual-linear polarization Doppler weather radar. *Plateau Mountain Meteor. Res.*, **30**, 36–41, doi: 10.3969/j.issn.1674-2184.2010.02.008. (in Chinese)
Zhang, P., Q. Guo, B. Y. Chen, et al., 2016: The Chinese next-generation geostationary meteorological satellite FY-4 compared with the Japanese Himawari-8/9 satellites. *Adv. Meteor. Sci. Technol.*, **6**, 72–75. (in Chinese)
Zhang, X. L., S. Y. Tao, and J. H. Sun, 2010: Ingredients-based heavy rainfall forecasting. *Chinese J. Atmos. Sci.*, **34**, 754–766, doi: 10.3878/j.issn.1006-9895.2010.04.08. (in Chinese)
Zhang, X. L., Y. Chen, and T. Zhang, 2012: Meso-scale convective weather analysis and severe convective weather forecasting. *Acta Meteor. Sinica*, **70**, 642–654, doi: 10.11676/qxxb2012.052. (in Chinese)
Zhang, X. L., B. Yang, W. J. Zhu, et al., 2016: Analysis of the EF4 tornado in Funing County, Jiangsu Province on 23 June 2016. *Meteor. Mon.*, **42**, 1304–1314, doi: 10.7519/j.issn.1000-0526.2016.11.002. (in Chinese)
Zhang, X. L., B. Yang, and J. Sheng, et al., 2018: Development of operations on forecasting severe convective weather in China. *Adv. Meteor. Sci. Technol.*, **8**, 8–18. (in Chinese)
Zhang X. L., Y. G. Zheng, and B. Yang, 2019: *Severe Convective Weather Research and Forecasting Technology*. China Meteorological Press, Beijing, 522 pp. (in Chinese)
Zhang, Y., 1979: Progress of heavy rainfall research and forecast in China. *Meteor. Mon.*, **5**, 1–3, doi: 10.7519/j.issn.1000-0526.1979.11.001. (in Chinese)
Zhang, Y., 1982: Nowcasting and joint defense of severe storm. *Meteor. Mon.*, **8**, 2–4, doi: 10.7519/j.issn.1000-0526.1982.02.001. (in Chinese)
Zhang, Y., 1991: Recent progress on torrential rain in China. *Adv. Water Sci.*, **2**, 137–144. (in Chinese)
Zhang, Y. P., M. H. Cheng, W. M. Xia, et al., 2006: Estimation of weather radar echo motion field and its application to precipitation nowcasting. *Acta Meteor. Sinica*, **64**, 631–646, doi: 10.11676/qxxb2006.062. (in Chinese)
Zhao, B. L., and F. B. Xue, 1963: Mechanism of hail growth. *Acta Meteor. Sinica*, **33**, 411–420, doi: 10.11676/qxxb1963.044. (in Chinese)
Zhao, K., H. Huang, M. J. Wang, et al., 2019: Recent progress in dual-polarization radar research and applications in China. *Adv. Atmos. Sci.*, **36**, 961–974, doi: 10.1007/s00376-019-9057-2.
Zhao, S. X., 1978: Characteristics of the satellite cloud images of extratropical cyclones. *Meteor. Mon.*, **4**, 11–12, doi: 10.7519/j.issn.1000-0526.1978.02.009. (in Chinese)
Zheng, L. L., J. H. Sun, X. L. Zhang, et al., 2013: Organizational modes of mesoscale convective systems over central east China. *Wea. Forecasting*, **28**, 1081–1098, doi: 10.1175/WAF-D-12-00088.1.
Zheng, Y. G., and J. Chen, 2013: A climatology of deep convection over South China and the adjacent waters during summer. *J. Trop. Meteor.*, **19**, 1–15.
Zheng, Y. G., Y. Chen, and P. J. Zhu, 2008: Climatological distribution and diurnal variation of mesoscale convective systems over China and its vicinity during summer. *Chinese Sci. Bull.*, **53**, 1574–1586, doi: 10.1007/s11434-008-0116-9.
Zheng, Y. G., Y. J. Lin, W. J. Zhu, et al., 2013: Operational system of severe convective weather comprehensive monitoring. *Meteor. Mon.*, **39**, 234–240, doi: 10.7519/j.issn.1000-0526.2013.02.013. (in Chinese)
Zheng, Y. G., M. Xue, and Z. Y. Tao, 2015: An overview of NOAA testbeds and spring experiment in the United States. *Meteor. Mon.*, **41**, 598–612, doi: 10.7519/j.issn.1000-0526.2015.05.008. (in Chinese)
Zheng, Y. G., F. Y. Tian, Z. Y. Meng, et al., 2016a: Survey and multi-scale characteristics of wind damage caused by convective storms in the surrounding area of the capsizing accident of cruise ship "Dongfangzhixing". *Meteor. Mon.*, **42**, 1–13, doi: 10.7519/j.issn.1000-0526.2016.01.001. (in Chinese)
Zheng, Y. G., W. J. Zhu, D. Yao, et al., 2016b: Wind speed scales and rating of the intensity of the 23 June 2016 tornado in Funing county, Jiangsu Province. *Meteor. Mon.*, **42**, 1289–1303, doi: 10.7519/j.issn.1000-0526.2016.11.001. (in Chinese)
Zhou, K. H., Y. G. Zheng, B. Li, et al., 2019: Forecasting different types of convective weather: A deep learning approach. *J. Meteor. Res.*, **33**, 797–809, doi: 10.1007/s13351-019-8162-6.
Zhou, X. J., 1977: (I) Meteorological satellite. *Meteor. Mon.*, **3**, 12–13, doi: 10.7519/j.issn.1000-0526.1977.07.005. (in Chinese)
Zhou, X. J., 2006: Research on meso-scale meteorology in Chinese Academy of Meteorological Sciences. *J. Appl. Meteor. Sci.*, **17**, 665–671, doi: 10.3969/j.issn.1001-7313.2006.06.004. (in Chinese)
Zhou, X. P., S. X. Zhao, and B. Y. Zhang, 1984: A numerical simulation of the meso-low formation on Mei-Yu front. *Scientia Atmos. Sinica*, **8**, 353–361, doi: 10.3878/j.issn.1006-9895.1984.04.01. (in Chinese)
Zhou, X. P., S. X. Zhao, K. S. Zhang, et al., 1988: A heavy rainfall numerical prediction model for the East Asian monsoon area. *Scientia Atmos. Sinica*, **12**, 60–78, doi: 10.3878/j.issn.1006-9895.1988.t1.05. (in Chinese)
Zhu, C. J., 1977: How to analyze satellite cloud images: (III) Analysis of synoptic-scale cloud systems. *Meteor. Mon.*, **3**, 13–15, doi: 10.7519/j.issn.1000-0526.1977.11.008. (in Chinese)
Zou, M. E., and S. Y. Tao, 1984: A study on the formation and maintenance of the inversion layer in the severe storms in Hunan Province. *Scientia Atmos. Sinica*, **8**, 135–142, doi: 10.3878/j.issn.1006-9895.1984.02.03. (in Chinese)

Tech & Copy Editor: Lan YI