Advances in Severe Convection Research and Operation in China

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ABSTRACT

This article reviews the advances in severe convection research and operation in China during the past several decades. The favorable synoptic situations for severe convective weather (SCW), the major organization modes of severe convective storms (SCSs), the favorable environmental conditions and characteristics of weather radar echoes and satellite images of SCW and SCSs, and the forecasting and nowcasting techniques of SCW, are emphasized. As a whole, Chinese scientists have achieved a profound understanding of the synoptic patterns, organization, and evolution characteristics of SCW from radar and satellite observations, and the mechanisms of different types of convective weather in China. Specifically, in-depth understanding of the multiple types of convection triggers, along with the environmental conditions, structures and organization modes, and maintenance mechanisms of supercell storms and squall lines, has been obtained. The organization modes and climatological distributions of mesoscale convective systems and different types of SCW, and the multiscale characteristics and formation mechanisms of large hail, tornadoes, downbursts, and damaging convective wind gusts based on radar, satellite, and lightning observations, as well as the related features from damage surveys, are elucidated. In terms of operational applications, different types of identification and mesoanalysis techniques, and various forecasting and nowcasting techniques using methods such as the “ingredients-based” and deep learning algorithms, have been developed. As a result, the performance of operational SCW forecasts in China has been significantly improved.

Key words: severe convective weather (SCW), forecasting and nowcasting, research and operation, advances, contemporary China

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1. Introduction

Severe convective weather (SCW) is an important and dangerous weather type leading to serious meteorological disasters and is closely related to mesoscale and microscale weather systems. The study of SCW is of great significance for disaster prevention and mitigation. In this paper, we review the advances in SCW studies in China over the past several decades. However, worldwide, there is still no strict definition of SCW, and its classification in China is also being developed. Currently, this type of weather in China is usually recognized as hail with a diameter of 2 cm or greater on the ground, convective wind gusts (CGs) of more than 17 m s⁻¹, a tornado on land, or short-duration heavy rainfall (SDHR) of 20 mm h⁻¹ or more. Since SDHR often occurs during heavy rainfall events, which are defined as 24-h rainfall of no less than 50 mm in China, and the heavy rain studies have been specifically reviewed in another article, this paper focuses only on studies of large hail, CGs (including downbursts), and tornadoes. Nonetheless, it should be noted that the above-mentioned SCW is often accompanied by SDHR, and SDHR that exceeds 50 mm h⁻¹ is also an extreme SCW event (Yu, 2012; Chen J. et al., 2013; Zheng et al., 2017). In contrast, in the USA, SCW is defined by the National
Weather Service as hail with a diameter of 2.5 cm or greater on the ground, CGs of 25 m s\(^{-1}\) or more, or a tornado on land.

Additionally, research on, and forecasting of, SCW rely on not only observations, but also numerical weather prediction (NWP) modeling (Yu et al., 2012b; Zheng Y. G. et al., 2015). Be noted that advances in NWP modeling is beyond the scope of this paper. Meanwhile, progress in SCW research in China is closely related to the development of observation technology and the deployment of weather radars, meteorological satellites, lightning positioning systems, and automatic weather stations (Zhang X. L. et al., 2020). Plus, it has benefited from field experiments concerning mesoscale convective weather carried out since the 1960s, such as the field observation experiment on severe mesoscale weather in the Yangtze River Delta in the 1960s; the heavy rain experiment for the pre-rainy season in South China in the 1970s; the field experiments in the 1980s and 1990s carried out at four mesoscale system experimental bases (the Pearl River Delta, the Yangtze River Delta, the Beijing–Tianjin–Hebei region, and the middle reaches of the Yangtze River) (Zhang X. L. et al., 2020); the heavy rain experiment in South China and the Huaihe River basin energy and water cycle experiment in 1998; and, in the 21st century, the Meiyu frontal heavy rain experiment in the middle and lower reaches of the Yangtze River, the South China heavy rain experiment, the observation experiment of the project “Observation, Prediction and Analysis of Severe Convection of China” supported by the National (Key) Basic Research and Development (973) Program of China, and the southern China monsoon rainfall experiment.

The main purpose of SCW studies is to improve forecast and warning of such weather. SCW forecasting can be divided into potential forecasting and nowcasting (or warning). Potential forecasting usually requires answers to the following questions: (1) Where are the environments favorable for the generation of deep moist convection (DMC; also called thunderstorms or convective storms) today? (2) What types of DMC are likely to occur? Are they multicell storms, supercell storms, or squall lines? Are the multicell or supercell storms likely to occur in isolation or in clusters? Is it possible for them to produce SCW? If SCW does happen, will it mainly consist of large hail? Or will it mainly be composed of CGs or tornadoes? Or will two or more of these three types happen simultaneously? On the other hand, nowcasting or warnings of SCW are mainly based on the echo characteristics of Doppler weather radar and the observations of automatic weather stations, satellites, and lightning to determine whether large hail, CGs (including downbursts) or tornadoes will occur in the next 0–2 h.

This paper reviews the studies of SCW in China in terms of the above-mentioned aspects. Section 2 concerns the favorable environmental conditions for SCW, followed in Section 3 by a discussion of the convective storm types producing SCW, such as supercells, squall lines, and mesoscale convective systems (MCSs). Section 4 discusses SCW itself and its forecast. Section 5 presents progress in operational forecasting and technology related to SCW at the Severe Weather Prediction Center (SWPC) of the Central Meteorological Office (the National Meteorological Center, NMC) of the China Meteorological Administration (CMA) since its foundation in 2009. Finally, Section 6 provides a brief summary and outlook.

2. Favorable environmental conditions for DMC and SCW

Generally, static instability, moisture, and lifting are considered as necessary conditions (ingredients) for the generation of DMC. DMC, or thunderstorms, will be generated any time and anywhere when these three conditions are satisfied simultaneously (Doswell III, 1987). If the triggering mechanism is initiated near the surface, the DMC generated is known as surface-based convection, whereas it is referred to as elevated convection if it is triggered above the surface layer (Colman, 1990). For surface-based convection, boundary-layer convergence lines and the topography are the main triggers, whereas low-level (925–700 hPa) shear convergence lines, topography, and gravity waves are the main mechanisms triggering elevated convection. Boundary-layer convergence lines include cold fronts, dry lines, thunderstorm outflow boundaries (gust fronts), sea-breeze convergence lines, terrain-induced convergence lines, horizontal convective rolls, and so forth. Deep-layer (0–6 km or 0–8 km) vertical wind shear with moderate or strong intensity is usually necessary for the occurrence of SCW including large hail, CGs, and tornadoes (Johns and Doswell III, 1992; McNulty, 1995; Doswell III, 2001; Moller, 2001). Some severe convective storms (SCSs), like severe multicell storms, supercells, and intense squall lines, generally occur in environments with significant deep-layer vertical wind shear. However, note that some SCWs can still be produced by pulse storms with weak deep-layer vertical wind shear (Chisholm and Renick, 1972).
2.1 Environmental background for thunderstorms (DMC) and SCSs

As early as 80 years ago, Woo (1938) discussed thunderstorms in China, and pointed out that these storms can be divided into two types: airmass thunderstorms, which occur in a uniform air mass; and front-cyclone thunderstorms. Front-cyclone thunderstorms can be divided into cold-front thunderstorms, warm-front thunderstorms, and warm-sector thunderstorms ahead of cold fronts. He also gave an example similar to T-logp diagram analysis. Considering the average buoyancy effect of a rising air parcel within the entire column of convection, Wang (1964), of Hunan Meteorological Bureau, derived an unstable energy index for operational forecasting of convection. Lei et al. (1978) proposed the idea of predicting severe convection based on energy variables. They defined total temperature, total dry-air temperature, and total saturation temperature, which were calculated by using radiosonde data; and they referred to the vertical profiles of these variables as specific energy vertical profiles. Such profiles were then used to obtain the local atmospheric stability, saturation, and moisture (relative humidity). In contrast with the lifting index, Showalter index, and K index, these profiles could provide more information about the potential generation of DMC (or thunderstorms). Lei et al. (1978) further proposed that isolines of “total temperature” (i.e., the sum of moist static energy and kinetic energy divided by the constant pressure specific heat) could be drawn on the surface map. They called the denser area of “total temperature” isolines the “energy frontal zone,” and the “high-energy area” and “low-energy area” were the high and low “total temperature” areas, respectively. DMC was more likely to occur near the energy front or in the high-energy area surrounded by the energy front. This theory and method has had a profound influence on forecasting technology for DMC in China. Many forecasters/meteorologists still use the concepts of “high energy zone” and “energy front” in their work. In fact, the so-called “energy front” corresponds to cold fronts, warm fronts, quasi-stationary fronts, or dry lines, each of which is an important triggering mechanism of DMC, while the “high-energy area” is actually the warm moist area. The concepts of “energy front” and a “high energy zone” should not be used anymore, as they can be replaced with other common concepts. Besides, a significant shortcoming of the method in Lei et al. (1978) is that it neglected the effect of vertical wind shear on SCW. Lei and Wu (1980) then proposed the concept of potential instability, which means that an air parcel is potentially unstable only when it is able to be lifted above the level of free convection. At that time, although the concepts of positive and negative areas related to the air parcel lifting process had already been put forward and the concept of convective available potential energy (CAPE) had already been defined (Moncrieff and Miller, 1976), it was still difficult to calculate accurate values of the positive area (i.e., CAPE) and negative area (i.e., convective inhibition) due to the limitation of computing power. Therefore, the concept of potential instability put forward by Lei and Wu (1980) still has certain application value.

Chao and Chen (1964) analyzed a set of linear and nonlinear equations and concluded that the structure of the convection airflow determines whether vertical wind shear is beneficial to the development of the convection. Wang (1965) pointed out that the warm-sector convection in spring in Fujian Province is closely related to the 850-hPa convergence zone. Tao (1980) presented three favorable conditions for SCSs in midlatitudes: (1) obvious conditional instability in the middle and lower troposphere; (2) strong vertical wind shear; (3) a very dry middle troposphere and a warm and moist low troposphere. Ding et al. (1981) obtained the differences in synoptic-scale conditions between heavy-rain processes and SCSs: heavy rainfall occurs in a deep ascending area with low-level convergence and upper-level divergence, where the intense warm advection at low or low–mid levels causes conditional instability, and the water vapor transported through the atmospheric boundary layer heavily converges; while in the areas where SCSs occur, upper-level divergence or negative vorticity is not obvious or does not exist, and mid-level cold advection plays an important role in the establishment of instability. Zou and Tao (1984) discussed the relationship between a warm and dry lid (inversion layer) and 42 SCW events with hail and CGs that occurred in Hunan Province, and found that 36 SCW events had the structure of a warm and dry lid and 30 had a low-level jet under the lid. Wang (1964) discussed the environmental conditions of SCSs in the Pearl River Delta region and compared them with those in midlatitudes.

Xu et al. (2014) proposed five basic synoptic-scale forcing patterns for SCW in China: cold advection forcing, warm advection forcing, baroclinic frontogenesis, quasi-barotropic, and elevated thunderstorms. Yu et al. (2012b) summarized the favorable environmental conditions for the occurrence of various types of SCW. Zhang et al. (2012) expounded some basic principles and specific methods for SCW analysis based on several ingredients (static instability, moisture, lifting, and vertical wind shear) favorable for SCW. Sun and Tao (2012), Wang X.
M. et al. (2014), and Zheng et al. (2017) illustrated and clarified some basic concepts in potential forecasting of DMC and different types of SCW, especially those that could be easily mixed up.

### 2.2 Lifting and triggering mechanisms for thunderstorms and SCSs

Ding (1978) pointed out that SCW and SCSs most likely occur in the area where arc cloud lines (gust fronts) intersect with fronts, squall lines, or cumulus lines (horizontal convective rolls). Sun and Zhai (1980) proposed that the fluctuation of low-level jets (the sudden increase of wind velocity of the low-level jet in a short time period) is an important mechanism to trigger DMC. Yang and Zhang (1992) analyzed the secondary circulation of a cold front during an SCW process on 28 April 1983 and pointed out that the ascending branch of the cold frontal vertical circulation might have been an important mechanism to trigger DMC. Zhao et al. (1982) found that there were very intense wind gust surges and strong updrafts in a gust front, and the strongest updraft area was about 200 m above the head area of the gust front. Zhai et al. (1989) found that the intersection of a cold front or a gust front with other mesoscale convergence lines is an important mechanism to trigger DMC. Liu et al. (2001) summarized the favorable environmental background for triggering DMC of sea breeze fronts. Wang et al. (2011) summarized the activity of sea breeze fronts in Bohai Bay of Tianjin and pointed out that DMC cannot be easily triggered by only a single sea breeze front, but can be easily triggered by the sea breeze front intersecting with other convergence lines. Gong et al. (2019) and Zheng et al. (2020) each studied a case from which they found that DMC could be triggered by the enhanced existing ground convergence lines together with the convergence line of other SCSs. Qi et al. (2006) discussed the role of narrow-band echoes of Doppler weather radar, which represent boundary-layer convergence lines, in the triggering and nowcasting of DMC. Huang Y. P. et al. (2019) examined a 5-yr summertime radar climatology of boundary-layer convergence lines and their associated DMC around the bend of the Yellow River in China, and identified a total of 323 such lines and found 44% of them associated with DMC.

Based on a study of several SCS cases, Diao et al. (2009) found that the gust fronts far away from the main part of SCSs and the convergence lines moving along surface winds are usually not able to trigger DMC under weak thermal conditions, and the collision between gust fronts or between a gust front and other convergence lines can trigger SCSs under favorable environmental conditions, while a convergence line near the surface alone can only produce local isolated DMC by itself under favorable environmental conditions. Yu et al. (2012b) presented a DMC case in Anhui Province that was triggered by collision between horizontal convective rolls and a gust front, as well as another case in Beijing that was triggered by the lifting induced by the blocking of the developing nocturnal low-level easterly jet by the West Mountains of Beijing. Yu (2012) and Chen M. X. et al. (2013) both pointed out that one cause of the extreme heavy rainfall in Beijing on 21 July 2012 was the backward building of SCSs triggered by the lifting induced by the blocking of the strong low-level easterly jet by the Taihang Mountains.

Sun and Meng (1992) analyzed a DMC process on 20 August 1985 and found that a north–south-oriented meso-γ-scale dry line in the west of Beijing was closely related to the triggering of the DMC. Wang et al. (2015) found that SCSs producing tornadoes in Northeast China are mostly triggered by surface convergence lines caused by confluent airflow accompanied by surface dry lines. Qin and Chen (2017) analyzed a DMC case triggered by the combination of a dry line and a cold front in the northwest of Beijing. Chen et al. (2017) studied the convection-scale dynamic and thermodynamic mechanisms causing the local generation and rapid enhancement of SCSs during an SCW event including three SCSs in the complex terrain area of the Beijing–Tianjin–Hebei region, and discussed the mechanism of convection generation and enhancement caused by the interactions among the topography, gust front, and low-level warm moist airflow.

Based on multiple sources of observations and high-resolution cloud model simulations, Bai et al. (2019) pointed out that the triggering process of the SCS in the plains to the north of the Yellow River in Henan Province on the evening of 3 June 2009 was that a set of cold surges (intermittent gust fronts) produced by preceding DMC continually rushed down the mountains first, encountering a dry line accompanied by confluent airflows in the plains, and finally triggering the SCS at the vertices of a scalloped pattern. Yu et al. (2020) presented different cases of DMC triggered by cold fronts, dry lines, gust fronts, convergence lines of sea breeze fronts, and terrain-induced lifting, and discussed their triggering mechanisms.

Combining the high-resolution multi-channel infrared (IR) images from geostationary meteorological satellites has been used to identify the initiation of DMC (or convection initiation, CI), which takes place about 10–30 min ahead of the CI on the radar echo. As the incipient
convection will increase the thickness of the cloud body, sharply decrease the temperature of the cloud top, and change the hydrometeor phases of the cloud top, these features can be identified by comprehensive multi-spectral analysis techniques to capture the CI (Qin and Fang, 2014). Some studies (Liu et al., 2012; Huang et al., 2017; Guo et al., 2018; Zhou X. et al., 2019) have extracted several indicators to comprehensively identify CI based on multi-channel IR brightness temperatures and their temporal changes from the Himawari geostationary meteorological satellite of Japan or the Fengyun 2F geostationary meteorological satellite of China.

Sheng et al. (2014) pointed out that the main triggering mechanism of the elevated convection behind cold fronts in southern China during 2010–2012 was the combination of low-level warm and moist jets and low-level convergence shear lines. On the basis of careful analysis, Yu et al. (2016) judged that the triggering mechanism of an elevated SCS that produced large hail and CGs in Shandong Province from the evening and into the night of 30 March 2007 was the large-amplitude trapped gravity waves on the leeward side of the mountains. Whilst analyzing the origin of the supercell storm that produced an EF4 tornado in Funing, Jiangsu Province on 23 June 2016, Zhang M. R. et al. (2019) found that a low-level elevated moist and absolutely unstable layer was conducive to weak vertical ascent that triggered an elevated MCS, and this MCS gradually developed into a surface-based MCS, part of which turned into the severe supercell storm that spawned this notorious tornado case.

3. Organization modes of SCSs

3.1 Supercell storms

The term “supercell” was coined by Browning (1964) in a study of an SCS in the United States, representing the quasi-steady state of the storm during its most intense period. In a review paper by Browning (1977), it was pointed out that the rotation within a supercell storm is the most important feature that distinguishes it from other types of storm. Subsequent theory (Davies-Jones, 1984) and numerical simulation studies (Klemp and Wilhelmson, 1978; Klemp et al., 1981; Rotunno and Klemp, 1982, 1985; Weisman and Klemp, 1984; Klemp, 1987) further proved that a mesocyclone is the most essential feature of a supercell storm, which then gradually became the consensus amongst the international radar meteorology community.

Wang and Xu (1983, 1985) divided supercells into three categories: (1) ones with a large bounded weak-echo region (BWER); (2) ones with a small BWER; and (3) ones with an unobvious BWER. They also pointed out that serious hail disasters can only be caused by the first category of supercells. Zhang et al. (1997) found that obvious low-level hook echoes exist in some SCSs occurring in Pingliang, Gansu Province, 90% of which are of cyclonic hooks and 10% are of anticyclonic hooks. Since no Doppler weather radar data was available at that time, mesocyclones could not be identified in those SCSs. In fact, among the SCSs in the study of Zhang et al. (1997), the cyclonic hook echoes corresponded to mesocyclones and the anticyclonic hook echoes to mesoanticyclones. These SCSs with obvious hook echoes were all supercells.

Zheng et al. (2004) analyzed a classic supercell storm in northern Anhui Province on 27 May 2002, using observations from the Hefei Doppler weather radar (S band), which was the first of China’s New Generation Doppler Weather Radars (CINRAD). They found that the mesocyclone in the supercell was purely cyclonic in rotation at low levels, had divergent cyclonic rotation at middle levels, and strong divergence with slightly cyclonic rotation at the upper-level storm top; the mesocyclone reached an altitude of 9 km vertically, corresponding to hook echoes at the low levels and BWER at the middle and upper levels. Zhao et al. (2008) analyzed a supercell that occurred in the rainbelt over the Taiwan Strait and found that the mesocyclone formed from the low levels in the beginning and then developed upwards; the diameter of the inner core was first large at the low levels and small at the middle levels, and then the inner core at the middle levels expanded and became nearly the same size as that at the low levels, so it grew cylindrical; and after that, it rapidly weakened. Pan et al. (2008) studied a supercell embedded in a squall line and found a strong mesocyclone near the hook echo, which originated from an altitude range of 3.5–5.0 km at the middle levels and then developed downwards and upwards. Yu et al. (2008) conducted a thorough and detailed analysis of the evolution and structural characteristics of a typical heavy-precipitation supercell storm that spawned an EF3 tornado at noon on 30 July 2005. The evolution of this supercell had three stages: band echoes, a typical heavy precipitation supercell, and bow echoes. At the stage of the typical heavy precipitation supercell, a large and deep heavy precipitation supercell and a thick strong mesocyclone with a diameter of 12 km formed; and then as the rear inflow formed, the low-level echo turned S-shaped and the mid-level echo appeared spiral in structure, and meanwhile, a tornado formed. Dai et al. (2012) found that the special environment of the warm sector in front of a bow-shaped squall line in East China on 5 June 2009.
was favorable for the generation of a supercell storm; the wind profiler data were used to compare the changes in the near-storm environments, and it was revealed that the enhancement of both 0–3-km vertical wind shear and the helicity relative to the storm played a key role in the development of the squall line and the supercell; and the squall line and the supercell formed a relationship like a “bow and arrow.”

Zhang et al. (2004) described the supercell storm splitting process that occurred in Pingliang, Gansu Province on 13 August 1976. Although the radar observations available were only conventional ones, the supercell could be identified by the typical hook echo, the BWER, and the splitting process of the cell. After splitting, the right-moving cell was significantly more intense than the left-moving one. The left-moving cell moved relatively fast, with its maximum echo less than 50 dBZ and a lifetime of 40 min; and the maximum echo of the right-moving cell was greater than 55 dBZ, and it moved slowly in a quasi-steady state and lasted for 100 min. Liao et al. (2007b) analyzed a supercell splitting process that occurred in northern Hunan Province on the afternoon of 29 April 2004. This supercell underwent three splitting processes. Each splitting point was located at the left-hand edge of the storm. After splitting, the right-moving parent storm played a dominant role and remained intense. The left-moving cell, with a mesoanticyclone, was relatively weak, and the mesoanticyclone lasted less than half an hour. In fact, before the split, there was a weak mesoanticyclone developing inside the parent cell with a dominant mesocyclone. The entire evolution was similar to the supercell split and evolution process in the environments with wind shear turning clockwise with height in the study of Rotunno and Klemp (1982). Wang F. X. et al. (2014) analyzed the splitting process of a supercell that occurred in central and southern Hebei Province on the evening of 9 July 2007. In this case, the wind shear turned counterclockwise with height, and multiple splitting processes of the storm occurred. Thereinto, three left-moving mesoanticyclone storms selectively strengthened after splitting, and some right-moving cyclone storms were significantly suppressed, which was basically consistent with the theory of supercell dynamics (Rotunno and Klemp, 1982; Klemp, 1987). Yu et al. (2020) analyzed the supercell splitting process that occurred in the Chaohu area of Anhui Province during the night of 21 May 2004, and found that the right-moving (cyclonic) and the left-moving (anticyclonic) supercells had nearly the same intensity after splitting.

Wang et al. (2009) simulated a supercell hailstorm that occurred in Beijing on 31 May 2005 using the Weather Research and Forecasting (WRF) model. Their results showed that the simulated supercell split into two storms, and the right-moving storm, with a significant mesocyclone, dominated the process. Although there was actually no obvious splitting process observed in this event, almost all supercells in the numerical simulations split. Using the Bryan cloud model, version 1 (http://www2.mmm.ucar.edu/people/bryan/cml1/faq.html), Yao et al. (2019) simulated a tornado that occurred during the heavy rainfall event on 21 July 2012 in Zhangjiawan town, Tongzhou District, Beijing, at a very high resolution (a nested model domain with the highest horizontal resolution of 100 m in the center area). The sounding data at 1400 BT (Beijing standard time, 8 h earlier than Universal Time Coordinated) on 21 July in Beijing were used as initial conditions, and the underlying surface used was uniform with no topography. The simulated tornado-producing supercell also experienced a splitting process (which was not observed in the actual supercell), and the more intense right-moving cell with a mesocyclone very much agreed with the observed tornado-producing supercell.

Liao et al. (2007a) conducted a detailed analysis of 22 supercells in 10 severe convective events that occurred in Hunan Province. Their results showed that (i) supercells could grow from isolated cells, multicell storms, and cells in MCSs; (ii) the supercells included low-storm-top supercells and miniature supercells; (iii) most of the supercells could last more than 1 h, while their shortest lifetime was 24 min; (iv) the maximum reflectivity of each of the supercells exceeded 60 dBZ; (v) the maximum rotational speed of the mesocyclones among the 22 supercells was 24 m s\(^{-1}\); and (vi) the supercell storms in Hunan Province could produce hail, CGs, tornadoes, and SDHR, but most often hail and CGs. Based on the structure and organizational features of radar reflectivity, Diao et al. (2011) classified 54 supercells observed by the CINRAD-SA radar in Jinan, Shandong Province, into two types: isolated ones and embedded ones. The isolated supercells produced hail, CGs, and tornadoes, while the embedded ones had a weaker capability to produce hail, especially large hail, but their capability to produce CGs was roughly equivalent to that of the isolated ones. Wu et al. (2013) analyzed statistically the environmental conditions, the radar reflectivity characteristics, and the SCW of 72 supercells that occurred in northern Jiangsu Province during 2005–2009. These supercells had long lifetimes and long-lasting mesocyclones. They usually also had BWERs or weak echo regions (WERs), and
could produce large hail, tornadoes, SDHR, and CGs or downbursts. They were classified into the following categories: classic supercells, heavy precipitation supercells, and complex storms with heavy precipitation supercells. Yu et al. (2012a) selected 228 supercells that occurred in China during 2002–2009 and conducted a statistical analysis of the key environmental parameters, and among which 150 supercells with better Doppler weather radar observations were chosen for analysis of their radar echo characteristics. The results showed that the peak frequency range of the CAPE value among the 228 supercells was 1500–2500 J kg$^{-1}$, and the CAPE values of 56% of all supercells were in this range. The peak frequency range of the 0–6-km wind shear among the total supercells was 15–25 m s$^{-1}$, and the supercells with these values accounted for 62% of the total. The peak frequency range of mesocyclone rotation speeds among the 150 supercells was 15–25 m s$^{-1}$, and those with these values occupied 86% of the 150 supercells. The peak frequency range of the vertical vorticity of the mesocyclones among the 150 supercells was (1.0–2.0) $\times 10^{-2}$ s$^{-1}$, and the peak frequency range of mesocyclone diameters was 4.0–7.0 km, with a maximum diameter of 14.5 km and an average of 6.2 km. Most of the lifetimes of the mesocyclones were between 30 and 130 min, and the longest lifetime was about 3.5 h.

### 3.2 Squall lines and bow echoes

A squall line refers to a quasi-continuous linear convective system that can bring CGs in a wider region (Yu et al., 2020), but a squall refers to a gale phenomenon with an average wind speed of 8 m s$^{-1}$ or more for at least 2 min (Doswell III, 2001), and the corresponding gust can easily exceed 15 m s$^{-1}$. A bow echo can be an isolated bow-shaped multicell storm consisting of multiple cells on the radar echoes; in most cases, however, a bow echo is embedded in a squall line, whose apex is more likely to produce CGs.

Lu (1935) described a squall line process that occurred in East China on 10–11 June 1932: “There was a squall line sweeping eastern China from north to south. Where it went, high winds blew suddenly, temperatures dropped rapidly, thunder and lightning occurred simultaneously, rain and hail fell alternately, trees were rooted out, houses were destroyed, and people got hurt and storage was damaged. What a catastrophe at the moment!”

Ding et al. (1982) analyzed the synoptic-scale flow pattern configuration and the key environmental characteristics of 18 squall lines that occurred during 1970–1981, and summarized four synoptic-scale flow patterns of squall lines: post-trough, pre-trough, post-high, and in-verted trough of typhoon or easterly wave. Zhang (1983) analyzed the environmental background and the weather radar echo characteristics of a loose squall line that occurred near Zhangjiakou, Hebei Province on 20 July 1980, and inferred the vertical circulation of the squall line at different development stages based on the radar echo characteristics. Cai et al. (1988) analyzed in detail a group of four squall lines that occurred in North China on 27 June 1983, and proposed a mesoscale weather model for the lifespan of squall lines in North China, which included three stages: organization, expansion, and dissipation; and their lifespans were 3–5 h. He et al. (1992) used satellite images, weather radar echoes, conventional upper-air and surface observations, and intensive observations from mesoscale experiments in East China to analyze a warm-sector squall line that occurred in the Yangtze–Huaihe River basins from the evening of 27 April to the early morning of 28 April 1983. They found the following results. When the squall line approached the axis of the low-level southwesterly jet, the convection strengthened. When it got far away from the jet axis, the convection weakened. When the squall line was passing through, the environmental upper-level wind speeds decreased, yet the environmental low-level wind speeds increased. In the area between about 30 km ahead of the squall line and about 50 km behind it, there were three narrow meso-$\beta$-scale systems that were low, high, and low pressure, respectively. Among the three systems, the band-shaped mesohigh behind the squall line was the strongest, in front of which the negative allobar reached 1 hPa km$^{-1}$, and was also the area where CGs were produced when the squall line was going through. The maximum CG reached 35.9 m s$^{-1}$ when the squall line was sweeping Nanjing.

Yao et al. (2008) analyzed a squall line across a vast area that affected Henan, Anhui, Jiangsu, and Zhejiang provinces, as well as Shanghai City, on 24 August 2008, based on conventional upper-air and surface observations and Hefei CINRAD-SA radar observations. During its 14-h lifespan, the squall line experienced multiple splits, regenerations, and reorganizations. They found that the significant features of mid-altitude radial convergence (MARC) were displayed clearly in the vertical section of radial velocity through the apex of the bow echo. Qi and Chen (2004) combined observations of the WSR-88D (Weather Surveillance Radar-88D) radar, made in the USA and installed at Shanghai, with wind profiler observations, which was rare at that time, to analyze the structures of the low-level warm moist inflow and the rear sinking flow of a squall line that occurred on 24 August 2008. Xie et al. (2007) analyzed the intense squall
line that occurred in South China on 22 March 2005 based on conventional upper-air and surface observations and Guangzhou CINRAD-SA radar observations. The original convection that afterwards developed into the squall line started in Guangxi Zhuang Autonomous Region on the afternoon of 21 March. The squall line then formed in Guangxi at about 0500 BT 22 March, entered Guangdong Province at 0800 BT, and moved into Fujian Province at around 1400 BT. At around 1700 BT, it dissipated when it was about to enter Zhejiang Province, with a lifetime of up to 12 h. Serious wind damage occurred in eastern Guangxi, the whole of Guangdong, and western Fujian. Strong CGs in excess of 30 m s\(^{-1}\) were observed at 10 national-level meteorological observation stations. Among them, the maximum wind gust of 40 m s\(^{-1}\) was detected at Yongchun national-level station in Fujian Province. The squall line was one of the most intense in China in the 21st century so far. Its gust front ahead kept close with the main echo body of the squall line, so the narrow-band echo of the gust front was unable to be identified, and the position of the gust front corresponded to the strongest radial velocity convergence zone. Vertical cross-sections showed that the reflectivity in the forepart of the squall line had clear overhang echoes and WERs, and the radial velocity field showed clear radial convergence regions. The squall line occurred in the environments of CAPE values below 1000 J kg\(^{-1}\) and a strong 0–6-km wind shear of 28 m s\(^{-1}\); plus, it was located in the warm sector in front of the cold front. Its main axis was almost perpendicular to the cold front.

Wang et al. (2007) used radial velocity observations from the Binzhou CINRAD-SC radar and Jinan CINRAD-SA radar in Shandong Province to derive dual-Doppler-radar winds, and analyzed the internal and peripheral airflow structures of an intense squall line that occurred in Shandong Province on 21–22 June 2004. Although the accuracy of the derived winds was quite limited, the winds still revealed features of a cyclonic vortex at the northern end of the squall line, an anticyclonic vortex at the southern end, and strong convergence between the southeasterly and the westerly in front of the narrow severe convection band in the middle of the squall line. Zhuang et al. (2010) analyzed the structure of a strong squall line that occurred in northern Xinjiang Uygur Autonomous Region on 26 June 2005 using the dual-radar derived wind field from observations of the Urumqi and Wujiapu CINRAD-CC radars. Their results showed that the airflow field of the squall line presented obvious low-level convergence lines, mid-level convergence, and upper-level divergence. The convergence at the low and middle levels successively initiated some new echoes at a certain distance from the right (southwest side) of the old echoes, and promoted rapid mergers among the convective cells, which led to the development of the squall line. Pan et al. (2012) analyzed the intense squall line that occurred in Guangdong Province on 23–24 April 2007 using dual-radar derived winds from radial velocities of the Guangzhou and Shenzhen CINRAD-SA radars, with a distance of 84 km between them. They pointed out that the airflow in the squall line presented a quasi two-dimensional structure, including the deep front-to-rear airflow in the front of the system and the rear-to-front airflow at the low levels in the rear of the system. These two airflows converged at the low levels of the front edge of the system, formed a dynamic high-pressure disturbance, and then triggered new convective cells, which was the main maintenance mechanism of this long-lived system.

Wang et al. (2010) simulated a squall line that occurred in Hubei Province using the WRF model with three nested domains and the finest grid spacing of 3 km. Their results showed that a strong and narrow updraft was ahead of the squall line, a wide and tilted front-to-rear updraft (from south to north) was above the middle levels, and a tilted rear-to-front downdraft (from north to south) was at the lower levels; plus, there were two inflows to the squall line at the low levels: southerly flow ahead and downdraft flow in the rear. Chen and Wang (2012) used a three-dimensional numerical cloud model with four-dimensional variational assimilation of radar data to analyze in detail the low-level dynamic and thermodynamic mechanisms for a squall line that occurred in North China on 20 July 2009. Their results showed that the squall line occurred in the environment of moderate vertical wind shear at low levels, and the interaction between the low-level environmental vertical wind shear and the cold pool was the key mechanism for the maintenance and propagation of the squall line. Sun J. H. et al. (2014) performed numerical experiments to simulate the effect of water vapor content on squall-line structure and intensity, and showed that different water vapor contents and vertical distributions in the environments would affect the intensity of the downdraft and the cold pool of a squall line, which would affect the organization, lifetime, and intensity of the squall line.

Tao et al. (2014) analyzed the bow echo process producing CGs that occurred in the Yangtze River Delta during the night of 13–14 July 2012, and found that, in the environments with high humidity at all levels, the en-
trainment of the warm dry airflow from south of the convective system at the middle and upper levels strengthened the cooling effects of liquid water evaporation in the system, which enhanced the downdraft significantly and was a key factor in producing straight CGs. Sheng et al. (2019) analyzed a squall line that swept across a vast area of Guangxi Zhuang Autonomous Region, Hunan, Jiangxi, Fujian, and Zhejiang provinces in early March 2018. This squall line was the most intense in South China since the case on 22 March 2005. The squall line reached its greatest intensity when passing through Jiangxi Province, with the maximum wind gust exceeding 37 m s$^{-1}$ at Lushan station. This study summarized the characteristics of the squall line and the causes of CGs as follows. (1) Due to the combined action of advection and forward propagation, the squall line moved very fast with a speed of about 100 km h$^{-1}$. (2) Between the strong thunderstorm high pressure behind the squall front (gust front) and the warm low pressure ahead of the front, a strong horizontal pressure gradient formed and was therefore very beneficial to the wind acceleration, and thus was conducive to producing straight high winds over a vast area. (3) They compared the north and south parts of the bow echo embedded in the squall line and found the differences in radar echo structure, indicating that the dry air inflow in the rear of the squall line drove liquid water particles to evaporate, resulting in a dramatic drop in temperature and forming an intense downdraft, which mainly caused extreme high winds, together with the downward momentum propagation of the dry inflow in the rear.

Based on mosaics of composite radar reflectivity during 2007–2009, Meng and Zhang (2012) analyzed statistically the squall lines preceding landfalling tropical cyclones (pre-TC) in China. Their main results are as follows. (1) Most of the pre-TC squall lines formed in a broken-line mode. (2) On average, they tended to form in the front right quadrant of the TCs, and occurred about 600 km from their center, with a maximum length of 220 km, a maximum radar reflectivity of 57–62 dBZ, a lifetime of 4 h, and a moving speed of 12.5 m s$^{-1}$. (3) The pre-TC squall lines were usually shorter in lifespan and length than typical squall lines in midlatitudes. The squall lines in East China were statistically analyzed by Meng et al. (2013), and their main results are as follows. (1) The identified squall lines had a maximum frequency of occurrence in North China near the boundaries between Shandong, Henan, Anhui, and Jiangsu provinces. The squall lines formed with a peak in July. (2) The squall lines had a dominant southwest–northeast orientation, an eastward movement with a speed of 14.4 m s$^{-1}$, a maximum length of 243 km, and a lifetime of 4.7 h on average. (3) The squall lines commonly formed in a broken-line mode with a trailing-stratiform pattern. (4) The midlatitude squall lines in East China tended to form in a wetter environment with comparable CAPE and weaker vertical wind shear relative to their counterparts in the USA. Zheng et al. (2014) studied the characteristics of the environments for the squall lines in the Yangtze–Huaihe River basins under the background of cold vortices in Northeast China. Their main results are given as follows. (1) Obvious mesoscale cyclonic circulations and convergence or dry lines existed at 850 and 925 hPa and at the surface. (2) In the low and middle troposphere, the temperature lapse rate was large, with significant conditional instability. (3) The vertical wind shear was strong, the winds at the low levels turned clockwise significantly with height, and a westerly jet existed at 400–500 hPa.

### 3.3 MCSs

Browning (1977) classified convective storms into single-cell storms, multicell storms, supercell storms, and multicell linear storms (some of them squall lines), based on weather radar echo characteristics, which has since been widely accepted. On the other hand, MCSs were originally defined on “window” infrared (IR) imagery. Maddox (1980) first defined the mesoscale convective complex (MCC), based upon the size and shape of the low brightness temperature region on IR imagery. Zipser (1982) referred to the convective systems on IR imagery as MCSs, which were required to have originated from convection and to have a horizontal scale in at least one direction exceeding 100 km. Houze et al. (1989) categorized MCS structures into two types according to radar echo characteristics of MCSs: linear structure and nonlinear structure. The squall line mentioned in the previous section can be regarded as a subset of linear MCSs. Due to the extreme importance of squall lines to SCW, we devote a special section (Section 3.2 of this paper) to discuss squall lines. In this section, MCSs are discussed from a broader perspective.

According to the standard of scale subdivision, MCSs based on IR imagery of geostationary meteorological satellites can be generally divided into $M_\alpha$CSs (meso-$\alpha$-scale convective systems) and $M_\beta$CSs (meso-$\beta$-scale convective systems). As MCSs also possess different shapes, $M_\alpha$CSs can be divided into MCCs (Maddox, 1980) and PECSs (persistent elongated convective systems) (Anderson and Arritt, 1998), and $M_\beta$CSs into $M_\gamma$CCSs and $M_\delta$ECSSs (Jirak et al., 2003; Fang and Qin, 2006).

Research on and application of meteorological satel-
Multi-channel brightness temperatures and their temporal variations can be used to identify the status of cumulus cloud in the initial stage of convection and associated textural features, as well as overshooting and microphysical features in the mature stage of convection. A number of convection case studies (Zheng et al., 2018; Gong et al., 2019; Sheng et al., 2019) found that some MCS cloud tops revealed on the high-resolution visible images had not only rough texture and overshooting features, but also certain features of rotation and fluctuation displayed through animation.

It is difficult to explain and understand the development, organization, and structure of MCSs using IR images only; therefore, a large number of studies have been conducted to analyze and reveal these characteristics of MCSs by comprehensively applying a variety of data. For example, Qin et al. (2004) used a variety of satellite data to comprehensively reveal the multi-scale characteristics, as well as the activities and evolution, of mesoscale rainstorm clouds (i.e., MCSs) during a heavy rainfall event. Using Doppler weather radar and satellite data, Shou and Xu (2007) analyzed the structural and evolutionary characteristics of an MCS that produced extremely heavy rain in the upper reaches of Shalan River in Heilongjiang Province on 10 June 2005, and found that the strong convection detected by radar mostly occurred in the region with large brightness temperature gradients. Some other case studies (Zheng et al., 2018; Gong et al., 2019; Luo et al., 2019) found that sometimes strong convection was mainly located in the active lightning areas with low brightness temperature and positive cloud-to-ground lightning flashes. Based on satellite IR images and Doppler weather radar data (especially the latter), Wang X. F. et al. (2014) statistically analyzed the types and characteristics of MCSs during the Meiyu period in the middle and lower reaches of the Yangtze River, and found that linear MCSs occur slightly more often than nonlinear MCSs, and eight types of linear MCSs exist: trailing stratiform MCSs, leading stratiform MCSs, training line/adjoining stratiform MCSs, back-building/quasi-stationary MCSs, parallel stratiform MCSs, broken line MCSs, embedded line MCSs (EL), and long line MCSs (LL), with two of the types (EL and LL MCSs) identified for the first time. Wu et al. (2019) analyzed the multi-scale structure of an MCC that occurred in northern Jiangsu Province on the evening of 3 July 2006, and found that the scale of the MCC in the mature stage was about 1000 km, and weather radar observations showed that it was actually an active bow-shaped squall line, 150–200 km in length, accompanied
by a mesoscale convective vortex with a scale of about 60 km, a meso-$\beta$-scale cold pool, a gust front on the ground, and a number of mesovortices with a scale of 4–5 km appearing in the front of the squall line.

Unlike using observations from weather radar, it is difficult to use only observations from geostationary meteorological satellites to directly identify heavy rainfall, CGs, hail, and tornadoes. However, the analysis carried out by Lu and Wu (1997) showed that cloud-top temperatures, temperature gradients, expansion of cloud clusters, and penetrating (overshooting) cloud tops have obvious correlations with precipitation intensity, but the correlations vary from region to region. Statistical analyses based on observations from geostationary meteorological satellites showed that monitoring and nowcasting CGs and hail need to especially focus on rapidly developing MCSs, PECSs, and isolated convective clouds on their right, and particularly the regions together with low IR brightness temperatures and their large gradients, large differences between IR and water vapor channel brightness temperatures, and their large gradients (Fang et al., 2014; Lan et al., 2014).

Since the late 1980s, using $-32$ or $-52^\circ$C of IR brightness temperature as the MCS identification threshold, a number of MCS census results have been obtained in China and the surrounding areas, such as southern China (Li et al., 1989; Jiang et al., 1990; Xiang and Jiang, 1995), the Qinghai–Tibet Plateau (Jiang et al., 1996; Yang and Tao, 2005; Li et al., 2018), the Yellow Sea and surrounding areas (Zheng et al., 1999), and Yunnan and surrounding areas (Duan et al., 2004). Ma et al. (1997) carried out a census of $M_\alpha$CSs with eccentricity of 0.5 or more and $M_\beta$CSs with a minor axis of 1.5° latitude and above in China and surrounding regions for the summers of 1993–1995, and obtained 234 $M_\alpha$CSs and 585 $M_\beta$CSs. Zheng et al. (2008) comprehensively obtained the climatological distribution of MCSs in China and surrounding areas using the threshold of $-52^\circ$C based on the IR brightness temperature data during summer over a 10-yr period, and found that, on the whole, the MCS active areas were distributed in three transmeridional bands, associated with each other by the summer monsoon over East Asia. Yang et al. (2015) further analyzed the climatological distribution of different types of MCSs in China based on the Fengyun-2 satellite data for May–August in an 8-yr period. Besides MCCs, PECSs, $M_\alpha$CCSs, and $M_\beta$ECSs, they also identified two other types of $SM_\beta$CCSs (smaller-scale circular $M_\beta$CSs) and $SM_\beta$ECSs (smaller-scale elongated $M_\beta$CSs). They found that 80% of MCSs in China are elongated MCSs. Ma et al. (1997) found that there are two types of diurnal variations in the life cycle of $M_\alpha$CSs in China: one type is generated at night and dissipates in the early morning, while the other is generated in the afternoon and dissipates at night. Zheng et al. (2008) analyzed the diurnal variations of MCSs in different regions of China, and found that the diurnal variations of MCSs are different in different regions, and there are two types of MCS diurnal variation: single-peak MCSs, which occur more often over plateaus or mountains, and multi-peak MCSs, which are more common over plains or basins. They also found that MCSs in the Sichuan basin develop remarkably more often during the nighttime. However, in the Guangdong–Guangxi region, MCSs over coastal areas propagate to land in the afternoon and to sea after midnight, and those over mountains propagate from mountains to plains after midnight; plus, there also exists a type of MCS with longer duration and less significant diurnal variation (Zheng and Chen, 2013). Note that the features of diurnal variation in convection revealed by different types of data vary somewhat.

4. SCW and its forecasting

4.1 Large hail

Ge (1966) analyzed and summarized 12 hailfall events in Beijing in 1964, and his main conclusions are as follows. (1) Hailstorms were sometimes arranged in a row, usually at an angle of 60°–90° to the cold front, rather than parallel to the cold front as the main rainbelt did. (2) Compared with thunderstorms without hail, the average vertical profile of reflectivity of the multiple hail events showed a stronger echo, and the height of the strong echo was higher. (3) During the processes of large hail, the RHIs (range height indicators) showed obvious echo overhangs and WER structures. Wang and Huang (1978) pointed out that there are several types of convective storms that produce large hail, such as supercell storms, multicell storms, and pulse storms (referred to as “symmetric hail clouds” in their paper). Yang et al. (1980) pointed out that: (1) There are mainly five echo types of hail systems that commonly occur in North China—namely, southward moving squall line echo bands, eastward moving squall line echo bands, airmass echo clusters, supercells, and multicells. (2) The typical morphology of large-hail echoes includes band echoes, hook echoes, and finger echoes. Gong et al. (1980) summarized the movement features of hail echoes in Pingliang, Gansu Province, and found that most of the hailstorms moved from northwest to southeast, accounting for 65%; some of them moved from north to south, accounting for 19%; some moved from west to east, accounting for 6%;
and a few moved against upper-level winds or stagnated, accounting for 5%. They also found that stronger echoes above 36 dBZ, extending to a height of more than 6 km above the ground, and large mid-level reflectivity, are good indicators in identifying hailstorms. Ma et al. (1980) pointed out that there are two different formation processes of finger echoes, which is one of the main characteristics of hailstorms. Lei (1983) divided hailfall into cold hailfall and warm hailfall according to whether the temperatures at 700 and 850 hPa are less than 3 and 12°C, respectively. Cold hailfall events account for only 19%, most of which occur in February, and a few of which occur in spring or autumn, and most of this type of hail is graupel or small hail. In warm hailfall events, there are many large hailstones, which often reach 2–3 cm in diameter, accompanied by CGs. Wang and Xu (1983, 1985) pointed out that only supercells with large BWER can bring forth serious hail disasters. Xu (1991) better identified hailstorms and non-hailstorms based on a combination of the following four factors: echo top height, strong echo top height, thickness of negative temperature zone, and echo shape. Ge et al. (1998) proposed an approximate structure of the airflows in a severe hailstorm that occurred in Beijing on 22 June 1995, using the C-band Doppler weather radar data of the Chinese Academy of Meteorological Sciences (CAMS). Using 25 years (1974–1998) of ground hail reports from spotters in Pingliang, Gansu Province, and observations from 711 conventional weather radars, Zhang et al. (2002) found that: (1) The echo top height above the ground of hailstorms in Pingliang generally exceeds 9.7 km, and the height to which the 30-dBZ reflectivity extends is a useful parameter to distinguish severe hailstorms from weak ones. (2) The maximum reflectivity of each hailstorm in Pingliang mainly appears at the height of 5–6 km above the ground, and the reflectivity at this level is about two times as intense as that in the 0°C layer.

Yu et al. (2005) pointed out the main indicators of large hail in Doppler weather radar observations, including the 45- or 50-dBZ reflectivity vertically extending above the height of the −20°C isotherm, the echo overhang, WER, BWER, abnormally large values of vertically integrated liquid water (VIL) or VIL density, three-body scatter spike (TBSS), and intense divergence at the storm top. Liao et al. (2007a) analyzed a series of SCW events in northern Hunan Province on 14 May 2002 based on Changde CINRAD-SB radar observations, and the TBSS phenomenon indicating large hail was observed for the first time in China. Liao et al. (2007c) conducted a statistical analysis of 23 convective storms composed of 11 SCW processes that generated TBSS in CINRAD-SA radar observations in different parts of China, and found that: (1) The core reflectivity of each convective storm with TBSS was above 60 dBZ. (2) The length of TBSS was positively related to the volume and maximum intensity of the core region of strong reflectivity. (3) In the cases with TBSS, hailstones above 2 cm in diameter were all observed on the ground. Diao et al. (2008) pointed out that VIL and its density are very capable of identifying hail, especially large hail, and a leap in the VIL value can also be used as an indicator to identify large hail. Hu et al. (2015) selected 12 hailstorm cells with large hail with a diameter of 2 cm or more in Guangdong Province, and analyzed the radar echo characteristics of the cells. Their results showed that: (1) The maximum reflectivity of all the hailstorm cells was over 65 dBZ, and the maximum reflectivity extended above a height of 5 km above the ground. (2) The TBSS phenomenon of all the cells was observed, and the timing for identification of this phenomenon allowed some lead time for a hail warning. (3) The reflectivity values at the height of the −20°C isotherm all exceeded 54 dBZ. Zhang and Li (2019) developed a hail recognition algorithm using machine learning technology based on observations of 10 CINRAD-SA radars in Guangdong Province. Their results showed that the hit rate of this new algorithm is 9% higher than that of the traditional recognition method using a series of threshold values.

Chen (1984) analyzed the environmental conditions for large hail in the Beijing–Tianjin area for the period 1964–1979 and found that most of the large hail events occurred at 1300–1700 BT and dissipated at 1600–2000 BT. When the cold vortex center at 500 hPa appears between Lake Baikal and Ulaanbaatar, the cold dry northwesterly at the upper and middle levels and the low-level warm and moist airflow meets in the Beijing–Tianjin area, conditional unstable stratification forms and deep-layer vertical wind shear is significant. Large hail in the Beijing–Tianjin area occurs in the high-temperature and high-humidity areas near the intersection of the 200-hPa polar front jet axis, the 500-hPa high winds, and the 850-hPa southwesterly jet. Li et al. (2011) analyzed 19 hail processes that lasted over three days in the Beijing–Tianjin–Hebei area, influenced by North China (Mongolia) cold vortices, from 1975 to 2008, and their results showed that there are four main types of synoptic situations causing continual hailfall influenced by these cold vortices, including a deep cold vortex type, shallow cold vortex type, stepped trough with cold vortex type, and nearly horizontal trough with cold vortex type. The
hailfall echoes influenced by cold vortices in central and northern Hebei Province are mostly band-shaped and have a low probability of producing large hail, while the hailstorms of southern Hebei Province are mostly severe multicell storms or supercell storms displaying block echoes, which have a higher probability of large hail. Lan et al. (2014) selected 27 hail processes that occurred in North China from 2010 to 2012 and classified them into three types according to their synoptic background, main systems of influence, and cloud system features, which were: the rear of cold vortex cloud system type, the pre-trough of cold vortex type, and the northerly airflow type. Cao et al. (2018) analyzed the environmental conditions of hail in the first-step and the second-step regions of China (using an altitude of 1 km as the threshold to distinguish between these two-step regions), and found that the hail in the first-step region often appears in environments with more unstable stratification, greater CAPE, more moisture, and stronger vertical wind shear. Yu et al. (2020) summarized the environmental background and radar echo characteristics of a large number of examples of large hail in China, and suggested that the environmental conditions of large hail include appropriate values of CAPE, 0–6-km wind vector differences that represent deep-layer vertical wind shear in the troposphere, and the height of the hail melting layer (the height of wet bulb temperature of 0°C above the ground); moreover, the radar echo features of large hail include a high overhang of strong echoes (55-dBZ strong echoes extend vertically above the height of the −20°C isotherm), strong echoes above 65 dBZ appearing at any position, abnormally large values of VIL, high and big echo overhangs and WER, BWER of supercells, TBSS, and intense divergence at the storm top.

Zhang et al. (2008) conducted a statistical climatological analysis using hail reports in China from 1961 to 2005, and found that: (1) Hail generally appears in mountainous areas and plains in northern China, and appears more frequently in the north of China than in the south. (2) In northern and western China, hail usually begins in late spring and ends in early autumn; while in southern and southwestern China, hail usually begins in early spring. (3) Hail occurs during 1500–2000 BT in most of China. Zhao J. T. et al. (2015) constructed a database of hail disaster cases for each county in the Chinese mainland for the period 1950–2009, and found that: (1) The spatial distribution of hail disasters presents a feature of one concentrated band along with multiple disaster zones, and the hail disaster band extends from Northeast to Southwest China. (2) Before 1987, the annual number of counties with hail disasters generally presents an upward trend, but after 1987 it shows a downward trend, and the period with the greatest frequency of hail disasters is from the 1970s to the mid-1990s.

Xu and Wang (1985, 1988, 1990) successively developed a one-dimensional hail cloud model, a two-dimensional hail cloud model, and a three-dimensional convective cloud model. Xu and Duan (2001) used the above-mentioned three-dimensional convective cloud model to explore the mechanism of hail formation and proposed the “acupoint” theory of hail growth. Guo et al. (2001a, b) developed a three-dimensional hail-categorization cloud model with different grades of hailstone, in which hailstones are classified into 21 grades and 5 categories. Chen et al. (2012) used the three-dimensional model of Guo et al. (2001a, b), combined with a three-dimensional particle growth model, to perform a numerical simulation of an actual supercell hailstorm. The structures of the storm, such as the mesocyclone, WER, and echo overhang, were well simulated and reproduced, showing that the model had good capability in simulating supercells. Their simulation showed that hail embryos were generated by freezing supercooled raindrops during the storm development, and were mainly distributed in the upper part of the main updraft. There were also a considerable number of hail embryos at the middle and upper levels to the northwest of the main updraft, and hail was mainly distributed to the east of the main updraft.

Using data of the first China dual-polarization S-band Doppler weather radar (CINRAD-SA-POL) constructed jointly by Zhuhai and Macao, Wang et al. (2018) analyzed a typical South China spring supercell hailstorm that occurred near Zhuhai and in which the maximum hailstone diameter was 2–3 cm. In the large hail area of the storm, in addition to the high reflectivity (above 60 dBZ), low correlation coefficient (less than 0.9) and low differential reflectivity (ZDR) (−1.0 to 0.5 dB) were observed. Feng et al. (2018) used data of the third CINRAD-SA-POL radar of China in Xiamen (the second is the WSR-88D in Shanghai upgraded with dual polarization function) to analyze a hailstorm in the southeast coastal area of Fujian Province. It was found that, during the descent of hail, ZDR and the specific differential phase turned from negative to positive, indicating that, during the period, dry hail particles gradually melted into heavy raindrops or hail particles enclosed by water film as the temperature increased. In general, the introduction of dual polarization function has enhanced the ability of new-generation weather radar to identify large
hail and hail status (dry hail, hail with water film, and a large number of smaller hail particles crowding together).

### 4.2 Downbursts and CGs

Downbursts refer to the strong downdrafts within a thunderstorm, which cause strong wind gusts above Beaufort Scale 8 on the ground. The lower part of a downdraft and the strong divergent winds on the ground as a whole are called a downburst (Fujita and Byers, 1977). CGs are also called thunderstorm high winds in China, which refer to non-tornadic straight strong gusts produced near the ground by DMC (thunderstorms or convective storms). CGs are mainly caused by a strong downdraft accompanied by downward momentum in DMC, and by the spread of the cold pool near the ground caused by the downdraft (the front of the cold pool is called the gust front) (Johns and Doswell III, 1992; McNulty, 1995; Moller, 2001). Most CGs occur accompanied by downbursts, and they are one of the direct results of downbursts. Squall lines and bow echoes, as discussed in Section 3.2, are two types among the main convective systems causing CGs.

Xu and Wei (1995) used a two-dimensional version of the three-dimensional convective cloud model developed by Xu and Wang (1990) to simulate a downburst that occurred in the USA. Sensitivity experiments were performed to discuss the effect on a wet microburst of precipitation intensity, precipitation particle phases and sizes, environmental vertical wind shear, and humidity, separately. Liu (2001) used the C-band Doppler weather radar (similar to the CINRAD-CC radar) data of Beijing Meteorological Bureau to analyze the structures of radial velocity of a wet microburst on 22 July 1997 in Beijing, and clearly identified the strong low-level divergence on a scale of 2–3 km. This was the first time that Doppler weather radar had detected strong low-level divergence of a downburst in China. He further employed the same model used by Xu and Wei (1995) to simulate the downburst process, and obtained a conclusion different from that obtained by Xu and Wei (1995) from the simulated downburst that occurred in the USA. Their simulation results showed that precipitation drag was the main driving force of the downburst. However, Xu and Wei (1995) concluded that precipitation evaporative cooling was more favorable for the downburst than precipitation drag.

Yu et al. (2006a) conducted a detailed and thorough analysis of a series of downburst events that occurred in Dingyuan and Hefei, Anhui Province, on the afternoon of 6 June 2003. The downburst events occurred in environ-
percell stage. (3) Based on the increase in radial velocity from radar observation, it was estimated that the effects of the three factors as below on the increase of CGs were nearly the same in the bow-echo squall line stage: the divergence of strong downdraft, the strong cold pool density current, and the evaporation of a number of precipitation particles of stratiform clouds. The cold pool merger was an important cause of the extreme CGs generated by the above-mentioned SCS in Shangqiu, Henan Province. Liang and Sun (2012) analyzed the numerical simulation results of this process, and especially emphasized the important contribution of the rear mid-level dry and cold airflow to the widespread CGs. Liu et al. (2012) pointed out through numerical simulations that the evaporative cooling of rainfall played a key role in the formation of strong cold pools during the process. Based on numerical simulations, Wang et al. (2013) further pointed out that, during this process, the 0–6-km deep-layer vertical wind shear was weak, but the 925–700-hPa vertical wind shear was strong. In this situation, low-level water vapor contents became an important factor influencing storm structures. Convective systems would evolve into a well-organized squall line in moderate or high-humidity low-level environment, while they would develop into poorly organized pulse storms in the low-humidity low-level environment. These results were similar to those of Sun J. H. et al. (2014).

On the night of 1 June 2015, the cruise ship “Oriental Star” suddenly capsized in heavy rain in the Jianli section of the Yangtze River in Hubei Province, causing 442 deaths. At that time, it was suspected that the cruise ship was captured by a tornado or a downburst. A joint investigation team was formed from the Department of Emergency Response, Disaster Mitigation and Public Services of the CMA, the Forecasting and Networking Division of the CMA, the NMC, the CAMS, Hubei Meteorological Bureau, Nanjing University, and Peking University. The investigation team first conducted a damage survey on the surrounding areas of the capsizing accident. Zheng et al. (2016a) summarized the results of the survey as follows. Combining satellite and radar observations and the damage survey of the surrounding land areas of the accident revealed that intense CGs caused by downbursts and a suspected tornado occurred over part of the Yangtze River and the surrounding areas roughly during 2100–2140 BT 1 June, with the maximum CGs exceeding Beaufort Scale 12; and the CGs were spatially discontinuously distributed, on multiple scales, with severe CGs on very small spatiotemporal scales. Furthermore, the radar data analysis group (Zhao K. et al., 2015) of the joint investigation team pointed out in a report to the CMA that the “Oriental Star” capsizing accident was caused by a microburst produced by a bow echo, and based on radar radial velocity observation and the downburst conceptual model, it was estimated that the intense CGs caused by the above-mentioned microburst exceeded 35 m s$^{-1}$ at the height of the cruise ship of the position where the “Oriental Star” was about to capsized.

Wang et al. (2016) applied the CINRAD-SA radar data at Shijiazhuang from 2006 to 2008 to statistically analyze the radar echo characteristics of CGs in central and southern Hebei Province. Their results showed that: (1) the echo types producing CGs include bow echoes, band echoes, and isolated block echoes, with band echoes (including squall lines without a bow echo) accounting for 67% of the total, bow echoes 20%, and isolated block echoes 13%; (2) the CG echos were featured with bow echoes, high-value areas of low-level radial velocity (which is the main feature of CGs), and gust-front echoes; (3) about 34% of convective storms that produced CGs were unable to be nowcasted because they did not have any of the features mentioned in (2). Yang et al. (2018) selected and analyzed 19 disaster-causing CG processes that occurred in Beijing from 2010 to 2014, and found that 78% of the CGs produced by band echoes and 100% of the CGs produced by bow echoes could be successfully nowcasted based on the high-value areas of low-level radial velocity, and 67% of the CGs could be nowcasted 30 min in advance. Yu et al. (2020) suggested that, in addition to low-level radial velocity over 20 m s$^{-1}$, bow echoes, significant MARC, and gust fronts with a speed exceeding 15 m s$^{-1}$, if an isolated block echo moves fast, it should be considered to issue a CG warning; however, different threshold values of the moving speed of the isolated block echo need to be determined in different places based on statistics of large quantities of radar echoes. Guo and Sun (2019) carried out a statistical and comparative analysis of CGs (speed $> 17$ m s$^{-1}$) caused by three different types of MCSs (linear MCSs, nonlinear MCSs, and isolated convective storms) in Hubei Province, including their spatiotemporal distribution, movement and propagation, and environmental characteristics. Their result indicated that: (1) nonlinear MCSs and isolated convective storms are the dominant systems causing CGs in Hubei Province, with the number of CGs caused by nonlinear MCSs accounting for 41.9% of the total and that caused by isolated convective storms 39.3% of the total; (2) although the proportion of MCSs with ground inflow CGs over 17 m s$^{-1}$ to all MCSs is very low, both the area of influence and the lifetime of MCSs with ground inflow CGs are much greater than the corresponding average values of
Tornadoes are a type of catastrophic microscale weather with great destructive power produced by convective clouds and rotational winds, and the most violent tornadoes have a maximum wind gust speed of 125–140 m s\(^{-1}\) at the surface (Davies-Jones et al., 2001). These results indicated that: (1) The high occurrence frequency of ICGs lies in central and eastern China. ICGs begin to appear in South China and the region south of the Yangtze River in March, reach central and eastern China in April, and then reach northern, northeastern, and northwestern China in May. (2) The environmental mid- and low-level vertical wind shear of ICGs in China is moderate, which is significantly lower than the mean value of their derecho counterparts in the USA. (3) Obvious dry layers exist in the middle troposphere. Yang X. L. et al. (2017) analyzed the spatiotemporal distribution characteristics of CGs above 17 m s\(^{-1}\) in China using 5 years of CG data (2010–2014), and found that CGs mainly occur in the warm season in eastern China. In spring, the highest occurrence frequency of CGs appears in Guangdong Province. In summer, the occurrence frequencies of CGs in northern China and Guangdong Province are relatively high. Ma et al. (2019) compared 95 cases of extreme CGs above 30 m s\(^{-1}\) with the same number of ordinary DMC cases in a 16-yr period of 2002–2017, to highlight the key environmental parameter characteristics of extreme CGs.

### 4.3 Tornadoes

Tornadoes are a type of catastrophic microscale weather with great destructive power produced by convective clouds and rotational winds, and the most violent tornadoes have a maximum wind gust speed of 125–140 m s\(^{-1}\) at the surface (Davies-Jones et al., 1992; Davies-Jones et al., 2001; Moller, 2001): mesocyclonic tornadoes (supercell tornadoes) and non-mesocyclonic tornadoes (non-supercell tornadoes). Mesocyclonic tornadoes are generated inside the mesocyclone of supercells, and most EF2 or more intense tornadoes are generated by supercells. Non-mesocyclonic tornadoes do not occur inside a mesocyclone, and the DMC producing this type of tornado is generally not a supercell. Non-mesocyclonic tornadoes can be further divided into two categories. The first type of non-mesocyclonic tornado appears in the meso-γ-scale vortex in the forepart of squall lines or bow echoes. The meso-γ-scale vortex is formed under completely different mechanism from that of the mesocyclone, and it not only can spawn a tornado, but also give rise to straight high winds (Trapp and Weisman, 2003). The meso-γ-scale vortex is of roughly the same size as the mesocyclone of a supercell, but is usually shallower than the mesocyclone in its vertical extent. The tornado formed in the meso-γ-scale vortex in the forepart of a squall line and/or a bow echo is usually weaker than that formed in the mesocyclone of a supercell, but the stronger ones can still reach EF2, and a few can even reach EF3. The second type of non-mesocyclonic tornado usually appears in a convergence shear line near the surface. A transient vortex generated in the convergence shear line meets the updraft of a cumulonimbus or a cumulus congestus, and its vertical vorticity is stretched to be amplified to tornado strength (Wakimoto and Wilson, 1989). This type of tornado is usually weak, with most being the weakest tornado type of EF0, and just a few reaching EF1. The occurrence frequency of tornadoes in China is much lower than that of the USA, but it still happens occasionally (Fan and Yu, 2015).

Shen (1990) analyzed 11 tornadoes that occurred in typhoon rain bands in Jiangsu Province from 1962 to 1984. He found that the generation of the tornadoes was related to the locations and intensities of the typhoons. Jiang (1997) analyzed the tornado that happened in Hongqili town, Panyu, Guangdong Province, on 19 April 1995, including analyses of the synoptic background, satellite images, and conventional weather radar echoes. From the radar echo structures given by Jiang (1997), we can tell that the tornado should have been produced by a supercell. Liu et al. (1998) analyzed the patterns of the upper- and lower-level synoptic circulations and the airflow near the ground during a tornado process near Xianyang in central Shaanxi Province on 4 September 1983. The reflectivity of conventional weather radar showed that the tornado appeared in an obvious bow-shaped echo in the tail of a squall line, so it was quite likely the first type of non-mesocyclonic tornado.

Yu et al. (2006b) conducted a detailed and thorough analysis of the environmental background, and especially the echo characteristics observed by a Doppler weather radar, of an EF3 tornado that occurred in Wuwei, Anhui Province at 2320 BT on 8 July 2003. The most obvious feature of this tornado analysis is the use of observations from the first operational CINRAD-SA radar of China at Hefei, Anhui Province. The results showed that the environmental background of this tornado had large CAPE (2800 J kg\(^{-1}\)) and 0–6-km vertical wind shear (the wind vector difference was 24 m s\(^{-1}\)), which was conducive to the formation and development of a supercell storm. In addition, the 0–1-km wind vector difference was 12 m s\(^{-1}\), the lifting condensation level was 650 m, and both of these two conditions favored the production of EF2 or greater tornadoes (Craven et al., 2002; Evans and Doswell III, 2002; Thompson et al., 2002; Shade and Doswell III, 1992; Davies-Jones et al., 2001; Moller
2003). The convective system that produced the intense tornado originated from a convective rainband in a large stratiform precipitation area during the Meiyu period, and gradually developed into a cluster convective system, at the south side of which the tornado was spawned by a supercell. At 2329 BT of the tornado process, the radar radial velocity at 0.5° elevation showed an intensely convergent mesocyclone enclosing a smaller-scale tornado vortex signature (TVS), and the vertical vorticity of the TVS reached up to $5.0 \times 10^{-2}$ s$^{-1}$. Yu et al. (2008) also used data from the CINRAD-SA radar of Xuzhou to conduct a detailed and thorough study of an EF3 tornado spawned by a heavy precipitation supercell at 1130 BT in Lingbi, Anhui Province on 30 July 2005. Liu et al. (2009) analyzed an EF3 tornado that moved from Tianchang, Anhui Province, to Gaoyou, Jiangsu Province on the afternoon of 3 July 2007, and focused on the evolution of the mesocyclone before and during the tornado process. The tornadic supercell was also embedded in the convective rainband during the Meiyu period. Zheng et al. (2009) summarized the environmental and Doppler weather radar echo characteristics of three mesocyclonic tornadoes greater than EF2 that occurred in Anhui Province, and compared them with those of supercells with large hail. Meng and Yao (2014) conducted an analysis of the damage survey, the environmental conditions, and the radar echo characteristics of a supercell tornado that occurred in Zhangjiawan town, Tongzhou District, Beijing, during an extreme heavy rain event on the afternoon of 21 July 2012. This damage survey was based on the enhanced Fujita scale (WSEC, 2004) in the USA, and was the first standard damage survey of a tornado in China. Zheng Y. Y. et al. (2015) analyzed and summarized the environmental and radar echo characteristics of tornadoes in the outer rainbands of tropical cyclones.

Fan and Yu (2015) conducted a statistical analysis of the spatiotemporal distribution characteristics of EF2 or greater tornadoes for the period 1961–2010, and EF1 or greater tornadoes for the period 2004–2013 in China based on the Handbook of China Meteorological Disasters, Annual Report of China Meteorological Disasters, and other documents. Some of their results are summarized here: (1) a total of 165 significant tornadoes were recorded during 1961–2010, including 145 EF2 tornadoes, 16 EF3 tornadoes and 4 EF4 tornadoes, with an average of 3.3 significant tornadoes a year; (2) there were 143 EF1 or greater tornadoes from 2004 to 2013, including 121 EF1 tornadoes, 19 EF2 tornadoes, and 3 EF3 tornadoes, with an annual average of 14.3 tornadoes; and (3) tornadoes mainly occur in the plains of both eastern China and parts of central China, including the plains of the Yangtze–Huahe River basins, the Lianghu plains (in Hubei and Hunan provinces), South China, Northeast China, and southeastern North China; but Jiangsu Province, especially its northern part, is the region with the greatest frequency of tornadoes. Wu et al. (2013) conducted a statistical analysis of the environmental background, radar echo characteristics, and SCW of supercells in northern Jiangsu Province for the period 2005–2009. One of their conclusions was that, during the five years, a total of 72 supercells occurred in northern Jiangsu, and a total of 11 supercell tornadoes occurred, which indicates that the probability of a tornado produced by a supercell (mesocyclone) in northern Jiangsu is 11/72 = 15.3%; however, owing to the small sample size, the probability must be regarded as only a very rough estimate.

On 4 October 2015, Typhoon Mujigae landed on the western coast of Guangdong Province. It was an EF3 tornado generated by a miniature supercell in one outer rainband that hit Foshan City of Guangdong Province at 1528–1600 BT and caused severe disasters, resulting in 4 deaths and more than 80 injuries. At the time, the most complete and clearest videos of a tornado taken in China were produced for this event. The CMA, the School of Atmospheric Sciences of Nanjing University, the Department of Atmospheric and Oceanic Sciences of Peking University, and the Foshan Tornado Research Center, participated in the damage survey. Li et al. (2017) analyzed the path, the rating, and the Guangzhou CINRAD-SA radar echo characteristics of the tornado. Zhao et al. (2017) and Bai et al. (2017) both analyzed and discussed the damage survey, the environmental background, and the structural characteristics of the mesocyclone of this intense tornado. Zhao et al. (2017) focused on the structure and evolution of the mesocyclone in the miniature supercell that spawned the tornado, and compared the mesocyclone with those in the outer rainbands of hurricanes in the USA. Bai et al. (2017) made an exhaustive and very clear analysis of the damage survey of the tornado, not missing any important details, and expressed their conclusions in a very straightforward and vivid way through fine pictures. They also clearly presented the characteristics of the environmental background and the mesocyclone evolution. During 1420–1500 BT 23 June 2016, a violent tornado generated from a large supercell attacked Funing County, Yancheng City, Jiangsu Province, causing heavy loss of life and property, including 98 deaths and 846 injuries, a large amount of infrastructure destroyed, and a certain number of large flying objects. It was the deadliest tor-
nado that caused the most casualties witnessed in China in the 40 years prior. This violent tornado was also accompanied by hail, straight CGs, and heavy precipitation. Around 1400 BT 23 June 2016, the chief forecaster of Jiangsu Meteorological Bureau called the Funing Meteorological Office and asked them to issue a tornado warning (Jiang, 2019, personal communication). The tornado warning was finally issued at 1439 BT, when the tornado was already developing, but it was still a valid warning because after that the tornado continued to develop for roughly 20 min. The CMA (the NMC and the CAMS), Nanjing University, Peking University, Jiangsu Meteorological Bureau, and the Foshan Tornado Research Center immediately conducted a joint damage survey, and ultimately determined that the tornado path was about 34.5 km long, the average path width was about 2 km, with the widest path being 4.1 km, and the maximum damage reached the EF4 level (Xue et al., 2016; Zheng et al., 2016b; Meng et al., 2018). Zhang et al. (2016) and Zheng et al. (2018) provided an analysis of the environmental, satellite image, and radar echo characteristics of this violent tornado. Meng et al. (2018) analyzed and discussed the environmental background, the radar echo characteristics, the operational warning process, and the damage survey of the Funing EF4 tornado, and pointed out that the rotational speed of the corresponding low-level mesocyclone reached 42 m s\(^{-1}\) when the tornado attained its most violent level, while the corresponding speed difference between the adjacent radial velocities of the TVS in the mesocyclone reached 85 m s\(^{-1}\). At about 1717–1747 BT 3 July 2019, a rare and violent EF4 tornado occurred in Kaiyuan, Liaoning Province. The length of the tornado path was about 14 km (Zhang T. et al., 2020), causing 7 deaths and more than 190 injuries. This was the first time that an EF4 tornado event was recorded with complete records from videos, eyewitnesses, and a damage survey in Liaoning Province. Zhang T. et al. (2020) and Zheng et al. (2020) produced a detailed damage survey and careful weather analysis of the tornado, respectively. Zheng et al. (2020) found that the precipitation produced in the early stage of the tornadic supercell significantly improved the low-level moisture conditions, which had earlier been of lower relative humidity unfavorable for tornado; and when the hook-echo part of the tornadic storm moved to the tornado forming area, the storm generated a relatively weak downdraft and a cold pool with suitable intensity, combining the effects of other favorable conditions, and then spawned the violent Kaiyuan tornado. Diao et al. (2014) analyzed the environmental and radar echo characteristics related to five non-supercell tornado processes (six tornadoes in total) that occurred in Shandong Province during 2006–2012. For two of these processes, the tornadoes appeared in the forepart of squall lines and/or bow echoes. The formation process of the EF3 tornado that occurred in Wenchang, Hainan Island, on the afternoon of 5 June 2016 was completely recorded by a camera monitoring a fishpond, which was extremely fortuitous and valuable. Wang and Yu (2019) suggested that the Wenchang tornado was an atypical supercell tornado, or rather a hybrid tornado, which had the characteristics of both a supercell tornado and a non-supercell tornado. Wu et al. (2019) analyzed the multiscale structures of an MCC from the evening of 3 July to the early morning of 4 July 2006, and found that the main part of the MCC was a squall line. Several meso-γ-scale vortices with a size of 4–5 km formed along the front of this squall line, and some of them developed into tornadoes, including 4 EF2 and 3 EF1 tornadoes. Huang X. X. et al. (2019) studied two tornadoes generated by different miniature supercells in the spiral rainbands of Typhoon Ewiniar on 8 June 2018, using data from the Guangzhou CINRAD-SA radar and X-band dual-polarization Doppler weather radar of Foshan Meteorological Bureau. The Foshan radar successfully captured the tornado debris signatures during the tornado process.

4.4 SCW forecasting

Sun J. S. et al. (2014) and Yu et al. (2020) both gave a clear, detailed, and complete description of SCW forecasting. There are two main methods for potential SCW forecasting: (1) the pattern recognition method (Miller, 1972; McNulty, 1995); and (2) the “ingredients-based” forecasting method (Doswell III et al., 1996; Moller, 2001). These two forecasting methods complement each other, and the best results can often be obtained by combining them. Currently, forecasting methods using machine learning technology are also developing constantly. Sun J. S. et al. (2014) discussed a broader scope involving almost all aspects of SCW forecasting. However, whilst they presented the potential forecasting methods in detail, nowcasting was given only a brief introduction. Regarding potential SCW forecasting, Sun J. S. et al. (2014) presented not only the pattern recognition method and “ingredients-based” method, but also a combination method of the two. Yu et al. (2020) not only elaborated and discussed nowcasting and warning of severe convection and SCW in great detail, but also presented the favorable environmental backgrounds of various types of SCW, which provided important references for SCW forecasting. Based on sounding and weather observations in
Beijing during the period May–September of 2007–2008, Lei et al. (2011) discussed the possibility of classified SCW forecasting using calculated key physical parameters from sounding data. Lei et al. (2012) further conducted an experimental study of classified SCW probability forecasting based on predictions of WRF rapid updated cycle assimilation and forecasting system of the Beijing Meteorological Bureau (BJ-RUC). Their study obtained the conditions favorable for SCW in Beijing using the special “sounding” data constructed from conventional sounding, microwave radiometers, and wind profilers, and analyzed the applicability of the “sounding” data from BJ-RUC predictions. Based on these results, they calculated the probability of the occurrence of severe convection on model grids. Furthermore, on the basis of the threshold ranges of different physical parameters of two types of weather: SDHR, and hail or CGs, they explored the possibility of classified SCW forecasting using the mesoscale NWP model predictions. For short-range forecasting of different types of SCW, including thunderstorms, SDHR, hail, CGs, and tornadoes, Zeng et al. (2015) first matched the time and sites of various types of SCW with those on the mesoscale NWP model grid using the proximity principle during the period February–September of 2001–2009 in Jiangsu Province, applied the fuzzy relative deviation matrix evaluation technique to obtain the weight distributions and to successively screen physical parameters, then obtained the different parameter sequences reflecting both obvious differences between severe convection and the climatological state and the SCW’s own relative stability, and further obtained the functions of the occurrence frequency distribution of the physical parameters according to the historical spectrum distribution of the parameters. Finally, based on mesoscale NWP model predictions, the historical SCW occurrence frequency distributions, and the weights of physical parameters, the technique of classified SCW probability forecasting in Jiangsu Province was constructed. Based on global NWP model predictions, Zhou K. H. et al. (2019) developed a deep learning forecasting solution for thunderstorms and classified SCW using a deep convolutional neural network, producing objective forecasting products that have become an important tool to support operational classified SCW forecasting at the NMC of CMA.

5. Progress in SCW operational forecasting at the NMC

5.1 History of SCW operational forecasting

By the 1980s and 1990s, operational meteorological departments in China had successively carried out operational short-term forecasting and nowcasting of SCW along with the deployment of conventional weather radar. In the 2000s, with the CINRAD radar network being developed, provincial operational meteorological departments and their subordinates have further improved their operations in monitoring, nowcasting, and warning of SCW. However, the NMC of China began to try forecasting of SCW from 2005, and before 2009 it only issued two types of forecasting products: thunderstorms and unclassified SCW.

In March 2009, the NMC founded the SWPC, and built up the first full-time and professional SCW forecasting team in China, in order to promote the development of SCW operation and forecasting technology. Since then, the NMC has gradually established a series of objective techniques and operations for monitoring, analysis, forecasting, forecast verification (Zheng Y. G. et al., 2015; Yang B. et al., 2017; Zhang X. L. et al., 2019), and damage surveys (Zheng et al., 2016a, b) of SCW; and what is more, all the monitoring and forecasting products have been being issued to meteorological departments and the public in real time or at fixed times.

Based on multi-source observations, the NMC issues real-time monitoring products of different types of SCW for different periods through the internet and the operational intranet (Fig. 1a). The deterministic forecasts and probabilistic forecasts of different types of SCW, including thunderstorms, hail, CGs, and SDHR, for the next 24 h are issued three times (at 0600, 1100, and 1800 BT) a day from April to September, and the forecasts of unclassified SCW for the next 48 h and 72 h, respectively, are issued once a day (at 1800 BT). In other months, the issue of forecasts or warnings is determined by the monitored and predicted SCW conditions. Figure 1b presents the forecasts of classified SCW for the period 0800–2000 BT 28 April 2015 issued at 0600 BT on the same day. Since 2015, the NMC has started issuing experimental short-term forecasts of classified SCW for the next 3–6 h within the meteorological departments of China. Since 2018, it has also launched an outlook of SCW for the next week within the NMC. In 2013, the NMC began to issue SCW warnings, which are divided into three levels: blue, yellow, and orange. The first yellow warning was issued on 28 April 2015 (Fig. 1), and no orange warning has yet been issued. Warnings are usually issued at a regular time in the same way that short-range forecasts are issued, but at 1500 BT 30 June 2016, the NMC issued a yellow warning of SCW for the first time at an irregular time (Gong et al., 2019). Verification results of the SCW forecasts of the NMC from April to September during
2010–2015 (Tang et al., 2017) show (in Fig. 2) that the SCW operational forecasting capability had an obvious increasing trend, and for the same forecasting period and lead time, the forecasting capabilities of thunderstorms, SDHR, and CGs or hail decreased in turn. The forecasting capabilities of CGs or hail were significantly lower than those of the former two categories, but the forecasting capabilities of CGs or hail that occurred across a vast area were usually higher, such as the forecasts of classified SCW on 28 April 2015. Verification of SCW forecasts in recent years exhibits the same trend as that in 2010–2015 (Zhang X. L. et al., 2020).

Fig. 1. Monitoring and forecasting products of different types of SCW issued by the NMC of the CMA on 28 April 2015: (a) 12-h SCW monitoring for the period from 1400 BT 28 to 0200 BT 29 April and (b) forecasts of thunderstorms and CGs/hail for the period from 0800 to 2000 BT 28 April issued at 0600 BT 28 April 2015. The first SCW yellow warning was issued by the NMC on the same day.
5.2 Objective forecasting and supporting techniques

The NMC has established a relatively complete objective technical support system for monitoring, analysis, forecasting, and forecast verification of SCW (Zheng Y. G. et al., 2015; Yang B. et al., 2017; Zhang X. L. et al., 2019). Based on multi-source observations from conventional surface stations, significant weather reports, automatic weather stations, lightning observation facilities, weather radars, and meteorological satellites, and through applying fuzzy logic, clustering, Kalman filtering, and other methodologies, the NMC has independently developed the automatic station data quality-control technique, the SCW and SCS information extraction and statistical analysis technique, and the real-time monitoring and extrapolation technique (such as identification and tracking of deep convective clouds, and that of thunderstorm cell using lightning data). Plus, the NMC has also improved the TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) algorithm (Han et al., 2009; Zheng et al., 2010, 2013; Zheng Y. G., 2015; Zhou et al., 2016), and has jointly developed the SWAN (Severe Weather Automatic Nowcasting System) with relevant provincial meteorological departments (Zheng et al., 2010; Han and Wo, 2018). The NMC has also improved the TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) algorithm (Han et al., 2009; Zheng et al., 2010, 2013; Zheng Y. G., 2015; Zhou et al., 2016), and has jointly developed the SWAN (Severe Weather Automatic Nowcasting System) with relevant provincial meteorological departments (Zheng et al., 2010; Han and Wo, 2018). The NMC has statistically analyzed the applicability and distributions of physical parameters of different types of SCW (Tian et al., 2015; Cao et al., 2018; Gong et al., 2019; Luo et al., 2019) and associated satellite image features (Fang et al., 2014; Lan et al., 2014). On the basis of the above-mentioned statistical results, a technical standard called “Mesoanalysis Specifications” including synoptic-scale analysis and mesoscale process analysis (Lan et al., 2013; Zhang et al., 2013; Zheng Y. G. et al., 2015) has been compiled and applied nationwide. Based on NWP (including ensemble) model products, the NMC has applied the “ingredients-based” method and deep learning (deep convolutional neural network) algorithm to develop probabilistic forecasting techniques of classified SCW (Zhang X. L. et al., 2019; Zhou K. H. et al, 2019). The high-resolution regional NWP model forecasts and their post-processing have been the main technical aid to short-term forecasting of SCW throughout the world (Zheng Y. G. et al., 2015). Although there are still many uncertainties in these products, the NMC has used “multimodel integration,” “neighborhood probability,” and “time-lagged ensemble,” as well as some other methods, to establish preliminary post-processing techniques for high-resolution NWP products (Zheng Y. G. et al., 2015; Yang B. et al., 2017; Tang and Zheng, 2019). The “Integrated Operational Platform for Severe Convective Weather Monitoring and Analyses” of the NMC has been a comprehensive support system for the operations of SCW monitoring, analysis, forecasting, and forecast verification, consisting of a data analysis and processing system, an automatic visualization system, and a web search and display system. This is an important supplementary tool to China’s Meteorological Information Comprehensive Analysis and Processing System (or MICAPS). The platform has been widely applied in operational weather forecasting departments at all levels through the operational intranet of the CMA (Zheng Y. G. et al., 2015; Yang B. et al., 2017; Zhang X. L. et al., 2019).

6. Summary and future outlook

This paper reviews the advances in research and operational forecasting of SCW that have taken place in China over the past several decades, with focuses on development of understanding on the synoptic background,
favorable environmental conditions, main organization modes of SCSs (including supercell storms, squall lines, and MCSs) and different types of SCW (large hail, downbursts/CGs, tornadoes), and Doppler weather radar echo and meteorological satellite imagery features of SCW. Finally, the history and current status of the operational forecasting of SCW at the NMC, CMA of China are briefly introduced. The review shows that Chinese scientists have performed a vast body of work in researching and operational forecasting of SCW, and the gap with the USA in this regard has gradually been narrowing.

The major advances in research and operation of SCW in China include the following. (1) The favorable environments for SCW in China have been investigated on the basis of the flow pattern recognition method or/and the “ingredients-based” method, and the results provide a solid foundation for the forecasting of potential SCW. (2) The lifting and triggering mechanisms of thunderstorms and SCSs have been studied and discussed, and the important roles of cold fronts, gust fronts, and other types of boundary-layer convergence lines (such as the convergence lines of sea breeze fronts) in the triggering and evolution of thunderstorms and SCSs have been mostly clarified. (3) Extensive, profound, and detailed observations and analyses have been made with respect to the organization modes of SCSs, such as supercells, squall lines, bow echoes, and MCSs. (4) On the basis of previous research by American scientists, the nowcasting and warning technologies of SCW, which are mainly based on Doppler weather radar observations and closely associated with the environmental conditions, have been studied, summarized, and widely applied. (5) The capability to forecast SCW has been significantly improved.

Finally, it should be pointed out that there are still some gaps between China and the USA in terms of the observation technology of SCW, especially in vast field experiments and research on the structure and evolution of SCSs and the underlying mechanisms of different types of SCW. In addition, due to the significant differences in synoptic and climatological backgrounds between these two countries, there are also significant differences in tornado research and operational forecasting. In the future, more profound and detailed studies are still needed on the mechanisms of CI and evolution, the organization modes of SCSs, the underlying mechanisms of different types of SCW, and the forecasting, nowcasting, and warning technologies of classified SCW. Regarding SCW operational forecasting, it is also necessary to further promote the application of high-resolution NWP model predictions in the potential forecasting and nowcasting of SCW, and to further apply artificial intelligence technology, such as recurrent neural networks and/or deep learning, to nowcast SCW. It is also urgent to establish a highly efficient platform for the automatic production and issuing of SCW warnings, with the time period from the time when the forecasters intend to issue one to the time when the users receive the one being less than a certain threshold period (which is 3 min at the National Weather Service of the USA). Finally, it should be noted that this paper focuses only on several aspects of the advances in SCW research and operation during recent decades in China; it certainly does not cover all of the achievements and contributions of all Chinese scientists.

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