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Review of Chinese atmospheric science research over the past 70 years: Synoptic meteorology

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Abstract Synoptic meteorology is a branch of meteorology that uses synoptic weather observations and charts for the diagnosis, study, and forecasting of weather. Weather refers to the specific state of the atmosphere near the Earth's surface during a short period of time. The spatial distribution of meteorological elements in the atmosphere can be represented by a variety of transient weather phenomena, which are caused by weather systems of different spatial and temporal scales. Weather is closely related to people's life, and its development and evolution have always been the focus of atmospheric scientific research and operation. The development of synoptic meteorology is closely related to the development of observation systems, dynamical theories and numerical models. In China, observation networks have been built since the early 1950s. Up to now, a comprehensive meteorological observation system based on ground, air and space has been established. In particular, the development of a new generation of dense radar networks, the development of the Fengyun satellite series and the implementation of a series of large field experiments have brought our understanding of weather from large-scale environment to thermal dynamics, cloud microphysical structure and evolution characteristics of meso and micro-scale weather systems. The development of observation has also promoted the development of theory, numerical model and simulation. In the early days, China mainly used foreign numerical models. Lately, China has developed numerical model systems with independent intellectual property rights. Based on the results of high-resolution numerical simulations, in-depth understanding of the initiation and evolution mechanism and predictability of weather at different scales has been obtained. Synoptic meteorology has gradually changed from an initially independent development to a multidisciplinary approach, and the interaction between weather and the change of climate and environment has become a hot and frontier topic in atmospheric science. This paper reviews the important scientific and technological achievements made in China over the past 70 years in the fields of synoptic meteorology based on the literatures in China and abroad, from six aspects respectively including atmospheric dynamics, synoptic-scale weather, typhoon and tropical weather, severe convective weather, numerical weather prediction and data assimilation, weather and climate, atmospheric physics and atmospheric environment.

Keywords Atmospheric sciences, Synoptic meteorology, Weather, 70-year progresses

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1. Introduction

Weather changes rapidly and is closely related to the people's life. The evolution of weather has always been a key area in the field of atmospheric research and operation. The atmospheric motion systems with typical characteristics, such as high pressure, low pressure, high pressure ridge, and low pressure trough, which cause various weathers, are called weather systems. Various weather systems of different spatial and temporal scales interact with each other, showing extremely complex evolution characteristics under the impact of topography. Generally speaking, weather systems of less than 2 km in horizontal are called micro-scale weather systems (e.g., thunderstorms, tornadoes) with a life span of several minutes to several hours. Weather systems of 2–2000 km in horizontal are called mesoscale weather systems (e.g., supercell, land-sea breeze, squall line, typhoon, front, cyclone, anticyclone) with a life span of several hours to several days, of which 200–2000 km in horizontal are also called synoptic-scale weather systems (e.g., typhoon, front, cyclone, anticyclone), with a life span of one day to several days. Weather systems of over 2000 km in horizontal are called large-scale weather systems (e.g., blocking high, subtropical high), with a life span of several days to over ten days. Weather systems that are equal to or larger than synoptic-scale are sometimes referred to as large-scale weather systems. Weather systems are always in the process of formation, development and dissipation. Various weather systems have different formation and dissipation conditions and sources of energy. Synoptic meteorology is mainly concerned with the physical mechanisms of the evolution rules, formation and dissipation conditions, energy sources and interactions of various weather phenomena in the atmosphere, as well as the principles and methods of weather analysis and forecast.

The development of synoptic meteorology is closely related to the development of observation systems, dynamical theories and computers. Before the 1920s, international synoptic studies mainly focused on the analysis of various pressure systems at surface and their distribution. Since the 1920s, due to the use of radiosonde, the study of synoptic meteorology has extended to three-dimensional space. The Norwegian School put forward the polar front theory, and the Swedish meteorologist put forward air mass theory. After the 1930s, synoptic meteorology began to combine with dynamic meteorology, and the development and application of Rossby wave theory have brought synoptic meteorology into a new stage of development. Large-scale weather systems in the westerlies, severe convective storms, tropical weather and atmospheric circulation have been studied extensively. Since the 1950s, the development of computer and meteorology satellites has greatly improved the capabilities of numerical simulation and diagnostic analysis of weather systems, and the research on tropical meteorology, mesoscale and microscale weather systems and severe weather have been further deepened (Lin et al., 1988).

Before 1949, China had only a few surface stations, lacking upper-air sounding and complete meteorological service system. In 1950, China began to set up observation networks. Since the 1950s, Chinese meteorologists have made a series of research achievements in atmospheric dynamics, westerly and tropical weather systems and their evolution mechanism (such as cold wave, front, Meiyu, typhoon and severe convective weather), numerical weather prediction and data assimilation. Atmospheric dynamics is the theoretical basis for the development of synoptic meteorology. Section 2 reviews the key research achievements on atmospheric dynamics in the past 70 years in China. Taking into account the multi-scale characteristics of weather systems, Sections 3–5 summarize the results of different scale weather systems. Specifically, Section 3 focuses on synoptic-scale weather systems related to precipitation, Section 4 focuses on typhoon and tropical weather, and Section 5 focuses on severe convective weather. Numerical weather prediction and data assimilation are the combination of observation, statistics and atmospheric dynamics, and are the most important means of weather forecasting at present. Section 6 focuses on the results of numerical weather prediction and data assimilation. Synoptic meteorology, as an important branch of atmospheric science, is closely related to other branches such as climate and environment. What are the characteristics of the evolution of weather systems in the context of climate change and how aerosols and air pollution interact with the evolution of weather systems are current frontier and hot topics. Section 7 focuses on the interdisciplinary research achievements in weather and climate, atmospheric physics and environment. Section 8 summarizes the achievements in various areas and suggests possible future development. In order to avoid duplication, this volume does not cover the content already covered by the volumes of atmospheric physics and environment as well as the climate and climate change of the this 70-year atmpospheric reasech progress series (such as the Qinghai-Tibetan Plateau impact, the abrupt change of atmospheric circulation, dust weather, the development of observational equipment such as radar and satellites, and the influence of weather on atmospheric pollution, etc.). Over the years, there have been a lot of research contents and achievements in the field of synoptic meteorology in China. Due to the length limit of the paper and the authors' level of knowledge, please understand if some achievements in various aspects are not included or summarized in the best way.

2. Atmospheric dynamics

Atmospheric dynamics is to examine the evolution of various dynamic processes in the atmosphere based on the fundamental principles of physics and fluid mechanics. The study of atmospheric dynamics originated in northern Europe. In the 1920s, the Norwegian School, represented by Vilhelm Bjerknes, put forward the theory of frontal cyclones. By the 1930s, with the use of radiosonde, understanding of upper atmospheric motion was greatly improved. Rossby proposed the theory of geostrophic adjustment (Rossby, 1938) and the theory of long wave (Rossby, 1939), which led to a series of studies on the energy dispersion of planetary waves, the jet stream in the westerlies and the instability of planetary waves. Since the 1950s, with the improvement of computer and observational methods, numerical simulations of meso-and-micro-scale dynamics, tropical wave, the formation of atmospheric circulation has been developed rapidly (Lin et al., 1988). The founder of atmospheric dynamics research in China is Zhao Jiuzhang, who put forward the theory of thermodynamics of trade wind formation as early as the late 1930s (Jaw, 1937). In the past 70 years, meteorologists in China have made a series of achievements in scale theory of atmospheric adaption processes, planetary wave dynamics, and atmospheric circulation.

2.1 Scale theory of atmospheric adaptation processes

Atmospheric adaptation and evolution processes are two basic dynamic processes in the atmosphere. It is a process of mutual adjustment and adaptation between wind and pressure. After Rossby (1938) first put forward the theory of geostrophic adjustment process, Yeh (1957) proposed the scale theory of adaptation process in the late 1950s, and pointed out that the direction of adaptation depends on whether the scale of atmospheric motion is larger than the radius of Rossby's deformation. In the early 1960s, Zeng (1963a, 1963b, 1963c) further proposed the time-scale separability and interaction between the process of geostrophic adjustment and quasi-geostrophic evolution. Chen (1963) then discussed the problem of thermal wind adaptation, and pointed out that if the thermal wind vorticity of the initial non-thermal wind flow is greater than the thermal wind vorticity of temperature, the ascending motion would be stronger, otherwise, the sinking motion would be stronger, thus the critical horizontal scale of adjustment between wind and temperature is proposed. After that, the scale concept of adaptation was further developed into the process of meso and microscale adaptation (Ye and Li, 1964).

In the late 1970s, Wu and Chao (1978) proposed multi-time scale characteristics of atmospheric adaptation based on the basic properties of the rotating fluid. At the same time, the scale concept in the process of atmospheric adaptation has been further extended to the process of rotational adaptation (Zeng, 1979a), i. e., under the rotation of the earth, the disturbance tends to adopt zonal circulation structure (Zeng, 1979a; Zeng and Ye, 1980, 1981, 1982). Based on the multi-time scale characteristics of atmospheric motion (Ye and Li, 1979; Li, 1979; Yeh and Li, 1982), Li (1982) discussed the potential vorticity adaptation process, and proposed that baroclinic atmospheric motion can be divided into geostrophic adaptation stage, quasi-geostrophic potential vorticity adaptation stage and equilibrium stage. The formation of potential vorticity adaptation was obtained by means of long wave dispersion of the unbalanced energy. It was proved that the quasi-geostrophic evolution of potential vorticity conservation in nonlinear cases leads to quasi-equilibrium, which is more common than geostrophic equilibrium. In the early 21st century, Wu et al. put forward the theory of thermal adaptation based on the potential vorticity (Wu and Liu, 2000; Liu et al., 2001), and discussed the principle of outward heating forced adaptation with the dynamic characteristics of the atmosphere in the presence of non-adiabatic heating, which explains the dispersion and development of the tropical atmospheric motion and the formation of subtropical high.

2.2 Planetary wave dynamics

The study of the instability of atmospheric motion is of great scientific significance for understanding the evolution of planetary waves. In 1946, Zhao first studied the baroclinic instability of vertical shear of mean flow (Jaw, 1946) and put forward the concept of planetary wave instability. He pointed out that the atmosphere can be unstable in baroclinic state, that is, the amplitude will increase with time and form the distribution and evolution of trough and ridge observed on the weather chart. This discovery has attracted great attention and wide recognition from international counterparts, laid the foundation for Charney (1947) and Eady (1949) to study the baroclinic instability and obtain the instability criterion of atmospheric long wave and baroclinic wave, and became one of the theoretical bases of modern weather forecast. Subsequently, Kuo (1949) obtained the barotropic instability criterion of atmospheric long wave (namely Kuo's theorem), and proposed that when the amplitude of perturbation and wave increases to a certain extent, nonlinear problem must be considered. Zeng (1989) extended the nonlinear stability theorem of two-dimensional incompressible ideal fluid proposed by Arnold (1965) to the general variational principle of instability in atmospheric motion. Corresponding to Arnold's first theorem, he obtained the instability criteria under various conditions, especially for the first time, the instability criteria for unsteady flow, topographic disturbed flow and ageostrophic flow. Mu et al., corresponding to Arnold's second theorem, established a series of nonlinear stability criteria for quasi-geostrophic fluid motion; in particular, they established the optimal nonlinear stability criterion for the classical Phillips model and the Eady model

(Mu, 1992; Mu et al., 1994; Liu and Mu, 1996): if the nonlinear stability criterion is broken, there must be linear unstable normal mode and thus it is linear unstable. In addition, Mu et al. (1996) also studied the nonlinear symmetric stability of finite amplitude disturbances.

Following Rossby's introduction of long wave theory, Yeh first introduced the group velocity into the evolution of atmospheric disturbance in the late 1940s, and put forward the theory of long-wave energy dispersion (Yeh, 1949). He pointed out that large-scale perturbation energy propagates at the group velocity of the wave and is closely related to its frequency. Using the phase velocity and group velocity difference of Rossby wave to characterize the dispersion of atmospheric disturbance, the "upstream and downstream effect" of large-scale disturbance in latitudinal airflow was explained in terms of dynamics, which laid a theoretical foundation for the two and three dimensional teleconnection dynamics of modern atmospheric circulation and initiated a new field of atmospheric wave dynamics. Long-wave energy dispersion theory has become one of the most important classical theories of atmospheric dynamics, and has been widely used in weather forecasting and large-scale atmospheric disturbance dynamics research.

With the introduction of long-wave dispersion theory, important progresses have been made in the studies of planetary wave dynamics that is related to teleconnection. The cause of formation of quasi-stationary planetary waves has been studied since the 1950s. Ye and Zhu (1958) pointed out that topography and non-adiabatic heating are the fundamental causes for the formation of quasi-stationary planetary waves. With the discovery of more observational facts, more and more attention has been paid to the propagation of large-scale disturbances in the three-dimensional spherical atmosphere and its interaction with basic flow. Huang and Gambo (1982a, 1982b, 1984) extended Rossby wave dispersion theory established by Yeh (1949) to the three-dimensional atmosphere of the sphere in winter and summer, theoretically and numerically studied the three-dimensional propagation characteristics of quasi-stationary planetary waves in winter and summer in the Northern Hemisphere from theory, observational facts and numerical simulation aspects. It was found that, due to forcing by topography and steady heat sources in winter, the middle troposphere in winter in the Northern Hemisphere are in negative phase in Asia and the east coast of North America, and the Rocky Mountains and the North Atlantic on the west coast are in positive phase (Figure 1a). It was pointed out that the three-dimensional propagation of quasi-stationary planetary waves in the basic flow cannot propagate directly from the lower troposphere of middle latitudes to the lower latitudes, but there are two waveguides, namely the polar waveguide and the low latitude waveguide (Figure 1b), in which the wave in polar waveguide travels vertically from the troposphere to the stratosphere at high latitudes and propagates toward the equator in the stratosphere, while the wave in low-latitude waveguide travels vertically from the lower troposphere at middle latitudes to the upper troposphere at low latitudes. Chen et al. (2002, 2003) obtained the interannual variation of planetary wave activity. Zeng (1982, 1983) used the wave packet concept to reveal the evolution rules of transient waves under heterogeneous basic flow. Wu and Chen (1989) used the primitive equation model to prove the no-acceleration principle proposed by Charney and Drazin (1961) that the waves do not interact with the basic circulation under certain conditions. These studies have systematically revealed the three-dimensional evolution of atmospheric circulation.

Concerning the most significant atmospheric teleconnection mode in the North Atlantic region, North Atlantic Oscillation (NAO), Luo et al. (2007) used the theoretical model

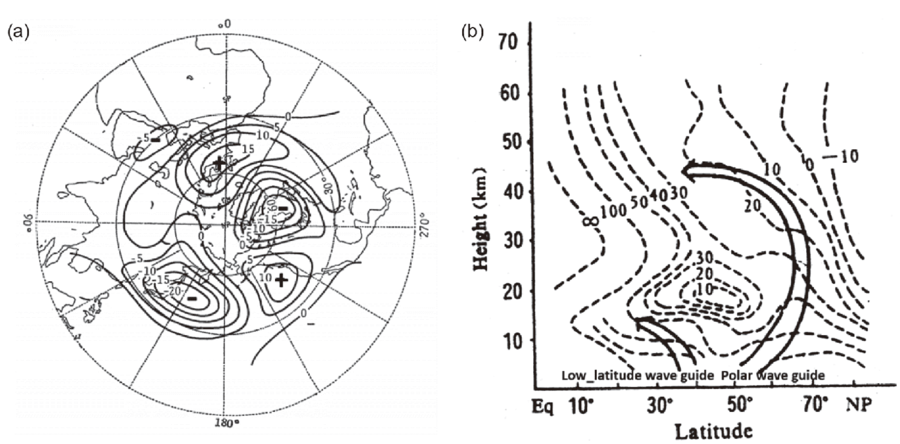

Figure 1 (a) The disturbance pattern of the observed 500-hPa geopotential height (units: dm) of planetary waves (zonal wavenumber 1–3) in January averaged over 1972–1997, responding to forcing by both the Northern Hemisphere topography and stationary heat sources (adapted from Huang and Gambo (1982b)); (b) sketch map of the propogation (solid arrow) of stationary wave 1 forced by ideal topography, and the dashed contours represent the distribution of the relative index square of wave for zonal wave number 1 (adapted from Chen and Huang (2005)).

that describs the interaction betweem the planetary-scale and synoptic-scale wave to study the formation and decay processes of NAO events, and pointed out that the NAO events are the result of the synoptic-scale wave evolution, and the activation of NAO depends on the spatial structure of vorticity forcing of preceding synoptic-scale eddy, which theoretically fully explained the life process for 10–20 d of the positive and negative phase events of NAO.

2.3 Atmospheric circulation and its abnormal phenomena

In 1950, Ye put forward the mechanism of the formation and maintenance of the atmospheric circulation in the mean state. In the 1950s, Chinese scholars studied the dynamic and thermal effects of the Qinghai-Tibetan Plateau on the formation of atmospheric circulation (Ye and Gu, 1955), the winter and summer mean structures of atmospheric circulation and their seasonal variations in East Asia and its adjacent regions (Staff Members of Academia Sinica, 1958, 1959a, 1959b). Wu (1984) pointed out that the response of atmospheric circulation to topography and heat is non-linear.

Blocking is a typical large-scale phenomenaon of atmospheric circulation at middle and high latitudes, which are equivalent barotropic, quasi biweekly and quasi-stationary. It occurs mainly in the lower part of the storm track of the Atlantic and Pacific oceans (Berggren et al., 1949; Rex, 1950), often accompanied by the appearance of meridional circulation and the large meander of the jet stream. Its formation, maintenance and decay are closely related to the sustaining or changing of weather processes. Numerous studies have shown that the formation of blocking circulation is related to wave-mean flow interaction, planetary wave-topography-heat source interaction and vorticity forcing of synoptic-scale waves (Zhu and Zhu, 1982; Ji and Tibaldi, 1983). Yeh (1949) and Ye et al. (1962) studied the movement of the Northern Hemisphere blocking anticyclone, the physical process of establishing, maintaining and collapsing, and related weather. He explained the formation and decay mechanism of blocking from the perspective of Rossby wave energy dispersion. Luo and Ji (1989) derived the Scrodinger equation for describing the atmospheric blocking amplitude from the potential vorticity equation, but failed to describe the blocking process and the jet stream meandering. In the late 1990s, the influence of sea surface temperature on the formation and maintenance of blocking anticyclone was paid attention. It was found that the sea surface temperature of the warm pool in the western Pacific Ocean was favorable for maintaining blocking anticyclone (Lu and Huang, 1996). The anomaly of tropical ocean heating would cause the response of the positive anomaly field in Ural region (Li et al., 2001), which was beneficial to the strengthening and becoming active of upstream transient waves in Ural region, thus led to the formation of blocking anticyclone there (Li et al., 2001). Subsequently, Luo (2000, 2005) and Luo D H et al. (2014) used the scale-separation hypothesis to establish a nonlinear theory describing the interaction between the blocking planetary wave and the synoptic wave, which can completely describe the life cycle of the blocking at 10–20 d and the role of the preexisting synoptic-scale wave in the formation of the blocking (Figure 2). They pointed out that the blocking is a nonlinear initial value problem and can explain the observed facts of the blocking. Mu and Jiang (2008) also proved that blocking is a nonlinear initial value problem, using the conditional nonlinear optimal perturbation (CNOP, which represents initial disturbances with the greatest nonlinear development at the time of prediction under certain physical constraints) method, which was proposed by Mu et al. (2003) to obtain the precursor condition of blocking onset.

3. Synoptic-scale weather

Studies on synoptic weather systems in China started from Zhu Kezhen, who first categorized the weather types of China in 1925 (Zhu, 1925). Then, Shen (1932) studied the Yangtze-Huaihe cyclone, and Li (1935) studied the relationship between the Southern Hemisphere and the northwest Pacific Ocean and proposed the interaction of the atmospheric circulation between the two hemispheres. Based on a small number of kite sounding observations, Tu and Lu (1938) studied the properties of different air masses in different seasons in China. In the past 70 years, studies of synoptic-scale weather in China have mainly focused on the high-impact weather, such as heavy rain, cold wave, freezing rain and snow.

Heavy rain is one of the main meteorological disasters in China. As the monsoon moves northward in summer, three rain belts appear successively in South China, Yangtze River Basin and North China from June to August, which are related to different weather systems. Since the 1950s, China has been paying attention to the research and forecast technology development of heavy rain (Tao et al., 1958a, 1958b; Xie, 1959). Tao et al. (1958a) discussed the beginning and ending of Meiyu and the seasonal variation characteristics of Asian atmospheric circulation. The Institute of Geophysics, Chinese Academy of Sciences (now the Institute of Atmospheric Physics, the Chinese Academy of Sciences) has published papers on the characteristics of atmospheric circulation in East Asia on Tellus, laying a foundation for the future study and forecast of heavy rain (Staff Members of Academia Sinica, 1958, 1959a, 1959b). These papers are highly innovative and forward-looking. Chinese meteorologists have also studied a number of extreme heavy rain events (e.g., July 1954 (Yangtze River), July 1958 (Yellow

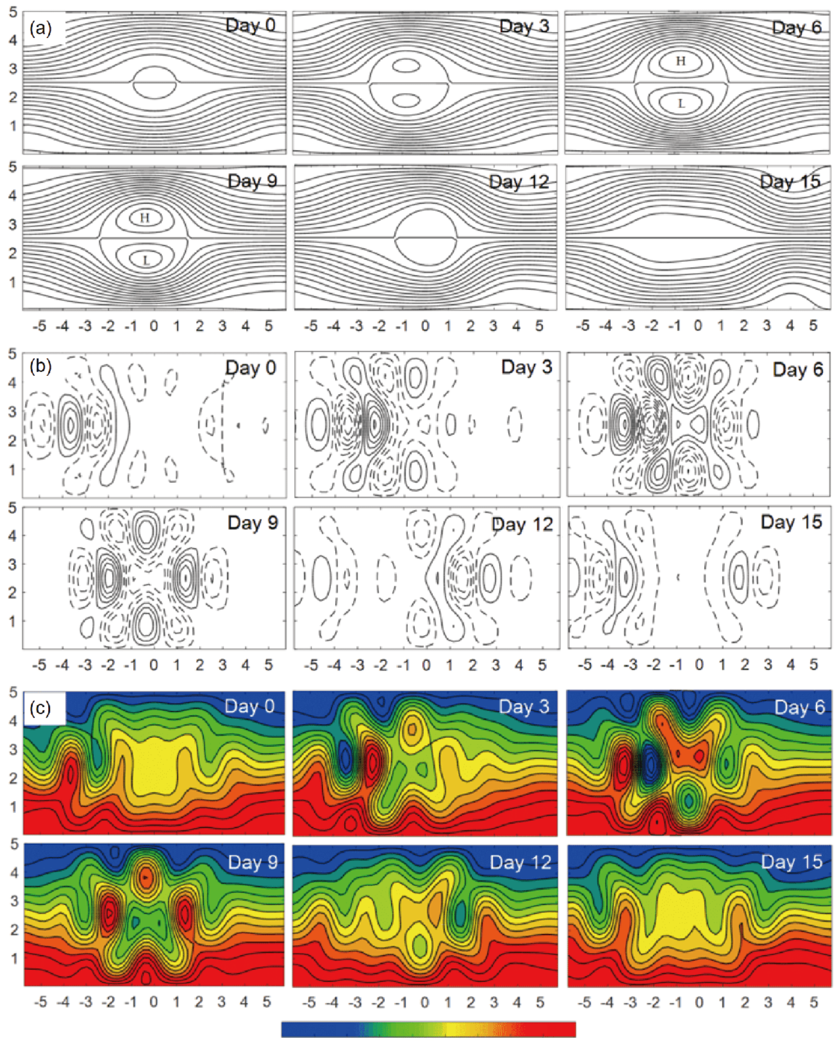

Figure 2 (a) Planetary-scale blocking circulations, (b) synoptic-scale wave flow fields, and (c) total flow fields of atmospheric blocking circulation. The results are based on NMI model. Adapted from Luo D H et al. (2014).

River), August 1963 (North China), August 1975 (Henan Province), July 1981 (Sichuan Province), June 1994 (Pearl River), July 1998 (Yangtze River), July 2003 (Huaihe River), July 2016 (North China, Beijing), July 21, 2012 (Beijing; Zhang et al., 2013; Zhong L Z et al., 2015)) (Tao et al., 1980, 2001; Ding et al., 1978; Ding, 1993; Zhou et al., 2003; Zhao et al., 2004; Ni et al., 2006; Tan and Zhao, 2010; Zhang and Liu, 2013). These studies revealed some common features of heavy rainfall in China, including the stagnation of large-scale circulation systems, the interaction between low and middle latitude systems, etc. with a series of innovative achievements obtained in the relationship between heavy rain occurrence and front, low vortex, and topography. In recent years, the research on the mechanism of heavy rain in China has advanced to convective evolution that produces heavy rainfall, especially by analyzing the data of high-resolution observation and numerical simulation (the minimum grid distance is 444 m), which reveals some new meso and micro-scale phenomena and mechanisms, such as the convective vortex warm bubble column that produces heavy rain, the stable mesoscale outflow boundary, and the importance of the arrangement of mesoscale convective rainbelts for generating extreme precipitation, as well as environmental thermal conditions, local surface forcing, isentropic uplift, convective feedback and their combined impact (Zhang M et al., 2009; Zhang and Zhang, 2012; Wang H et al., 2014; Luo and Chen, 2015; Wu and Luo, 2016; Liu X et al., 2018). The mechanism of the coupling of cloud microphysical processes with the internal dynamic processes of the convection system to influence the fine distribution of the heavy rain was also revealed (Luo et al., 2010).

3.1 Front

The front is the interface between different air masses, often accompanied by heavy rain and/or severe convective weather. In the early 1950s, Xie and Chen (1951) found that the structure of East Asian front and jet stream was significantly different from that of North America in the Western Hemisphere, and that the Asian "tropical front" and associated subtropical jet stream are stronger than those of North America. They first revealed the reason why China's warm front is not significant and the existence of multi-layer frontal structures in East Asia. They found that above the polar front there is a subtropical front, below the polar front there is arctic front, and the frontal area corresponds to the upper-level jet. This study identified the existence of high-altitude subtropical jet stream in East Asia and their interaction with polar-frontal jet. They further found that the multi-layer frontal zone and double jets are the result of the interaction between the northward moving of the warm wet monsoon flow from tropical zone and the active cold air in East Asia. The convective unstable layer at the low-level frontal zone is favorable for the convective activity. This multi-structure study of East Asian front and jet stream modified Palmén's classical polar-front conceptual model, emphasizing that there is still a great deal of baroclinicity in the warm air above the polar front. Up to now, double jets and its interaction are still important scientific questions in the study of atmospheric circulation.

In the late 1990s and early 20th century, on the basis of mesoscale experimental data, Chinese scientists carried out in-depth research on the structure and dynamics of strong cold front in East Asia in spring (Li and Zhao, 1996, 1997) and mesoscale disturbances on front (Wu et al., 2004). Tan and Wu (1990, 1991) put forward the Ekman momentum approximation theory for the first time in the world and applied it to the study of mesoscale frontal dynamics, established a set of complete equations and conservation laws for discussing the interaction between boundary layer and frontogenesis and pointed out that the time of boundary layer frontogenesis is longer than that of free atmosphere, which better solves the argument of effect of friction on frontogenesis and also has played a pioneering role in establishing the theoretical framework of surface front dynamics. Tan and Wu (2000a, 2000b), using a simplified two-layer front model taking topography and boundary layer friction into account, discussed the dynamic effects of topography and boundary layer on the structures of cold and warm fronts and their circulations, and revealed that the tilt of the front is mainly related to the distribution of the geostrophic current in warm sector, the movemment of the front, and the relative position of the front and the topography.

Different from the "classic" front, the zone with high gradient of equivalent potential temperature (high gradient zone of humidity) often appears in the Meiyu process in the Yangtze-Huaihe river basin in China, which is the interface between the cold air from the north or northwest and the warm and wet air from the south and has the characteristics of front (Zhao et al., 1953). Based on this, Xie (1956) put forward the concept of Meiyu front. He emphasized that equivalent potential temperature should be used instead of temperature in vertical analysis to identify Meiyu front effectively. Later, Chinese meteorologists pointed out that Meiyu is one of the major systems of the summer circulation, one of the monsoon phenomena in East Asia (Tao et al., 1958a), and a manifestation of monsoon trough in atmospheric circulation in early summer (Chen, 1983). The beginning and ending of Meiyu are closely related to the seasonal variation of atmospheric circulation in East Asia, especially the onset of Indian monsoon.

The structure of Meiyu front is very complex, varying in its eastern and western sections, at different troposphere heights, in different development stages, and in the initial and peak stages of summer monsoon onset. In the lower troposphere, wind shear often occurs between the southwesterlies and the easterlies, and the Meiyu precipitation is directly related to the water vapor convergence on the shear line. Because the temperature in the northern continent is higher than the temperature in the monsoon from the sea, the Meiyu front tends to tilt to the south, which may be a reflection of the multi-layer frontal structure or the southward tilting of the vertical axis of wind shear during the Meiyu period (Xie, 1956). At the same time, the southward tilting of Meiyu front may lead to the separation of Meiyu front from the shear line (Xie, 1956), which was confirmed by later studies (e.g., Qiu and Ding, 1979). Wang (1963) found that with the formation, maturation and dissipation of the shear line, Meiyu front gradually becomes steeper and steeper from backward tilting, and finally tilts southward. Qiu and Ding (1979) found that the baroclinicity in Meiyu period increased gradually from 850 hPa to 450–600 hPa from the beginning to the development and peak, and that the lower layer gradually adopts the characteristics of southward tilting tropical convergence zone. The eastern and middle sections of Meiyu front have features of typical mid-latitude baroclinic front, while the western sections have warm-core structure, weak horizontal pressure gradient, and strong low-level horizontal wind shear (Chen and Chang, 1980), which was also confirmed by Hu (1997). Meiyu front has baroclinic structure at upper level of troposphere and equivalent barotropic structure at lower levels of troposphere (Wang and Wei, 1982; Ding, 1993). Meiyu front is usually accompanied by 850–700 hPa low-level jet associated with the southwesterlies of monsoon and the subtropical upper-level jet associated with the subtropical upper-level front in the north side (Zhang and Zhang, 1990; Zhang, 1999; Tao et al., 1980). The low-level jet provides water vapor for the heavy rain during the Meiyu period, and the upper-level jet and the South Asian high provide the divergence for the heavy rain during Meiyu period.

3.2 Jets

Jets are important weather systems that affect weather in East Asia and China. In the early 1950s, Chinese scientists mainly focused on the upper-level jet. Qiu (1956), based on observations, found that the East Asian coast was the center of the strongest upper-level jet stream in the Northern Hemisphere in winter. The seasonal transition of atmospheric circulation in East Asia and the beginning and ending of rainy season in most parts of China are closely related to the north-south movement and intensity variation of upper level westerly jet. The beginning and ending of Meiyu in East Asia is closely related to the twice northerly jumpings of the southern branch of upper-level westerly jet in Asia in June and July (Tao et al., 1958a). The northerly jump and southward shift of the upper-level westerly jet is also one of the important manifestations of the sudden changes of atmospheric circulation in June and October (Ye et al., 1958).

In the 1980s, the influence of low-level jet on heavy rain in China began to be paid attention. Low-level jet has become the hot and frontier topic of atmospheric science because of its important influence on extreme weather, aviation safety, regional climate, wind energy and air pollution. The low-level jet in East Asia occurs in the lower troposphere, which is different from the North American low-level jet in the boundary layer. Gao and Sun (1984) put forward that the super-geostrophic characteristics of sub-synoptic-scale low-level jet are mainly caused by the superposition of allobaric wind on the geostrophic wind field, and the mass adjustment of the upper and lower level troposphere caused by the interaction of the upper-level and low-level jets is an important reason for the occurrence of allobaric wind in lower layers. With the increase of observation data and the improvement of numerical model capability, the research on the spatial distribution, evolution and formation mechanism of low-level jet are further deepened. Du et al. (2012, 2014) and Du et al. (2015a) found that there are two types of low-level jet in China, namely boundary layer jet and synoptic-scale jet, which have different spatial and temporal characteristics and formation mechanism. The low-level jet in the south and northeast of China is a low-level tropospheric jet related to Meiyu front and the cold vortex in the northeast, while in the Tarim basin and Qinghai-Tibetan plateau, there are mostly boundary layer jets. All these jets have diurnal variations in different degrees, and the inertial oscillation plays an important role in the diurnal variations of boundary layer jet, and the land-sea thermal contrast and topography have effects on the formation of coastal boundary layer jet in the southeast coastal areas. Liu et al. (2012) revealed the spatial and temporal distribution characteristic of low-level jet in the east of the Yunnan-Guizhou Plateau. He et al. (2016) pointed out that the radiation heating of the surface is the key factor to determine the formation and development of the low-level jet associated with southwesterlies at night, followed by the terrain of the Yunnan-Guizhou Plateau. Du and Rotunno (2014) established Du-Rotunno's theoretical model, successfully explained the activity of low-level jet in eastern China (Du et al., 2015b), and quantitatively revealed the formation mechanism of low-level jet in the United States.

In terms of the relationship between jet and heavy rain, Tao et al. (1980) pointed out that heavy rain mostly occurs at the left front of the low-level jet, which is 2–3 degrees of latitudes away from the jet. Zhang et al. (2010) examined the relationship between the various heavy rain types and the jet in 2007, and found that the coupling of the high- and low-level jet was important to the long lasting of the quasi-stationary frontal heavy rain. When heavy rain associated with typhoon, cold front, southwest vortex and northeast cold vortex occurs, only upper-level jet or low-level jet may exist. However, the occurrence of local heavy rain is usually caused by local heating or topographic uplift, which lacks the dynamic impact from upper- and low-level jets. Li and Zhang (2014) pointed out that the intensity and location of Meiyu heavy rainfall in China are related to the different juxtaposition of the East Asian subtropical jet and polar front jet, and the further understanding of the East Asian subtropical jet and polar front jet will lead to the improvement in precipitation forecasting. Du and Chen (2018) revealed the relationship between low-level jet and different types of heavy rain in South China from the perspective of ensemble prediction and high-resolution simulation, and suggested that the synoptic-scale low-level jet is related to the inland frontal heavy rain, while the boundary layer jet is closely related to the heavy rain in coastal warm sector, and put forward a conceptual model (Du and Chen, 2019), which describes how double low-level jets initiate heavy rain in warm sector (Figure 3).

3.3 Low vortex

One of the important low-pressure systems associated with heavy rainfall in the northern China is the northeast cold vortex. Cold vortex is a low-pressure circulation which is different from frontal cyclone and often occurs in mid-high latitude area. In the 1960s and 1970s, on the basis of the earliest cold vortex study (Hsieh, 1949) in the world, Xie (1956) discussed the relationship between the cold vortex and the heavy rain in North and Northeast China, and put forward that the cold vortex is a nearly upright and deep cold system extending from the ground to the lower stratosphere, and there exists cyclone formation and development at the lower layers. This work is pioneering and of great theoretical significance and application value.

The research on cold vortex heavy rain in China became active in the 1980s. Tao et al. (1980) pointed out that the northeast low pressure or cold vortex is one of the main heavy rain-producing systems in China. Under the unstable

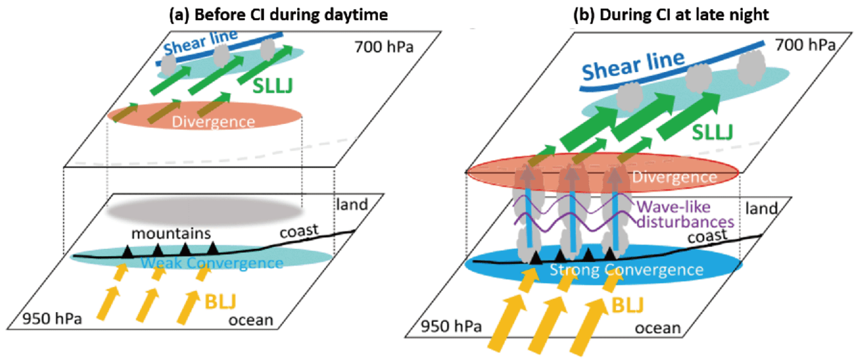

Figure 3 Schematic diagram depicting the convective initiation (CI) near the coast associated with double LLJs. (a) Before CI, convergence at 950 hPa near the coast is relatively weak at the exit of weak BLJ. The divergence at 700 hPa related to the entrance of SLLJ is far from the coast. (b) With southward approaching of cold front (shear line) and the development of the BLJ, enhanced low-level convergence and mid-level divergence occur near the coast and collectively produce updrafts. The mesoscale lifting further generates wavelike convection with small-scale disturbances. Adapted from Du and Chen (2019).

conditions of upper cold air, lower warm air and the water vapor transportation of low-level jet, heavy rain or thunderstorms often occur in Northeast China and North China. The heavy rain often occurs in the east side of the cold vortex. Sun et al. (2002) pointed out that the upward motion in the cold vortex center and its western side is restrained by the large-range strong downward motion in northwest side in upper troposphere, while the upward motion in the east side of the cold vortex is fully developed due to the blocking high, which results in stronger low-level convergence and upper-level divergence and vorticity in eastern side than in the western side. The axis of high energy wet tongue and the maximum water vapor flux are also located on this side, which makes the east side of the cold vortex center become the center of heavy rainfall.

The activity of the northeast cold vortex also affects Meiyu and the heavy rain in the pre-summer rainy season in South China. He et al. (2006) found a significant positive correlation between the precipitation of Meiyu and the intensity of the northeast cold vortex, which may be due to the southward propogation of the dry cold air from the north meeting the low-level wet warm southwestlies on the northern edge of Meiyu area, which is helpful to strengthen the unstable layer, and leads to the excessive amount of precipitation during Meiyu period in strong cold vortex years. Similar to the Meiyu situation, there is also a significant positive correlation between the precipitation of the pre-summer rainy season in South China and the intensity of the cold vortex in Northeast China (Miao et al., 2006), which may be due to the southward deviation of western Pacific subtropical high, weaker early East Asian winter monsoon, earlier and stronger onset of the East Asian summer monsoon in the same period which carries a large amount of warm moist air to the north in strong cold vortex years. As a result, the baroclinic circulation in South China increases, and the ascending of low-level air develops, resulting in more precipitation. In addition, when the northeast cold vortex is combined with the northward moving tropical system (such as the inverted trough of northward-moving typhoon and the peripheral easterly zone of typhoon), the severe heavy rain may occur (Zhao et al., 1980).

Non-frontal mesoscale low-pressure (disturbance) is also a very common heavy rain-producing system in China (Zhao, 1988), in which southwest vortex is one of the most important types. The study of southwest vortex began with Gu (1949). In the early 1980s, Tao et al. (1980) summarized the occurrence and development characteristics of the southwest vortex based on a large number of cases, pointing out that the southwest vortex is shallow in the vertical extension with a warm-core cyclone at 700 hPa in the early stage, while there is usually a high pressure or a high pressure ridge at 500 and 300 hPa. They found that the “Yabu-Kowloon” area, Heihe area and the Sichuan basin are the three most prone sources of the southwest vortex. The main paths of southwest vortex include the eastward, southeastward and northeastward, among which the eastward path is the most frequent. The eastward moving southwest vortex may cause heavy rainfall in the Yangtze River Basin, Huaihe River Basin, North China, Northeast China and South China. Gao (1987) pointed out that the formation of the southwest vortex is related to the basin and valley terrain and airflow stratification. The interaction between topography and the stably stratified flow formed by the high and low level flow is favorable for the formation of the vortex. Wu et al. (1999) proposed the slantwise vorticity development mechanism of southwest vortex formation, and pointed out that isentropic surface slantwise caused by topography is an important condition for slantwise vorticity development. The interaction between the northward southwesterlies of monsoon and the plateau terrain forms strong vertical shear of the southerly wind. The combination of the two factors leads to slantwise vorticity development and the rapid increase of the vertical vorticity. Jiang et al. (2014) used TRMM data to study the heavy rain of southwest vortex and pointed out that the southwest vortex precipitation in the developing stage is mainly located in the southeast side of the vortex and appears as a mixture of stratiform and convective precipitation under a large area of stratus.

3.4 Rainstorms in the pre-summer rainy season of South China

The most concentrated and strongest heavy rain area in China is South China in the pre-summer rainy season from April to June. The heavy rain in South China is very difficult to forecast due to its complicated topography and lack of observational data in the upstream of heavy rain over South China Sea during the pre-summer rainy season. Tao et al. (1980) pointed out that the circulation pattern of heavy rain in the pre-summer rainy season of South China is characterized by the joint impact of the southern and northern branch troughs. The mid-latitude westerlies is relatively flat with a short-wave trough moving eastward to steer the cold air to the south. At the same time, the southern branch westerlies has a trough moving eastward from the southern side of the Qinghai-Tibetan Plateau, carrying a large amount of wet warm air in front of the trough. The above two flows interact with each other to the south of Nanling mountains, resulting in heavy rainfall in South China; According to the juxtaposition of the key weather systems such as surface front and low-level jet, four types of synoptic patterns of heavy rain in the pre-summer rainy season in South China were given from the perspective of operational forecast: front with trough type, interfrontal low-level jet type, front with low-level jet type and low vortex with front type. The synoptic-scale disturbances closely related to the regional extreme precipitation in the pre-summer rainy season of South China are mainly anomalies associated with cyclone type and front with trough type (Huang et al., 2018). The formation and intensification of these disturbances can be attributed to surface sensible heat heating on the Qinghai-Tibetan Plateau (Li et al., 2014; Wan et al., 2017). Sea surface temperature of Tropical Pacific Ocean and Indian Ocean may significantly affect the inter-annual variation of rainfall in the pre-summer rainy season of South China, mainly through stimulating Matsuno-Gill Rossby wave train and warm atmosphere Kelvin waves which result in southwest wind anomalies in the northern South China Sea in low-level troposphere (Gu W et al., 2018; Yuan et al., 2019).

On the sub-day timescale, the co-existence of double rain belts is often observed in South China (Luo et al., 2019). The northern rain belt is closely related to the dynamic uplift of the subtropical synoptic systems, where the westerly extension of the western Pacific subtropical high and the intensification of the southwesterlies of monsoon play an important role in transporting warm moist air to South China. Compared with the northern rain belt, the southern rain belt is smaller in horizontal scale and often occurs inland or in coastal warm sector of South China. The heavy rain in the warm sector of South China is characterized by strong convective and great disasters (Huang et al., 1986). Due to the weak forcing environment, the heavy rain in warm sector is more difficult to forecast. The most catastrophic flooding in South China since 1915 was caused by warm sector heavy rain in June 1994 in the Pearl River basin, which might have been caused by the abnormal summer monsoon circulation in 1994 (Tao, 1996). The wind field of the boundary layer and the trumpet topography may have important contributions to the enhancement of the precipitation (Sun and Zhao, 2002a, 2002b). The results showed that inland warm-sector precipitation is the result of interaction between surface heating, local topography lifting, urban heat island and sea breeze (Wu et al., 2019), and coastal warm-sector precipitation is related to low-level jet (Du and Chen, 2019), sea breeze (Chen X C et al., 2016), mountains near coastline (Wang H et al., 2014) and cold pools formed by convective activities (Wu and Luo, 2016; Liu Z et al., 2018).

3.5 Cold wave, freezing rain and snow

China is located in the eastern part of Eurasia. Cold wave, freezing rain and snow occur frequently and are major disasters in winter. Since the 1950s, Chinese meteorologists have carried out a lot of research on the outbreak of East Asian cold wave, the structure of cold front and the cold wave. Tao (1959) put forward three main paths of the cold wave invading China, which revealed the characteristics of the large-scale weather processes in East Asia at the onset of cold wave. He found that although the Qinghai-Tibetan Plateau is a barrier, the low pressure trough is often frequent on the plateau causing strong cold wave activities. If the middle and upper-level troughs in the northern and southern plateau merge over the plateau, longitudinal extension of the plateau trough may occur, making cold air invade the southeastern part of the plateau, and forming cold waves. In addition, strong cold waves crossing the equator may also cause tropical cyclones and heavy rainfall in the Southern Hemisphere (Zhao and Zeng, 2005).

In January 2008, a high-impact event of low temperature, freezing rain and snow occurred in the southern China. This event was caused by the blocking high in the middle and high latitudes of Asia and the long-term maintenance of the cut-cut-off low east of the Caspian Sea (Tao and Wei, 2008). The external forcing factor for the continuing of the blocking high might be the positive anomaly of temperature in the North Atlantic Ocean (Li and Gu, 2010). Based on a study on the same case, Sun and Zhao (2010) proposed a multiscale conceptual model for long-duration freezing precipitaton over the southern China and the structure of quasi-stationary front and stratification conditions for freezing precipitation

(Figure 4) by studying the interactions between the synoptic patterns, quasi-stationary fronts, eastward propagating cloud clusters from the Tibetan Plateau, surface conditions, and atmospheric stratification processes. Specifically, an east–west-oriented quasi-stationary front system in the southern China, which is rare during the Asian winter monsoon season thus is the condition of "summer-like winter", was responsible for producing freezing precipitation and snowstorms. Larger horizontal gradient of pseudo-equivalent potential temperature, higher temperatures in the inversion layer, enhanced low-level moisture convergence in the western part of the quasi-stationary front, the weak wind with surface temperature maintained at −1°C to −3°C are all beneficial to the strengthening and maintaining of the freezing rain.

4. Typhoon and tropical weather

Tropical region is an important heat and water vapor source of global atmospheric circulation, and its meteorological state has critical influence on global atmosphere. The air-sea interaction in this region is remarkable, which often results in worldwide weather and climate anomalies by influencing monsoon circulation, Walker circulation, Hadley circulation and atmospheric low-frequency oscillation. The region is also an active place for typhoon, monsoon trough, tropical convergence zone, tropical wave motions and other weather systems, among which typhoons cause great disasters to human society every year. Therefore, since the 1960s, typhoons and tropical meteorology have been hot topics in the study of atmospheric science. In the past 70 years, Chinese scholars have carried out systematic and in-depth research in this field, and obtained fruitful research results.

4.1 Typhoon and tropical atmospheric dynamics

4.1.1 Typhoon

Typhoon is one of the main disastrous weather systems in China. On average, nearly half of the 26 typhoons generated in the northwestern Pacific region each year are in the adjacent sea of China, of which 7 land in China. It has been well known that typhoons mostly develop from the surface low pressure perturbations induced by the easterly wave, the baroclinic disturbance, the high-altitude cold vortex as well as the disturbances in the intertropical convergence zone (Chen and Ding, 1979), and there are usually middle and low level jet preceding the formation of offshore typhoons (Zhang, 1978). The jet is the wind surge in the two-stage model of typhoon formation summarized by Gray (1998). In recent years, Chinese scholars have further pointed out that monsoon gyres and the synergy between different tropical wave motions have important influence on typhoon formation (Zhang W L et al., 2009; Wu et al., 2013; Chen and Chou, 2014; Fang and Zhang, 2016). Based on the high-resolution numerical simulation, the mechanism of wind surge and monsoon gyres affecting typhoon formation (Yi and Zhang, 2010; Liang et al., 2014), the multi-scale characteristics, and self-similarity of vortices in typhoon formation (Fang and Zhang, 2010, 2011) have been discussed in detail.

The development and evolution of typhoon are influenced by large-scale environmental flow, surrounding weather

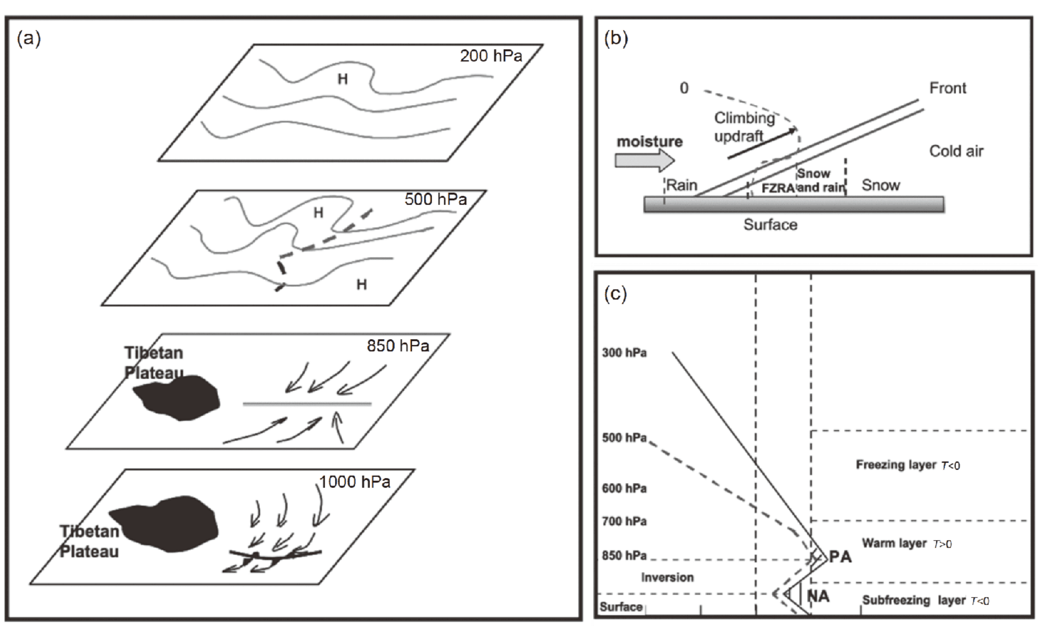

Figure 4 The multiscale conceptual model for long-duration freezing precipitation events over the southern China: (a) synoptic weather pattern, (b) structure of a quasi-stationary front, and (c) stratification conditions for freezing precipitation. Adapted from Sun and Zhao (2010).

systems, underlying surface characteristics and its own structure (Chen and Ding, 1979). Under the influence of these factors, the track of a typhoon sometimes exhibits sudden change, such as rapid turning, spinning, wobbling, and snaking, etc. (Zhang X R et al., 2018). Chinese scholars have put forward many new viewpoints on the abnormal track of typhoons. It was found that the complicated interaction between typhoons and the topography may cause the typhoon to leap or stagnate when it passes through the Taiwan Island (Meng et al., 1998; Gong et al., 2018). Meng et al. (1998) further pointed out that a pair of dipole vortices resulted from the interaction between typhoon circulation and Taiwan topography can lead to the sudden turning of the typhoon's track. In addition to the interaction between typhoon and topography, Wu et al. (2011b) and Liang and Wu (2015) proposed that the typhoon can cooperate with the low-frequency circulations (e.g., quasi-biweekly oscillation, Madden-Julian Oscillation (MJO)) to induce strong southwesterly flow on the south side of the typhoon and causes the typhoon to deflect northward.

Due to the influence of external forcing and the internal mesoscale and micro-scale processes, the structure and intensity of typhoon usually undergo complicated variations in its life span. Zhang et al. (2005a, 2005b) discussed the role of vortex Rossby wave in the interaction of concentric eyewalls and revealed the cause of the formation of the large eye of super typhoon Winnie (1997). It was found that the outer-core moisture inhibits the enhancement of the inner core while promoting the enhancement of the main circulation and the horizontal expansion of the typhoon. Zhang M et al. (2009) and Zhong and Zhang (2014) developed a theory of vortex Rossby gravity mixing wave which can explain the formation of spiral rain band in typhoon. Gu et al. (2015, 2016) pointed out that the vertical wind shear can lead to the asymmetric structure of typhoon, and the associated eddy fluxes tend to destroy the warm core and reduce the efficiency of typhoon engine. Gu J F et al. (2018, 2019) further proposed, under the condition of clockwise-rotating vertical wind shear, typhoon vortex is easier to precede to the up-shear sides, which is beneficial to the vertical alignment of the typhoon vortex and then the intensification of the typhoon. The concentric eyewall usually appears in a strong typhoon. Since its formation usually corresponds to the sudden changes of typhoon intensity, the concentric eyewall has been a hot topic in tropical cyclone dynamics. Via the high-resolution simulation, Qiu et al. (2010) and Qiu and Tan (2013) put forward a new mechanism of the formation of double eyewalls, i.e., the low-level convergence of asymmetric inflow and the forced lifting are responsible for the formation and maintenance of convection in the early stage of double eyewall formation. As for the structure of a typhoon, it is worth mentioning that Wu D et al. (2018) performed the large eddy simulation of the eyewall with a horizontal resolution of 37 m, which illustrates fine structures such as the tornado-scale vortices in the eyewall region (Figure 5). In order to better describe the structure of typhoon wind field and its effect on typhoon intensity, Guo and Tan (2017) introduced a new parameter, namely fullness, which is closely related to typhoon intensity. Stronger typhoons generally have larger fullness (Figure 6). Xu and Wang (2010, 2015) also found that typhoon intensification rate is inversely proportional to the maximum wind radius and the size of the typhoon. The underlying ocean is vital to typhoon intensification. Xu et al. (2016) suggested that the sea-surface temperature not only determines typhoon maximum potential intensity, but also affects typhoon maximum potential growth rate significantly. Guo and Tan (2018) also found that rapidly decreasing El Nino causes rapid intensification of typhoon to occur in the western region of the western Pacific Ocean.

Typhoon precipitation is influenced by typhoon structure, the interaction between typhoon and other weather systems, topography and so on, and thus is a complicated issue in typhoon studies. The precipitation is mostly located in the left front quadrant of typhoon before landfall and mostly in the right front quadrant after landfall. The change of water vapor supply caused by typhoon landfall can change the precipitation location by changing the distribution of wet static stability (Chan and Liang, 2003). Small-scale topographic lifting can greatly enhance typhoon precipitation (Tao et al., 1980; Ding, 2015). The joint-impact of several favorable factors often leads to the extremely heavy rain in typhoon. For example, under the monsoon background, the strong low-level jet provides abundant water vapor while low-level warm and wet air enhances the atmospheric instability, which, together with the various uplifting mechanisms, led to the extremely heavy rainfall after the landing of typhoon Bilis (2006) in Hunan and Jiangxi provinces (Gao et al., 2009). The asymmetric precipitation structure of the typhoon during its landfall mainly depended on the vertical wind shear of the environmental field (Shi et al., 2009). The extreme precipitation caused by typhoon Morakot (2008) in Taiwan was mainly caused by the topographic uplift and the interaction between typhoon and monsoon depression, warm wet air flow and another typhoon nearby (Wu, 2013). The interaction between Morakot and the low-frequency monsoon airflow led to the asymmetric structure of precipitation (Wu et al., 2011a). In addition to local precipitation, typhoons can also lead to long-distance precipitation under its interaction with the midlatitude westerly trough (Wang and Li, 2009; Wang et al., 2015). The long-distance heavy rain events mainly occur in the Bohai Sea and Sichuan-Shanxi border in July when the typhoon moves to the South China Sea from the west or northwest, or when the typhoon moves in a turning track in the coast area of the southern, southeastern or eastern China (Cong et al.,

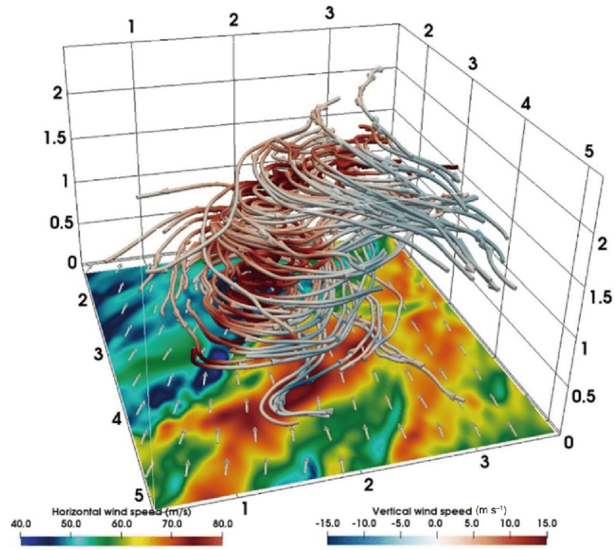

Figure 5 The 10-m wind speed (shading) and the stream fields of the perturbation horizontal winds associated with the tornado vortex. The warm (cold) color of the streamline denotes the upward (downward) motion. The typhoon center is located outside the upper left corner, and the unit of the number on the coordinate is kilometer. Adapted from Wu L G et al. (2018).

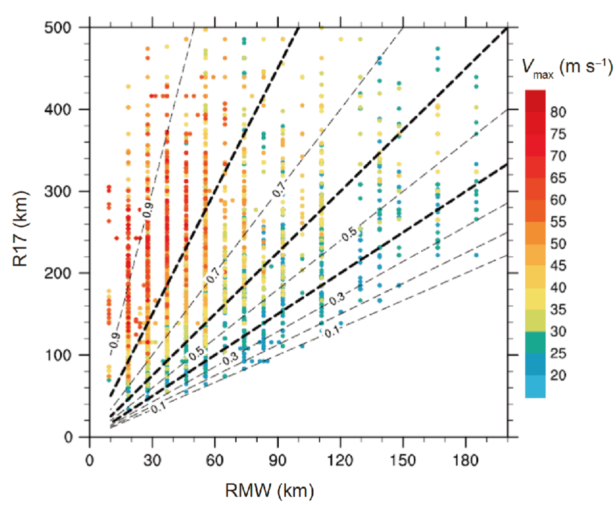

Figure 6 Relation among TC intensity V_{max} (color dots), the radius of maximum wind speed, and the radius of 17 m s^{-1} wind speed in different values of TC fullness (TCF). The dashed lines denote the fullness with different values: TCF≤0.4, 0.4<TCF≤0.6, 0.6<TCF≤0.8, and TCF>0.8. The bold dashed lines denote fullness values of 0.4, 0.6, and 0.8. Adapted from Guo and Tan (2017).

2012; Wang et al., 2009; Wen et al., 2015).

4.1.2 Subtropical high

The influence of subtropical high on weather and climate in China is very prominent. Subtropical high is one of the most important weather systems that affect the progress and retreat of summer rain belt in China. In the 1950s and 1960s, Chinese scholars made extensive studies on the influence of the western Pacific subtropical high and the Qinghai-Tibetan high on weather in China (Ye et al., 1958; Ye and Zhu, 1958; Tao, 1963). These works systematically illuminate the formation and development features of the subtropical high. It was found that the evolution of the western Pacific subtropical high is closed related to the South Asian high over the Qinghai-Tibetan Plateau. When the latter moves eastwards, the former usually extends westwards. The forecast criterion of east and west progress and retreat of the subtropical high has also been put forward.

After the 1970s, the study on the subtropical high was more comprehensive and profound. It was found that the air over the Qinghai-Tibetan Plateau during the summer is a warm anticyclone due to the heating (Ye and Gao, 1979; Ji et al., 1984). The subtropical high is a component of the part of the East Asian-Pacific teleconnection pattern from Southeast Asia to North America and its north-south position is influenced by the convection activity changes induced by the sea-surface temperature anomalies in the warm pool region of the Western Pacific (Huang and Li, 1988).

Due to the data shortage, the comprehensive research work on the formation and evolution of subtropical high did not begin until the 1990s. Through the theoretical analysis and numerical simulations, Chinese scholars found that the mechanism for subtropical high formation is different from that for the Hadley circulation. It is argued that the low-tropospheric sinking motion in the main body of the subtropical high is a feature accompanying the intensification of the high instead of being the causes leading to the formation of the high. Furthermore, Chinese scholars developed "atmospheric thermal adaptation" theory, which suggests that the sensible heating and radiative cooling are the primary factors contributing to the formation and asymmetrical structure of the subtropical high, respectively, while the latent heating associated with the convection plays secondary roles in the formation of the Western Pacific subtropical high and South Asian high. Based on these works, the formation of subtropic high was summarized as the result of the "quadruplet heating pattern" (Wu and Liu, 2000, 2003; Liu et al., 1999a, 1999b; Wu et al., 1999, 2002).

4.1.3 Tropical wave and MJO

In addition to the well-known weather systems such as typhoon, subtropical high and monsoon trough, there are abundant synoptic-scale tropical waves, for example, Kelvin wave, Rossby-Gravity mixed wave, and gravity wave (Matsuno, 1966). Early on, these theoretical results of wave motions were not associated with tropical convective weather until Wheeler and Kiladis (1999) pointed out that tropical wave motions and atmospheric convection are coupled together and control tropical weather changes. Since then, tropical waves have become hot topics in tropical meteorology.

The study of the relationship between tropical wave and convection is an international frontier topic in recent years. Han and Khouider (2010), by establishing wave and convection mathematical models, revealed the effects of different levels of wind shear on waves. Using a simple mathematical model that parameterizes the momentum transfer of convective flows, Zhou and Kang (2013) successfully obtained an unstable Rossby-Gravity mixed wave, similar to the observed tropical two-day wave, and revealed the important influence of the convective momentum on the tropical wave. However, most of the existing theoretical results on tropical wave and convection cannot explain that convectively-coupled waves are much slower than their dry counterparts, and the most difficult problem is the understanding and parameterization of convection. Liu et al. (2019) pointed out that the reason for "short wave disaster" (Emanuel et al., 1994) in the wave-CISK theory proposed by Guo in the 1970s is that it was difficult to produce slow atmospheric long wave. Instead, they considered the long neglected convective memory effect in the wave-CISK parameterization scheme and obtained Kelvin wave solutions whose zonal movement speed is comparable to those observed in nature. This study brought Wave-CISK, which has gradually faded away from the field of tropical convection, back to people's view, which will have an important impact on the study of tropical convection.

The MJO is an important intraseasonal weather phenomenon in the tropical region. It features periodic oscillation of tropical atmosphere in wind, pressure and cloud every 40–50-day. It is mainly a zonal wavenumber 1–2 phenomenon propagating from west to east. Its initiation, development and propagation mechanisms involve thermodynamics, air-sea coupling, radiation transfer, convection and boundary layer atmospheric dynamics. This MJO phenomenon was first discovered by Xie Yibing when he analyzed the sounding data in 1963 (Xie et al., 1963). In studying the relationship between the basic tropical flow and the occurrence frequency of typhoons, Xie et al. found that during the boreal summer, the intensity and range of the prevailing westerly flow in the middle and lower troposphere of the Indian Ocean and the tropical western Pacific prevailing westerly flow oscillated quasi-periodically with the period of about 40–50 days. Figure 7 (adapted from Figure 2 of Xie et al. (1963)) shows the time series of 700-hPa zonal winds at three radiosonde stations in the summers of 1958, 1959 and 1960 at Thiruvananthapuram (No. 43371) at the southern tip of India, Ho Chi Minh City (No. 48900) in the southern Vietnam and Zamboanga (No. 98836) in the southern Philippines. These graphs clearly show that 700-hPa zonal flow in the Indian Ocean and the tropical western Pacific Ocean exhibits quasi-periodic characteristics at intraseasonal time scale. Xie et al. (1963) concluded that typhoons are more frequent when the equatorial westerly is anomalously strong and biased northward and eastward of its climatological position. They further pointed out that the quasi-periodic oscillation of the intensity and range of the westerly wind may help the medium-term forecast of the typhoon's occurrence frequency. Unware of Xie's study, Madden and Julian also analyzed the tropical Pacific sounding data in 1971 and 1972, using the FFT spectral method newly developed at the time to further analyze the 40–50 d oscillation of the tropical zonal wind, and connected it with the whole tropical atmospheric circulation (Madden and Julian, 1971, 1972). This is now widely known in international academia as MJO. It has long been believed by international peers that the intraseasonal oscillations in tropical zonal winds were first discovered by Madden and Julian, while Xie's study was mostly unnoticed until 2018. Li T et al. (2018) reproduced Xie's synoptic analysis published in their pioneering 1963 paper, and rightfully attributed the original discovery of the MJO to Xie et al., which was eight years earlier than that of Madden and Julian. The discovery is an important contribution of Chinese scholars to modern meteorology.

The work of Chinese scholars on the MJO has been active since the middle and late 1980s. Li (1985) first introduced the CISK theory into the study of atmospheric intraseasonal oscillation, and obtained a theoretical CISK wave to explain the 30–50-day oscillation of the South Asian monsoon trough. Lau and Peng (1987) pointed out that the interaction between convection and dynamics can produce a "dynamic" wave-CISK mechanism, which partly explains the slow eastward moving speed of the MJO along the equator. Wang (1988) then pointed out that the instability of waves mainly depends on the vertical distribution of static energy of water vapor. The latent heat release caused by internal waves causes the wave to move slowly to the east by decreasing the thermal damping. Li (1990) proposed the CISK-Rossby wave mechanism, which can move both eastwards and westwards, and the phase speed is consistent with the activity of the 30–50-day oscillation in the tropical atmosphere under the condition of tropical atmospheric heating. Wang and Xie (1998), on the basis of pattern analysis, pointed out that the air-sea interaction plays an important role in maintaining MJO. Wang et al. (2012) found that subtropical cold surge in the early stage of the MJO formation can strengthen and accelerate the MJO convection and promote the formation of the MJO. Bao and Hartmann (2014) studied the complex response of MJO heating with a simple shallow water model, and successfully reproduced the quasi-stationary Rossby wave at the exit region of the midlatitude upper tropospheric jet, providing a simple explanation for the MJO's influence on mid-latitude weather through its interaction with high-level jet in the Pacific Ocean. At present, the MJO is used for a wide range of problems, e.g., precursor for typhoons, mid-latitude weather and short-term climate in tropical regions of the world. The initiation and development mechanisms of the MJO and its eastward propagation characteristics are important research topics in tropical atmospheric dynamics; the simulation of MJO is still an important challenge for dyna-

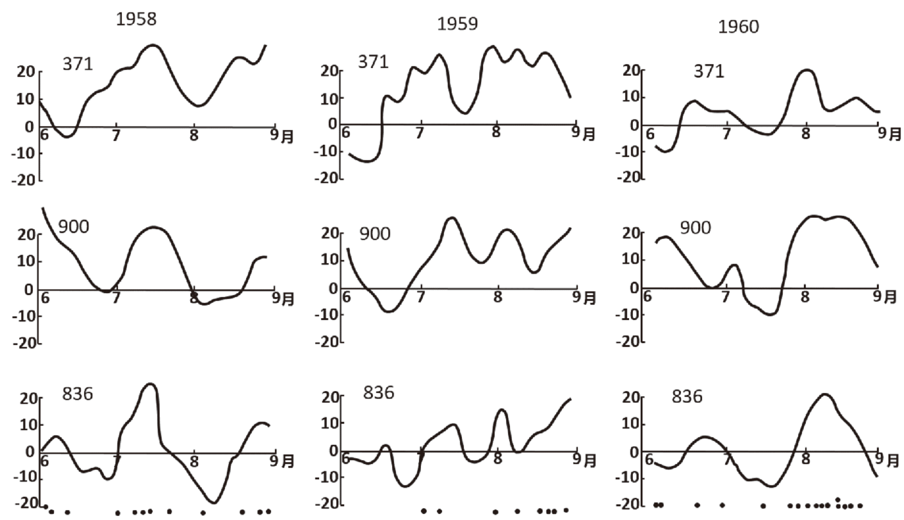

Figure 7 Five-day averages of the 700 hPa east-west wind speed and the dates of typhoon formation at stations 371, 900 and 836. The positive (negative) values denote westerly (easterly) wind (unit: $m\ s^{-1}$), and black dots denote the dates of typhoon formation. Adapted from Xie et al. (1963).

mical models.

4.2 Observation on typhoon and tropical atmospheric processes

In the early period, the available data for typhoon and tropical weather research in China were mainly the conventional observation data and some radar and satellite data, which were obviously not enough to support the comprehensive researches on typhoon and tropical meteorology. Such a situation was changed with a series of field scientific experiments conducted after the 1990s. In the early 1990s, China participated in the international tropical cyclone observation program "SPECTRUM-90". In the summer of 1993 and 1994, China carried out the China Abnormal Typhoon Experiment. Later on, China Landfalling Typhoon Experiment (CLATEX) was performed from 2002 to 2004, which was the first comprehensive field observational experiment on landfalling typhoons in China. From 2009 to 2019, the National Key Basic Research Projects (973 Program) about landfalling typhoons, entitled "Unusual Variations of Landfalling Tropical Cyclones and Associated Physical Mechanisms" and "Monitoring and Forecasting of Finescale Structure and Impact Assessment of Landfalling Typhoons", carried out a series of field experiments. Meanwhile, the radar, wind profiler, distrometer, meteorological tower and satellite as well as many other meteorological instruments were gradually employed to observe and monitor typhoon and tropical atmospheric processes.

In the course of the observation experiments, Chinese scholars have also begun to develop new observation techniques and strategies. Most notably, the target observation on typhoon with the FY-4 satellite was successfully performed for the first time with the interactive "observation-forecast" mode in the typhoon season of 2018. During this experiment, the numerical model was ran first to determine the sensitive area of a typhoon, and then the intensive observation with the time interval of about 15 min was conducted with the geosynchronous interferometric atmospheric vertical sounding (GIIRS) in the sensitive area. The observational data was transferred back in real time. With these real-time data, the four-dimensional variational assimilation forecast system ran again to determine the sensitive area for the next time, which guided the next observation of the satellite.

The abundant observation data offers great help to the understanding of the structure evolution and the microphysical processes in typhoon. Zhao et al. (2016, 2017) revealed the triple-eyewall wall structure in typhoon with the radar data. Tang et al. (2018) and Ming and Zhang (2018) found that momentum flux, turbulence kinetic energy and dissipative heat energy all increase with the increase of wind speed during typhoon landfall. Wu D et al. (2018) pointed out that warm rain and ice-phase processes are the main factors leading to the heavy rainfall in the inner-core and outer-core regions of typhoon, respectively.

4.3 Numerical forecasting techniques for typhoon and tropical atmospheric processes

Numerical model is not only an indispensable tool for typhoon and tropical atmospheric process forecast, but also an important tool for understanding their development and evolution mechanisms. However, for a long time, the numerical forecasting models of typhoon and tropical weather system in China were mainly introduced from abroad. Entering the 21st century, with the establishment of a new generation of Global and Regional Assimilation and PrEdiction System (GRAPES), the typhoon numerical prediction technology in China has been developing rapidly. At present, China's typhoon numerical forecasting systems mainly include GRAPES-TCM developed by China Meteorological Administration (CMA) Shanghai Typhoon Research Institute (STI) based on GRAPES (Huang et al., 2007), the regional mesoscale typhoon numerical forecasting system GRAPES-TYM developed by the National Meteorological Center based on GRAPES-Meso (Ma and Chen, 2018) and the T-RAPS developed by the Chinese Academy of Meteorological Sciences. The latest evaluation on the prediction of typhoons in the South China Sea and Northwestern Pacific shows that the 24, 48 and 72 h forecast errors produced by the three prediction systems are about 90, 152 and 265 km, respectively, which are far less than those of ten years ago. However, as compared with the international advanced models, the typhoon prediction systems in China still have much room to improve (Chen et al., 2019; Table 1).

Although the numerical prediction on the track has been improved remarkably, the above-mentioned numerical models do not exhibit evident forecast skills in typhoon intensity (Qian et al., 2012). In order to change this situation, Lei et al. (2019) developed a new generation of regional mesoscale coupling model system for typhoon, which includes GRAPES-TCM, the estuarine coastal and ocean model (ECOM) and wave model (WAVEWATCH III). This forecasting system performed very well in the flood seasons in 2016 and 2017, especially on the prediction of sudden changes of typhoon.

The observation data collected from a series of field observation programs play an important role in the improvement of the numerical models for typhoon in China. First, the in-depth analysis of the observed data reveals the key physical processes and critical parameters in typhoons, which promotes the improvement of the physical parameterization schemes in the model. Tang et al. (2018) found that the vertical vorticity dissipation rate of landing typhoon momentum is significantly higher on land than that over the sea. It was pointed out that the numerical prediction of landfalling typhoon should adopt the parameterization scheme of different momentum vertical vorticity dissipation rates over sea and land respectively. Based on the unique micro-physical characteristics of landing typhoon in China, Wen et al. (2017) fitted the Z-R relation of typhoon precipitation, the axis-length relation of raindrop and μ-Λ relation, which helped improving micro-physical parameterization of model. Secondly, the intensive observational data can be assimilated to provide better initial conditions for the numerical prediction system, which not only benefits the improvement in the prediction of the models but also accelerates the development of the data assimilation theories and techniques. In this field, Chinese scholars have made many attempts to implement the assimilation of radar data, automatic meteorological station data and so on. With the ensemble simulations based on the radar data assimilation, Zhu et al. (2016) found that the predictability of typhoon precipitation depends on typhoon's initial intensity and location as well as its interaction with the steering flow. Most notably, the GIIRS data has been successfully assimilated in the GRAPES model self-developed by Chinese scientists. By this way, the ability of GRAPES in describing the typhoon structure, track and intensity changes has been improved considerably. Based on the development of the techniques in data assimilation, numerical prediction as well as satellite observation, the target observation on typhoon Ampile (2018) was successfully conducted in the interactive "observation-prediction" mode, which provided a new way for the observation and prediction of typhoon track, intensity, structure and precipitation in China.

5. Severe convective weather

Severe convective weather is a kind of high-impact severe weather characterized by fast development, strong locality and large destructive effects. Because of its small space-time scale and strong non-linear characteristics, it has always been a bottleneck problem in weather forecasting. Severe convective weather includes short-duration heavy rainfall of more than 20 mm h^{-1} accompanied by thunderstorm, thunderstorm gales with a 2-min average wind speed exceeding 17.2 m s^{-1} or gusts exceeding 20 m s^{-1}, hails and tornadoes. Severe convective weather is often caused by mesoscale weather systems. Mesoscale weather systems refer to weather systems with a horizontal scale of 2–2000 km and a time scale of several tens of minutes to a few days. The horizontal scale 2–20 km is meso-γ scale, 20–200 km is meso-β scale and 200–2000 km is meso-α scale. Severe convective weather belongs to the category of meso-γ and meso-β scale systems. The meso-γ scale system corresponds to the relatively isolated severe convection system or the strong storm cells, and the meso-β scale system corresponds to the organized mesoscale convection system (MCS). The disasters caused by severe convective weather are second only to typhoons and floods in China, and even equal to typhoons in some years. In the past 70 years, the study of severe convective weather in China has undergone an evolution from the analysis of the meso-α scale synoptic background to the study of the meso-γ scale structure and physical mechanism.

5.1 Observation

Mesoscale weather system is often difficult to be captured by conventional ground-based observation and sounding network, owing to its small space-time scale. The understanding of its initiation and development needs to depend on the

Table 1 The mean track error obtained by using the objective track prediction method in 2017[a)]

Method		24 Sample size	24 Mean error (km)	48 Sample size	48 Mean error (km)	72 Sample size	72 Mean error (km)	96 Sample size	96 Mean error (km)	120 Sample size	120 Mean error (km)
Global model	NCEP-GFS	194	71.9	143	122	101	194.7	74	260.5	58	347.1
	ECMWF-IFS	172	62.3	128	107	94	204.1	71	295.5	54	387.8
	UK	181	68.7	145	111.1	105	186.6	79	290.3	59	374.3
	JMA	374	77.2	288	139.9	210	237.6	/	/	/	/
	T639	301	98.7	243	192.2	183	307.9	138	450.6	109	657.9
	KMA GDAPS	182	77.9	138	121.5	104	205.2	77	627	59	1050.2
Regional model	Australia NWP	176	85.7	128	154.6	90	285.1	/	/	/	/
	Guangzhou NWP	293	68.5	211	115.6	152	220.8	/	/	/	/
	CAMS T-RAPS	170	84.7	133	129.3	96	211.6	/	/	/	/
	STI TYM	253	89.1	198	151	146	242	/	/	/	/
	GRAPES-TYM	280	82.1	205	135.3	137	256.5	96	495.8	66	823
	GRAPES-TCM	253	89.4	187	151.2	130	263.9	/	/	/	/
Other objective method	Shanghai integrated method	335	65.7	260	107.5	189	180.3	/	/	/	/
	Fujian optimal weighted probability	106	78.5	79	129.5	55	230.8	/	/	/	/
	Guangxi Hereditary Neural Network	197	81	142	156.9	101	260	/	/	/	/

a) KMA denotes Korean Meteorological Agency and JMA denotes Japan Meteorological Agency. Adapted from Chen et al. (2019)

intensive field observation and mesoscale observation network, and intensive network observation using various advanced non-conventional observation instruments (weather radar, weather satellite, etc.). Because weather radar can observe the three-dimensional fine structure of mesoscale systems, it has been always the main observation tool of mesoscale weather.

Mesoscale observational experiments in China began in the middle 1960s. In the summer of 1963 and 1964, the Central Institute of Meteorological Sciences and the Institute of Geophysics of the Chinese Academy of Sciences jointly carried out the first severe weather mesoscale observation experiment in China in the Yangtze River Delta (Wang and Li, 2001). The adopted method was mainly time-intensive observation at conventional surface and sounding weather stations to obtain synoptic-scale background observation of mesoscale systems. In the late 1980s, with the support of the national science and technology project "Severe Weather Monitoring and Short-term Forecast Research", CMA built four mesoscale severe weather monitoring and ultra-short-term forecasting test bases in the Pearl River Delta, Yangtze River Delta, the middle reaches of the Yangtze River and the Beijing-Tianjin-Hebei area. Breakthroughs were made on the key technology of high-speed automatic transmission, acquisition, analysis, processing and displaying equipment for data from automatic weather stations, atmospheric wind profilers, Doppler weather radars and mesoscale detection networks. In the 1990s, several provincial-level mesoscale meteorological bases were established in Fujian, Beijing, Shanghai, Shenzhen, and so on.

In 1998, China carried out the "South China Sea Monsoon Experiment and South China Heavy Rainfall Experiment", the "Huaihe River Basin Energy and Water Cycle Experiment and Research " (Zhou et al., 2003; Tao et al., 2003; Zhao and Ding, 1999), and the National scientific climbing special project "Heavy Rainfall Experiment over Taiwan Strait and Its Periphery" (hereinafter referred to as the "South China Heavy Rainfall Experiment") (Zhou, 2000), which strengthened the application of automatic weather station observation, Doppler radar, wind profiler, meteorological satellite and GPS in monitoring and predicting the meso-β scale structure and the evolution of heavy rain, and gained a relatively reliable and standardized data base of intensive observations of heavy rain process. The mesoscale structure and evolution mechanism of heavy rain during the pre-summer rainy season in the southern China and Yangtze-Huaihe River Basin were studied through mesoscale comprehensive field observation experiments, synoptic dynamics analysis and mesoscale numerical simulation. Among them, in the observation of Meiyu rain belt in Yangtze-Huaihe

River basin, three X-band Doppler radar synchronous observations were carried out for the first time, which revealed the structure of meso-γ scale vortex in Meiyu system. From 1999 to 2008, China organized three major national key basic research programs to carry out intensive observation on the meso-α scale and meso-β scale convective systems that cause heavy rain at Meiyu front in South China and Yangtze-Huaihe River basin, developed satellite and radar monitoring and forecasting methods for heavy rainfall, and deepened the understanding of the formation mechanism of these two systems (Ni et al., 2006).

Since 2000, China's atmospheric detection technology has developed rapidly. The integrated operational meteorological observation network, including weather satellite, sounding, Doppler radar, automatic weather station, GPS/Met, wind profiler radar and other observation systems has been established, which has reached the world advanced level in terms of the severe convective observation ability, size, density and so on, and has been able to capture and detect the formation and organizing processes of mesoscale convection. In particular, the average density of the new generation Doppler radar network in China is the highest in the world (216 Doppler radars) (Yu et al., 2012), which significantly improves the monitoring and early warning ability of severe convective weather. At the same time, the successful launch of new generation of satellites (stationary and polar orbit) has further strengthened the capability of monitoring mesoscale severe weather.

In 2013, the national key basic research program "Observation, Prediction and Analysis of severe Convection of China", which was the first project in China to focus on severe convective weather, was launched (Xue, 2016). From June to July during 2014–2016, the project carried out observation experiment on the meso-γ scale severe convection in the Yangtze and Huaihe River Basin and obtained the observation data of fine structure and evolution characteristics of several different typical severe convection processes (Squall line, local severe convection, Meiyu frontal convection, etc.). In the key region of meso-γ scale system, the integrated observation of multiple dual-polarization Doppler radar close-range networking and superstations was implemented for the first time. The dual-polarization radar network was mainly used to observe the dynamics and micro-physical structure of meso-γ scale severe convection, while the superstations (including comprehensive observations of microwave radiometer, mobile wind profiler, raindrop spectrograph, vertically pointing radar and GPS sonde) were used to observe the vertical structure of atmosphere and precipitation as well as the micro-physical characteristics of surface precipitation. Since 2013, CMA has initiated and organized the southern China Monsoon Precipitation Experiment (Luo et al., 2017), which is a research and development project of the World Weather Research Program of the World Meteorological Organization (WMO). From May to June of each year, a comprehensive precipitation observation experiment is conducted in South China. The cloud-precipitation superstations and the severe convection superstations are established step by step, which achieves joint observation of vertically pointing cloud-precipitation radars with multiple different wavelengths and the network observation of multiple dual polarization radars and phased array radars. This experiment has obtained the observation data of the fine structure and evolution characteristics of frontal and warm-sector heavy rainfall during the pre-summer rainy season in the southern China.

At present, China's FY-4 geostationary satellite has been put into operation. China's operational weather radar network is also in the process of dual-polarization technology upgrade. Several megacities, such as Beijing, Guangzhou and Shanghai, have basically completed building the X-band dual-polarization radar monitoring network. Tornado detection by dual-polarization phased array radar also began to be tested. The improvement of these high spatial-temporal resolution detection methods has laid a solid foundation for the improvemnet of severe convective weather monitoring and early warning abilities.

5.2 Characteristics and mechanism of convection initiation and development

Studies on the dynamics of cumulus began in the early 1960s in China, when the inititaion and development characteristics of cumulus in different stratification and wind field were analyzed. Chao (1980) found that the gravity wave can generate severe weather under the condition of horizontally uneven stratification, which can be used to explain the fact that the left front area of the low level jet is prone to heavy rain. Based on the mesoscale experiment data from the 1960s, Micro- and Meso-Scale Weather Systems Test Base Collaboration Group in Eastern China (1978) revealed the formation condition and activity features of the meso and microscale weather systems, and their relationship with weathers. They found that the low-level mesoscale or sub-synoptic-scale convergence line and gravity wave are important initiation mechanisms. Cold front, topography, low-level jet, discontinuity of wind speed, dew point front, land-sea breeze, and density current can also initiate severe convection. The most possible initiation location is where discontinuous boundaries meet or cross each other. Consolidation of mesoscale systems may also result in convection initiation (Xu, 1977a, 1977b). Based on the data of South China Heavy Rainfall Experiment, Zhou et al. (2003) revealed meso-β scale thermal and dynamic structures and mechanisms of heavy rainfall in South China. In the early 1980s, Ding et al. (1982) systematically analyzed the synoptic environment, initiation conditions, and the thermodynamic and kinetic conditions for the formation of squall lines in China.

With the establishment of radar network in China, studies on the formation and development of meso and micro-scale weather systems that cause severe convective weathers in China have been deepened. Meng and Zhang (2012) systematically studied the statistical characteristics of squall lines preceding tropical cyclones and their differences with squall lines in the middle latitudes. They found that squall lines preceding tropical cyclones occur mostly in the transition zone of the typhoon and the subtropical high. The typhoon itself contributes to the formation of squall lines by enhancing water vapor, instability, and low-level convergence. Meng et al. (2013) obtained the statistical features of spatial and temporal distribution, length, intensity, life span, movement, orientation, formation and organization modes, formation environment and dissipation modes of squall lines in China under the impact of its unique terrain and monsoon climate, in comparison with the characteristics of squall lines in the United States. It was found that the high-incidence areas of the squall lines in China are located at the border areas of Anhui, Henan, Shandong and Jiangsu provinces, with the highest frequency in July and three diurnal peak values (Figure 8). The life span of the squall lines in China is about half that of the United States. The humidity of the environment is about twice that of the United States. The degree of instability and vertical wind shear is about the same as those of the United States. Zheng et al. (2013) revealed differences in the organization of squall lines in a dry from wet environment. He et al. (2017) used tilt T-mode principal component analysis to classify the synoptic patterns of daytime and nocturnal mesoscale convective systems in the eastern China. It was found that 62.2% of daytime mesoscale convective systems and 67.7% of nocturnal mesoscale convective systems occur in the longitudinal circulation pattern of low-pressure systems from the east side to the west side of subtropical high in the western North Pacific. The relationship between synoptic pattern and mesoscale convective system is also revealed.

Chinese scholars have systematically studied the characteristics of convections in different regions of China from the perspective of radar climatology using long-term radar observation data. Luo et al. (2013) analyzed the convective characteristics of the precipitation system in South China and Yangtze Huaihe River basin under the background of the East Asian summer monsoon by using the TRMM satellite-borne rain radar and the CloudSat/CALIPSO satellite-borne cloud observation of many years. They found that the convective intensity of rainfall systems in South China and Yangtze-Huaihe River basin increases from the pre-monsoon onset to the monsoon period and to the post-monsoon period, which is consistent with the change of the atmospheric thermal conditions. They also found that the average total rainfall in South China during monsoon period is more than that in the Meiyu period of Yangtze and Huaihe River basin. The contribution of heavy precipitation (>50 mm d^{-1}) to the total precipitation in Yangtze-Huaihe River basin is greater than that in South China, likely due to its stronger front and low vortex of monsoon rainfall system and thus stronger convective intensity of rainfall system than that in South China. Chen M X et al. (2014) studied the diurnal variation characteristics of the warm season convection systems in North China under different prevailing wind conditions, and pointed out that the thermal circulation induced by the North China topography is the main mechanism for the formation of convection at noon on the hillside and the downhill pro-

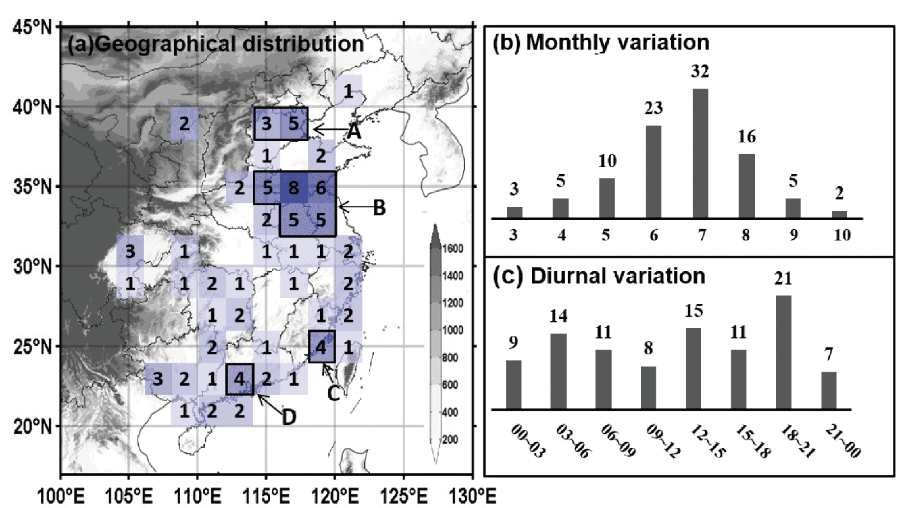

Figure 8 The geographical distribution (a), monthly variation (b), and diurnal variation of squall lines' formation frequency (c). Darker shading in blue in (a) denotes higher frequency. The numbers represent the frequency of squall lines whose centroids of their 40-dBZ echo band are located within the 2°×2° grid box at their formation times in 2008 and 2009. A, B, C, D denote 4 high-frequency areas. The gray shadings denote the terrain height. Adapted from Meng et al. (2013).

pagation at night. It was found that the different prevailing winds in the middle (500 hPa) and lower layer (925 hPa) have significant effects on the diurnal variation of convective systems. Chen X C et al. (2014, 2015) revealed that the diurnal variation of the convection and precipitation in the pre-summer rainy season in South China has a large nocturnal maximum value, which is possibly caused by the convergence of the land breeze and the mountain-valley breeze with the prevailing southwest warm and moist flow; it was found that the prevailing wind speed and humidity are the important factors affecting the diurnal variation of the coastal precipitation. It was suggested that the increase of friction convergence in coastal area caused by low-level jet is the main dynamic mechanism for the high frequent convection near the coastal line in summer (Chen et al., 2017). This theory is different from the previous studies which paid more attention to the jet itself or the influence of thermally forced land-sea breeze circulation on the heavy rainfall along the coast.

Based on observation and cloud resolving numerical simulations, the understanding of the detailed structure of severe convective systems has been deepened. Based on real-world simulation, Meng et al. (2012) confirmed the theory of book-end vortex formation of squall line bow echo which was obtained from ideal experiment, and found that the book-end vortex can also be formed through the downward tilting of mid-level horizontal vorticity. Luo Y L et al. (2014) found that the mesoscale convective system that causes extreme precipitation along the Meiyu front of the Yangtze-Huaihe River basin has a distinct type of squall line organization (Figure 9), i.e., multiple back-building west-east or southwest-northeast orientated convective lines becomes parallel to each other, forming a larger mesoscale convective system and moving to the southeast as a whole. Overlapping of lines with backbuilding cells and the system with backbuilding lines causes the superposition of two scales of train effect, which can lead to the occurrence of extremely heavy rainfall in the affected area. This train-line structure was also observed during extreme rainfall along the South China coast (Wang H et al., 2014; Wu and Luo, 2016). The formation of this organization mode was attributed to the rapid splitting and reconstruction of the bow-shaped convective lines within the mesoscale convective system by Liu X et al. (2018), which requires three conditions: abundant warm and humid air from the sea, a quasi-stationary mesoscale flow boundary, and strong inflow at the back of the bow convective line intersected with outflow boundaires at the southwest end of the convective line. In recent years, the cloud-precipitation-microphysical characteristics of squall lines have also achieved innovative results. Wen et al. (2017), through dual-polarization radar observation analyses on the microphysical structure of severe convection in Yangtze-Huaihe River basin, found that raindrop spectrum

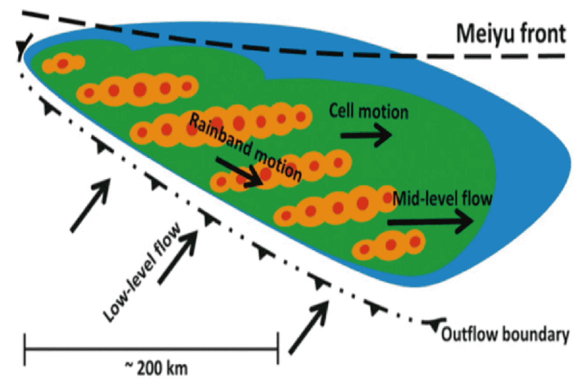

Figure 9 The schematic diagram of the backbuilding, echo and rainband training organization pattern of MCS. The orange, green, and blue shadings represent radar reflectivity echo of 50, 35, and 20 dBZ, respectively. Adapted from Luo Y L et al. (2014).

transits from continental convection at the initial stage of the squall line to oceanic convection at the mature stage of the squall line (Figure 10). The warm rain process plays an important role in the squall line precipitation.

The study of severe convective system, especially the initiation mechanism of squall line, has been examined in a more detailed way. Bai et al. (2019a) found that the interaction of a dry line and a scallop-like gust front generated by previous convection can trigger convection near the intersection of the gust fronts. Su and Zhai (2017) proved the positive contribution of n=1 gravity wave to convection inititaion. The gravity wave was generated by the early convection in the upper troposphere. The lower level convergence associated with the rising branch of the gravity wave overlapped with the weak convergence associated with the surface convergence line initiated the convection. Zhang M R et al. (2019) revealed that low-level jet can initiate convection by forming moist absolute unstable layer (MAUL) through adiabatic cooling associated with horizontal advection of water vapor and upward motion.

Great progresses have also been made in the study of tornadoes and supercells in China. About 50–100 tornadoes occur each year in China, which is about 10% of those in the United States (Chen J Y et al., 2018). With the widespread use of Internet and multimedia technologies in recent years, especially smartphones, and several high-impact tornado events, tornadoes are attracting more and more attentions from the operational and research meteorological units as well as the public. Due to the small space-time scale of tornadoes, studies on the generation, development and damage characteristics of tornadoes are mainly based on damage surveys and radar observation analyses. The on-site damage survey in China is becoming more professional and systematic, changing from previous photo-taken at severe damage area to all-path ground and unmanned aerial vehicle (UAV) damage survey. This damage survey effort played a

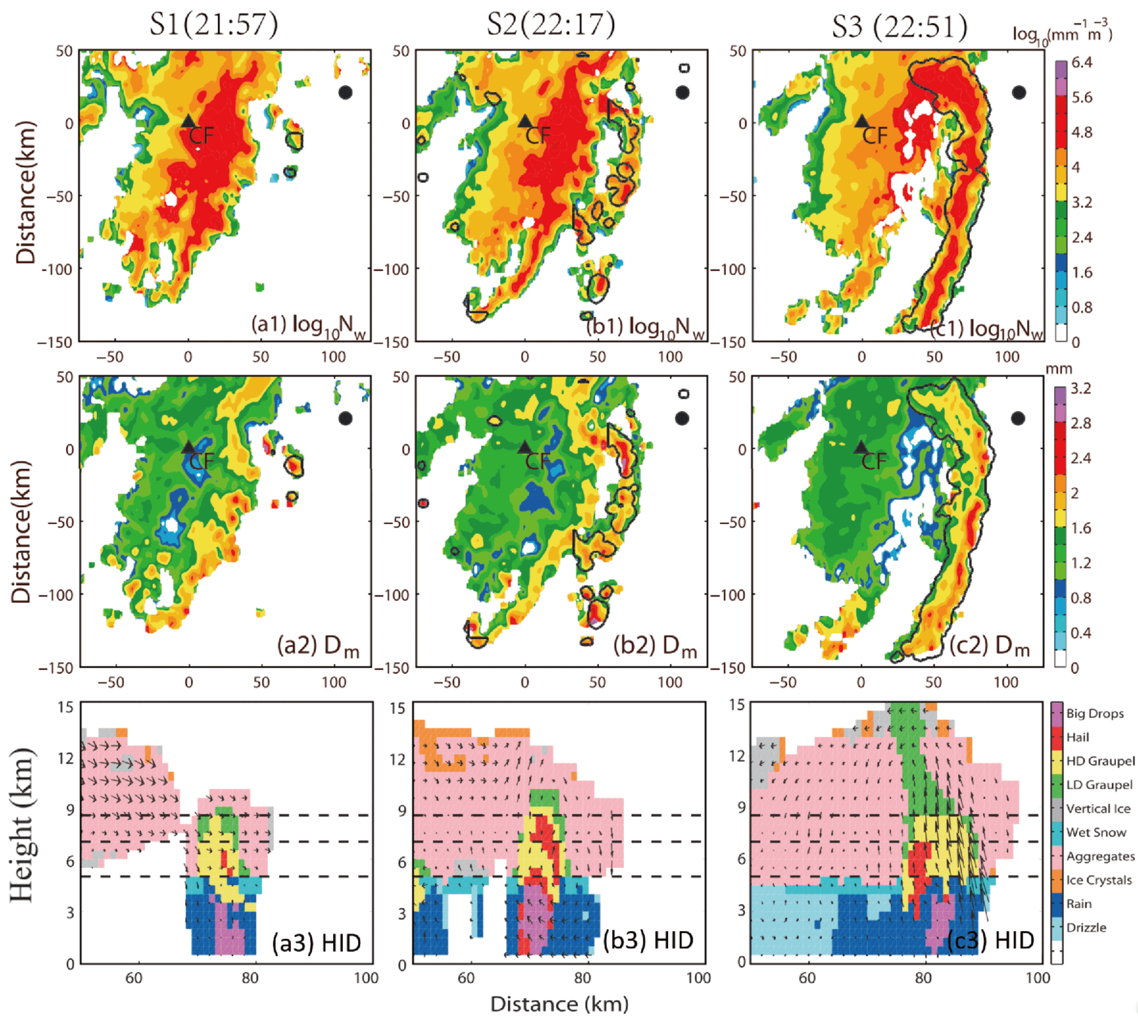

Figure 10 The spatial distribution of retrieved particle number concentration ((a1), (b1), (c1)) and particle size ((a2), (b2), (c2)) in the initial ((a1)–(a3)), development ((b1)–(b3)) and maturation ((c1)–(c3)) stages of squall line, and the vertical distribution of the particle phase ((a3), (b3), (c3)). Adapted from Wen et al. (2017).

key role in the determination of convective system that caused wind damage in Beijing in the extremely heavy rainfall event on July 21, 2012 (Meng and Yao, 2014) and the shipwreck event of Oriental Star in Hubei Province on June 1, 2015 (Meng et al., 2016). Bai et al. (2017) carried out for the first time in the world a comprehensive damage survey and radar analysis of the EF3 tornado caused by a typhoon (Mujigae) in Foshan, Guangdong Province on October 4, 2015. The damage distribution and near-surface wind features of the tornado were obtained. The consistency between the EF wind speed estimation and the estimation of wind speed based on tornado movie, the association of the ground diameter of the funnel cloud and the EF2 isopleth, deviation of the ground position of the tornado from the tornado vortex signature on radar, and the relationship between the intensity of tornado vortex observed by radar and ground damage intensity were revealed (Figure 11). Bai et al. (2019b) further analyzed the spatial and temporal distribution and environmental characteristics of tornadoes associated with landfall tropical cyclones in China from 2006 to 2018. They found that about 30% of the landfall tropical cyclones in China produce tornadoes, and the occurrence frequency of the tornado is 5 each year on avergae. At the same time, the differences between tropical cyclone tornadoes in China and their counterparts in the United States were revealed. The environmental characteristics of the first outbreak event of tornadoes in China, which was caused by Typhoon Yagi in 2018, were also examined. On June 23, 2016, an EF4 tornado occurred at Funing in Jiangsu province, which caused the highest number of deaths in the past 43 years in China. Meng et al. (2018) carried out detailed damage survey and radar analysis on this tornado and revealed the importance of the minutely surface observation data in tornado monitoring and early warning.

Progresses are also made on the formation mechanism of supercells especially tornadic supercells. Zhao et al. (2017), using radar retrieved wind, quantitatively analyzed the mechanism of the formation mechanism of the tornadic super-

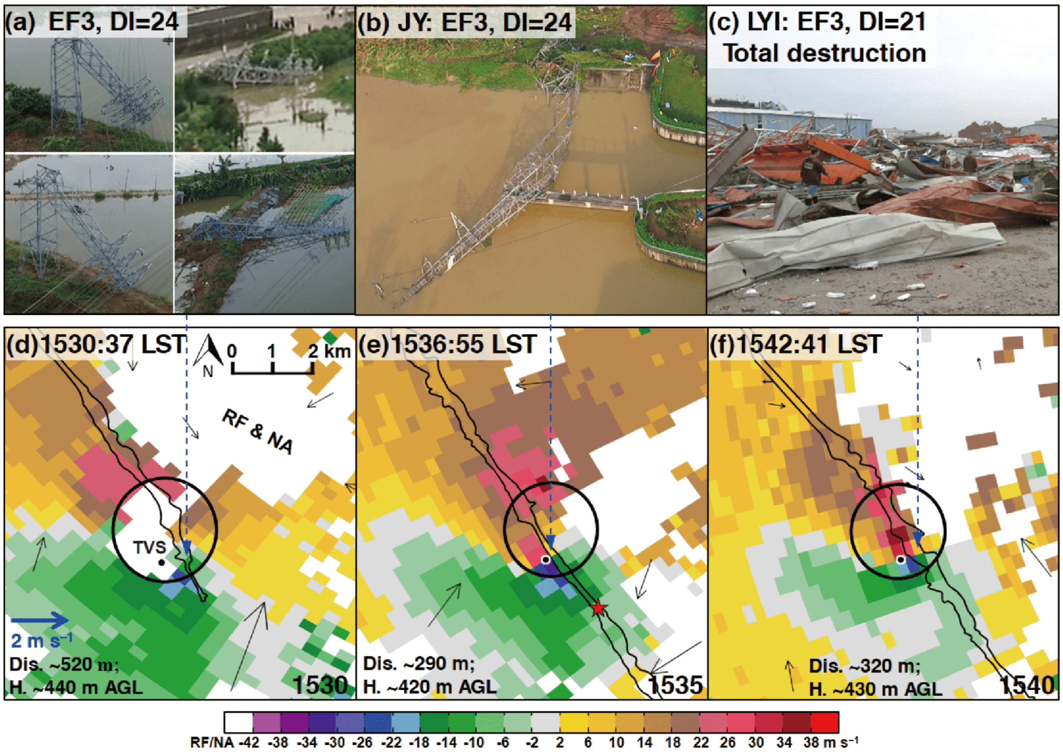

Figure 11 The corresponding relationship between the condensation funnel and disaster path at the ground of the Foshan tornado on Oct 4, 2015, and the mesocyclone (black circle) and tornado vortex signature (TVS, black dot) detected by radar. The red star in (e) represents the surface location of the tornado. Adapted from Bai et al. (2017).

cell in typhoon "Mujigae" in Foshan, Guangdong Province for the first time from an observational point of view. They found that the supercell formed mainly due to the tilting of horizontal vorticity followed by rapid stretching of vertical vorticity. Xue et al. (2019, personal communication) performed high-resolution assimilation and simulation of tornadic supercell for the first time in China, obtaining decent low-level vortex structure, wind and pressure fields. They found that the horizontal vorticity produced by the surface friction may be the main source of vorticity near the ground, as a supplement of the baroclinic vorticity that has been considered to be the main source of vorticity in foreign studies. It was also found that the probability distribution of the simulated updraft storm helicity could be a good indication for the generation of tornadoes.

Relative to tornadoes, straight line wind is a more common convective weather in China. Yang et al. (2017) analyzed the temporal and spatial distribution of gale events from 2010 to 2014 in China. They found that gale events mainly occur in the afternoon of warm season in East China, but rarely occur in the western region. The highest frequency appears in spring in Guangdong with two sub-high frequency centers in North China and the middle and lower reaches of Yangtze River. Meng et al. (2016), using a drone for meteorological damage survey for the first time in China, revealed that the "Oriental Star" ship encountered a downburst at the apex of the bow echo of the squall line when it capsized on June 1, 2015.

5.3 Forecast and early warning

Severe convective weather forecast has always been a big challenge. As early as the 1970s, a number of scientific research institutes in China have jointly set up the Northern Heavy Rain Research Group, and performed a lot of work on the spreading of the heavy rain forecasting methods and application of theoretical research results in the northern China (Xie et al., 1978; Tao et al., 1980). The short-term operational forecast of severe convective weather in China began in 2004 (Zheng et al., 2010). Beijing Meteorological Service first built BJ-RUC short-term weather forecasting system (Chen M et al., 2009). Since the end of 2007, CMA started to develop Severe Weather Automatic Nowcast System (SWAN System) (Han et al., 2007). At present, SWAN system is capable of performing display and alarm of disastrous weather, creating two-dimensional and three-dimensional radar mosaic, radar quantitative estimation of precipitation, area tracking (Tracking Radar Echoes by Correlation, TREC) and echo extrapolation forecasting, extrapolation forecasting of precipitation for 0–1 h, storm cell identification every 6 min, and extrapolation prediction of 30 and 60 min (Thunderstorm Identification Tracking Analysis and Nowcasting, TITAN). The system has used the prediction of mesoscale numerical models with high spatial and temporal resolution, severe convective weather classification identification and forecasting technology, the technique of using satellite data to rapidly identify severe convective clouds and analyze cloud convective characteristics parameters, and the three-dimensional analysis field of basic elements generated by LAPS rapid integration and analysis system, and cloud analysis algorithm and so on.

In 2009, CMA established Storm Predication Center (SPC), begun to perform national operational forecasting for severe convective weather, built a real-time monitoring system for classified severe convective weather based on multi-source data, a mesoscale weather analysis standard and platform, an objective classified forecasting system and so on. SPC also launched a classified severe convective weather forecasting product (He et al., 2011). In the aspect of monitoring, the real-time monitoring of severe convective weather in the whole country was implemented by using the conventional observation data, WS report (important weather report), automatic station, lightning, infrared data of stationary satellite and cloud classification data, which can monitor the distribution of thunderstorm, hail, tornado, strong wind, short-term heavy precipitation and deep convective clouds in recent 1, 3, 6, 12 and 24 h. In the aspect of analysis, based on the analysis of synoptic environment, the ingradients method has been applied to analyze the physical conditions and structural characteristics of severe convective weather, including synoptic-scale environmental conditions, mesoscale mechanism, juxtaposition, structure analysis and so on. The objective analysis and diagnosis technology of numerical weather prediction have been developed. The comprehensive analysis map for classifying the environmental conditions of severe convective weather has been configured and become an important basis for short-term and potential forecasting of severe convective weather. Mesoscale rapid updating analysis technology and operational products have been developed for key areas and key periods, based on rapid analysis of forecasting data and multi-source observation data. In the aspect of forecasting, extrapolation is often used for the 0–2 h nowcasting, and short-term forecasting of 2–12 h depends more on fast-updating numerical model system or high spatial-temporal resolution mesoscale model ensemble forecasting system. The short-term forecasting mainly starts from the mechanism of initiation and development of the severe convective system and the environmental conditions it depends on. According to the indication of different diagnostic physical quantities for different types of severe convective weather, the classified severe convective weather forecasting is carried out, namely, the ingradients method. Because the initiation and development of severe convective weather require many physical conditions, other methods such as fuzzy logic and machine learning begin to be used in the forecasting. The short-term probabilistic forecasting technique for severe convection based on ensemble numerical prediction is an important approach of current forecasting techniques. The assessment of the flood season forecasting in 2010 shows that the TS score of 6-hour interval thunderstorm is 18%, the short-term heavy rainfall is 2.6%, and the hail and thunderstorm are 2.1%.

In recent years, the occurrence of many high-impact tornado events has prompted CMA to start tornado monitoring and early warning services. In August 2013, the Guangdong Foshan Tornado Research Center was officially established. In April 2015, the Severe Weather Alert and Track CompreHensive platform (SWATCH) developed by Jiangsu Provincial Meteorological Bureau was put into operation (Meng et al., 2018), which implemented the key technologies of severe weather comprehensive alerting and tracking, such as multi-source data display application, objective identification and extrapolation of severe convective weather, rapid early warning and joint real-time forecasting at provincial and county levels, and operational activity recording and analysis. It played an important role in the early-warning process of sudden disaster weather such as Funing tornado on June 23, 2016. Starting in 2017, CMA conducted monitoring and early warning quasi-operational experiments in five provinces of Jiangsu, Anhui, Hubei, Zhejiang and Guangdong. So far, the Foshan Tornado Research Center has successfully issued three tornado warnings, including China's first tornado warning in June 2018 and two tornado warnings during the landfall of Typhoon "Mangkhut" on September 17, 2018, one of which was made even an hour earlier before tornadogenesis.

In general, at present, China's operational forecasting level of classified severe convective weather in specific location at specific time and quantity is not high, and the ability to monitor, forecast and warn tornadoes is especially weak. The fundamental way to solve these problems lies in strengthening the construction of high spatial-temporal resolution radar network and developing a rapid updating mesoscale ensemble numerical weather prediction system based on high spatial-temporal resolution data assimilation.

6. Numerical weather prediction and data assimilation

The numerical weather prediction and data assimilation research and operational application in China can be divided into two stages. One is the early stage which was almost synchronous with the development of international numerical weather prediction, and the other is the establishment of modern operational numerical weather prediction system and independent innovation development stage which began in the 1980s.

6.1 Research progress on numerical weather prediction model

China was one of the countries that carried out numerical prediction in earlier times, and made a great achievement that had broad influence in the world (Blumen and Washington, 1973). The research of numerical prediction in China began in 1954. In the 1950s and early 1960s, Ye Duzheng's theoretical research on the dynamic and thermal effects of the Tibetan Plateau (Ye, 1952; Ye et al., 1957), the adaptation theory of atmospheric motion and the theory of atmospheric dispersion, the equilibrium relationship of wind pressure fields (Ye and Li, 1964), and other theoretical researches had directly or indirectly guided and promoted the development of numerical prediction in China. In 1961, based on the adaptation process theory of atmospheric motion, Zeng (1961) proposed a "Semi-implicit (or semi-explicit) Time Difference Scheme", which adopted implicit time-stepping approach for the fast waves. Thereby, the time step could be extended, which enhanced the computational stability and reduced the computing cost. Several years later, Robert (1969, 1982) further enriched and developed the semi-implicit scheme, and combined with semi-Lagrangian method to construct the semi-implicit semi-Lagrangian method, which is widely used in the operational numerical prediction models in the world today.

After Charney's first successful numerical prediction using barotropic vorticity equations, the importance of baroclinic primitive equations rather than simplified quasi-geostrophic equations for predicting real weather processes was recognized soon. Zeng (1961) made the real weather forecasts by using the primitive equations for the first time, and the model that Zeng developed was put ino operation in the Moscow World Meteorological Center, which was five years earlier than the United States who began to use the primitive equations in 1966. In view of the computational complexity caused by terrain in numerical model, Zeng (1963d) proposed a hydrostatic extraction (or reference atmosphere extraction) approach, which could reduce the computational error by extracting the basic state in calculating the pressure gradient force. This method of hydrostatic extraction later played an important role in spectral model and semi-Lagrangian advection calculation for mitigating the errors due to the steep topography (Simmons and Chen, 1991; Temperton et al., 2001). Zeng carried out a series of studies on the fundamentals of mathematical physics in the numerical weather prediction, and built the mathematical physics theory of numerical weather prediction (Zeng, 1979b). In summary, Chinese scientists have made important contributions to the early research and development of numerical prediction.

The period of the 1970s–1980s was the important times for NWP from earlier development stage to full operations, during which NWP began to be indispensable in daily weather forecast. This stage was marked by the establishment of the European Center for Medium-Range Weather Forecast (ECMWF). The research and application of numerical prediction entered a period of great development. The study of numerical prediction research in China mainly focused on the designment of computational schemes during this period. Zeng and Ji (1981) proposed a difference scheme with implicit advection term and total energy conservation, which is computationally stable with time difference and any initial values, and has the characteristics of energy conservation, general energy conservation and averaged-scale conservation. Although this implicit full energy conservation scheme is computationally stable, it is difficult to solve in practice and requires a lot of work. The explicit fully squared conservation scheme (Wang and Ji, 1990) overcomes this difficulty and is a breakthrough in the construction of conservation scheme. Zhong (1997) constructed and proved two theorems of the time difference fidelity scheme for the general quadratic and cubic physical conservation laws. Some previous schemes of the main time discrete conservation schemes can be provided as two special cases of these laws, thus these laws provide an applicable mathematical basis for solving the basic problems in constructing the time-space discrete fidelity scheme for a wider class of time-space discrete schemes. The semi-implicit high-order total energy conservation scheme for the global spectrum-vertical finite difference model of baroclinic primitive equation is constructed and implemented by using this new theorem, which can effectively improve the systematic deviation of energy and quality conservation in the traditional forecast scheme. Wang and Ji (2006) introduced the symplectic geometry algorithm into the atmospheric and oceanic numerical simulation, and discussed the linear and nonlinear conditions of the atmospheric dynamical equations.

The 1980s is also the period when numerical models were developed in China (Zeng et al., 1985; Zheng, 1980). Important achievements include the seven-layer hemispheric spectral model developed by Zheng (1980), the earliest operation-oriented three-layer primitive equation model (A model), the five-layer grid-point model (B model) of the Northern Hemisphere with simple physical processes, the atmospheric circulation model with a horizontal resolution of 5°×4° (IAP AGCM-I; Zeng et al.,1985), the HLAFS (the High-resolution Limiting Analysis and Forecasting System), and the AREM (the Advanced Regional Eta-coordinate Model, Yu et al., 2004) for steep terrain, the GAMIL (the Grid-point Atmospheric Model of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP)) developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences, and SAMIL model and so on (Wang et al., 2004; Wu et al., 1996). In the beginning of the 21st century, GRAPES, a new generation non-hydrostatic numerical prediction model had been developed by the CMA (Xue and Chen, 2008; Shen and Zhou, 2013). The GRAPES is an important achievement in term of the self-development through domestic efforts for the operational applications, and greatly promotes the assimilation and application of radar, satellite and other remote sensing data. The development of GRAPES and its fully operational use in global and regional NWPs not only start a new era of NWP in China, but also begin to have impacts in the world NWP society.

In recent years, with the development of supercomputers, the scalability and computational efficiency on multi-core high-performance computers have become an important area for the development of the next generation of high-precision forecasting models in main NWP centers, including the climatological model community. The research on numerical algorithms with high scalability, high precision and conservative property is the focus for the future NWP model development. Shen and his research team have studied and developed a new approach for solving the fully compressible atmospheric equations (Chen C G et al., 2014, 2015). This approach is an extension of traditional finite volume method (FV) through introducing the multi-moment constraints, and is called multi-moment constrained FV (MCV). This method strictly guarantees the conservation of numerical values. Compared with the traditional FV, the MCV has features of high degree of local freedom, good flexibility at various grids, no global communication and locally intensive computation etc. The MCV has been recognized as one of the representative algorithms with high accuracy by international NWP society.

In addition to the development of numerical weather prediction model, China has also made great achievement with international influence on the study of atmospheric predictability. Mu et al. (2003) proposed the CNOP method, which was used by Mu and others to study early signals of weather or climate events such as the blocking anticyclone (Mu and Jiang, 2011), the North Atlantic Oscillation (Dai et al., 2016), and the MJO occurrence (Wei et al., 2019). Interestingly, they also found that the best early signals of these events and the fastest-growing initial errors in prediction have similarity in spatial structure. These characteristics lay the foundation and provide the idea for improving the prediction technique of these events and carrying out target observation. On this basis, they were also trying to apply the CNOP method to construct initial perturbations for ensemble forecasts (Jiang and Mu, 2009; Duan and Huo, 2016). Wu et al. (2013) effectively acoounted for the uncertainty of the model physical processes by using a combination of multi-physical parameterization schemes in an ensemble, which increased the proportion of ensemble members that captured a squall line by 10%. The simulation effect of a squall line was improved linearly with the linear improvement of quality of the initial field, which was different from that of an American squall line simulation in which the non-linear improvement of initial field was achieved. It was also found that the simulation of the squall line is most sensitive to the initial water vapor.

6.2 Development and application of operation numerical weather prediction

In 1954, China began to develop the quasi-geostrophic model. In 1960, the meteorological observatory of National Central Weather Bureau began the application of numerical prediction map (Shen and Mou, 1965). After 1978, CMA in collaboration with the Institute of Atmospheric Physics, Chinese Academy of Sciences, established an operation-oriented model of the Asia-Europe regional Numerical Weather Prediction (then known as the A model) in July 1980. The model is a three-layer adiabatic primitive equation model for the 48-hour forecast. During 1981–1985, a joint effort from the CMA, the Institute of Atmospheric Physics, Chinese Academy of Sciences and Peking University, was organized and succeeded in establishing the B model, which includes a five-layer limited area model and a five-layer Northern Hemispheric model with a horizontal grid size of 381 km and very simple physical processes. The B model was equipped with data processing and objective analysis. The B model had been in operation for about nine years. The achievements in developing the B model and constructing the operational system with high degree of automation played an exemplary role in the future development of the numerical prediction service in China (Figure 12).

The research and development of China's global medium-range numerical prediction system began in the middle 1980s. Considering the great gap between the research and development capability of China's numerical prediction system and the supporting environments comparing with the advanced countries, the policy to import from abroad advanced NWP centers was adopted. During 1986–1990, a cross-sectoral joint research team was organized by CMA with nearly 300 participants from 17 organizations. Taking the global spectral model introduced from ECMWF as the core, the T42L9 global forecasting system on the domestic Galaxy computers was established and was put into operation in the early 1990s. This spectral model system was upgraded several times in the 1990s and early 2000s (T106, T213, T639). It had played important roles in the national meteorological forecast operation and service, and laid an important foundation for the independent research and development of numerical models in the future (Figure 12).

With the development of the global medium-range prediction system, supported by the national key science and technology project of "Typhoon and Heavy Rain Severe Weather Monitoring and Forecasting", Chinese scientists had developed their own nested limited-area fine grid data assimilation and forecast system LAFS, which was put into operation in 1991 (Guo et al., 1995) and replaced the “B model”. In 1996, LAFS was upgraded to the High-resolution Limited Area Analysis and Forecasting System (HLAFS), and formally replaced LAFS in 1997 as the main operational system of the National Meteorological Center for a long time. In addition, on the basis of global and regional models, a tropical cyclone numerical prediction model had been developed to provide guidance for operational tropical cyclone forecasting.

At the beginning of the 21st century, CMA set up the innovation base of meteorological numerical prediction, and made the important decision that the future numerical prediction service system was changed from importing from abroad countries to self-development. Starting from 2001, with the support of the National Key Science and Technology Research Project of “Innovative Research on China Meteorological Numerical Prediction Science and Technology”, GRAPES had been developed independently by CMA in collaboration with other organizations. Later, after more than ten years of efforts, for the first time in China, a complete numerical prediction system covering deterministic and ensemble forecasts from 3–10 km resolution in regional area to 25–50 km in globle has been established. Especially, a professional team is established, which is constituted by the experts and groups whose majors cover the whole chain of NWP system. Through the research and development of GRAPES, several achievements have been made, including the nonhydrostatic dynamic core, four-dimensional variational assimilation technique, cloud microphysics, high-accurate numerical algorithms, direct assimilation and bias correction approach of satellite data. The accumulation of research achievements and well-trained team will be the solid foundation of future NWP development in China (Figure 13).

6.3 Research progress on data assimilation method

In the 1950s when the numerical weather prediction was just in its infancy, along with Charney et al. (1950) using the computer to make the first successful numerical weather prediction, Chinese meteorologists has begun to study the initial value problem of numerical weather prediction. Gu (1958a, 1958b) theoretically equated the initial value problem of weather prognostics prediction to extrapolation prediction using the historical evolution of weather, and believed that it is feasible to use past observation data in numerical prediction. The idea of using the evolutionary distribution of certain meteorological quantities over a per-

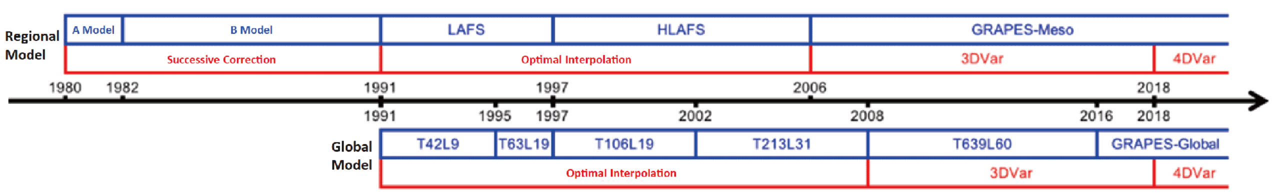

Figure 12 Regional and global numerical prediction systems and their data assimilation methods operated by CMA since 1980.

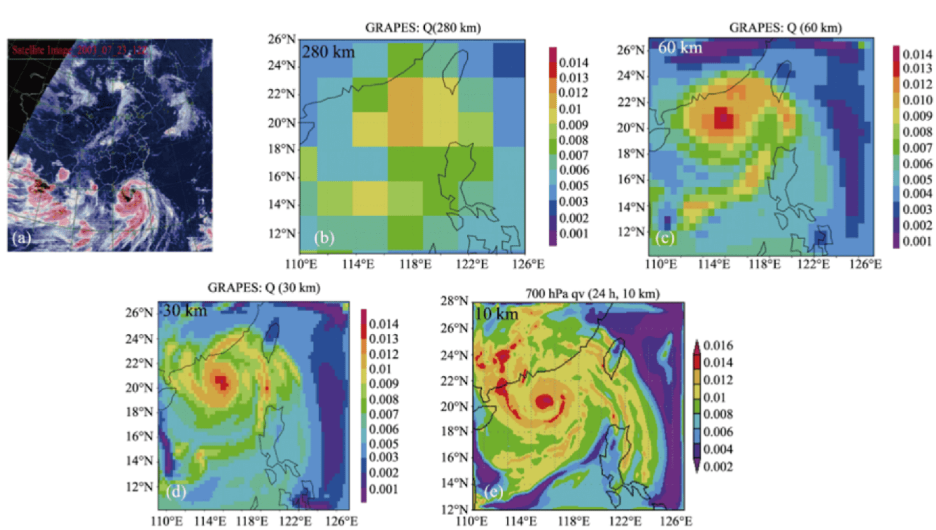

Figure 13 The observed satellite imagery (a) and the simulated specific humidity (unit: kg/kg) with the horizontal grid spacing of 280 km (b), 60 km (c), 30 km (d) and 10 km (e) at 600 hPa by GRAPES model at 1200 UTC 22 July, 2003. Adapted from Chen et al. (2008).

iod to predict their future changes is actually the earliest theoretical exploration of the four-dimensional variational data assimilation method. In the late 1950s and early 1960s, Chou (1974) performed further studies and derivations of Gu's theory. He transformed the problem of solving the differential equation used to approximate the atmospheric process into the problem of functional extremum, and proved that the possible solution of the functional extremum in barotropic conditions is close to that of the differential equation as well as the atmosphere, while in baroclinic conditions, the solution of the functional extremum problem is closer to that of the atmosphere. This mathematical deduction is theoretically integrited and practical. Based on this work, Gu Zhenchao and Chou Jifan began to conduct numerical experiments on the prototype of modern variational data assimilation method in the early 1960s (Gao, 2013), which is nearly 10 years earlier than the similar studies conducted by Charney et al. (1969) in the United States.

With the continuous development of numerical weather prediction model, scientists in our country are constantly exploring the methods and theories of data assimilation. Chou (2007) proposed that numerical weather prediction is not only an initial value problem, but also an inverse problem. In the same way, mathematicians closely link the data assimilation method with the regularization theory of the inverse problem of mathematical physics, especially Tikhonov regularization, by combining the method that deals with the inverse problem of mathematical physics with the variational data assimilation, and making the optimal estimation and determination of the initial conditions, boundary conditions and model parameters. In order to overcome the ill-posed difficulties, such as the estimation of spatiotemporal-dependent model parameters, Huang et al. (2004) introduced the idea of regularization in the inverse problem, added the stable functional analysis in the objective functional analysis, and overcame ill-posed difficulties and computational instability. At the same time, based on the optimal control theory of differential equations and nonlinear functional analysis, Han (2003) established a unified theoretical framework of variational data assimilation. This theoretical framework is simple and easy to use. It is suitable for continuous mode and discrete mode, suitable for adjoint estimation of initial conditions, boundary conditions and model parameters, and suitable for various forms of objective functional. He also proposed the idea and method of first-order information assimilation for observation data, which transforms variational data assimilation from approximation in L^2 space to approximation in H^1 space.

In the mathematical theory of data assimilation, it is often assumed that the observation data contains random noise, so it is necessary to systematically examine the asymptotics of the posteriori distribution generated by the analysis step, i.e. the information of higher order moments, with the Bayesian theory. Ding et al. (2018) introduced the concept of posteriori contraction function and used the method of deviation-variance decomposition to prove that the steady-state equation can make the second-order moment (variance) of 4D-Var analysis disperse to zero with the expansion of the time window by adjusting the initial background field under linear observation, ensuring the asymptotics of the data assimilation method in some special conditions.

In order to reduce the extremely complex programming and model requirements of 4D-Var in practice, a 4D-Var method based on singular value decomposition (SVD) was proposed by Qiu and Chou (2006) and Wang and Li (2009), which simplifies 4D-Var into a linear inversion problem. Hybrid methods, such as SVD-En4DVar (Qiu et al., 2007) and SVD-En3DVar (Xu et al., 2011a, 2011b), were also developed based on this method, which effectively improves short-term heavy rainfall predictions. In order to solve the problem of insufficient ocean observation data in the initialization of tropical cyclone in both variational and ensemble data assimilation methods, Wan and He (2012) proposed a multi-scale/block-by-block variational data assimilation techniques, which can reasonably and efficiently use the ocean meteorological observation data, and can better meet the flow-dependent background error covariance requirements of the assimilation of tropical cyclone data. This is an effective way to initialize circulation of tropical cyclone with high quality.

At present, the data assimilation system has been able to absorb conventional surface and upper-air observations, but there are still challenges in the assimilation of remote sensing observations, such as radar and satellite observations. Due to the relatively late establishment of the nation-wide weather radar network in China, the radar data assimilation started relatively late. In the early years, most of the research works focused on the inversion of the atmospheric wind field observed by Doppler radars using a simple adjoint function method (Qiu and Xu, 1992), the VAP method (Tao, 1992) and the IVAP method (Liang, 2007), or combining inversion data with physical initialization method to provide the initial conditions for mesoscale prediction (Qiu and Yu, 2000).

With the improvement of computing resources and data assimilation techniques, recent studies focus more on the use of different methods to directly assimilate Doppler radar observations, and have done a lot of research on how to improve the assimilation of radial winds. Gao et al. (2011) improved the analysis of variational radar radial velocity assimilation by considering the contribution of the raindrop terminal velocity to the total radial velocity. Luo Y et al. (2014) added the information of radial wind's spatial variation to the equation of radar radial velocity, making more use of the radar's high-resolution observations. Zhao et al. (2012) demonstrated the improvement on the track, intensity, and precipitation forecast of Typhoon "Meranti" (2010) with

3DVar assimilation of ground-based radar observation in mainland China and Taiwan, concluding that radial winds are more important than reflectivity, and assimilating multiple radars outperformed assimilating single radar; if one radar has a good coverage over the core region of the typhoon, it is possible to achieve the impact of assimilating multiple radars through more assimilation cycles with the one radar. Zhu et al. (2016) demonstrated the significant improvement on typhoon intensity and precipitation prediction by assimilating radial wind observations from the Guangzhou radar using the EnKF method for the first time in China. Similar to Zhao et al. (2012), Yue et al. (2017) used the EnKF method to further examine the influence of the coverage of radar radial wind observations to the typhoon core region on the data assimilation and prediction of typhoon track and precipitation. It was found that assimilating radar radial winds with a better coverage of typhoon core will generate a better analysis, while assimilating radar radial wind farther away from the center of typhoon may lead to increased errors. At the same time, it also suggested the importance of using multiple radars to examine the analysis of assimilating radar radial wind.

Doppler radar is the most important data source in storm-scale and mesoscale data assimilation. Xu et al. (2011a, 2011b) showed the importance of radar radial wind assimilation in severe convective weather with an SVD-En3DVar method. Lan et al. (2010a, 2010b) performed data assimilation experiments assimilating radar observations with EnKF at storm scale. The results showed that using multiple microphysics schemes has a significant positive impact on the analysis of velocity, potential temperature and specific humidity when considering the model error resulted from micophysics schemes, but it degrades the analysis of microphysical properties. All model fields show improvements when the microphysics scheme of the control experiment is used in the EnKF experiment and using multiple microphysics schemes that only consider ice processes leads to further improvements. With the gradual upgrading of China's weather radar network to dual-polarization Doppler radars, the observations used by storm-scale and mesoscale data assimilation research have also begun to develop from radial velocity and reflectivity to dual-polarization parameters (such as differential reflectivity, or ZDR; Zhang and Zhang, 2018).

In addition to radar data assimilation, satellite observation assimilation is another frontier of remote sensing observation data assimilation. Han and McNally (2010) introduced the regularization idea of inverse problems in mathematical physics to satellite data assimilation, made the direct assimilation of the ozone channels of satellite hyperspectral infrared sounders possible, solved the problem of the lack of ozone observations in winters, and successfully applied it to the operational prediction system of ECMWF in 2011. Han and Bormann (2016) developed the technology of constrained adaptive bias correction (CBC) of satellite observations, which greatly improved the assimilation of satellite data when systematic model bias occurred. This technology was introduced into ECMWF's 4DVar system operationally in 2018 and improved the assimilation of satellite observations in the stratosphere.

In order to make full use of the multiple payloads onboard the same satellite and make up for the lack of information from channels of a single instrument, China's meteorologists developed a comprehensive cloud and precipitation detection algorithm, and established the assimilation of microwave thermometer (MWTS), sounder (MWHS), imager (MWRI) and occultation observation (GNOS) onboard FY-3 satellite in the GRAPES operational system (Li and Liu, 2016; Wang et al., 2019). In 2016, FY-4A, the new generation of geostationary meteorological satellite in China, was successfully launched. The GIIRS onboard FY-4A is the first hyperspectral instrument in a geostationary satellite worldwide. The numerical prediction research team of CMA independently developed observation operators (Di et al., 2018), channel selection technology based on the background error covariance of observation area (Yin et al., 2019), key technologies of the online bias estimation and correction algorithm suitable for large array detectors (Yin et al., 2019, personal communication). The assimilation of radiance data in GRAPES global 4D-Var system was operational in December 2018.

6.4 Development of data assimilation system for the operational numerical prediction model

Since the establishment of the National Meteorological Center in 1978, lot of work has been done in the research and development of operational numerical prediction models and corresponding data assimilation systems (Yan et al., 2010). In the early 1980s, the data assimilation system for Model A and Model B originated from JMA, using the objective analysis scheme of successive correction (Zhang et al., 1985; Liao, 1990). Since the 1990s, the data assimilation system of global medium-range numerical prediction operation system T42L9, T63L19, T106L19, T213L31, and T639L60 models in China came from the optimal interpolation scheme of the ECMWF (Yan et al., 2010); the data assimilation system of T639L60 model was upgraded to 3D-Var scheme. The data assimilation part of LAFS and HLAFS (Section 6.2) uses the optimal interpolation scheme (Guo et al., 1995; Yan et al., 1997).

At the beginning of the 21st century, based on the experience in the development of data assimilation in the world, CMA began to develop the regional-to-global multi-scale data assimilation and numerical prediction system "GRAPES" (Chen and Shen, 2006). Early GRAPES system used 3D-Var method for data assimilation, and RTTOV was introduced as the observation operator to directly assimilate satellite radiance data (Xue, 2006). In the development and improvement of the data assimilation system of GRAPES in correspondence with the global model of GRAPES, several key technical problems have been solved, including online model bias correction, satellite radiance data bias correction, observation error adaptive estimation (Han and Xue, 2007), and FY-geostationary-satellite cloud wind retrieval altitude correction and assimilation (Han et al., 2006). The GRAPES global 3D-Var assimilation system was established in 2007.

After completing three rounds of one-year cycling assimilation and prediction tests, the GRAPES Global Prediction System became a quasi-operational system in March 2009. This was the first time that a global data assimilation and prediction system that was completely developed by China was running stably in real-time quasi-operationally. After that, several key technologies of the GRAPES 3D-Var data assimilation system have been improved and optimized, such as changing from analysis at isobaric surface to non-hydrostatic analysis at model surface for model variables (Ma et al., 2009), improving the structure and the estimation of background error covariance (Wang J C et al., 2014; Wang et al., 2015), developing constraint bias correction technology of satellite data (Han, 2014), improving the quality control scheme for background field inspection of satellite radiance data (Wang and Zhao, 2005), and diagnosing and exmining on each type of observations (Hao et al., 2013; Liu and Xue, 2014; Zhuang et al., 2014; Wang J C et al., 2016). In early 2015, the GRAPES system outperformed the operational T639 system for the first time in retrospective forecast experiments. GRAPES passed the operational tests at the end of 2015 and began running operationally in June 2016 (Shen et al., 2015; Wang J C et al., 2017).

After being operational, the data assimilation part of GRAPES began to evolve from 3D-Var method to more advanced 4D-Var method. The development of GRAPES 4D-Var data assimilation system adopts the incremental assimilation strategy of 4D-Var method that most operational weather prediction centers worldwide adopt; that is, the optimization process with the largest amount of computations is carried out at a lower resolution, but the integration of nonlinear prediction model and the calculation of nonlinear observation operators are carried out at the full resolution, which not only ensures the accuracy of the prediction trajectory and the innovation vector, but also saves the computational costs. However, unlike most of the operational centers, the tangent linear model of GRAPES 4D-Var system also adopts the non-hydrostatic prediction model (Liu Y Z et al., 2017), with which a relatively more complete tangent linear physical process is established (Liu Y Z et al., 2019) with a conjugate gradient minimization algorithm, which significantly reduces the number of inner iterations (Liu Y Z et al., 2018). In July 2018, GRAPES 4D-Var data assimilation system started operational running (Zhang L et al., 2019). Through the development and improvement of satellite radiance data assimilation, the operational GRAPES global assimilation system is able to assimilate observations covering the whole world within the 6-h time window (As shown in Figure 14, the data assimilated in this time window include: satellite microwave thermometer (NOAA15_AMSUA channel 9, NOAA18_AMSUA, NOAA19_AMSUA, METOP-A_AMSUA, METOP-B_AMSUA); NPP microwave sounder (ATMS, channel 10); FY3C microwave humidity sounder (MWHS-II, channel 6); METOP-B hyperspectral infrared interferometer (IASI, channel 6); atmospheric infrared sounder (AIRS, channel 6); interferometric atmospheric sounder of FY-4 satellite (GIIRS, channel 6); sounding data (TEMP); cloud wind retrieval data (SATOB); ship data (SHIPS); ocean winds data (SCATWIND); ground-based atmospheric precipitation data (GPSPW); and radio occultation refractivity (GNSSRO)), and improved the analysis of regions where conventional observations are scarce.

7. Interdisciplinary studies on weather and climate, atmospheric physics and environment

Climate warming can change global and regional temperature distribution, then readjust the large-scale circulation structure, global and regional water cycle, and further alter the spatial and temporal distribution and intensity of weather systems, convections and precipitation. Changes in atmospheric environment have an important impact on weather and climate change through the greenhouse effects and aerosol-radiation-cloud-precipitation interactions. The interdisciplinary study of weather and climate, atmospheric physics and environment has become a hot topic and frontier atmospheric science.

Before the 1980s, subject to the development of the discipline, when people made weather and climate forecast, the evolution of weather and climate systems was often regarded as the result of changes in meteorological elements themselves. From the late 1970s to the early 1980s, the international scientific community began to realize that the climate system is composed of the five layers and the interactions among the five layers. The four major scientific programs for the interaction of the five layers—the World Climate Research Programme, the International Geosphere Biosphere Programme, the International Programme of Biodiversity Science and the International Human Dimensions Programme on Global Environmental Change were developed in 1980, 1986, 1991 and 1996. Although Chinese researchers have also participated in the four major scientific programmes, there was still a large gap in the earlier inter-

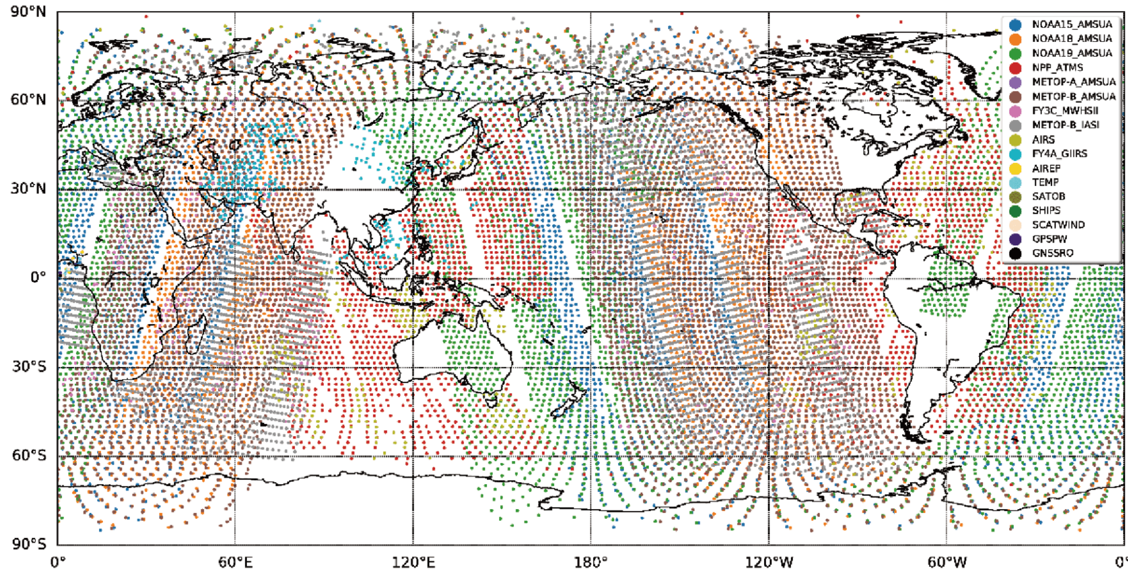

Figure 14 The spatial distribution of different observations assimilated by GRAPES 4D-Var system in the time window of 0300–0900 UTC on 5 July, 2019.

disciplinary research.

Since the beginning of the 21st century, the Department of Geology of the Chinese Academy of Sciences and Chinese National Committee for the International Union of Geodesy and Geophysics (CNC-IUGG) have carried out a great deal of work to promote interdisciplinary research. Starting from 2014, the Congress of Geodesy and Geophysics in China has been organized, which greatly promoted the development of CNC-IUGG and the participation of the scientists from the Chinese Committee of the Four Scientific Programs in combination with the "Future Earth" Program launched by the Global Alliance for Science and Technology for Sustainable Development, and provided a platform for Chinese geoscientists to exchange and cooperate with top researchers in international related fields. Since the end of the 20th century, China has made a series of innovative achievements in the interdisciplinary fields of weather and climate, atmospheric physics and environment.

7.1 Long-term evolution of weather with climate change

The occurrence and development of weather systems are all embeded in a certain climate background. Since the 20th century, the frequency and intensity of extreme precipitation in the middle and high latitudes of the Northern Hemisphere have increased significantly (Alexander et al., 2006) with global warming. Based on the observations and analysis of extreme precipitation events over the past 50 years in China, meteorologists in China have shown that the frequency and intensity of extreme precipitation events have increased under the background of global warming, but there are obvious regional differences. Extreme precipitation events tend to increase over the Yangtze River valley, the southeastern and northwestern China, but decrease over the north, northeast and southwest parts of China. The trend of extreme precipitation is similar to that of total precipitation (Zhai et al., 1999; You et al., 2011). In terms of seasonal changes, the extreme precipitation decreases in autumn in most of China, and increases apparently in winter, while in summer, it increases apparently in the south and west, but decreases in the northern parts of China (Wang et al., 2010). Studies show that the extreme hourly precipitation over Shanghai and the Pearl River Delta has a remarkable growth trend different from the surrounding areas in the past 30 years of rapid urbanization (Liang and Ding, 2017; Wu et al., 2019).

On the climatic distribution and long-term trends of hail frequency and intensity, Chinese scholars, based on the systematic observation data sets of hail frequency and intensity for several decades, have found that the hails in China mainly appear on the plateau and the northern plains. The highest frequency occurs in the middle of Qinghai-Tibetan Plateau, mainly from early spring to early autumn and mostly from 3 pm to 8 pm (Li X F et al., 2018). After 1980, hails in various regions of China have decreased apparently (Ni et al., 2017). In addition, the possible physical mechanisms affecting the hail frequency and intensity changes (Li M X et al., 2016; Li X F et al., 2017) were discussed from the aspects of large-scale circulation and atmospheric aerosols. Zou et al. (2018) found that the decreasing number of thunderstorms and hail days in a warming climate over the Tibetan Plateau is mainly because of a drier midtroposphere, an increased elevation of the melting level and a weaker wind shear.

7.2 Response of Extreme Precipitation to Future Climate Warming

Greenhouse gas emissions from human activities are the main drivers of current climate warming. In order to alleviate climate change caused by human activities, the international community reached the *Paris Agreement* in 2016, striving to maintain an increase in the global average surface temperature by the end of the century within 2°C or even 1.5°C relative to the pre-industrial era. Wang Z L et al. (2017), using global ensemble simulations, pointed out that the average surface temperature increase from 1.5°C to 2°C can lead to a significant increase in extreme precipitation in most parts of the world. The increase in extreme precipitation is highly dependent on greenhouse gas emission scenarios, greenhouse gas/aerosol forcing ratio and greenhouse gas concentration. They also found that different heavily polluted areas have different response characteristics. The findings also suggest that in order to assess the impacts of global warming, not only the total amount of radiative forcing and level of global warming, but also the chemical components of the emission scenarios need to be considered. Lin et al. (2018) further used coupled earth system model simulations to examine the possible responses of China's seasonal climate extremes in the late 21st century to the 2016 *Paris Agreement*'s warming standards. The results showed that if the global average temperature increases by 1.5°C and 2°C at the end of this century relative to those before the industrial revolution, the extreme floods similar to the flood over the southeast China in 2010 will increase by twice and 3 times respectively compared to the period of 1976–2005 (Figure 15). The results indicate that it is important to limit the global warming to 1.5°C by reducing greenhouse gas emissions, so as to reduce the high incidence of future extreme weather events in China. Many climate model studies have shown that the climate warming can aggravate extreme precipitation events in China. For example, Zhang et al. (2006), using the PRECIS (Providing Regional Climate for Impact Studies), showed that extreme precipitation events in most regions of China have an overall upward trend, especially in the southeast coastal areas, the Yangtze River valley and the northern China, where more extreme precipitation events will occur in the future; Similar results were obtained for RCP4.5 (Representative Concentration Pathway) and RCP 8.5 scenarios by Chen et al. (2012) using data from coupled atmospheric circulation models in the IPCC AR4 (the 4th Assembly Report of the United Nations International Panel on Climate Change), and Chen (2013) using the Coupled Model CMIP5 (the Coupled Model Intercommunication Project, phase 5).

One of the main reasons for the increase in extreme precipitation caused by climate warming is the increase of atmospheric water vapor. According to the Clausius-Clapeyron equation, for every 1 K increase in surface temperature, the atmospheric water vapor increases by about 7%. Although the growth rate of extreme precipitation is closely related to the increase of water vapor, it is not simply equivalent to the growth rate of water vapor. The latent heat release caused by precipitation will further affect the intensity of extreme precipitation by changing the thunderstorm circulation. Such factors related to thunderstorm dynamics may strengthen or weaken the increase of precipitation driven by water vapor. Nie et al. (2018) used an idealized model to investigate the coupling effects of water vapor driving and latent heat-related storm dynamics by simulating a real-world extreme precipitation process in the background of today's climate and a warmer climate, quantitatively revealing that global warming led to the increase of water vapor in the atmosphere and the increase of latent heat feedback in extreme rainfall, which furthermore results in the enhancement of large-scale uplift and ultimately leads to a doubling of the water vapor driving response in the climate warming background (Figure 16).

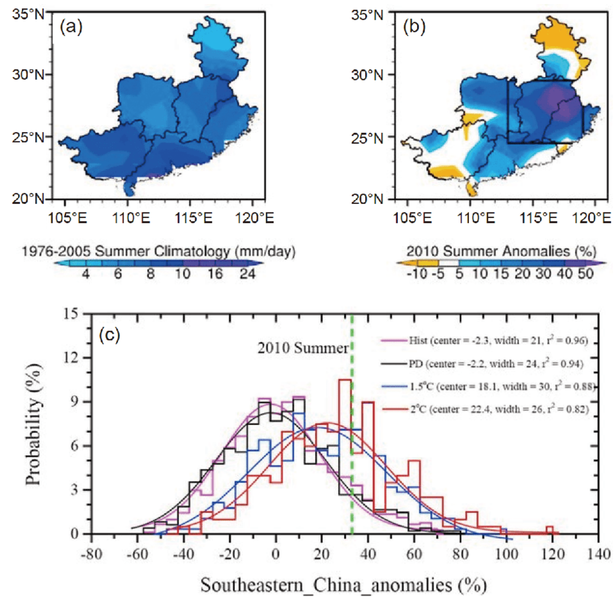

Figure 15 (a) The 1976−2005 summer climatological precipitation (unit: mm d^{-1}) and (b) anomaly for the 2010 summer flood in observation (units: percent) and (c) histogram and probability density functions of simulated anomalies of summer precipitation averaged over the southeastern China during the historical (Hist), present-day (PD), 1.5°C, and 2°C periods (unit: percent). All simulated anomalies are relative to the 1976−2005 summer climate. The vertical dashed line in (c) is the observed 2010 summer flood anomaly. Note that the width of fitted normal distribution curve increases in future warming scenarios, suggesting larger interannual variability in the future. Adapted from Lin et al. (2018).

7.3 Response of long-term variation characteristics of precipitation and thunderstorm to air pollution

The relationship between weather systems and air pollution

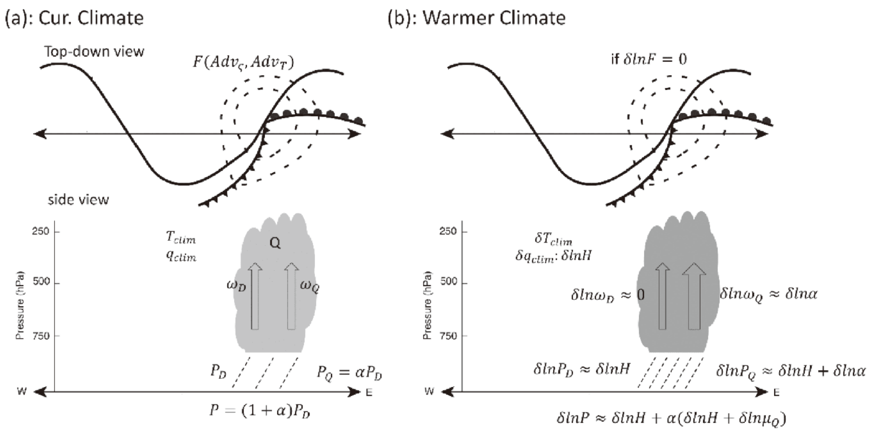

Figure 16 A schematic of the scaling of precipitation extremes with temperature in a Column Quasigeostrophic (CQG) system. (a) is under the current climate. The upper panel shows an upper level synoptic wave, lower level fronts, and a low-pressure center. The lower panel shows the side view of the convection and precipitation region over the low-pressure center. (b) is as (a) but in a warmer climate: the fractional changes of vertical motion and precipitation if the large-scale adiabatic QG forcing F (and moisture advection) is unchanged. The darker color of the cloud cartoon indicates that the convective system is stronger in a warmer climate. Adapted from Nie et al. (2018).

is complex. Atmospheric aerosols play an important role in the weather system through radiation, cloud precipitation physics and water cycle processes. Atmospheric aerosols are the most uncertain source for predicting future climate change due to their complex chemical composition, optical properties, and their role in cloud formation.

Aerosols may significantly alter the efficiency and intensity of precipitation. Through investigating the effects of different aerosol characteristics on rainfall and convection in the whole of China (Jiang et al., 2016), the Guanzhong Plain (Yang et al., 2013), the North China Plain (Guo X L et al., 2014), the Yangtze River Delta (Yang and Li, 2014) and the Pearl River Delta (Guo et al., 2016), Chinese researchers revealed the contribution of anthropogenic aerosols to the diurnal (Guo et al., 2016; Lee et al., 2016), weekly (Yang et al., 2016) and long-term (Yang et al., 2013) variations of rainfall and thunderstorm. Zhao et al. (2006) put forward a feedback mechanism for the decrease trend of precipitation caused by the increase of aerosols in North China, namely, the emission of aerosols in North China causes the increase of atmospheric stability, inhibiting the upward movement and precipitation, and thus leading to the further increase of pollution. They found that the proportion of unstable days in North China decreases from about 34% in the late 1980s to about 17% in the 2000s. Yang et al. (2013) found that air pollution in the Central Shannxi Plain reduces the frequency of weak mountain precipitation and thunderstorms. Guo J P et al. (2014) further pointed out that the indirect effects of aerosols reduce the frequency and magnitude of weak precipitation in the mountainous areas of East China, but increase the weak precipitation in the plains. Fu and Li (2014) found that the increase of aerosols makes the heavy precipitation in South China stronger and the weak precipitation weaker. Yang and Li (2014) further found that from 1990 to 2012, with the reduction of visibility, there has been an apparent increase in thunderstorms and lightning activities at plain stations in the southeastern China, while there has been no similar trend at alpine stations. This significant difference of thunderstorms and lightning activities between plain and alpine stations may be due to an apparent difference in aerosol concentrations. Guo et al. (2018) compared the vertical structure of radar reflectivity under pollution and non-pollution conditions in the Pearl River Delta region, and found that the convective precipitation region under pollution conditions has stronger and deeper echoes, while the echoes of stratus clouds and shallow convective precipitation are shallower and weaker. These studies partly explained the observed fact that the frequency and magnitude of weak precipitations decrease in East China, while the frequency and magnitude of heavy precipitations increase in Southeast China.

Anthropogenic aerosols have an important effect on the movement of monsoon rain belt. Chinese researchers have systematically studied the interaction between aerosol and monsoon systems in China (Wu et al., 2016) and the whole Asian region (Li Z et al., 2016). In the past decades in China, the aerosol may have contributed to the change of precipitation distribution by changing the land-sea thermal differences and weakening the East Asian summer monsoon circulation. Yang et al. (2015) found that global warming makes the East Asian monsoon rain belt move 300 km northwest in China from the last glacial period to the mid-Holocene. Thus, they predicted that China's summer rain belt would move northward with global warming over the past few decades. However, Yu et al. (2016) believed that Yang et al. (2015) ignored the effects of anthropogenic aerosols, and suggested that only apparent reduction of anthropogenic aerosols could result in the northward shift of the rain belt. In addition, the response of monsoons to different types of aerosols is different. Liu Y et al. (2009) investigated the effects of black carbon and sulfate aerosols on the East Asian monsoon in China. The difference of direct effects between the two types of aerosols is the absorption of black carbon and scattering of sulfate. Their results showed that the forcing effect of black carbon aerosol is weak, and the effect of black carbon and sulfate aerosol is more similar to the scattering characteristics of sulfate as the effect of mixed aerosol is not simply linear summation. Song and Zhou (2014) examined the effects of natural forcing and human activity forcing on the East Asian summer monsoon. They found that, relative to natural forcing, aerosol forcing reduced sea-land temperature differences by lowering land temperature and caused high sea level pressure in North China, which played a major role in weakening the circulation of lower layer of the East Asian summer monsoon. In the upper layer, both natural and anthropogenic forcings can affect the southward movement of the East Asian subtropical jet by changing the meridional temperature gradient. Chen G X et al. (2018) pointed out that the increase of anthropogenic aerosols would also change the seasonal variability of summer precipitation in East Asia. The change of spatial distribution of monthly precipitation is related to the west extension and the strengthening of the West Pacific subtropical high caused by the increase of aerosol. The west extension and strengthening of the West Pacific subtropical high strengthens the ground divergence in the southwest and the convergence in the north and west of the subtropical high, which results in the decrease of precipitation in the southeast and the increase of precipitation in the north and west of the subtropical high. Lin et al. (2016) used the Earth system ensemble simulation to investigate the rate of the increase in extreme precipitation caused by anthropogenic emissions of greenhouse gases and aerosols in the 21st century. Their results showed that the increase rate of extreme precipitation caused by anthropogenic aerosol emission is much higher than that caused by anthropogenic greenhouse gas emission.

Using the global climate model to evaluate the response of extreme precipitation to future aerosol changes requires that the numerical model be accurate enough to describe the aerosol-cloud interaction. The results of comparison experiments by Lin et al. (2018) using CMIP5 multi-model sets showed that only partial models can simultaneously capture the characteristics of the decrease in the extreme precipitation in India and North China and the increase in the extreme precipitation in South China from 1979 to 2015. These models considered the cloud-aerosol interaction comprehensively, including both the direct effects of aerosols, and indirect effects (including the effects of aerosols on cloud optical thickness and cloud lifetime), while models considering only direct effects of aerosols perform less effective. The results suggested that the use of models that do not take aerosol-cloud interactions into account may underestimate the increase of regional extreme precipitation caused by aerosol reduction. In fact, the systematic error in estimating indirect aerosol effects in the global climate model is equal to 50% of estimates of indirect aerosol effects, which was discovered in 2003 but has not been solved so far. Fan et al. (2013) summarized the theory that aerosols affect the development of deep convective systems, namely, the influence of aerosols on the development of deep convective systems comes not only from the influence of aerosols as cloud condensation nuclii, but also from the influence of indirect effects on the latent heat release of atmospheric water vapor. Yan et al. (2014) pointed out that the second influence mechanism can greatly extend the range of the anvil of high cirrus cloud of deep convection, which can have an impact of 0.5 W m^{-2} on the energy balance of the earth. The impact hasn't been considered in the existing global climate model. The magnitude of the impact is comparable to the systematic error in evaluating the indirect effects of global aerosols in current global climate model, and the local impact may be greater (Peng et al., 2016).

7.4 Response of short-time variation of precipitation and thunderstorm to air pollution

Compared with the long-term precipitation trend, the influence of aerosol on a specific weather process is more complex. Ding et al. (2013) investigated a heavy haze process in Nanjing, and found that the combined pollution of the biomass burning and fossil fuel burning associated with apparent secondary aerosols may reduce solar radiation, sensible heat and temperature by more than 70%, more than 85%, and almost 10 K, respectively, leading to a reduction in precipitation during both day and night. For the first time, this study provided direct observational evidence of how combined air pollution changes the weather, and reveals quantitatively how air pollution affects the weather through pollution-boundary layer dynamics-aerosol-radiation-cloud feedback (Figure 17). A further research on the same process by Huang et al. (2016) found that the cooling of the near-surface layer in the biomass-burning area caused thunderstorms near the city to be suppressed during the day. Meanwhile, the heating of the aerosol layer enhanced the convective activity over the biomass-burning area, leading to an increase of thunderstorms at night in the downstream area. Guo X L et al. (2014) and Zhong S et al. (2015) found similar phenomena near Tianjin and Beijing, respectively, where precipitation increases in the downstream by 17%. The decrease of precipitation in the upstream may be due to the weakening of evaporative cooling and convection caused by smaller cloud droplets, while the increase of precipitation in the downstream may be due to more cloud droplets freezing. These studies underscored the importance of interdisciplinary research on the impacts of combined pollution from biomass and fossil fuel burning on environment,

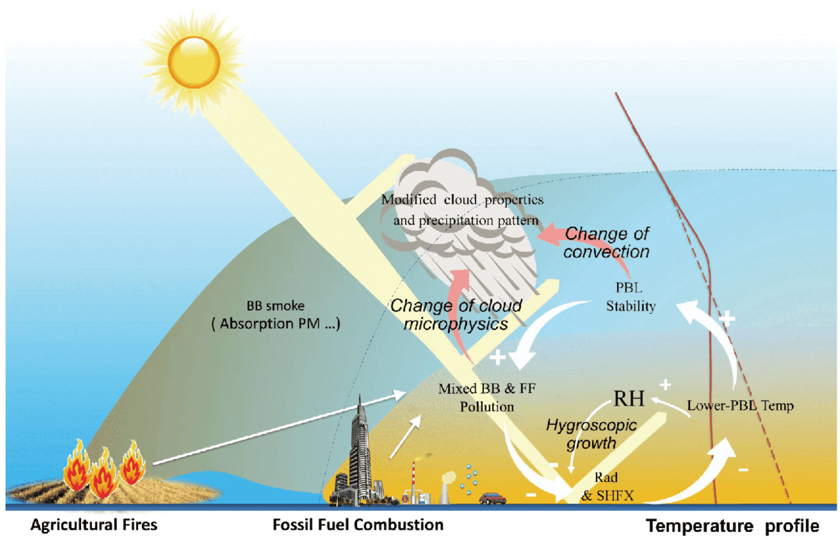

Figure 17 A schematic of interactions of air pollution-PBL dynamics and aerosol-radiation-cloud interaction under a condition of mixed agriculture burning plumes and fossil fuel combustion pollutants. Note: yellow bands show the radiative transfer of solar radiation. The brown solid and dashed lines denote the air temperature profiles for episode and non-episode cases, respectively. The black thin dashed line represents the top of fossil fuel combustion plume under a non-episode condition. The plus (+) and minus (−) signs denote enhancement and reduction of a target process, respectively. Adapted from Ding et al. (2013).

weather and climate. Guo et al. (2016) found that heavy rainfall and lightning activity in the Pearl River Delta region under polluted conditions would be delayed.

In China, researchers have also studied how direct radiation effect of aerosol affects convective systems. Fu et al. (2017) studied the influence of the radiation effect of black carbon aerosols on a squall line in North China through sensitivity tests, and found that black carbon aerosols reduced water vapor in the initial stage of the squall line by reducing evaporation on the ground, but increased water vapor in the later stage by increasing large-scale convergence through heating effect. In general, the radiation effect of black carbon aerosols had no significant effect on the intensity of squall line cold pool and low-level wind shear, so there was no significant change in the development and precipitation rate of the squall line. Liu Z et al. (2018) studied the influence of aerosols on deep convection in the Pearl River Delta region and found that the direct radiation effect of aerosols on the upper and middle troposphere could not be ignored. Due to the decrease of water vapor evaporation near the surface and the weakening of the ascending motion, the relative humidity in the middle and upper troposphere would decrease leading to the reduction of formation of clouds and deep convection, which could offset the direct radiation effect of aerosols by 20%.

Besides the influence of climate and environment change on weather, the influence of weather on aerosol distribution has been an important scientific topic in atmospheric environment. The distribution of aerosols is influenced by meteorological conditions such as wind, stability and water vapor. Many results showed that the vertical distribution of aerosols is influenced by local circulations such as mountain-valley breeze and land-sea breeze (Chen Y et al., 2009; Liu S H et al., 2009; Miao et al., 2015). The mountain-valley breeze can change the boundary layer structure of mountain and plain through dynamic advection and thermal change, and the rise of the valley wind and the accompanying sea-breeze can bring the aerosol to the top of the boundary layer to form a raised pollution layer.

8. Summary

With the continuous improvement in observation and computer capability and the deepening of physical understanding, Chinese meteorologists have made great innovative achievements in synoptic meteorology in the past 70 years. A complete and advanced ground-, space- and sky-based meteorological observation network has been established, and synoptic meteorology has developed from qualitative analysis of synoptic-scale environment to quantitative examination of meso to microscale weather systems and their structures (Figure 18), which have contributed to the establishment of national operational forecasting systems and improvement of forecast level. Although Chinese scientists have made a series of innovative achievements in synoptic meteoroology, the current level of research and operational forecast in China still have much room to improve compared with the international leading level in many aspects. This section summarizes briefly the main research achievements in China in the field of synoptic meteorology and its perspectives.

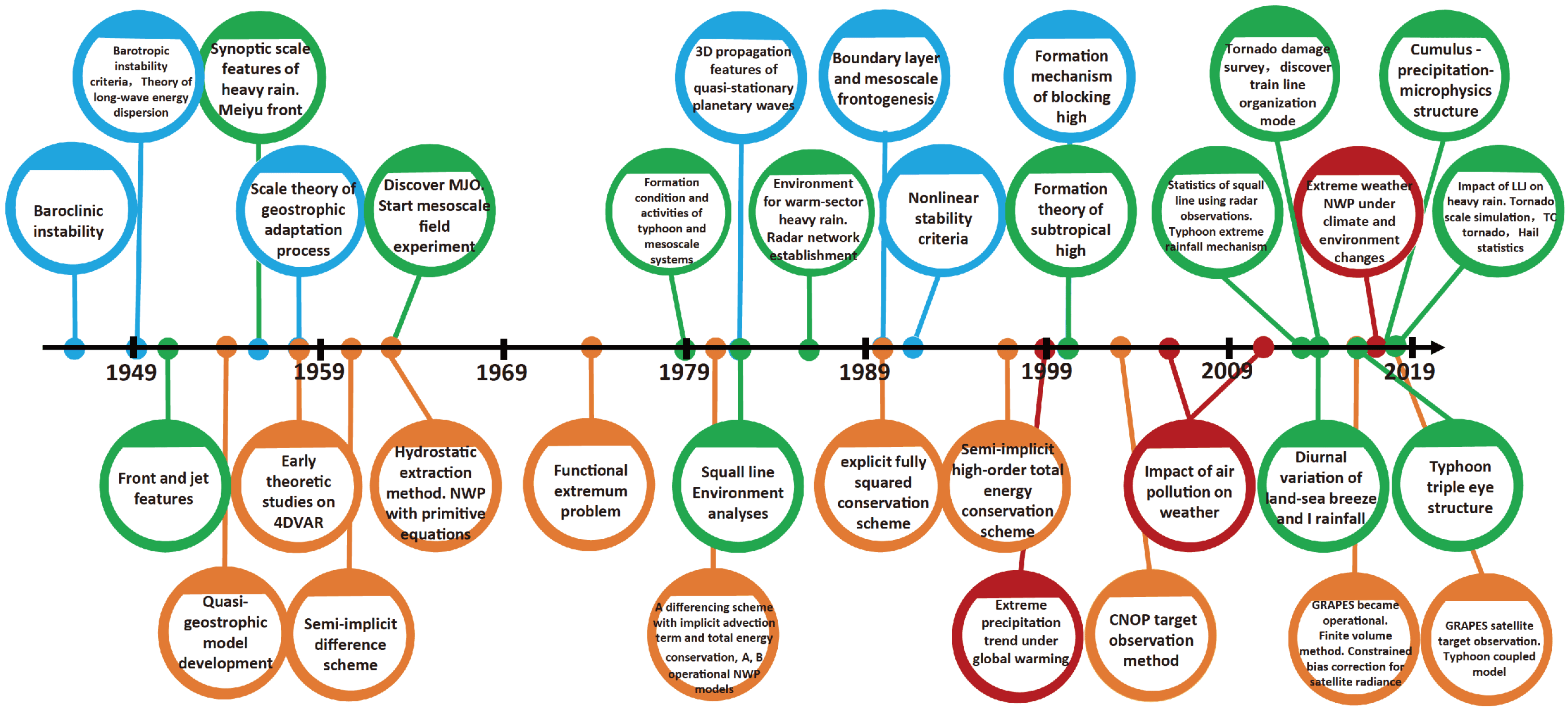

Figure 18 Milestones in weather research during the past 70 years in China: atmospheric dynamics in blue, synoptic analysis in green, numerical weather prediction and data assimilation in orange, and interdisciplinary work between weather and climate/environment in maroon.

On atmospheric dynamics, the scale theory of geostrophic adaptation process and the concept of planetary wave instability were put forward. The barotropic instability criterion of atmospheric long wave, the instability criterion of unsteady flow, terrain disturbed flow and ageostrophic flow, as well as the nonlinear stability criterion of quasi-geostrophic flow were obtained. The energy dispersion theory of long wave was put forward. The three-dimensional propagation characteristics of quasi-stationary planetary wave in winter and summer in the Northern Hemisphere were studied theoretically, observationally and numerically. The mechanism of the formation and decay of the blocking was explained. It was proved that the blocking is a nonlinear initial value problem. In recent 30 years, with the further warming in the Arctic, and the decrease of the longitudinal gradient of the mid-latitude potential vorticity, the complexity in the nonlinear behavior of the large-scale circulation in the middle-latitude have been aggravated. In the future, it is necessary to further study the nonlinear atmospheric dynamics, which will be quite important in understanding the mechanism of mid-latitude disastrous weather.

On synoptic-scale weather characteristics, Ekman momentum approximation theory was proposed for the first time and applied to mesoscale frontal dynamics research. A set of complete equations and conservation laws for discussing the interaction between boundary layer and frontogenesis were established. The effects of topography and boundary layer on frontal structure and circulation dynamics were revealed. The structure of the East Asian multi-layer front and the double jets were revealed to be different from those in North America. The concept of Meiyu front was proposed, which is characterized by the high equivalent potential temperature gradient. The complex structure of Meiyu front and its relationship with the upper-and low-level jets were obtained. The spatial and temporal distributions of the low-level jet and its relationship with weather systems as well as the formation and evolution of heavy rainfall were discussed. The theoretical model of jet was established, and the activity of low-level jets in eastern China was interpreted. Besides, the physical mechanism of typhoon extreme heavy rainall caused by the interaction between different scale weather systems was examined. MJO was discovered for the first time in the world. The mechanism of tropical convective activity affecting MJO and tropical fluctuation, and the interaction of MJO and tropical fluctuation with typhoon and mid-latitude weather processes have been investigated systematically. On the basis of theoretical research and field observation, the evolution law, the key influencing factors and influencing mechanism of typhoon formation, track, structure and intensity in the northwestern Pacific were revealed. The typhoon numerical prediction/assimilation system was developed independently, which have greatly improved the objective forecast accuracy of typhoon in China.

On severe convective weather, with the improvement in radar, satellite and ground intensive observation methods, by means of mesoscale field experiments, dynamic analysis and mesoscale numerical simulation, our understanding of the formation and evolution mechanisms of severe convective weather gradually expands from meso-α scale to meso-β and meso-γ scale structures and their mechanisms. Systematical studies were performed on the statistical characteristics of squall lines in China, especially those preceding landfall tropical cyclones and their differences from mid-latitude squall lines. The mechanism of diurnal variation of convections in the northern and southern China were revealed. The formation mechanism of book-end vortices of bow echo was improved. A new train-line organization mode of squall lines was found. The evolution of raindrop spectrum during the development of squall lines was revealed. Some convection initiation mechanisms were proposed such as interaction between gravity wave and surface convergence line, interaction between gust front and dry line, and MAUL. A series of damage surveys covering the full path of tornadoes and detailed damage features were carried out based on both surface- and air-based surveys. For the first time, the corresponding relationship between the ground damage characteristics of a typhoon tornado and radar signatures was presented, and the formation and evolution mechanisms of tornadic supercells in typhoon were examined quantitatively based on wind retrievals from radar observation.

Compared with world advanced level, there are still gaps in the observation of weather systems in China, especially in the observation quality of high spatial-temporal resolution observation instruments such as radar and satellite. The processing and application of observation need to be improved. There are also significant gaps in the study of dynamics and forecast methods of meso and microscale systems. In order to improve the research and forecast capability on disastrous weather, we need to enhance basic theoretical research, especially in leading new research fields. We need to further study the nonlinear problems of meso and microscale dynamics, multi-scale interaction, structure and evolution mechanism of meso and microscale disastrous weather systems. In addition, China has not systematically carried out field experiments in the tropics, and the observation of typhoons is limited only to before and after landfall. At the same time, the processing and integrating of various observations, as well as the promptness and authority of observations need to be further improved.

On numerical weather prediction and data assimilation, many groundbreaking researches on numerical methods and assimilation theory were performed. For example, the semi-implicit (or semi-explicit) difference scheme, the hydrostatic extraction (or standard stratification extraction) method, the difference scheme for the implicit advection term of total energy conservation, the explicit fully squared conservation scheme, time discrete fidelity scheme for the general quadratic and cubic physical conservation laws, and the semi-implicit high-order total energy conservation scheme for the global spectrum-vertical finite difference model of baroclinic primitive equation. For the first time, real-world weather forecast was made with primitive equations in China. The functional extremum problem and the CNOP method were proposed. Based on the optimal control theory of differential equations and nonlinear functional analysis, a unified theoretical framework for variational data assimilation was established, a 4D-Var method based on singular value decomposition (SVD) was proposed, and the original technology of "correction scheme for data bias of constrained satellite CBC" was developed. By introducing, learning and absorbing advanced systems and technologies from abroad, and according to the special climate and weather featues in China, a number of global- and regional-scale numerical weather prediction and data assimilation systems have been developed independently, especially GRAPES.

The resolutions of global models across all major operational centers worldwide are getting higher and higher, approaching the fine resolution of regional models. The parameterization of physical processes in the model and the coupling between atmospheric, ocean, land surface and sea ice models are becoming more and more complicated. Ensemble forecasting techniques have also received more attentions and developments. On data assimilation, ECMWF and NCEP have used the hybrid method combining variational and ensemble data assimilation techniques in their operational global data assimilation systems. The analysis error of the data assimilation system can be reduced by the combination of the isotropical, prescribed background error covariance matrix from the variational method and the flow-dependent background error covariance matrix of the ensemble method. In addition to the assimilation studies on the all-sky microwave radiance observation from satellite, with the launch and operation of new generation of geostationary meteorological satellites such as Himawari-8/9 of Japan, GOES-16/17 of U.S., and FY-4A of China, the assimilation of all-sky infrared radiance observation from geostationary satellites has become a hot topic in scientific research and operational tests in recent years. In order to reduce the dependency of our forecast results on foreign forecast products, we need to continue to improve our own numerical forecasting model, the refined forecasting techniques, the application of ensemble forecast products, and coupling data assimilation.

In the interdisciplinary field of weather, climate and environment, studies have revealed the increasing trend of the frequency and intensity of extreme precipitation in China with global warming. The spatial and temporal distribution and trend of hails in China, as well as the possible physical mechanism of hail frequency and intensity variation have been revealed. The response characteristics and mechanism of extreme precipitation to future climate warming and aerosol concentration changes were investigated. It was proposed that with global warming, the frequency of extreme precipitation in most parts of the world would increase apparently and highly depend on greenhouse gas emission scenarios, greenhouse gas/aerosol forcing ratio and greenhouse gas concentration. The latent heat release from precipitation may further affect the intensity of extreme precipitation by changing the thunderstorm circulation. It was found that aerosol-radiation-cloud interaction can be used to interpret the decrease of frequency and magnitude of weak precipitation in East China, and the increase of the frequency and magnitude of heavy rainfall in Southeast China. Anthropogenic aerosols were found to play an important role in the movement of monsoon rain belt, especially the changes in the precipitation distribution in summer (such as drought in the northern China and flood in the southern China). The importance of the direct and indirect radiation effects of aerosals in the simulation accuracy of extreme precipitation by numerical models was revealed. For the first time, direct observational evidence of how combined air pollution changes the weather was obtained, and the mechanism that biomass burning makes urban thunderstorms being inhibited during the day but thunderstorms in downstream regions being enhanced at nighttime. Although a lot of research has been carried out in the interdisciplinary field of weather, climate and environment in China, there are still many scientific problems unsolved. It is necessary to carry out field experiments organized by multi-disciplines, obtain multi-dimensional and high-resolution observation data of weather, physics of clouds and precipitation, and aerosols, establish earth observation system, and develop multi-source data assimilation technology and global multi-scale general forecasting system. We also need to disclose, from basic research, the effects of atmospheric circulation on pollution in different seasons in different regions of China, and the feedback of pollution on atmospheric circulation, weather and climate, so as to construct the theoretical framework of the interaction mechanism between atmospheric circulation and atmospheric pollution. In addition, we need to establish an atmospheric chemical coupling model based on China's independent intellectual property rights to provide scientific support for further understanding of the evolution mechanism of weather systems in the context of climate and environment changes, as well as decision-making of national disaster prevention and mitigation and air pollution control, international climate negotiations and implementation of relevant economic development strategies.

To sum up, on the basis of the important academic achievements made over the past 70 years, we need to grasp the development trend of the international weather field and enhance the research on synoptic meteorology, which is a weak discipline of atmopsheric sciences, especially in the observation and numerical prediction technology of high-impact weather, such as meso and microscale severe convective weather and typhoons. We need to improve model resolution and develop more accurate physical parameterization schemes, to assimilate non-traditional observation data such as infrared and microwave all-sky satellite radiation using the most advanced ensemble variational coupling data assimilation technology in the world, to develop a multi-scale seamless ensemble forecast system with cloud-resolving resolution, and to further improve the capability of monitoring, forecasting and warning of high-impact disastrous weather to help improve our capability in disaster prevention and mitigation, as well as in dealing with climate and environmental changes.

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