Advances in Urban Meteorological Research in China

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(Received September 17, 2019; in final form February 17, 2020)

ABSTRACT

Over the past decades, a large number of studies have been carried out in the field of urban meteorology in China. This paper summarizes the main progress in urban meteorology research from four aspects: urban meteorological observation network and field campaign, multi-scale model of urban meteorology, interaction between urban meteorology and atmospheric environment, and the impacts of urbanization on weather and climate. Major advances are as follows. China’s major cities have established or are improving comprehensive urban meteorological observation networks characterized by multi-platform, multi-variable, multi-scale, multi-link, and multi-function. Beijing, Nanjing, Shanghai, and other cities carried out urban meteorological field campaigns, which were included in the WMO research demonstration project. Wind tunnel experiments and scale-model outdoor experiments were successfully conducted. Multi-scale urban meteorological and air quality prediction numerical model systems have been developed and put into operational use. The urban heat island effect; urban impacts on precipitation, regional climate, and air quality; urban planning; and interaction between urban meteorology and atmospheric environment are extensively investigated. Finally, efforts to improve observational technology, data assimilation, and urban system modeling, to explore the impacts of urbanization on environment and human health, and to provide integrated urban hydro-meteorological climate and environmental services are planned ahead.

Key words: urbanization, urban meteorology, observation network, field campaign, multi-scale numerical modeling, atmospheric environment

Citation: Miao, S. G., W. M. Jiang, P. Liang, et al., 2020: Advances in urban meteorological research in China. J. Meteor. Res., 34(2), 218–242, doi: 10.1007/s13351-020-9858-3.

1. Introduction

As a relatively new subject of atmospheric science, urban meteorology and associated research were initiated in China in the 1970s–1980s. Urban meteorology stems from the underlying surface changes caused by urban constructions, which subsequently alter meteorological environment over urban areas. Rapid urbanization further intensifies such changes, leading to unique characteristics of weather, climate, and atmospheric conditions in the urban areas.

Remarkable progress has been made in the research and application of urban meteorology in China as a result of a wide range of observational experiments and basic theoretical studies. Urban climate effects such as the urban heat/dry/wet/rain/low-visibility island, are first described and summarized in Zhou and Zhang (1985) in the 1980s. Investigations on urban heat island were conducted in big cities such as Beijing, Tianjin, Chongqing, Nanjing, Suzhou, Lanzhou, Hangzhou, etc. By the end of the 1990s, accelerated construction of urban meteorological observation networks and implementation of field
observation experiments in cities and urban agglomerations provided enriched data for urban meteorological research and applications. The Beijing City Atmospheric Pollution Observation Field Experiment (BECAPLEX, 2001–2003) (Xu et al., 2004, 2010), the first comprehensive experiment on meteorological observations in mega cities in China, and several other experiments such as the Beijing Urban Boundary Layer Experiment (BUBLEX, 2004–2005) (Li and Shu, 2008; Li and Dou, 2014) and the Study of Urban-Impacts on Rainfall and Fog/Haze (SURF, 2015–2017) (Liang et al., 2018), are examples of the field observation experiments conducted during this period of time.

In the 2000s, studies of the structure of urban boundary layer were conducted by use of both numerical simulations and observational data analysis. Three-dimensional structural characteristics and parameter distributions of the urban boundary layer were first introduced into multi-scale simulations of various urban processes. Moreover, technologies to describe urban heat island, anthropogenic heat and water vapor, and morphological characteristics of urban buildings were developed to better represent urban land surface processes in the urban canopy layer (including both buildings and vegetation). An urban surface and boundary layer parameterization scheme has been successfully developed (He et al., 2009; Wang and Jiang, 2009). In addition, new turbulent closure technologies such as computational fluid dynamics (CFD) and large eddy simulation (LES) have been implemented and applied to air quality simulations (Liu et al., 2008; Jiang et al., 2009). These studies are associated with a key project funded by the National Natural Science Foundation of China in 2004, which was titled “Research on the Three-Dimensional Structure of the Urban Boundary Layer.” Results of this project have attracted considerable attention and are well recognized internationally (Souch and Grimmond, 2006).

Furthermore, observational analysis and numerical weather forecast studies were conducted with specific emphasis on the influences of complex underlying surface of urban agglomerations on weather systems, under the support of “Research on Key Technologies in High-Impact Weather Forecast for the Beijing–Tianjin–Hebei Urban Agglomerations,” a project sponsored by the Ministry of Science and Technology of China in 2008 (Li and Dou, 2014; Miao and Chen, 2014). In addition, Liu S. H. et al. (2009, 2013) conducted systematic investigations on coupled modeling of the interaction between complex underlying urban surface and atmospheric boundary layer in the Beijing–Tianjin–Hebei region.

In the 2010s, the direct climate effects of urban agglomerations, the wide-spread air pollution and highly-polluted areas in China associated with urban agglomerations, and the influence of extensive urbanization on the East Asian monsoon were investigated (Ding et al., 2013; Wu and Yang, 2013; Wan and Zhong, 2014). New technologies for ground-, tower-, and boat-based measurements and aircraft observations of key meteorological elements and major pollutants in the atmospheric boundary layer, as well as platforms for multi-data fusion and normalization have emerged. Part of the studies came from the project “Vertical Detection Technology for Air Pollution in the Terrestrial Boundary Layer” funded by China National Key R&D Program in 2017. Urban meteorology studies have targeted city areas of Northeast China (Li L. G. et al., 2012), Northwest China (Liu et al., 2003; Wang T. J. et al., 2013), and Southwest China (e.g., Sichuan and Chongqing; Wang Y. W. et al., 2013).

Accompanying the urban meteorological studies, prediction of atmospheric environment has also been developed. A regional nested air quality prediction model system (NAQPMS) was established by Wang et al. (2006) and has been extensively applied to multi-scale operational air quality simulations. The China Meteorological Administration Unified Atmospheric Chemistry Environmental (CUACE) Forecasting System (Gong and Zhang, 2008) was established, improved with a correction model (Lyu et al., 2018), and has performed well in real-time air quality forecasting at the national level. The Nanjing University City Air Quality Numerical Prediction System (NJU-CAQPS) has been developed for research purposes. It employs an urban land surface scheme and can run on multiple scales and with high resolution. Comparative analysis of the NJU-CAQPS simulations with the atmospheric environment wind tunnel experiments at NJU indicates that the model performance is reasonable (Liu H. N. et al., 2009).

In terms of urban meteorological applications, a comprehensive meteorological environment assessment system for urban planning and construction was jointly constructed by the Beijing Meteorological Service, NJU, and others (Wang G. T. et al., 2005). As a crucial information system tool for sustainable development and planning, the Urban Climate Map (UCMap) has been widely applied globally in recent years; for example, in Beijing, Hong Kong, Xi’an, and Kaohsiung of Taiwan of China (Ren and Wu, 2012). It can be seen that substantial progress has been made in urban meteorological applications over the past two decades.

As pointed out by Lee et al. (2015), the study of the atmospheric boundary layer in urban agglomerations is one of the five priority areas in boundary layer meteorology.
The influence of urbanization on regional climate and air quality has become a research focus in recent years. Wang et al. (2017) proposed a new perspective in this regard, with unequivocal arguments. Zhang N. et al. (2019) compiled three volumes of research collections concerning atmospheric diffusion and urban meteorological studies that were conducted in the Atmospheric Environmental Wind Tunnel Laboratory and Atmospheric Environmental Simulation Laboratory of NJU.

Substantial achievements in the research of urban meteorology have been obtained in various aspects for decades, as seen from the limited descriptions above. Furthermore, this line of research also promotes innovative scientific and technological activities, leads to international cooperation and academic exchanges, and creates a new prospect for in-depth and comprehensive exploration on urban meteorology, which will have important applications in various associated fields.

Based on the above discussion, the research progress in urban meteorology will be illustrated next from the perspectives of urban meteorological observation networks and experiments, urban meteorological multi-scale modeling, interactions between urban meteorology and the atmospheric environment, and the influence of urbanization on weather and climate. Conclusions are then reached and prospects are proposed.

2. Urban meteorological observation networks and experiments in China

2.1 Urban meteorological observation networks

An integrated urban meteorological observational network has been established in all cities of China to meet the needs of urban meteorology research and urban weather/climate forecast and service. In general, mesoscale monitoring of weathers in urban areas and monitoring of meteorological characteristics in the boundary layer are covered by such a kind of observational networks, such as experimental networks for urban heat balance, urban heat flux, and urban heat island (UHI) observations. Urban meteorological observation networks in three major urban agglomerations, i.e., the Beijing–Tianjin–Hebei region, the Yangtze River Delta, and the Pearl River Delta, are the most developed urban meteorological observation networks in China. These observational networks are also developed for predicting urban weather and providing observational data for decision makers in related government departments, apart from serving for scientific researchers.

Consistent with the national strategy of Beijing–Tianjin–Hebei coordinated development, an integrated urban meteorological observation network designed for serving safety operation, refined management, and disaster prevention and mitigation in cities has come into being, with a core target of promoting the ability to observe and predict high-impact weathers such as heavy precipitation and haze in the Beijing–Tianjin–Hebei region and better serve the community. Specifically, for example, a mega-city meteorological support and service monitoring network that is based on ground and airborne observations has been established in Beijing to meet the demands of safe and rapid urban development, emergency response to disaster prevention and mitigation, and service guarantee related to major meteorological events, which features thermodynamics, dynamics, atmospheric physics, and atmospheric chemistry observations in complete categories and reasonable layout. Meanwhile, an observational system combining urban meteorology with urban boundary layer structure is also included (Liang et al., 2018).

In the Yangtze River Delta urban agglomerations, an urban and environmental meteorological observation network system composed of ecological and agricultural meteorology, marine meteorology, traffic meteorology, urban environmental meteorology, climate resources, drought monitoring, lightning monitoring, hydro-meteorology, and the like professional observational networks has been established. For instance, in Shanghai, an integrated meteorological observational system (i.e., SUI-MON—Shanghai Urban Integrated Meteorological Observation Network, see Fig. 1) that combines ground-based and space-based observations for the mega city has been constructed (Tan et al., 2015); a city heat island monitoring network specifically designed for UHI effect research has been set up in Suzhou, Jiangsu Province in accordance with the needs of urban development; an integrated air pollution monitoring system equipped with complete monitoring projects has been built in Hangzhou, Zhejiang Province; and a city traffic visibility monitoring network has been developed in Nanjing, Jiangsu Province, which is a part of the traffic weather forecasting service within the refined prediction service of Nanjing City.

In southern China, an integrated urban meteorological monitoring and observation network consisting of dense automatic weather stations, a variety of ground-based remote sensing devices (including weather radar, Doppler sodar, wind profile radar, etc.), urban atmospheric composition monitoring stations, and GPS/MET water vapor monitoring facilities, has been established in the Pearl River Delta urban agglomerations. For example, a relat-
ively comprehensive meteorological disaster monitoring (with enhanced spatiotemporal resolution of observation, coordinated radar observation, emergency mobile observation, sensitive area target observation, and so on) and a climate monitoring system (including local climate observation, climate resources observation, greenhouse gases and atmospheric composition observations, etc.) have been set up in Shenzhen, Guangdong Province since 1994 (Mao et al., 2013).

Moreover, meteorological observation towers provide superb observational platforms for the research of urban meteorology. For example, the 325-m tower in Beijing (Hu et al., 1999, 2005; Miao et al., 2012; Miao and Chen, 2014), the 225-m tower in Tianjin (Huang et al., 2011), and the 356-m tower in Shenzhen (Li et al., 2020) play an important role in the study of physics and atmospheric environment of the urban boundary layer.

Based on the current operational observation networks in three mega cities (Beijing, Shanghai, and Guangzhou), a super urban-observation network including stereoscopic observations of atmospheric temperature, humidity, wind, water condensates (clouds and precipitation), and vertical profiles of aerosols, has been configured, with ground-based remote sensing as the
core observation resource. This super network was set up under the sponsorship of a China National Key R&D Program (Wang Z. C. et al., 2018).

As indicated by Tan et al. (2015), observation networks established in all cities of China are either characterized by or are evolving to possess the following features: (1) multiple platforms—ground meteorological observations (e.g., automatic weather station), radar meteorological observations (weather radar), urban boundary layer observations (wind profile radars, tower weather stations, etc.), environmental meteorological observations (e.g., atmospheric component monitoring stations), mobile meteorological observations (emergency monitoring vehicles), and the like, are included; (2) multiple variables—observed variables include elements in the fields of thermodynamics, dynamics, atmospheric chemistry, bio-meteorology, and ecology; (3) multiple scales—the integration of synoptic scale, mesoscale, urban scale, street scale, and building scale, etc. is taken into account based on observations from various platforms mentioned above; (4) multiple links—the above-mentioned platforms collect observed data through automatic remote sensing, ground-based remote sensing, satellite remote sensing, online observation and sampling, etc. An integrated observation network is formed thanks to the mutual links between various observation platforms; (5) multiple functions—the network plays a vital role in refined prediction, and it can meanwhile meet the needs of research on high-impact weather and urban boundary layer, as well as the needs of many other studies and services such as urban safety, environment and health applications, etc.

2.2 Field experiments

Observational and experimental studies on urban meteorological conditions and atmospheric processes are the basis for enhancing our understanding of urban weather, climate, and environment. Various projects of observational and experimental research on urban meteorology have been conducted abroad and in China since the 1970s–1980s. A great number of large field experiments concerning various research topics such as boundary layer meteorology, weather, climate, and air pollution in urban areas have emerged globally from the end of the 20th century to the beginning of the 21st century (Grimmond, 2006). Among the above research fields, boundary layer meteorology and air pollution are two major hot topics. During the corresponding period mentioned earlier (see Section 1), several representative experiments were conducted in China, including the BECAPEX (Xu et al., 2004, 2010) and the BUBLEX in Beijing (Li and Shu, 2008; Li and Dou, 2014), and the urban boundary layer observation project in Nanjing for research of typical three-dimensional structure of boundary layer (Liu et al., 2008). Among these experiments, the BECAPEX (from 2001 to 2003) is the first large-scale integrated urban meteorological observation experiment conducted in a mega city in China. The three-dimensional features of atmospheric boundary-layer dynamics, thermodynamics, and atmospheric chemistry in Beijing City were obtained from this experiment. As revealed by the experiment, non-uniform secondary-scale heat islands accompanied by urban secondary circulations were distributed over the urban area, affecting the distribution of local air pollutants, and there was a close relationship between the urban air pollution in Beijing and pollution sources in the surrounding areas. These pollution sources affected the environmental and climatic characteristics of urban communities, leading to significant interdecadal trends of sunshine hours, foggy days, low-cloud formation, and visibility.

A lidar was installed by NJU in the downtown area of Nanjing for observational research on the structure of urban boundary layer and specifically for studies of the urban mixing layer, entrainment area of convection, and cloud feedback. Sponsored by the National Natural Science Foundation of China in 2004, several 10-day observational experiments were conducted for determining the parameterization scheme of urban boundary layer and the urban mixing development mechanism (Mao et al., 2006, 2009). The experimental results are appreciated by researchers in China and abroad.

There are growing concerns on high-impact weather events in cities since extreme weather events have occurred more frequently in the past decade under the global climate warming. Urban meteorological observation experiments during this period were more focused on research of the mechanisms for high-impact urban weather and its mitigation (Baklanov et al., 2018), the influence of urban effects on the weather, and the feedback loops between urban aerosols and weather. Moreover, the observational range was extended from a single city to several cities (urban agglomerations, metropolitan areas). The SURF experiment was conducted in the Beijing–Tianjin–Hebei urban agglomeration region from 2015 to 2017 (Liang et al., 2018). Field measurements (Fig. 2) were jointly performed by researchers from universities and research institutions in China, the United States, and Britain to investigate urban impacts on heavy precipitation.
and haze. Based on these measurements, in-depth understanding of the turbulent characteristics of urban near-surface layers and the complex land–atmosphere exchange processes as well as the three-dimensional (3D) structure of the boundary layer has been obtained, and the mechanisms, types, and uncertainty of numerical simulation of urban impact on precipitation have been proposed. The effects of meteorological conditions such as the regional circulation over the Beijing–Tianjin–Hebei urban agglomerations on haze were revealed, and the fine forecasting system RMAPS model at high resolutions was improved with better forecast skills for urban precipitation and haze. Observational and experimental projects conducted in the regions such as Shanghai and Beijing have been included in the Global Atmosphere Watch (GAW) Urban Research Meteorology and Environmental (GURME) project by WMO (http://mce2.org/wmogurme).

2.3 Wind tunnel experiments

Compared with outdoor observational experiments, wind tunnel experiments have advantages due to the easy control of experimental conditions, the convenience for measurements, and low cost. For the first time in China, fluid physics simulation methods have been used in the atmospheric environment wind tunnel. That is, physical simulation experiments of urban meteorology and urban environment application were conducted in the atmospheric environment wind tunnel, such as the wind tunnel at NJU (Jiang et al., 1991; Jiang, 1994), and unique results were achieved (Jiang et al., 1998, 2003; Ouyang et al., 2003). In the early stage of the development of the Pudong New Area in Shanghai, simulation experiments of waste gases discharge in this area were performed in the NJU wind tunnel (images of the experiment are shown in Figs. 3a, b). Meanwhile, an experiment was also conducted in the NJU wind tunnel (the model and image are shown in Figs. 3c, d) with a focus on the relationship of urban planning and construction with meteorological conditions and air pollution in Beijing. Multiple measurements of airflow distribution and pollutant concentration in a residential area in Beijing as well as airflow and pollutant concentration distributions around the buildings were carried out. These measurements were compared with numerical model simulations and they are consistent with each other. The wind tunnel experiment could realistically reproduce the urban street canals and the building effects on airflows and pollutants dispersion, as well as the impact of different airflow conditions on dispersion distribution of pollutants from ground emission sources. The characteristics of airflow and the distribution of pollutants in individual buildings and surrounding areas were also revealed. Utilization of the above-mentioned scientific and technological methods shows that, following the rapid development of computing and
electronic information technology in China, significant progress has been achieved in the application of new technologies in the research field of urban meteorology.

2.4 Scale-model outdoor measurement of urban meteorology

Scale-model outdoor measurement is an experimental method in urban meteorology study, which can well simulate urban canopy ventilation, UHI mechanism, and urban surface–atmosphere coupling process. Scale-model outdoor measurement of urban climate and health (SOMUCH) was conducted in the suburb of Guangzhou during 2016–2017, by using idealized urban area models designed by the research group of Professor Jian Hang in Sun Yat-sen University. Two scale-model experiments were conducted by this group (Wang D. Y. et al., 2018; Chen et al., 2020). Figures 4a and 4b present schematic details and real site photos of the two experiments. Thermodynamic conditions similar to that in real urban areas, reasonable specification of thermal parameters of the buildings, and sufficient thermal inertia were implemented. Covering an area of 4800 m², the experimental site is far from surrounding buildings and the land surface is impervious. As shown in Fig. 4a (Chen et al., 2020), the idealized street canyon models are composed of about 2000 cement building blocks, and each building block is 1.2 m high (H = 1.2 m), with wall thickness of 1.5 cm, and with varying width (e.g., B = 0.4, 0.6, 1.2 m). The hollow interiors of these cement building blocks make it easy to change parameters such as aspect ratio and building density through moving their positions. There are two sets of blocks. One set has small hollow heat capacity and the other is filled with sands to increase heat capacity of the building.

The influences of building heat capacity and street height-to-width ratio on two-dimensional (2D) street canyon turbulence and spatial–temporal characteristics of temperature under typical unstable weather conditions have been studied through the outdoor experiments (Fig. 4a) by Chen et al. (2020). It was found that (1) the narrow street canyon (H/W = 3) has a smaller sky-viewing factor and a better shading effect with less solar radiation received during the day in comparison to the wide street canyon (H/W = 1). In this case, the temperature of
the wall on the side of the narrow street canyon is lower in the daytime. Nevertheless, the wall temperature on the side of the wide street canyon drops faster since the wall on the side of the wide street canyon experiences stronger convection and ventilation and it also has larger heat dissipation ability caused by longwave radiation. (2) Since the building block filled with sands has a larger heat capacity and more heat storage during the day, its temperature rise is slower than that of the hollow inside model. However, the building block filled with sands has a higher temperature because more heat is stored during the day. Furthermore, a 3D scaled-model outdoor experiment was also carried out to investigate the daily urban surface energy balance in high-rise compact urban districts, as shown in Fig. 4b (Wang D. Y. et al., 2018). Simulations with empty building blocks and with water-filled blocks were compared. The results revealed that the building heat storage is the main source or sink in the surface energy balance; it is much larger in summer than in winter; and the ratio of heat storage to surface net radiation is greater for building blocks filled with water than that for empty building.

3. Multi-scale numerical modeling study of urban meteorology

3.1 Multi-scale numerical simulation of urban meteorology

Complicated exchange processes are found between the underlying urban surface and the above atmospheric boundary layer from the building scale (several meters) to the city scale (dozens of kilometers). As a result, there can be co-existence of eddies from turbulence in urban street canyon to heat island circulation or urban plumes over the whole city (Oke et al., 2017) with timescales...
ranging from several minutes to several hours. This multi-scale attribute of urban boundary layer is important to the design of observations, simulations, and application schemes in urban meteorology. In general, the physical/chemical processes in the urban boundary layer can be divided into the urban full boundary layer process, the urban near-surface layer process, and the urban canopy layer process, in line with the needs of urban observations and numerical simulations. These processes in different vertical layers correspond to the urban weather and climate scale (i.e., larger than mesoscale), urban local (boundary layer) scale, and urban microscale. Increasing research and service requirements concerning multi-scale numerical simulation of urban meteorology have been raised for urban planning, urban atmospheric environmental governance, urban building design, and urban wind safety, etc. Hence, various numerical simulation tools are needed to address these issues on different scales (Jiang et al., 2010).

More specifically, the horizontal scale of urban meteorological processes can be divided into mesoscale, urban scale, neighborhood scale, and building scale, according to characteristics of different urban problems (Fang et al., 2004). Among them, mesoscale and urban scale are concerned when simulating urban weather/climate effects and UHI circulations with a focus on the impact of the underlying urban process on the upper-level atmospheric processes. The influence of refined dynamic and thermal processes on urban street canyons and buildings can be examined on the neighborhood scale and building scale. The horizontal grid spacing of weather/climate models at the mesoscale/urban scale and above ranges from 1 km to dozens of kilometers, while that of the models at neighborhood scale/building scale are mostly less than 10 m. In these two types of numerical models, treatment of urban buildings and their impacts is quite different. The mesoscale/urban scale models focus more on description of statistical status of a large number of buildings, while, more emphasis is placed on the geometric characteristics of the buildings in the neighborhood-scale and building-scale models. Based on the relation of horizontal dimension of typical buildings to grid spacing of individual numerical models, Jiang et al. (2009) indicated that urban multi-scale numerical models can be divided into two categories. One is to implicitly deal with the influence of buildings, i.e., to conduct parameterization of the overall role of all the buildings. This type of models are mainly used to simulate weather and climate on mesoscale/urban scale, and they often employ an urban canopy model to describe the process of urban land surface. The other is to explicitly deal with the influence of buildings, or to describe physical characteristics of buildings through presenting details of the morphological structure of buildings within individual grids. This type of models is used to simulate processes on neighborhood scale or building scale. Examples can be found in Zhang et al. (2002).

As early as in 2009, a multi-scale urban boundary layer numerical model system was successfully developed in China (Jiang, et al., 2009). Its schematic diagram is shown in Fig. 5. The planetary boundary layer (PBL) models in this system are aggregated over three scales, i.e., regional scale, urban scale, and neighborhood scale. An urban canopy model that considers building shadow, drag effect of winds, and building impacts on turbulence is coupled to the urban-scale PBL model. In addition, high-resolution geographic information, satellite surface parameters, anthropogenic heat release, and building morphological data are also taken into account. In the neighborhood-scale PBL model, the building impacts are

![Multi-scale urban boundary layer numerical model system](image)

**Fig. 5.** The multi-scale urban boundary layer numerical model system developed in China (Jiang et al., 2009).
considered explicitly. Furthermore, the PBL models are coupled with atmospheric chemistry model or transport and diffusion model for air quality simulations.

3.2 Development of the urban canopy model

The urban canopy layer (UCL) refers to the near surface layer below the top of urban buildings (Oke et al., 2017). In this layer, urban buildings have a direct influence on the dynamic and thermal processes that occur in the PBL, such as longwave/shortwave radiative transfer, wind, and turbulence. Meanwhile, active human activities in the UCL lead to excessive water, heat, and pollutant emissions. In traditional numerical models, these urban effects have been represented by merely changing the underlying dynamic and thermal parameters. Considerable observational studies demonstrated that the energy balance process on the 3D surface of the buildings in the UCL and subsequent flux exchanges between the near-surface layer and atmosphere are markedly different from those over a flat underlying surface (Hu et al., 1999, 2005; He et al., 2006; Miao et al., 2012; Peng and Sun, 2014). Therefore, special considerations are necessary for urban canopy processes in the UCL.

The dynamic, thermodynamic, and radiative processes in the urban land surface and the upper atmosphere and their interactions are usually described by the UCL scheme implemented in the mesoscale and urban-scale numerical models (Chen et al., 2011). Researchers in China have recognized the importance of the UCL model for a long time. He et al. (2009) established a single-layer UCL model based on the town energy balance (TEB) scheme of Masson (2000) and illustrated the influence of urban buildings on radiative process. Basic assumptions of urban street canyons were applied in this scheme, which was later coupled with the NJU multiscale urban numerical simulation system. Based on the assumption of the detached cube building model, Wang and Jiang (2009) further developed the NJU UCL model by considering the differences in radiative characteristics of the walls of buildings with different orientations. The above two UCL schemes participated in the international urban energy balance models comparison project in 2009 (Grimmond et al., 2010), and their results were satisfactory. Furthermore, human activity related urban processes (e.g., anthropogenic sensible and latent heat fluxes) have been added into the UCL as an integral part of the urban canopy model. Miao and Chen (2008) and Miao et al. (2009a) developed a parameterization scheme to describe anthropogenic sensible heat flux, which has been implemented in the single-layer urban canopy model in the mesoscale Weather Research and Forecasting (WRF) model. Zhang et al. (2016b) further improved the anthropogenic heat scheme in the WRF model. Zheng et al. (2017) introduced the influences of anthropogenic sensible and latent heat fluxes from the refrigeration system of buildings. Zhou et al. (2010) coupled a dynamic canopy scheme with the UCL model to simulate the urban boundary layer. Miao and Chen (2014) developed a numerical simulation method for urban surface latent heat flux based on the observational experiment. Yang J. B. et al. (2015) considered the impact of urban vegetation such as green belt and other factors and further developed the urban boundary layer model. Li et al. (2017) derived a building index using the fractional dimension method and introduced this index into the UCL model, which can yield finer simulation effects on urban meteorological elements.

Following the improvement in various numerical models for urban meteorology study, the models have been widely applied to scientific research and operational weather and climate services. Beijing Meteorological Bureau is the first agency to apply the UCL model for operational forecast in China and to provide high-resolution urban weather forecast products. The results show that the forecast of near-surface meteorological elements can be improved to a certain extent when the UCL model is incorporated into the numerical weather forecast model. Meanwhile, the capability for simulating the characteristics of urban boundary layer can also be effectively improved (Miao and Wang, 2014).

Development of complicated UCL models also implies high demand for refined parameters of underlying urban surface. Establishing high-resolution urban morphology datasets that include data obtained from 3D building databases, digital elevation datasets, and observations of airborne lidar and satellites is an imperative task for development of numerical models for urban meteorology. For instance, American scientists have established a UCL parameter dataset called the National Urban Database and Access Portal Tool (NUDAPT) for major cities in North America (Ching et al., 2009). Miao and Chen (2008) and Miao et al. (2009a, b, 2011) also applied fine UCL parameters in their numerical study of urban boundary layer structure and precipitation, which yielded reasonable results. Dai et al. (2019) used satellite remote sensing and other methods to retrieve building height in cities like Guangzhou. Meanwhile, with such methods, the modeling capability for urban meteorology and air quality has been remarkably enhanced. Currently, it is still imperative to set up a national-scale high-resolution UCL parameters dataset in China.
3.3 Development and application of the urban neighborhood-scale model

In an urban neighborhood-scale model, the morphological characteristics and corresponding data of buildings should be distinguished to better represent direct dynamic and thermal effects of urban structures and building elements that have unique shapes and street canyon structures. Moreover, high-order local turbulence closure parameterization scheme is often used in the simulation as the turbulence process on this scale is often intense with high locality. Zhang et al. (2002) set up a building-resolvable-scale wind field model based on the $k$-$\varepsilon$ closure. On the basis of this work, Miao et al. (2002) introduced thermal processes such as the impact of buildings on radiation, and established an urban neighborhood-scale model. The LES technology has been widely used in numerical simulations on urban neighborhood scale (Cui et al., 2008). Zhang and Jiang (2006) simulated the dispersion characteristics of pollutant emissions at different locations around a building using a building-scale wind field model that was developed based on LES in combination with the Lagrangian random walk model. Yan et al. (2020) introduced the impact of street trees into the LES model, and further improved the model ability to describe complex underlying surface of the city. Li H. F. et al. (2018) developed and applied a new approach to coupling mesoscale models with LES. Liu et al. (2011) studied pollutants dispersion in urban street canyons in Macao using LES. Hang et al. (2009, 2012) also studied the problem of urban environmental ventilation in various urban configurations.

The CFD software and the commercial software ENVI-met are widely applied in microscale numerical simulations of urban microclimate process, atmospheric environment, and urban planning. With these tools, Jiang et al. (2018) studied the influence of urban neighborhood-scale roof greening on urban thermal environment. Nonuniform grids that are widely implemented in CFD can be used for better distinguishing different forms of buildings, and thus will be increasingly used in the simulation of urban microclimate. Fluent, a commercial software, and OpenFOAM, an open resource model, are two major models. For example, Chen C. Y. et al. (2015) simulated the diffusion characteristics in urban neighborhoods using OpenFOAM, and Dong et al. (2019) simulated the urban atmospheric diffusion using the WRF coupled with Fluent. Based on a semi-empirical model and a Lagrangian stochastic model, a rapid diagnosis model for wind field and pollution diffusion was developed by Zhang et al. (2016a) on the urban building scale to meet the demand for urban emergency application. This model overcomes the shortcoming of massive calculations with traditional atmospheric models and CFD methods in the simulation of urban small-scale process.

4. Interaction between urban meteorology and atmospheric environment

Urban air pollutants in China have changed from traditional primary pollutants to secondary pollutants (e.g., fine particles, ozone, etc.). To make things worse, composite air pollution has been present due to regionally mixed multi-type pollutants caused by transport and reciprocal influences between urban agglomerations. Factors that affect the concentration of urban air pollutants include pollutant emissions, transport diffusion, sedimentation, chemical processes, and interactions with weather and climate. The most important factor in the formation of air pollution is the combination of 1) large emissions of pollutants and their precursors and 2) meteorological conditions conducive to dispersion and removal of pollutants. Topics such as relationship between meteorological elements/variables and air pollution, impact of regional weather and climate change on air pollution, and interaction between boundary layer meteorological conditions and air pollution are main concerns in research of urban meteorology and air pollution. China has witnessed substantive progress in elucidating the relationship between urban meteorology and atmospheric environment.

4.1 Influences of urban meteorology on atmospheric environment

Meteorological factors are key factors affecting air quality, which inevitably affect physical and chemical processes of air pollutants in the atmosphere over urban areas, where unique urban meteorological conditions form due to the underlying urban surface (Zhu et al., 2015). Xu et al. (2004, 2006) proposed a physical diagram of 3D air pollution termed as urban “atmospheric dome” based on the integrated observational experiment of BECAPEX conducted in Beijing. They indicated that the urban boundary layer not only affects the spatial and temporal distributions of local air pollutants in cities, but also generates regional air pollution due to complicated dynamic and thermal structures between urban clusters. Moreover, UHI is believed to have a significant influence on the dispersion of urban pollutants. Based on analysis of vertical dynamic structure of the lower urban
boundary layer in Beijing and its relationship with the distribution of pollutant concentrations using tower data, Zhou et al. (2005) clearly showed that the turbulence characteristics of urban boundary layer are critical factors affecting the transport and diffusion of pollutants. Studies on diurnal variations of local circulations and their impacts on atmospheric diffusion and pollution have been attracting more attention in China (Zhang et al., 2003; Wang et al., 2014). Fan et al. (2006) proposed a conceptual model, indicating that characteristics of the atmospheric boundary layer are jointly influenced by sea–land breeze, UHI, and valley winds over the Pearl River Delta. This model can well explain the cause of regional high air-pollution index (API) events and the occurrence of haze weather.

The drag effect of urban buildings on the wind field is the main dynamic mechanism for the influence of urban meteorological conditions on air pollution. This effect attenuates wind speed in cities, and subsequently prevents dispersion of pollutants. Meanwhile, 1) change of the thermodynamic properties of the urban surface and 2) the UHI effect owing to release of anthropogenic heat, are two major thermal mechanisms for interaction of urban meteorology and air pollution. The influence of combined effects of cities on air pollution has been presented in a mass of studies. For instance, Wang X. M. et al. (2005) detected that variations in ground-level ozone and PM$_{10}$ concentrations caused by urbanization in the Yangtze River Delta and Pearl River Delta are critical factors that lead to temperature rise and higher boundary layer height. Based on Wang et al. (2009a), the urban expansion leads to secondary organic aerosol (SOA) increases by 3%–9% in major cities of the Pearl River Delta region. Liu et al. (2015) studied the influence of urbanization on urban meteorology and pollution diffusion. They found that the atmospheric diffusion capability in Hangzhou, capital city of Zhejiang Province, was decreasing due to urban development and the urban pollutant concentrations increased. To make things worse, the mean concentration of urban PM$_{2.5}$ increased by 2.3 μg m$^{-3}$, reaching up to 30 μg m$^{-3}$, and the mean “clean-down capability” of pollutants increased by 1.5 h. The variation in pollutant concentrations caused by urbanization is a result of combined effect of changes in meteorological conditions such as urban temperature rise and wind speed decrease.

The effect of certain factors in urban meteorology such as anthropogenic heat and urban greening on air pollution has been studied separately. By investigating the impact of urban vegetation coverage and vegetation types on air quality in Suzhou, Jiangsu Province, Yang et al. (2018) found that daily mean concentrations of major air pollutants decreased significantly when vegetation cover fraction reached 40% over certain urban area. Zhu et al. (2016) conducted numerical sensitivity experiments to distinguish the thermal and dynamic effects of cities. They found that the intensification of UHI could increase the atmospheric instability, generate heat island circulations that converge in central urban areas, increase ascending motions in urban areas, and enhance the capability of atmospheric diffusion in cities. Meanwhile, the concentration of pollutants would decrease at ground, whereas it would increase at the height of about 400 m. Wind speed in urban areas decreases substantially due to the dynamic effect of urban buildings, which subsequently weakens the capability of atmospheric diffusion and increases the pollutant concentration. The UHI thermal effect is opposite to the dynamic effect of the building, while the latter is greater than the former.

There is no consensus about the numerical simulation research results on the influence of urban dynamics and thermal effects on air pollution, since various factors responsible for air pollution in the urban environment are intricate and complex. They are associated with a variety of factors such as concrete urban morphology and climate background.

### 4.2 Influences of air pollution on urban meteorology

The transport, dispersion, sedimentation, and chemical processes of air pollutants in urban areas are controlled by urban meteorological conditions. Meanwhile, surface air temperature, UHI, atmospheric heating rates, and local circulations of urban atmosphere are affected by pollutants through the aerosol radiative effect. Zou et al. (2017) indicated that the increase in aerosol loading may cause a mean decline of 67.1 W m$^{-2}$ in downward shortwave radiation and a mean increase of 19.2 W m$^{-2}$ in downward longwave radiation in urban areas based on observational data. Zhong et al. (2017) studied a heavy pollution event in Beijing. They found that the near-surface air temperature declined sharply due to the aerosol–radiation interaction, and an inversion layer formed at the early stage of PM$_{2.5}$ accumulation. Wang X. R. et al. (2018) showed that stable stratification is hard to form over urban areas when the aerosol optical thickness increases. The combined effects of aerosol radiation and urban underlying surface are a major factor that influences meteorological elements in the urban boundary layer. Ren et al. (2019) studied turbulence characteristics during heavy fog–haze pollution events in
Beijing. They found that the heat flux, latent heat flux, momentum flux, and turbulent kinetic energy over urban and suburban areas were all affected by the pollution. Moreover, mass and energy exchanges between the surface and the atmosphere were also suppressed. Cao et al. (2016) found that the difference in pollution level during haze events between urban and rural areas is a major factor controlling the surface UHI during nighttime in China. The mean contribution of haze to the surface UHI at night is $0.7 \pm 0.3$ K for semi-arid cities, which is stronger than that under humid conditions due to strong longwave radiation effect of aerosols.

4.3 Interaction between urban meteorology and atmospheric environment

There is an important interaction between air pollution and urban meteorology. On the one hand, the transport, diffusion, sedimentation, and chemical processes of air pollutants are dominated by meteorological conditions of the boundary layer; on the other hand, ground temperature, atmospheric stability, height of the urban boundary layer, and local airflows in cities are affected by pollutants through the aerosol radiative effect. Among these factors, the height of the urban boundary layer is particularly important and plays a critical role in the degree of vertical mixing of air pollutants. In general, PBL height is negatively correlated with aerosol concentration (Quan et al., 2013), and pollutant concentrations in the boundary layer are far higher than that in the free atmosphere (Zhang et al., 2011). According to Wang et al. (2015), the height of the boundary layer and the intensity of the turbulent diffusion of the boundary layer are crucial for the formation of urban haze.

The stability of the boundary layer is also affected by the presence of aerosols. It is generally believed that the impact mechanism is that during the period of heavy pollution, the presence of aerosols will reduce the surface air temperature, and the absorptive aerosols heat the upper boundary layer and change the vertical distribution of temperature, leading to enhanced atmospheric stability (Ding et al., 2013; Quan et al., 2013; Gao et al., 2015). In their study of the feedback of pollution to the meteorological field during a mixed pollution process caused by fossil fuel and biomass combustion, Zhou et al. (2018) revealed that ground temperature was significantly changed in the mixed pollution area. The accumulation of pollutants in the boundary layer was promoted by the decrease in surface temperature and the heating tendency in the upper atmosphere (Huang et al., 2018). Based on Zhong et al. (2017), contribution of a more stabilized boundary layer within the first 10 h of the PM$_{2.5}$ accumulating stage accounted for about 84% of the explosive growth of PM$_{2.5}$ during a heavy pollution event in Beijing. Sun et al. (2017) found out that the feedback between haze and meteorological conditions can increase the concentration of PM$_{2.5}$ by up to 15%, when studying a large-scale heavy pollution process in the Yangtze River Delta region.

Local circulations and their interaction with air pollution have been studied by many Chinese researchers since the 1980s. Moreover, obvious interactions are also found between local atmospheric circulations such as sea–land breeze, valley wind, and UHI circulations in coastal cities. According to Liu S. H. et al. (2009), sea–land breeze, valley wind, and UHI circulation and their coupling effects can be found at the same time in the atmospheric boundary layer over the Beijing–Tianjin–Hebei region under the control of weak weather system. In this case, a convergence zone of the wind field along the terrain orientation, or the convergence belt of pollutants, might form and exert vital influences on the accumulation and transport of atmospheric pollutants in Beijing.

4.4 Urban air quality forecasting and related applications

Offering scientific support to the management of urban atmospheric environment and providing urban air quality forecast are two major societal demands and also crucial research topics concerning the urban atmospheric environment. Potential forecasting, statistical forecasting, and numerical forecasting are major methods for predicting air quality in cities. In China, numerical forecasting has been substantially advanced in both operational applications and research outcomes of all levels.

The CUACE haze–fog system of CMA provides forecasts of concentrations of six air pollutants (e.g., PM$_{2.5}$) and AQI. The forecasts serve as guidance products for environmental meteorological forecasting (Gong and Zhang, 2008). Various bias correction models appropriate for different regions of China have been established by Lyu et al. (2018) to correct the CUACE model prediction, and satisfactory results have been achieved. In addition, a variety of numerical forecasting systems have been constructed in different areas like North China, East China, and South China (Zhou et al., 2015; Deng et al., 2016; Zhao et al., 2016).

The NAQPMS developed by Wang et al. (2006) is a limited-area multi-scale urban air quality numerical model, which has been applied to many regions in China. It can be used to track various physical and chemical processes by source category and source region of emission. The transport process and the contribution rate of pollution emissions can be quantitatively analyzed through on-
line coupling of the NAQPMs with the pollution sources identification and tracking modules (Li J. et al., 2012).

The NJU-CAQPS has been established by Nanjing University. This model system is composed of WRF-Chem, urban boundary layer model (UBLM), atmospheric chemical composition transport and diffusion model (ACTDM), and pollution source disposal model. It includes urban land surface processes and is characterized by multiple scale, high resolution, and fine grid. UBLM is a refined urban atmospheric boundary layer model with an $E-\epsilon$ turbulence closure. ACTDM contains multiple substance transport, diffusion, wet and dry deposition, and chemical transformation. WRF-Chem provides initial fields and boundary conditions of meteorological elements and pollutant concentrations to UBLM and ACTDM, respectively (Liu H. N. et al., 2009). A large number of numerical simulation tests and applications have been carried out by using WRF-Chem. The results indicate that the air quality predictions by this model in some small and medium-sized cities are satisfactory. Furthermore, experimental comparisons and simulations were also conducted in the self-built NJU atmospheric environment wind tunnel. Again the results are reasonable (Jiang et al., 2003; Ouyang et al., 2003, 2007; Wang X. Y. et al., 2007).

5. Influences of urbanization on weather and climate

5.1 Analysis of UHI effect

The UHI effect is the most direct expression of urban effects on weather and climate. Early studies show that UHI in China increased by 0.1°C over the 30-yr period of 1954–1983 (Wang et al., 1990). Zhou et al. (2004) indicated that UHI in China is more prominent compared to that in other countries. Also, slight decrease in the diurnal variation of urban temperatures is found, which is due to urbanization in the Yangtze River basin and southern part of China. A growing number of automatic observation stations have been used to assess urban meteorological elements, which has greatly improved the accuracy of the UHI effect since the beginning of the 21st century (Yang et al., 2013). Shen et al. (2017) revealed the multi-center structure characteristic of UHI in Shanghai (see Fig. 6) using high-resolution quality-controlled automatic observation data collected by the integrated urban meteorological observation system in Shanghai. Figure 6 clearly indicates that the refined multi-center feature cannot be found in conventional data. Moreover, seasonal changes of UHI in Shanghai are also affected by seasonal changes of atmospheric circulation and local sea–land breeze.

![Fig. 6. Distributions of annual mean urban heat island intensity (°C) of Shanghai, China from 2006 to 2013 based on observations from (a) automatic weather stations and (b) conventional weather stations ("*" represents Xujiahui station) (from Shen et al., 2017).](image-url)
Rapid urbanization and enhanced UHI effect affect not only the distribution of urban temperature, but also the climate warming recorded by most of the primary meteorological stations in China. About 20%–40% of the rising trends of surface air temperature are caused by urbanization in mainland China, although the contribution rate of urbanization to global or hemispheric land mean temperature rise is less than 10% (Ren et al., 2010). In addition, the occurrence frequency of extreme temperature is also affected by the climatic effect of urbanization. Wang J. et al. (2013) found that the contribution of rapid urbanization in Beijing to the increasing (decreasing) tendency of extremely warm (cold) nights is 12.7% or 2.07 day (10 yr)\(^{-1}\) [29.0% or 5.06 day (10 yr)\(^{-1}\)] over the past three decades. Thus, urbanization effect has remarkably strengthened the decreasing tendency of extremely cold night events that could last for more than 3 days by up to 34%.

The fact that urbanization can cause regional warming is a consensus of most investigations. However, discrepancies emerge regarding the quantitative results of temperature rise in the numerical simulations of urbanization impact on air temperature. Zhang et al. (2010) proposed that the mean surface temperature in urban areas can rise by \((0.45 \pm 0.43)°C\) in winter and \((1.9 \pm 0.55)°C\) in summer based on sensitivity experiments. Feng et al. (2012) suggested that the annual temperature in China has increased by 0.13°C due to changes in underlying urban surface. Furthermore, temperature rises in cities of significant urbanization such as those in the Yangtze River Delta region could reach up to 0.84°C. By conducting high-resolution nested simulations over three major urban clusters in China, Wang et al. (2012) presented that the surface air temperature in urban areas could increase by about 1°C due to urban land use. The significant effect can be especially observed in summer. Chen et al. (2009) considered the influence of anthropogenic heat on the urban boundary layer structure in Nanjing and Hangzhou, by use of an urban boundary layer model. Feng et al. (2012) found that the regional surface air temperature in China has increased by 0.15°C due to anthropogenic heat release associated with urbanization; and markedly, the temperature rise in the Yangtze River Delta can reach up to 0.89°C.

5.2 Impact of cities on precipitation

The impact of urbanization on spatial and temporal distributions of precipitation is another expression of the urbanization effect. Unlike the UHI, studies on the impact of urbanization on precipitation are mostly conducted in the 21st century.

5.2.1 Observational analysis

Investigations on urbanization impact on precipitation mainly rely on precipitation observations collected at surface meteorological stations as well as satellites and ground remote sensing observations. The impact of cities on regional precipitation amount and its spatial distribution has been analyzed in a number of studies (Chen et al., 2003; Sun and Shu, 2007; Wang X. Q. et al., 2009; Liang and Ding, 2017). Yang P. et al. (2017) showed that the impact of urbanization on the spatial distribution and change trend of precipitation demonstrates obvious regional differences due to different regional climate regimes and city sizes. Spatial distribution of the storm frequency and its changing trend indicate that Shanghai, for example, presents a more significant attribute of urban rain island during its rapid urbanization process than other cities that experience slower urbanization (Liang et al., 2013). Dou et al. (2015) suggested that the UHI intensity (UHII) can be taken as a critical factor to distinguish the type of influence of cities on precipitation, i.e., precipitation in urban areas would increase with higher intensity under larger UHII, whereas it would decrease due to precipitation bifurcation caused by the effect of the rough underlying urban surfaces when UHII is weak (see Fig. 7). Similar to an individual city, urban clusters also exert influences on precipitation distribution. Specifically, urban clusters in the Yangtze River Delta have experienced significant increase in precipitation compared to the adjacent plains (Zhao et al., 2011), and the high precipitation center is generally located 20–70 km downstream of the city down town area.

As can be seen in many studies, urbanization is a cause for increased precipitation amount and rising number of heavy precipitation events in large cities. For example, it is found that the number of days with heavy rain (including heavy rain, torrential rain, and extremely heavy rain) increased owing to urbanization in Nanjing (Zhou et al., 2003) and Guangzhou (Liao et al., 2011). An obvious rain island effect can also be found in short-term precipitation, the frequency of catastrophic storms above 100 mm (Hu, 2015), and the intensity of low-temperature rain and snow events in Beijing, although the effect of urbanization on precipitation is dominated by the dry island effect (Han et al., 2014). Analysis of satellite-based remote sensing products by Meng et al. (2017) indicates that UHI and rain islands are consistent in spatial distribution during the heavy rain period on 21 July 2017 in Beijing, and they had the best correlation during the period of maximum rainfall intensity. Yu et al. (2017) found that precipitation events occurrences increase fol-
lowing the enhancement of ground sensible heat flux and wind field convergence. Yang P. et al. (2017) also proved the consistency in spatial distributions of heavy short-duration precipitation in Beijing and the heat island center, although the occurrence of rainfall often lags behind the UHI by more than three hours.

By analyzing the hourly precipitation data covering nearly 100 yr from 1916 to 2014 in Shanghai, Liang and Ding (2017) concluded that extremes of hourly heavy precipitation in Shanghai significantly increased in the past 100 years (Fig. 8). In terms of spatial distribution, the frequency of hourly heavy precipitation events and the variation trend of total precipitation demonstrate the characteristics of urban rain islands. The urbanization in Shanghai contributes to not only the occurrence of heavy precipitation in urban areas, but also the increase of pre-

![Fig. 7](image_url) Two types of impacts of underlying urban surface on precipitation with the urban heat island intensity (UHII) as key factor: (a) weak UHII–precipitation bifurcation, (b) strong UHII–precipitation enhancement in downtown area of Beijing (Dou et al., 2015). Green shading denotes terrain height (Z). Purple contours refer to normalized total rainfall amount (%). High urban precipitation areas are shaded in pink. The blue vector on the lower left corner indicates 850-hPa wind from southwest. The blue curves with arrows in (a) show a bifurcating streamline.

![Fig. 8](image_url) Annual evolutions of maximum hourly precipitation (mm) based on (a) records at Xujiahui, covering almost 100 yr, (b) records for entire Shanghai, covering nearly 50 yr, and (c) spatial distribution of the 99.9th percentile of annual hourly precipitation maximum in Shanghai since 1916 (Liang and Ding, 2017).
cipitation intensity, and thus further increases the total amount of hourly heavy precipitation. UHI has an amplifying effect on heavy precipitation. Furthermore, Shanghai is a coastal city, where convergence of airflows easily occurs in central urban area due to the combined effects of sea breeze and UHI, so the occurrence and strength of the extreme heavy precipitation are also promoted with the water vapor transport from the sea.

5.2.2 Numerical simulation

Urban land use, anthropogenic heat release, and the effects of aerosols on precipitation have been hot topics in existing numerical experiment studies concerning the impact of urbanization on precipitation. According to considerable high-resolution numerical simulation investigations, land use change resulted from urbanization may significantly reduce precipitation in summer in Beijing (Guo et al., 2006; Zhang et al., 2009), the Yangtze River Delta, and the Pearl River Delta (Wang et al., 2012). Miao et al. (2011) showed that the squall line in the urban area is often broken into a convective cell due to the urbanization effect, and the changing magnitude of precipitation is determined by the level of urbanization, in accordance with numerical experiment results on different urban land use scenarios. In addition, as pointed out by Feng et al. (2014), anthropogenic heat release caused by urbanization has increased summer precipitation in the Pearl River Delta and the Yangtze River Delta, especially in urban areas, whereas summer precipitation in the Beijing–Tianjin–Hebei region has not changed significantly. Regarding the impact of coupled sea breeze with heat islands on precipitation, Li et al. (2003) presented that sea breeze, river (lake) wind circulation, and UHI effect are mutually strengthened, which might easily generate the convergence of horizontal winds along the Yangtze River Delta. It is directly related to precipitation increase in the area. Lin et al. (2008) found out that convection can be promoted by UHI circulation and the uplift on the mountain windward side. Furthermore, sensitivity experiments conducted on a heavy precipitation process in Taiwan indicated that the larger the city scale, the more significant the precipitation increase in the downwind direction of the city. Based on the numerical simulation study on two precipitation processes in Beijing, the influence of cities on precipitation is different under different UHI conditions (Zhang et al., 2017). Guo et al. (2019) demonstrated that mixed precipitation can be produced easily in downtown in line with a numerical simulation study of a snowfall process in Beijing. Moreover, it is also found that urban aerosols have a significant and complicated impact on precipitation (Chen W. D. et al., 2015, 2017). Since individual weather processes have been selected in most of the above numerical simulations with distinct study areas and time spans, there is a big uncertainty in simulation results concerning the influence of urbanization on precipitation (Yu et al., 2018).

5.3 Urban meteorology and urban planning

Urban meteorology and urban planning are closely related, complementary, and mutually affected. Not only local meteorological conditions such as wind direction, wind speed, temperature, and precipitation, but also extreme weather and climate events such as high temperature, heat waves, heavy rain, floods, and storm surge (Baklanov et al., 2018), should be taken into account. Conversely, changes in the underlying surface such as the layout of urban buildings and human activities can also affect elements of urban meteorology.

Application of urban meteorology in urban planning involves regional planning, urban overall planning, urban ventilation corridor planning, green space planning, industrial layout and site selection, sponge city planning, architectural layout, and morphological design, as well as ecological protection red line delimitation and climate adaptive urban planning with the consideration of meteorological disasters and climate carrying capacity (Miao et al., 2013; Liu, 2014; Du et al., 2016; Fang et al., 2018).

Wind is the most concerned factor in traditional urban planning. Wind-rose diagram or prevailing wind direction is commonly applied in guiding the allocation of urban functional areas, especially in selecting locations of industrial areas, that is, “upwind direction, or downwind direction” (The Geographical Society of China, 1985).

The influence of meteorology and atmospheric environment on urban planning has not been concerned until the end of last century and the early 21st century. Since then, studies of the interaction between urban planning and meteorological environment have been gradually and systematically conducted in China. A relevant project was supported by the National Key S&T Program and the Beijing S&T Program (Research Group of “The Relationship of Urban Planning and Construction in Beijing with Meteorological Conditions and Air Pollution,” 2004). On this basis, numerical simulation systems, evaluation index systems, and evaluation systems for the impact of urban planning and construction on atmospheric environment have been established. Detailed and accurate meteorological references have been provided for formulating, optimizing, and adjusting urban planning
schemes through conducting spatial analysis on wind speed, wind direction, temperature, humidity, and atmospheric pollution dispersion. These information items are combined with urban planning and urban design (Wang G. T. et al., 2005; Wang, 2007; Miao et al., 2009a; Zheng et al., 2014). Meanwhile, deriving regional rainstorm intensity formulas, categorizing rainstorm patterns based on minute-level meteorological observations, and calculating meteorological parameters for building heating, ventilation, and air conditioning design, etc. have also become an integral part of urban planning and adaptation to climate change (Ministry of Housing and Urban–Rural Development and China Meteorological Administration, 2014; Li M. C. et al., 2018).

With the advancement of numerical simulation and 3S technology (Du et al., 2017; Yu et al., 2019; Zhang P. et al., 2019), more refined and accurate meteorological simulation and prediction technology with enhanced spatial coverage has been required by urban planning. In this case, the horizontal resolution of the numerical models needs to be in the range of 10 m to 3 km. Moreover, it becomes possible to consider the layout of different functional areas in the overall urban planning or regional planning, and the influences of buildings and the fine underlying surface on local meteorological conditions and pollution diffusion in detailed neighborhood planning. The rapid progress in remote sensing and geographic information technology could have facilitated the integration of various meteorological element maps superposed with terrain and landscape maps as well as land use and urban layout maps to form a U<Map (Ren and Wu, 2012; He et al., 2015; Liu et al., 2016).

5.4 Urbanization and climate change

Urbanization and climate change are two major challenges facing the human society, and their relationship becomes closer. The local climate background has a crucial influence on the climatic effects of urbanization (Zhao et al., 2014; Cao et al., 2016; Liao et al., 2018). Unlike North America and other countries/regions, UHI with high intensity occurs in small and medium-sized cities in the semi-arid region of West China rather than in megacities of East China. Thus, the fog–haze radiation effect may be one of the dominant factors for temperature rise in these cities (Cao et al., 2016). Meanwhile, climate warming leads to increases in the frequency and intensity of extreme weather/climate events, and causes serious risks for urban areas located in coastal and valley regions, where population and physical asset agglomeration are high (IPCC, 2012). As projected by climate models, urban heat waves will become more severe and frequent under global warming. For example, the frequency of extreme heat wave occurrence like the one that occurred in 2013 in East China might increase by 50% (Sun et al., 2014, 2016). On the other hand, a range of climatic and environmental problems, local high-temperature and heat-wave weather (Yang X. C. et al., 2015, 2017), as well as frequent air pollution events (Ma et al., 2010) have already resulted from the rapid urbanization.

A dynamic downscaling method of regional climate model (RCM) coupled with urban canopy model has been adopted to study urban climate change characteristics under the combined effects of future climate change and urbanization. Using the dynamic downscaling method, Chen and Frauenfeld (2016) stated that urban areas can lead to a temperature rise of 1.9°C especially in summer and in the evening in local areas, based on simulations by the global climate model under a low-emission scenario. Moreover, urbanization will also result in uneven distributions of precipitation, strong monsoon in the summer, and weak monsoon in the winter. The interaction between urbanization and climate change has become one of the hot topics in climate change study.

5.5 Influences of urbanization in China on regional climate and air quality

The change from the natural underlying surface to the man-made underlying surface alters the exchange of energy, momentum, moisture, and trace gases in the vegetation–soil–atmosphere continuum, which in turn affects local and regional circulations and climate as well as the dispersion of pollutants and air quality (Fig. 9) (Wang X. M. et al., 2007; Wang et al., 2009a, b; Zhang et al., 2010, 2016b; Ma et al., 2019). Moreover, a series of urban environment problems such as extreme weather, sea level rise, and poor air quality will exacerbate if no reasonable planning is conducted under the context of global warming, which will impose negative impacts on public health and sustainable development in China.

The high heterogeneity of the urban underlying surface makes its boundary layer more complicated in space and time, which has a significant influence on the persistence of pollutants in the atmosphere. As reported by Wang et al. (2009b), an increase in urban area might result in an increase of air temperature at 2 m above the ground level (AGL) and boundary layer height, and a decrease in wind speed at 10-m height. Significant changes can be found in concentrations of $O_3$, $NO_x$, VOCs, SOAs, and $NO_3$ free radical on the surface resulted from changes in meteorological conditions (Wang et al., 2009a, b). The concentration of $O_3$ is increased by 2.9%–4.2% during the daytime and 4.7%–8.5% at the nighttime,
while NOx and VOCs concentrations are decreased by 4 and 1.5 ppbv, respectively. The concentration of NO3 free radical on the surface of major cities is increased by approximately 4–12 pptv. In general, the areas where the concentrations of O3 and NO3 free radical increase correspond to the areas where the temperature rises and wind speed decreases; the Aitken modal SOA is greatly affected by urbanization (–3% to 9%), of which, the SOA produced by aromatic precursors is the most remarkable (at the growth of 14%). Similar results can also be found in Beijing–Tianjin–Hebei region (Yu et al., 2012).

6. Concluding remarks

Numerous studies have been carried out to build urban meteorological observational networks, conduct field experiments, develop urban meteorology multi-scale models, investigate the interaction between urban meteorology and atmospheric environment, and probe the impact of urbanization on weather and climate over the past decades in China. Major cities in China have established or are improving their integrated urban meteorological observation networks featuring multiple platforms, multiple variables, multiple scales, multiple links, and multiple functions. Also, campaign-style urban meteorological observational experiments in Beijing, Nanjing, and Shanghai are included in the research demonstration project of WMO. Wind tunnel experiments and scale-model outdoor measurements of urban meteorology were conducted. Meanwhile, multi-scale urban meteorology and air quality forecasting numerical model systems have been established and applied for operational service. Furthermore, substantial progress has been made in research fields such as urban heat island effect, urban impacts on precipitation, urban meteorology and planning, urbanization impacts on regional climate and air quality, and the interaction between urban meteorology and atmospheric environment. All of these activities have significantly accelerated the development of urban meteorological research and application in China.

In order to realize the leap of China from a large meteorological country to a strong meteorological country, the following aspects should be prioritized to integrate the future development of urban meteorology with urban system science and social science and to address needs of urbanization, ecological civilization construction, disaster prevention and mitigation, and appropriate response to climate change.

1) Application of new observation technology and observation data assimilation. The Doppler wind/temperature/humidity lidars, optical fiber temperature measurements, unmanned aerial vehicles (UAVs), and other new technologies make it possible for 3D atmosphere observations at a higher resolution. Besides, mobile phone positioning based on geographic information systems, automotive temperature reports and the like technologies will provide more observational data for urban meteorological research. All the above would provide new opportunities for researches concerning urban meteorology. Special attentions should be paid to the assimilation of observational data in urban areas because of the multi-scale heterogeneity of the urban underlying surface and the spatial representation of observations in urban areas.

2) Urban system model development. Human activities occupy an extremely active and core position in the urban system, directly affecting the urban atmosphere. Human activities and their impacts on transportation systems, energy systems, water systems, etc. should be considered in the urban land surface model, the atmospheric model, and the chemical model for investigation on the
coupling mechanism of human, land, and atmosphere. A multi-scale urban system model that can reflect the characteristics and influences of human activities and to perform applied studies on urban planning and construction as well as urban safe operation, etc. should be established. By building up an urban master dataset, the human activities, meteorological big data, and machine learning (including deep learning) can be applied to urban system model research.

3) The influence mechanism of urbanization on weather and climate. The occurrence, development, and movement of weather systems are affected by urbanization through thermodynamic, dynamic, and microphysical processes, forming unique urban weather and climate characteristics. The types and quantitative influences of urban processes on the formation and development of heatwaves, precipitation, and fog/haze, and their contributions to regional climate changes should be further investigated.

4) Impacts of urbanization on atmospheric environment and human health. Urbanization and UCL/boundary layer structure are crucial factors affecting air quality in cities. Countermeasure on the impacts and adaptation of urban climate on/to the atmospheric environment and human health should be carried out.

5) Integrated urban hydro-meteorological, climate, and environmental services (IUS). The IUS Guide was approved by the 71st Session of the Executive Council of the World Meteorological Organization in Geneva, Switzerland on 18 June 2019, indicating that an urban meteorological observation system, a multi-scale numerical model system, a multi-hazard early warning system, and an IUS platform that satisfies IUS requirements should be set up for IUS implementation.

Acknowledgments. The authors gratefully acknowledge the help provided by Yizhou Zhang and Jiayi Cai from Institute of Urban Meteorology and Jian Hang from Sun Yat-sen University during the writing of this paper.

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