Research Progress on the Impact of Urbanization on Precipitation in Beijing

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Abstract. This paper analyzes and summarizes the main approaches and conclusions of previous studies. The approaches are divided into the observation-based method and the model-based method. These researches aimed to find out the trend in precipitation in Beijing and the influencing schemes. The difficulties they faced include coupling induction of urban and terrain as well as the complexity of urban canopy simulation. In the end, it can be concluded that different research approaches may produce different results, thus it is important to improve the weather models and Urban Canopy Model in order to solve the difficulties such as coupling induction and the complexity of urban canopy simulation. The improvement in data analysis and models can both lead to a more accurate result.

1. Introduction
Beijing (40ºN, 116ºE) has experienced a rapid urbanization process in the past two decades. The total area of urban land use has increased from 500 km\textsuperscript{2} in 2000 to 1,300km\textsuperscript{2} in 2019 and the urban population in Beijing has exceeded 21 million\cite{8}. At the same time, the frequency and intensity of extreme rainstorms in summer also increased significantly in Beijing\cite{5}, leading to serious urban waterlogging and brought great losses to social and economic development. The researches of urban modification on precipitation in Beijing can not only deepen the understanding of the mechanism of urbanization on regional climate thus support the urban planning, but also play an important role in improving the weather forecast technology in urban areas which can help with the establishment of urban disaster prevention and relief system in Beijing. Although a large number of researches in this field have been carried out, the relevant research conclusions and their potential influencing mechanisms are still controversial so far. The content of this research can be divided into the following parts: First is the development of researches in this field. Second is the analysis of current studies based on two different research approaches. Third is the difficulties and breakthrough in current studies. The purpose of this study is to summarize the previous studies, analyze the existing problems at the current stage, and put forward suggestions and possible research directions in the future, so as to provide references for other researchers in this field.

2. Development and status in quo
Studies on the impact of urbanization on precipitation can be traced back to the 1970s, Changnon, G. Dzurisin et al. conducted METROMEX (Metropolitan Meteorological Experiment) in St. Louis, the USA\cite{1}. This project involved 4 research groups planning and working cooperatively to study the man-made changes in precipitation. METROMEX field measurements in the summer of 1971 involved 220 rain gages and hail pads, 3 radar sets, 70 rainwater collectors, 14 pibal stations, 4 meteorological aircraft, unique atmospheric tracers, and a wide variety of standard and unusual meteorological equipment.
Obviously, this is a research based on observation. According to the research, in the immediate downwind areas of St. Louis, the summer precipitation increased by 10–17%, moderate rain days increased by 11–23%, heavy rainstorms increased by 80% and thunderstorms increased by 21%. Shepherd et al. [3] and Mote et al. [2] based on TRMM (Tropical Rainfall Measuring Mission) satellite observations and ground radar data analysis respectively, found that the summer monthly precipitation in Atlanta, the USA increased by about 28% in the 30-60 km downwind direction of the city, thus further confirming the conclusions of METROMEX. After that, some scholars studied the influence mechanism of urbanization on precipitation, which can be divided into three aspects: First, the urban heat island effect enhances convection and forms a convergence center in urban area. Second, urban buildings increase the surface roughness and change the movement of near-ground airflows, which is beneficial to the formation of convergence center. Third, the increase of aerosol changes the distribution of condensation nuclei.

To focus on Beijing, the annual precipitation in Beijing has been decreasing significantly in the past 50 years, especially in summer due to the weakening of the East Asian monsoon. However, it is noteworthy that research done by Hou in 2012 [4] showed that though there is a fluctuant downward trend in long term precipitation during the flood season (June-September) in Beijing, there has been an obvious increase in precipitation during the flood season in recent years (1998-2010), and the proportion of precipitation in the flood season is increasing as well. Hou came to this conclusion through observations from ground weather stations and analysis of TMPA (TRMM Multi-satellite Precipitation Analysis) data. This research suggests that urbanization may be the driving force behind this change. In addition, some researchers studied the impact of urbanization by analyzing the frequency and intensity of precipitation, the number of precipitation days, and the spatial distribution of precipitation in Beijing. However there are some difficulties and limitations in explaining the urban modification on rainfall currently. For example, the research done by Xu et al. [5] reveals the spatial variation of precipitation in Beijing. The precipitation is much lower in urban areas than in rural areas. The precipitation decline in Haidian district is especially obvious. This change might be linked with the urbanization, but the authors believed the influences of topographic factors are more responsible for this phenomenon. The urban area is located in the plain area in the south of Beijing, while Beijing has the Yan Mountains in the north and the Taihang Mountains in the west. The warm and moist air from the southeast forms orographic rain on the windward slopes. Differences in natural conditions make it difficult to discuss the impact of urbanization in isolation.

3. Comparison of different research approaches and results

3.1 Based on observation

Observation-based research approaches mainly refer to the analysis of rainfall data from ground weather stations, radars and remote sensing satellites by statistical means. This is a research method that infers causes based on established facts. This research mainly analyzes two observation-based studies to compare their similarities and differences. The first research is done by Sun in 2010[6]. Based on the precipitation data in Beijing area from 1961 to 2007, the climate characteristics and the changing trend of the heavy rain in Beijing area were analyzed by using polynomial curve fitting and Morlet wavelet method. Sun chose three weather stations that are located at Nanyuan, Xijiao and Shahe to represent the regional climate characteristics of upwind direction, urban area and downwind urban area respectively and compared the change trend of summer rainstorm days in the three stations from 1961 to 2007. All three stations showed a decreasing trend, but the decreasing trend in Shahe was the least significant, which may be related to the rain-increasing effect in downwind urban area. This coincides with the conclusions of another study which is conducted by Li et al. in 2011[7]. Unlike the Sun, in Li’s research, weather stations in Haidian and Chaoyang districts were selected to represent precipitation in urban areas while stations in Miyun, Shunyi and Huairou districts were selected to represent the downwind direction. Li summarized rainfall data for various precipitation levels (light, moderate and heavy precipitation) in all regions of Beijing over the past three decades and came to the following conclusions:
First, the general trend of light rain throughout Beijing is decreasing (-2.31mm/10 years), while the decreasing rates in urban (-0.88mm/10 years) and downwind areas (-0.51mm/10 years) are much slower. Second, both moderate rain (4.75mm/10 years) and heavy rain (14.5mm/10 years) are increasing in urban areas. But in downwind areas moderate and heavy rainfall events are decreasing. Li suggests the possible explanation of the observation above is that when the large-scale stable precipitation system (e.g. East Asian monsoon or Mongolian high pressure) is weak, the urban effect can be seen. The large concentration of condensation nuclei due to the emission of pollutants, and the existence of heat island circulation can lead to an obvious increase in precipitation in urban areas and downwind direction. However, if the large-scale weather system is strong, the effect of urbanization on local precipitation is quite weak.

The advantage of the observation-based approach is that it can eliminate the effects of climate system variability, for example the global warming. But the disadvantages are as follows: First, such methods need to select representative sites that can represent the characteristics of the underlying surface of urban in the analysis period. Second, the consistency of the data sequence of the sites also needs to be strictly controlled. For example, the Xijiao weather station has experienced many relocations so the consistency of data is influenced. Meanwhile, with the impacts of urban expansion, Some suburban weather stations have become urban weather stations. Both of these studies indicate that urbanization can produce an urban rain island effect, leading to the increase in precipitation in urban areas and downwind areas. But Li’s research also reveals that the decrease of precipitation in Beijing is still the main feature, and argues that the influence of urbanization on local precipitation is limited compared with the large-scale climate change.

3.2 Based on model
Model-based research approaches refer to simulate the long-term climate characteristics and the physical mechanism by using numerical meteorological models (such as WRF, MM5, etc.) or theoretical physical models. In general, the model-based research approach is based on individual case analysis. The basic idea is to select a number of rainfall events that can represent the mechanism of universal causes of precipitation in the region, simulating the change of factor field (water vapor flux, temperature, wind speed, etc.) through sensitivity numerical test (change of the underside surface conditions, land use type, etc.), and to analyze the influence mechanism from the perspective of weather science.[8]

The research done by Guo et al. in 2006 stimulated urban modification on precipitation in Beijing based on the convective precipitation system that occurred in Beijing on June 4th, 2013 by using MM5 (Mesoscale Modeling System).[9] Guo investigated the impacts of land surface change on the precipitation in Beijing by assuming an increase in land roughness and albedo and a decrease in thermal inertia and moisture availability. The conclusion of this research are as follows: First, the total accumulated precipitation in Beijing would decrease significantly, especially in urban areas, because of the increase of surface roughness over land that enhances the lower convergence. Second, the precipitation intensity and distribution are also simulated by MM5, and the core of high precipitation intensity is found downwind of the urban. The peak rainfall located near the borderline is 40mm for the non-urbanized condition and 65mm for the urbanized condition. The second conclusion is more consistent with the observation in Beijing.

Another model-based research done by Wang in 2012 [10] focused on the impacts of land surface change on precipitation which is similar to Guo’s research. However, it is quite different from the previous one. Wang’s research is a long-term simulation based on WRF (Weather Research and Forecasting Model). This research studied the annual precipitation between 2007-2009 in North China (includes Beijing) and simulated the precipitation trend. It is interesting that Wang believed urbanization will reduce precipitation by elevating the planetary boundary layer height thus reducing the instability of the lower atmosphere, however, the WFR model simulation shows that precipitation will increase in North China, which is apparently contrary to his hypothesis but consistent with the observation. For this unexpected simulation, Wang believed it is the result of another thermodynamic mechanism that is not mentioned in his research.
Compared with the observation-based research method, the advantage of the model-based approaches is that they can explain the physical mechanism of precipitation with the help of sensitive numerical experiments and explain the impact of urbanization from a mechanical point of view. The disadvantage is that individual analysis of regional climate characteristics is often limited in representativeness, and the conclusion is less replicable. In addition, the accuracy of the model itself will bring uncertainty to the simulation results. In most cases, the interaction between the various influencing factors makes precipitation simulation more difficult.

4. Research difficulties and breakthroughs

4.1 Coupling induction of urbanization and terrain

Beijing is located on the northern edge of the North China Plain, surrounded by Taihang and Yan Mountains in the west, north and northeast of the city. The orographic factor plays an important role in affecting the precipitation pattern in Beijing. The research done by Hou [4] shows that the spatial distribution of precipitation in Beijing is consistent with the topography, decreasing from northwest to southeast. Fig.1 below is the topographic map of Beijing. Fig.2 below is the distribution of precipitation days between 2000-2009.

Fig.1. the topographic map of Beijing [7].

Fig.2. Distribution for rain days in Beijing during 2000-2009 [7].
The impacts of a topographic factor on precipitation have been discussed in many researches, but the effects are still quite controversial. The coupling effect between city and terrain makes it complicated to analyze the precipitation mechanism in Beijing, especially for observation-based researches. Currently, the effects of terrain on rainfall cannot be separated from the observed data, resulting in a more or less inaccurate understanding of the urban modification on rainfall. In many researches, suburban weather stations (such as Miyun) are often selected to compare with urban sites, and the difference between stations is attributed to the impact of the urbanization. However, Yang [8] holds that the usual choice of suburban stations is located near the mountains as well as in the downwind direction, the local climate there have significant differences with the urban sites, so the precipitation difference between urban and suburban stations is the overlay effect of urban and topographical impact. The possible solutions to cope with the coupling induction of urban and topography are as follows: First, numerically based research methods can separate cities from terrain by means of sensitivity testing. Second, future research ideas can use spatial analysis methods (such as principal component separation) to extract the influence of topography on the spatial distribution of precipitation separately and remove it from the spatial field of precipitation[8].

4.2 Complexity of urban canopy simulation

In early meteorological models, the underside of the city was used as a "plate" with high roughness and special thermal properties, and the geometric characteristics of urban areas were not taken into account. However, there is significant non-uniformity in both horizontal and vertical directions of the underside of the city, such as the height, orientation and spatial distribution of buildings according to Liu et al.[11]. Fig.3 shows the conditions of the underlying surface around Beijing 325m meteorological tower.

![Fig.3. The condition of the underlying surface around Beijing 325m meteorological tower](image)

In recent years, breakthroughs in numerical simulation methods and models like UCM improved description of urban geometry, material properties and thermodynamic processes. The Urban Canopy Model (UCM) is usually used to describe the complex characteristics of urban underlying surfaces in numerical weather models. UCM also improves the accuracy of simulation results based on WRF.
5. Conclusion
In recent years, the rapid urbanization in Beijing has brought about significant changes in regional precipitation. The researches in this field can be divided into two categories according to the researching approaches. First, in observation-based researches, the precipitation data were analyzed and it was found that there was a significant increase in precipitation in urban areas and downwind direction of urban areas, but the causes of this phenomenon is still controversial. Second, in model-based researches, MM5 and WRF are the most widely-used simulation models. Results from different models and spatial-temporal scales may vary. Third, the current limitations in researching the urban modification on rainfall over Beijing include: a) the coupling induction of urbanization and topography. b) the complexity of urban canopy simulation. Fourth, to improve the accuracy of future researches, efforts can be focused on a) enhancing real-time monitoring of rainfall with high-precision Doppler weather radar and improving methods of data statistics and analysis. b) improving the functions of UCM in describing the influence of urban underlying surface on energy and momentum transmission process in the meteorological model. c) removing the influence of topography on the spatial distribution of precipitation by using methods like principal component separation, therefore reduce the coupling induction.

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