Review

Research Progress for Dynamic Effects of Cities on Precipitation: A Review

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Abstract: Citization significantly changes original surface properties. City areas can cause surface winds to decrease; furthermore, ground friction can be transferred layer by layer through the momentum exchange of air movement, which affects the air layers above. Precipitation modification by city environments has been an active research area. Under the conditions of high wind speed, the dynamic effects of cities on precipitation are relatively obvious. Generally, the dynamic effects fall into two main categories: (1) for weather systems under weak forcing synoptic backgrounds, such as local convective systems, shorter-lived extreme precipitation events and fronts and city barrier effects can delay the movement of weather systems, directly change the horizontal distribution characteristics and occurrence time for precipitation, change the flow field and structure, cause the bifurcation of weather systems, and change the horizontal distribution characteristics of precipitation; (2) for weather systems under strong forcing synoptic backgrounds, such as extratropical systems (with large-scale moisture transport), monsoon systems, landfalling tropical cyclones, and supercell storms, the impact of the dynamic effects of cities cannot lead to the bifurcation of the weather system, nor can it change the horizontal distribution characteristics of the whole precipitation field, but it can have an impact on the local precipitation intensity and distribution. However, currently, people do not agree on the impact of cities on precipitation, especially regarding tropical cyclones. Hence, we provide a review and provide insights into the dynamic effects of cities on precipitation.

Keywords: cities dynamic effects; barrier; bifurcation; precipitation; tropical cyclone; citization

1. Introduction

The industrial revolution led to the rapid development of city areas. This has continued unremittingly over the last 200 years or so. Citization, which refers to the process of population concentration to city areas and which causes the continuous expansion of city areas, is accompanied by the replacement of natural land surfaces by artificial surfaces that significantly change the original surface properties of the land where the city is located. Parameters that are uniquely modified by citization include land use, surface roughness, green vegetation fraction, albedo, volumetric heat capacity, and the thermal characteristics of soil [1,2]. In most city areas, the surface properties are heterogeneous, which has significant implications for energy budgets, water budgets, and weather phenomena within the part of the earth's atmosphere in which humans live. This paper focuses on the latter, specifically reviewing the impact of citization on precipitation. As early as the 1920s, Horton noted that some cities in the northeastern United States might be more likely to experience thunderstorms [3]. By the 1950s, the first documented case of city-induced changes in precipitation was shared by Landsberg in Tulsa, OK, USA. He found indications that the city was causing increased precipitation [4]. During the 1970s, the Metropolitan Meteorological Experiment (METROMEX) study, which was an intensive field campaign conducted in St. Louis, MO, USA, uncovered a strong relationship between city land cover

and precipitation enhancement [5,6]. The impact of citization on precipitation has been extensively examined following the METROMEX study in the late 1970s. Modeling and observational studies show that citization has induced detectable precipitation anomalies both over and in downwind city areas [7–15]. In addition to local changes, citization can also make large-scale alterations, forcing temporal and spatial changes in precipitation patterns. Studies have also revealed that city land cover can have an impact far beyond its physical boundaries, such as storm splitting, the modification of large-scale precipitation patterns, the modification of storm morphology, or the alteration of the spatial location of storm cells due to increased frictional convergence [7,11,16–19]. Precipitation modification by city environments has been an active area of research for the last 50 years. A number of studies have theorized that these modifications are facilitated through city-related thermodynamic and dynamic factors, which can significantly influence mesoscale circulation and the resultant convective activities. Collectively, the impacts of cities on precipitation involve thermodynamic, dynamic, and chemical effects. Mechanistically, there are three nonexclusive primary mechanisms hypothesized to explain the phenomenon: thermodynamic effects (urban heat island (UHI) effects), dynamic effects (canopy effects, barrier, and friction), and chemical effects (condensation nuclei and aerosols) [9,20–27]. However, city-induced changes in precipitation tend to be subtle and less detectable than changes in visibility, winds, and temperature. Despite the numerous studies demonstrating the important role that city clusters play in enhancing precipitation in city areas, opposite effects of citization on precipitation have also been found among different cities; some studies have even found an opposed signal among different seasons or areas in the same city [28–43]. There is still uncertainty and scientific debate about whether city environments increase precipitation, decrease precipitation, or have no effect on precipitation. Furthermore, the mechanisms responsible for the city–precipitation relationship are not fully understood; Up until now, there have been many reviews and studies on the influence of the urban heat island effect on precipitation [28,44–46]. It should be highlighted that dynamic effects remain relatively poorly understood; specifically, the literature on the "building barrier effect" is relatively scarce.

More specifically, dynamic effects involve increases in surface roughness and enhancements to the drag and lift effects on the airflow. This is due to increased city roughness. The enhanced convergence favors the increase in vertical velocities, thus leading to more storms over city areas [21,47,48]. In addition, precipitation systems have also been found to move around citized region due to the building barrier effect in the city canopy, which results in the bifurcation of precipitation distribution over and around the city [10,21,29,49,50]. It is worth mentioning that, on one hand, the factors of citization that influence precipitation are very complex and are affected by both natural factors, such as atmospheric circulation, weather system, water vapor transport, atmospheric stratification instability, and human activities; on the other hand, various influencing factors are dynamically changeable. For example, with the continuous expansion of a city area and with the increase in high-rise buildings, the "precipitation enhancement effect" will be more significant. Therefore, it is necessary to conduct a comprehensive analysis of the existing research results on the impact of citization on precipitation, which calls for increased research on "building barrier effect" topics. We are currently working on this problem. This paper reviews the findings related to dynamic influences of cities on precipitation, especially regarding tropical cyclones (TC), and describes a meaningful prospect for the future. In the next section, the dynamic effects of cities are reviewed. Furthermore, insights into the dynamic effects of cities on precipitation are given in Section 3.

2. Review on Dynamic Effects of Cities

Buildings can produce pressure and viscous forces, which alter wind speeds and increase turbulent mixing [51]. As we know, one of the most remarkable characteristics of the complex underlying surfaces of cities is high-rise buildings. Carraca and Collier found that high-rise buildings over relatively small areas may have just as much of an

impact as somewhat lower buildings covering a much larger area [51]. In order to understand the dynamic effects of cities more intuitively, the complex underlying surface of a city with high-rise buildings is regarded as "city–building topography" or "man-made city topography" [49,52,53]. To some degree, the dynamic effects of cities are similar to the terrain forcing effect. Specifically, roughness length is a parameter to measure the complexity of a surface by averaging land–surface feature heights compared to the square area of land–surface features [54]. Higher land–surface values indicate a rougher surface, meaning higher turbulence and slower wind speeds. A roughness length value closer to zero indicates a flat, more homogenous surface, allowing for elevated wind speeds both at the surface and above. City environments have a complex surface, allowing for slower wind speeds due to higher roughness lengths. As wind flow slows, the wind is either directed around or over a land–surface feature. As a result, the perturbation displaces the air above and on the leeward side of a city object. In some cases, the entire city area may impact the air flow around a city. The city perturbation in air displacement is similar to the process of leeward cyclogenesis at a synoptic scale with natural terrain, but in these instances, this occurs at a meso or local scale with anthropogenic surfaces. The spin or eddies induced by the wake of the topographies of human-made cities can cause air to converge and rise, thereby allowing convection to take place downwind of city objects, such as large and tall buildings. These features that can appear due to rougher city surfaces are schematically depicted in Figure 1 by Cotton and Pielke [55,56].
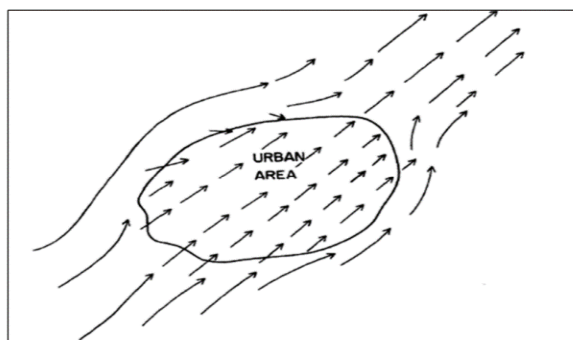

Figure 1. Schematic of low-level airflow over and around a city area due to changes in surface roughness. Notice the size of wind flow vector arrows over the city compared to wind vectors upwind, around, and downwind of cities (Cotton and Pielke [55,56]).

2.1. The Dynamic Effects of Cities on Wind Field

Urbanization affects the 10 m wind speed and direction; for example, city buildings increase surface roughness length z0 values, increasing the frictional drag over a city [54]. As surface winds encounter the increased roughness of city areas, horizontal speeds tend to notably decrease. Zhou highlighted that with the development of Shanghai, China, the wind speed in the city area has a decreasing trend year by year at different heights that can be measured by a wind meter. At the same time, the wind speed in the city is obviously lower than that in the suburbs. The closer the city is, the smaller the wind speed is, and the greater the horizontal gradient of the wind speed appears [57]. Xu used meteorological data from 1971 to 2002 to analyze the distribution characteristics of wind speed and direction when typhoons with different paths affected Shanghai. It was found that the intensity of the typhoons that affected Shanghai in recent decades did not show a weakening trend, but the wind speed in city and suburban areas decreased gradually. He suggests that this is due to the continuous expansion of the city area due to the development of Shanghai, resulting in the increase in underlying surface roughness. Under the influence of the typhoon, the wind speed in the city area is small, and the higher the wind speed in the suburbs is, the more obvious the effect of wind speed weakening is [58]. Researching the influence of Shanghai on the near surface wind field, Su showed that the frequency of small amounts of wind in the city areas has increased significantly. The wind speed in cities tends to be

below 200 m in the summer, which is less than the summer wind speed in the suburbs, and the height seems to be greater in the winter [59]. Tian et al., through analyzing the observation data of the Guyuan structure influence in Hebei Province, China, concluded that the attenuation effect of barriers on wind speed has a great relationship with the background wind speed. With the increase in wind speed, the influence of barriers is enhanced. As the ground friction resistance is affected by the ground friction during the air movement in the near ground layer, the ground friction can be transferred layer by layer through the momentum exchange of air movement, which affects the air layers above. The larger the wind speed, the stronger the attenuation effect [60]. Studying the influences of city building complexes on the ambient flows over the Washington–Reston region, Zhang et al. show that the thermodynamic and horizontal wind fields in the city's boundary layer and above can be significantly modified by buildings of different scales [61]. Their results indicate the importance of incorporating building heights and a multilayer city canopy scheme into numerical weather prediction models for the study of city boundary layers. The above analysis shows that city areas can cause surface winds to decrease; furthermore, the ground friction can be transferred layer by layer through the momentum exchange of air movement, which affects the air layers above.

2.2. The dynamic Effects of Cities on Weather System

2.2.1. Weather Systems under Weak Forcing Synoptic Background

The vertical structure of buildings and its effects on local mesoscale circulation are hypothesized to redirect or bifurcate existing thunderstorms around the periphery as they approach city areas [62]. A few studies have investigated the effects of city areas on storm movement and the occurrence of storm bifurcation [21,22,49,63]. Some other studies have also highlighted that city land cover affects storm movement through its building barrier effect [21,29]. Studying the effects of New York City (NYC) on frontal movement, Loose and Bornstein found that the city area of NYC is capable of retarding the movement of synoptic-scale fronts as they pass from the relatively smooth non-city areas around the city to the rougher central city area. This retardation was probably due to the increased surface frictional drag exerted on the front by the increased surface roughness of the city compared to that of its surroundings [49]. Investigating the influence of citization on a typical frontal precipitation event that occurred in June 2008 over the greater Beijing metropolitan area (GBMA), Zhong and Yang found that the underlying city surface retards the movement of cold fronts. Their diagnostic results show that the weaker-than-normal cold advection and the subsequent smaller pressure jump during the frontal passage over the GBMA are the major mechanisms behind citization effects, which lead to the retardation of the movement of cold fronts [64]. Based on ensemble simulations, Zhong and Yang investigated the effect of the city on a typical frontal system in the GBMA in China. The underlying city surface was not only found to influence the spatial distribution of precipitation but also to slow the cold front movement during precipitation events. Moreover, slow-moving cold fronts delay the occurrence of peak precipitation but enhance the maximum precipitation intensity [65]. Taking the municipality of Beijing as a case study and by analyzing the hourly precipitation data from 20 automatic weather stations for the period of 2011–2015, Zhu et al. found that the city's high buildings can slow down air masses, hence lengthening precipitation events [66]. It can be seen that city barrier effects can delay the moving speed of a weather system or change its moving direction and can then also change the precipitation intensity, horizontal distribution characteristics, and the time of the precipitation peak.

Furthermore, the modulation of storm movement due to the climatic influences of the city region could result in storm bifurcation, as suggested by Gaffen and Bornstein, who analyzed a slow-moving front passing through NYC on 10–11 March 1966. Due to the initial slow speed of the front, the surface roughness of NYC was able to retard its movement, resulting in a horizontal split in the vertical structure between the surface front and upper segments [67]. However, one facet of city precipitation that remains poorly understood is the impact of storm bifurcation. Of note, Bornstein and Lin defined storm bifurcation as "a

group of storms [that] moves in two directions from a specific location (such as upwind of city)". This phenomenon differs from storm splitting in that splitting is "a single initial storm [that] splits into two separated supercells, given appropriate vertical wind shear conditions", while it is possible for storm splitting and bifurcation to occur in multiple types of precipitation events (frontal, convective, and tropical) [21]. Heretofore, Bornstein and LeRoy termed this diffluence as the "building barrier effect" [50]. Studying bifurcation is important on the basis of the following reasons: First, it contributes to providing a baseline for future investigations on bifurcation, a topic which has only been minimally examined and characterized in a climatological context. Second, an improved understanding of bifurcation occurrence can also aid forecasters in city regions, both at a meteorological level as well as for local and regional climate modeling. Finally, results from analyses could potentially be used to inform city planners in considerations such as assigning appropriate zoning types for precipitation-enhanced regions [68]. Bornstein and LeRoy showed that the building barrier effect could affect mesoscale and synoptic flow patterns and systems passing over NYC. They found that preexisting thunderstorms moving toward the city tended to bifurcate and move around the city area. Analyses of surface flow patterns, surface convergence fields, tetroon vertical velocities, and double theodolite velocity fields all point to the city barrier effect as the most significant factor altering such flows over NYC [50]. Bornstein and Lin shed light on storm bifurcation in Atlanta. They showed that when regional winds are strong, surface diffluence occurs, causing the storm to bifurcate, as the storm encounters the increasing surface roughness of the city center [21]. Niyogi et al. argued that storms were commonly altered by the city landscape of Indianapolis, Indiana. They found that more than 60% of storms changed structure over the Indianapolis area as compared to only 25% over rural regions. Furthermore, daytime convection was the most likely factor to be affected, with 71% of storms changing their structure compared to only 42% at night. An analysis of radar imagery indicated that storms split closer to the upwind city region and merge again downwind. They suggested that the friction and drag force from tall buildings appear to be the causes of bifurcation [11]. Recently, Lorenz et al. investigated the direct influence of city areas on storm events (heavy precipitation above 17 mm/hr) for Berlin, Germany, based on an 11-year climatology of summertime precipitation. They found that around 60% of the events showed typical patterns of storm alteration by the city. Most storms were suppressed, deflected, or split by the city [69]. It can be seen that the delay of the weather system caused by the city's blocking effect can alter flow and change storm structure and can then result in bifurcation.

Additionally, observational and modeling investigations have suggested that the increased surface roughness of city canopies can cause a bifurcation or diversion of precipitation systems while passing over cities, further modifying precipitation distribution [10,11,14,21,49,50,70]. Storm bifurcation has been shown to influence the location of maximum precipitation in NYC [2,49]. Climatological precipitation studies and case studies of thunderstorms found possible city barrier-influenced precipitation minima over Phoenix and Atlanta, respectively [71,72]. Dixon and Mote showed that the process of storm bifurcation tends to produce precipitation maxima on the downwind periphery of the city region (where confluence occurs) and precipitation minima in the city center [22]. Ntelekos et al. investigated the occurrence of storm bifurcation. They confirmed this suggestion by observing a multicell storm that split into two elements as it reached Baltimore and by attributing the bifurcation to frictional effects caused by the city canopy, resulting in increased precipitation totals and lightning flashes along the western edge of Baltimore and Washington D.C [63]. Miao et al. conducted a case study on the effects of city processes on summer precipitation over Beijing using a three-dimensional mesoscale model. They indicated that the presence of the city leads to the breaking of the squall line into convective cells over the city area and that high-rise city cores may bifurcate the path of precipitation and increase the area percentage of heavy precipitation [10]. Dou et al. investigated interactive effects from the Beijing city area on wind and precipitation using hourly automatic weather station data from June to August 2008. The results showed that

afternoon and evening southerly winds were bifurcated by a city building-barrier-induced divergence. Summer thunderstorms also thus bifurcated and bypassed the city center due to the building barrier effect during both daytime and nighttime weak-UHI periods. This produced the precipitation minimum in the city center and directly downwind of the city area, with maximum values along its downwind lateral edges [73]. It can be seen that the bifurcation of the weather system caused by the city barrier effect can alter the horizontal distribution characteristics of precipitation. Although the present research hypothesizes that storm bifurcation occurring in cities is likely to produce precipitation enhancement, evidence suggests that the interaction between the city's land surface and storm movement is complex.

From the above analysis, we can determine that for weather systems under weak forcing synoptic backgrounds, such as local convective systems and shorter-lived extreme precipitation events and fronts, the city barrier effect can delay the movement of the weather system, directly change the horizontal distribution characteristics and occurrence time of precipitation, change the flow field and structure, cause the bifurcation of the weather system, and change the horizontal distribution characteristics of precipitation. In fact, the distribution of synoptic precipitation delivery mechanisms (e.g., frontal, tropical, and convective) differs from city to city, which actually depends on the synoptic and local systems that induce the precipitation process, thereby likely contributing to spatial variations in city–precipitation interactions, including storm bifurcation.

2.2.2. Weather Systems under Strong Forcing Synoptic Background

Thus far, much progress has been made in understanding the impacts of cities on precipitation associated with local convective systems in the warm season. Although several modeling studies have indicated that city environments can influence the spatial distribution and quantity of precipitation even under strong large-scale forcing, they have generally focused on shorter-lived extreme precipitation events during the warm season [13,25,74]. However, Yeung et al. found that while organized thunderstorms associated with strong dynamic forcing change structure and initiate new cells more frequently over the city area, these storms do not split as they approach from the west [15]. These results differ from those that consider weakly forced convection, suggesting that the complexities of precipitation modification caused by cities during organized, sustained synoptic-scale forcing merit further investigation. In fact, our knowledge of the impact of citization on various synoptic systems and their related precipitation processes remains incomplete, especially for severe storm events under strong synoptic forcing, including extratropical systems (with large-scale moisture transport), monsoon systems, landfalling tropical cyclones, and supercell storms [75–79]. Extreme precipitation associated with these storm events and the resultant flooding has plagued city dwellers and sustainable city development in recent decades. For instance, Yang et al. investigated the impact of urbanization on a severe thunderstorm under strong large-scale forcing over the Milwaukee–Lake Michigan region. Their analyses show that urbanization does not change the cloud structure at regional scales, while it can modify space–time organizations of extreme precipitation around the city [13]. Studying the influence of a great plain city environment on a simulated supercell, Reames and Stensrud found that precipitation patterns in the simulations were not well correlated with city location. They suggested that organized convective processes are less susceptible, on a large scale, to the effects of city areas, but that storm-scale deviations (e.g., mesocyclone strength and track) can be modified by a large city area [79]. Debbage and Shepherd provide an extension of past research that has primarily addressed the precipitation effects of cities under synoptically benign conditions (i.e., warm season convection) by analyzing possible city-induced alterations of precipitation during an event with prominent synoptic-scale forcing [75]. Paul et al. argued that there is a limited number of studies on understanding the impact of citization in India regarding summer monsoon precipitation, which is traditionally believed to be governed and dominated by large-scale circulations [77]. Debates exist in the scientific community on the impacts of local-scale

urbanization regarding large-scale monsoon driven extremes. Recently, Zhang et al. suggested that more high-resolution observational and modeling studies on the impacts of city-scale building complexes on larger-scale flows over different city areas should be performed in order to generalize the above conclusions [61]. The above analysis shows that compared to the impact on the weather system regarding weak forcing, the dynamic effects of cities on the weather system regarding strong forcing cannot lead to the bifurcation of the weather system, nor can it change the horizontal distribution characteristics of the whole precipitation field; however, it can have an impact on the local precipitation intensity and distribution.

Recently, Yang et al. examined the impacts of the urban canopy on two convective storms with contrasting synoptic conditions over Nanjing, China. They found that there is a strong convergence zone over the urban–rural interface that is induced by building complexes, leading to intensified convection for a storm with strong synoptic conditions but bifurcated moisture fluxes for a storm with weak synoptic conditions [80]. In order to facilitate reader understanding, the dynamic effects of cities on weak and strong weather systems are summarized in Table 1. However, there is not enough relevant work at present, which is worthy of further study. As is well known, there are many tropical cyclones making landfall every year; they often strike city areas. Relative to extratropical systems with large-scale moisture transport, monsoon systems, and supercell storms, forecasting the precipitation distribution associated with landfalling tropical cyclones continues to be a challenge. In the next subsection, the impact of urbanization on precipitation from TC is reviewed in detail.

Table 1. Dynamic effects of cities on weather systems.

Forcing Synoptic Background	Weak	Strong
Weather system type	Local convective systems, shorter-lived extreme precipitation events and fronts	Extratropical systems (with large-scale moisture transport), monsoon systems, landfalling tropical cyclones, and supercell storms
Bifurcation/slowing down	yes	no
Changing the distribution characteristics of the whole precipitation	yes	no
Changing local precipitation intensity	yes	yes

2.2.3. Tropical Cyclone

A TC is a strong weather system with more clouds and a high wind speed. Compared with the other two mechanisms of city impacts on precipitation, the dynamic effect is more significant. Generally, studies on urbanization's impact on TC that have been completed to date can be divided into three categories as follows:

- Completely excluding TC: Occasionally, a typhoon or a tropical depression hits Japan, and this causes high precipitation with a distribution that usually shows a marked topographic effect. Data were excluded from study on days when a typhoon or a tropical depression had an influence on the weather in Tokyo, Japan, as Yonetani studied the increase in the number of days with heavy precipitation in August in the Tokyo city area [81]. Similarly, Shimadera et al. focused on local-scale citization impact on precipitation in Osaka, Japan; the days on which a tropical cyclone controlled the meteorological conditions in the target region were excluded from the target period in order to minimize the effect of synoptic-scale precipitation [82]. Niyogi et al. studied citization impacts on heavy summer precipitation climatology over the eastern United States; tropical cyclone/hurricane-related heavy precipitation events were also excluded. Daily precipitation was excluded if there were landfalling tropical cyclones or hurricanes 1 or 2 days prior to the rainy day [83]. This kind of research regards TC as an interference factor. As a result, TC was completely ruled out.

- Indirectly considering the influence of TC circulation background: Meng et al. studied city effects and summer thunderstorms in a tropical cyclone-affected situations over Guangzhou, China, and argued that though local thunderstorms were evidently influenced by the city effects, the tropical cyclone itself may also contribute to thunderstorm initiation and development to a certain extent [84]. This kind of research does not exclude the possible influence of typhoons. However, typhoons are not regarded as the main direct influence factor.

- Directly studying the impact of citization on precipitation from TC: Shanghai is a typical coastal city affected by 2–3 typhoons every year on average. Since the 1980s, some scholars have conducted research on the impact of citization on typhoon precipitation in Shanghai. Zhou et al. analyzed a typhoon inverted through a precipitation process in the Shanghai area on 19 September 1980 and found that high-value closed isohyets appeared in the city area, which was a manifestation of the effect of citization on increasing precipitation associated with typhoons [85]. Based on the precipitation process of 14 typhoons affecting Shanghai from 1984 to 1988, Li highlighted that the city barrier effect was more obvious in typhoon rainstorms accompanied by higher wind speed, and the precipitation intensity in the city area was significantly greater than that in the suburban area in 71% of the typhoon-affected periods [86]. In view of the 17 typhoon precipitation processes affecting Shanghai from 1999 to 2007, Yin and Liang highlighted that 59% of the precipitation intensity in city areas was greater than that in suburban areas during the period of typhoon influence and considered that the city barrier effect caused the overall movement speed of air flow to slow down and the residence time in city areas to increase, leading to the increase in precipitation intensity and precipitation time in city areas, which had a significant and obvious impact on typhoon precipitation [87]. Based on numerical simulation, Qi and Zhao analyzed the impact of the rainstorm process in Shanghai caused by the tropical depression on 5–6 August 2001. They believed that the enhancement of local surface citization in Shanghai resulted in the warm dry characteristic effect of the air near the surface layer and the convergence of the wind speed in the upper wind of the city area, which led to the changes in the mesoscale dynamic and thermal characteristics in the rainstorm system [88]. Wu and Tang studied a heavy rain process related to the residual cloud system of typhoon Nuri (0812) in Shanghai on 25 August 2008. They showed that the citization of Shanghai makes the rainstorm process produce more precipitation in central and windward areas, and the precipitation in the city's leeward area is reduced; the dynamic effect of the change in land surface roughness is caused by citization on the low-level wind field in city areas. They also highlight that the main reason for the increase in precipitation in windward areas is that the vertical upward movement and water vapor increase in the windward area [89]. Recently, some scholars have studied the impact of citization on precipitation associated with typhoons in the Pearl River Delta region of China. Based on the numerical simulation from WRF coupled urban canopy model of typhoon Nida (1604), which landed in Shenzhen in Guangdong Province in China in 2016, Yang et al. highlighted that the increase in city's underlying surface roughness strengthened the vertical convective movement and increased the unstable energy in the region, which is conducive to precipitation enhancement, especially in the underlying surface of citization, where the maximum increment of accumulated precipitation in 6 h can exceed 20 mm after a typhoon lands [90]. Using rain gauge data from 76 stations in Guangdong Province, China, from 1981 to 2015, Yan et al. investigated precipitation characteristics from TC landings along the South China Coast and revealed that the precipitation amount shows a significant increasing trend both in city and non-city areas. However, there has consistently been more precipitation in city areas than in non-city areas during TC landfall. In addition, the difference between the precipitation amount in city and non-city areas also shows an increasing trend over the last 35 years. These results indicate that the precipitation characteristics associated with TCs have been experiencing significant changes because

of the process of citization, which indicates that the precipitation produced by TCs has been enhanced with the accelerated process of citization [91]. Similarly, Category 4 landfalling hurricane Harvey distributed more than a meter of precipitation across the heavily populated Houston area, leading to unprecedented flooding and damage; however, limited attention has been paid to the potential effects of citization on the hydrometeorology associated with hurricane Harvey. Using the Weather Research and Forecast model and statistical models, Zhang et al. quantified the contribution of citization to precipitation and flooding. They found that citization not only exacerbated the flood response but also the total storm precipitation; overall, the probability of such extreme flood events across the studied basins increased by approximately 21 times on average in the period 25–30 August 2017 due to citization [78]. Of course, there are different or even opposite views on the impact of citization on precipitation from TC. Hayes used Multi-Precipitation Estimator and Next-Generation Weather Radar stage III data to examine the effect of city areas on precipitation associated with hurricanes and tropical storms from 1976 to 2005. They displayed that 69.2% of city areas had greater precipitation in the upwind area and also revealed that there is a larger range of higher precipitation values in the upwind area and a smaller range of lower precipitation values in the downwind area; however, they proposed that there is a relationship between the distribution of precipitation and city areas but that there is no relationship between city areas and enhanced precipitation [30]. As Wang et al. investigated the correlation between precipitation frequency, intensity, and extremes and cities extent under different climate conditions over the Pearl River Delta, China, they revealed that precipitation characteristics are less correlated with citization extent during typhoon events. In contrast, the precipitation characteristics of typhoon events have the poorest relationship with citization extent [31]. The above analysis shows that, at present, the research methods determining the effect of citization on TC precipitation include observation and numerical simulation, and analysis methods include individual cases and statistical analysis. Case simulation research shows that citization contributes to the enhancement of precipitation in central city areas and windward areas. Statistical analysis shows that the precipitation intensity in urban areas is greater than it is in suburban areas. Obviously, some research results hold that citization enhances city precipitation, while others hold that the relationship between cities and TC precipitation is weak or even that there is no connection between the two. Hence, at this stage, people do not agree on the impact of cities on TC precipitation. In fact, the effect on precipitation from TC by citization is still poorly understood. This is exactly the significance of our current work, and we hope to draw sufficient attention to it.

3. Insights into the Dynamic Effects of Cities on Precipitation

Objectively, many meaningful research results have been obtained on the impact of the dynamic effects of cities on precipitation, most of which fully reflect the significant impact of the dynamic effects of cities on precipitation. However, some studies believe that for small cities with few high-rise buildings, although the roughness increases, it is not enough to hinder the movement of large-scale weather systems [92,93]. It should be considered that the influence of city roughness is not the main factor for a city's precipitation mechanisms. It can be seen that the influence of the dynamic effects of cities on precipitation is very complex and that it is also related to the scale of the city and the weather system.

At present, there are observation and numerical simulation studies on the influence of city dynamics on precipitation. It should be highlighted that the dynamic effects of cities can be further divided into the city barrier effect and city friction effect. The former emphasizes the influence of the city as a whole on the weather system; for example, the existence of the city may cause the upwind convergence to strengthen, and it may the flow around the city may cause the convection system to split and the weather system to slow down. Their impact on the distribution of precipitation may cause the different

distribution of precipitation in the upwind side of the city, on both sides of the city, and in the city area. This effect is similar to that of the low irregular terrain; on the other hand, the change in precipitation caused by city friction is often influenced by the internal dynamic process of the weather system through turbulence, drag, and other dynamic processes, thus affecting precipitation in the city. In fact, the city barrier is at a more macroscale, while city friction corresponds to a microscale. However, careful analysis shows that many studies only describe the impact of the city barrier effect on precipitation in general but do not analyze the respective roles of the city barrier and city friction in the same weather process in detail. In the future, a more in-depth analysis must be conducted.

Finally, analyzing the present study results of the effects of citization on precipitation carefully, we can draw the following conclusions:

1. There is a lack of three-dimensional high-resolution meteorological data in the boundary layer of cities and their surrounding areas, which warrants further study;
2. There is no in-depth analysis of the relationship between wind direction, wind speed and humidity transmission, and local precipitation area and intensity in cities;
3. The key dynamic and thermal factors affecting precipitation area and intensity regarding the city barrier effect have not yet been not revealed;
4. Sensitivity numerical study does not carefully consider the influence of the underlying surface characteristics of cities, such as height, density, orientation of high-rise buildings, and city scale, on the local precipitation area and intensity;
5. There is a certain proportional relationship between the weather system and the city horizontal scale. The impact of this relationship on precipitation distribution and intensity needs further quantitative analysis based on multiple samples.

More detailed initiatives are given in Table 2, which contribute to conducting further research in the future.

Table 2. Thoughts on dynamic effects of cities on precipitation.

Research Focus	Present	Future Insights
Background field analysis	case	Multi-sample classification synthesis analysis
Distinguish between city barrier effect and friction effect	inexplicit	Quantitative diagnostic analysis
Three-dimensional analysis field in boundary layer of city	Default	Establish high spatiotemporal resolution 3D field based on multivariate data
The effect of wind direction, wind speed, and humidity transmission on local precipitation	case	Diverse synthesis and numerical simulation
The effect of height, density, orientation of high-rise buildings on local precipitation	inexplicit	Numerical simulation and sensitivity test
The effect of weather system and city horizontal scale ratio on local precipitation	case	Multi-sample synthesis analysis, numerical simulation, and sensitivity test

There is no denying that the role and impact of built-up areas on precipitation are obviously complex and differ for each city with different characteristics and geographical settings; the relative importance of cities and geographic effects and their net effects in combination depends on many factors related to their form and characteristics as well as their location with respect to latitude, orography, and proximity to large water bodies (e.g., coastal cities) [32]. In addition, they are also closely related to the characteristics of weather systems or seasons. Although methods and data availability continue to improve, the attribution of citization effects on precipitation is nevertheless still challenging.

Author Contributions: Conceptualization, C.Y. and Z.H.; writing—original draft preparation, C.Y.; writing—review and editing, C.Y., Z.H., W.G., and X.A.; supervision, Y.T.; project administration, W.G. and Y.T.; funding acquisition, C.Y. and X.A. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data set available on request to corresponding authors.

Conflicts of Interest: The authors declare no conflict of interest.

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