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REVIEW

Urban Impacts on Precipitation

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Abstract: Weather and climate changes caused by human activities (e.g., greenhouse gas emissions, deforestation, and urbanization) have received much attention because of their impacts on human lives as well as scientific interests. The detection, understanding, and future projection of weather and climate changes due to urbanization are important subjects in the discipline of urban meteorology and climatology. This article reviews urban impacts on precipitation. Observational studies of changes in convective phenomena over and around cities are reviewed, with focus on precipitation enhancement downwind of cities. The proposed causative factors (urban heat island, large surface roughness, and higher aerosol concentration) and mechanisms of urban-induced and/or urban-modified precipitation are then reviewed and discussed, with focus on downwind precipitation enhancement. A universal mechanism of urban-induced precipitation is made through a thorough literature review and is as follows. The urban heat island produces updrafts on the leeward or downwind side of cities, and the urban heat island-induced updrafts initiate moist convection under favorable thermodynamic conditions, thus leading to surface precipitation. Surface precipitation is likely to further increase under higher aerosol concentrations if the air humidity is high and deep and strong convection occurs. It is not likely that larger urban surface roughness plays a major role in urban-induced precipitation. Larger urban surface roughness can, however, disrupt or bifurcate precipitating convective systems formed outside cities while passing over the cities. Such urban-modified precipitating systems can either increase or decrease precipitation over and/or downwind of cities. Much effort is needed for in-depth or new understanding of urban precipitation anomalies, which includes local and regional modeling studies using advanced numerical models and analysis studies of long-term radar data.

Key words: Urban impacts, precipitation, urban heat island, surface roughness, aerosols, urbanization

1. Introduction

The global population has become concentrated in cities (UN, 2012). Urbanization is accompanied by artificial changes in land use/land cover, creating substantial contrasts in land surface characteristics between urban areas and surrounding rural areas. Urban areas have features different from surrounding rural areas. Urban areas are composed of numerous man-made structures, so the urban surface is generally rougher than its surrounding rural surface. The urban surface covered with materials such as concrete and asphalt has large thermal inertia and accordingly stores great amounts of heat. In built-up urban areas, the sky-view factor is small. Hence, incoming shortwave radiation and outgoing longwave radiation are trapped in street canyons. Anthropogenic heat is released into the urban atmosphere. In addition, the urban atmosphere is more polluted than the rural atmosphere mainly because of pollutants emitted from automobiles. A considerable number of observational studies show that urban areas cause changes in temperature, wind, humidity, and rainfall, produce peculiar circulations, and affect local or even regional weather and climate (Landsberg, 1970; Oke, 1987; Cotton and Pielke, 1995).

The most well-known and highly-documented phenomenon appearing in cities is the urban heat island, that is, higher near-surface air temperature in the urban area than in its surrounding rural area. The urban heat island is most pronounced on calm, clear nights (e.g., Jauregui, 1997; Klysik and Fortuniak, 1999). The intensity of the urban heat island exhibits diurnal and seasonal variations (e.g., Kim and Baik, 2002; Lee and Baik, 2010) and is influenced or modulated by mesoscale or synoptic weather conditions (e.g., Morris and Simmonds, 2000; Gedzelman *et al.*, 2003). Causative factors of the urban heat island are well known and include impervious surfaces, anthropogenic heat, air pollution, and three-dimensional urban geometry (encompassing additional heat stored in walls, radiation trapping, and wind speed reduction) (Oke, 1982; Ryu and Baik, 2012). The urban heat island can induce or modify local flow/circulation. Reviews of the urban heat island are given, for example, in Arnfield (2003).

Anthropogenic aerosols released into the urban atmosphere are of various sizes and chemical compositions. Anthropogenic aerosols, together with gaseous pollutants, lead to deterioration in the urban air quality and are harmful to human health. In particular, aerosols smaller than 100 nm in diameter, called ultrafine aerosols, are known to be very harmful. Aerosols can serve as cloud condensation nuclei, and their sizes and chemical compositions greatly influence the size distribution of drops nucleated in a cloud (Houze, 1993; Pruppacher and Klett, 1997), affecting the subsequent evolution of clouds and precipitation. Aerosol-cloud-precipitation interactions have been extensively investigated because of the importance of aerosols

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in weather and climate (Khain, 2009). However, the roles of aerosols in clouds and precipitation in urban areas with higher aerosol number concentrations have not been extensively investigated.

Many observational studies have indicated that cities affect precipitation and specifically that precipitation tends to increase over and/or downwind of urban areas. Theoretical studies have been attempted to gain an understanding of the essential dynamics responsible for the precipitation enhancement. Numerical modeling studies have been made to find causes and mechanisms of the precipitation enhancement. Precipitation is one of the key elements of the water and energy cycles of the atmosphere, and understanding precipitation processes under a wide range of environmental conditions is an important problem in meteorology. This study conducts a literature review of urban impacts on precipitation. In section 2, observational studies of urban-related changes in convective phenomena, especially precipitation enhancement over and/or downwind of urban areas, are reviewed. In section 3, causes and mechanisms of the precipitation enhancement are reviewed and discussed. In section 4, a summary and conclusions are given.

2. Observational evidence

During the past several decades, abundant observational evidence of urban-related changes in convective phenomena has been reported. In 1968, Changnon presented an interesting finding, an anomalous behavior of precipitation in the La Porte area downwind of Chicago, that is, an observational evidence for precipitation enhancement downwind of Chicago (Changnon, 1968). This anomaly is known as the La Porte anomaly (Fig. 1). Changnon's pioneering work initiated many studies aimed at detecting precipitation anomalies over and/or downwind of major global cities and at finding causes and mechanisms of such precipitation anomalies.

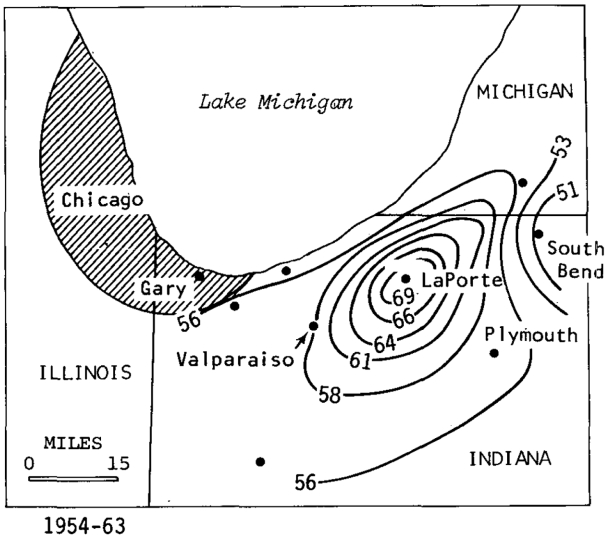


Fig. 1. Average warm season (April-September) rainfall pattern (cm) in the La Porte-Chicago area during 1954-63. [after Changnon (1980a).]

An intensive field campaign of inadvertent weather modification, the Metropolitan Meteorological Experiment (METROMEX), was conducted in the St. Louis area from 1971 to 1975 to dimensionalize urban-related anomalies in precipitation and severe weather and to find possible causes of these anomalies (Changnon *et al.*, 1977; Ackerman *et al.*, 1978). Analyses of

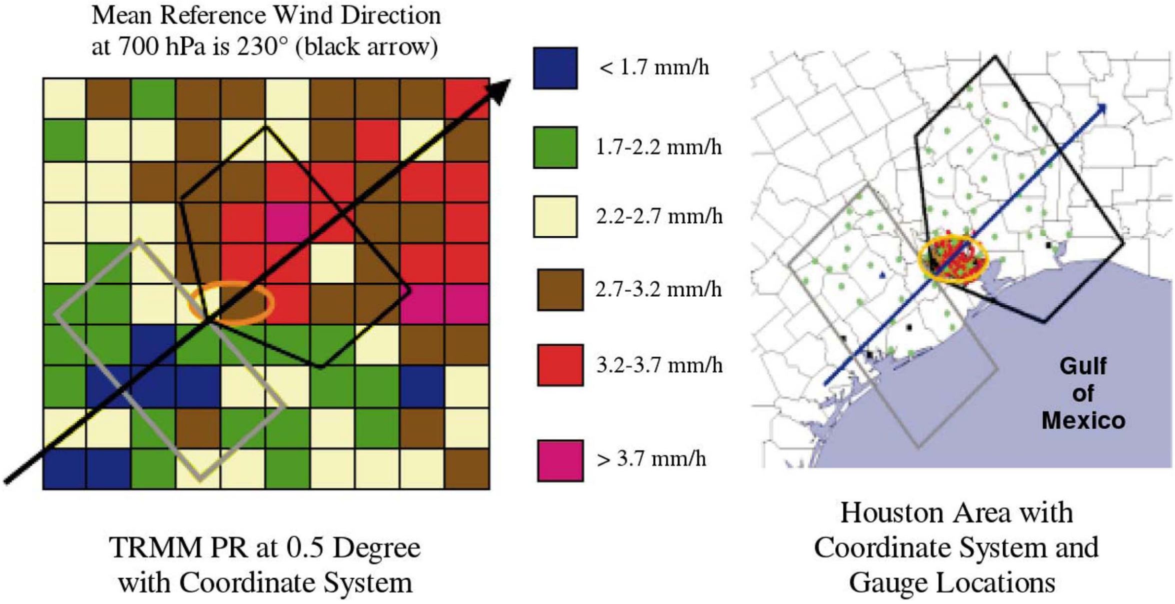


Fig. 2. Mean annual distribution of the Tropical Rainfall Measuring Mission (TRMM)-derived rainfall rates from January 1998 to May 2002 (excluding August 2001). The oval is the approximate Houston urban zone. The vector indicates the mean annual 700-hPa wind direction over the Houston area. The pentagon-shaped box is the downwind urban-impacted region, and the rectangular box is the upwind control region. [after Shepherd and Burian (2003).]

Table 1. Observational studies of urban-related changes in convective phenomena over and around cities.

City	References
Asia	
Pearl River Delta, China	Li *et al.* (2011)
Shanghai, China	Chow and Chang (1984)
Kolkata, India	De and Rao (2004), Rao *et al.* (2004), Mitra *et al.* (2012)
Mumbai, India	Khemani and Ramana Murty (1973), De and Rao (2004), Rao *et al.* (2004), Kishtawal *et al.* (2010)
Tel Aviv, Israel	Goldreich and Manes (1979), Goldreich (1987), Halfon *et al.* (2009)
Tokyo, Japan	Yonetani (1982), Inoue and Kimura (2004), Fujibe *et al.* (2009)
Seoul, Korea	Kar *et al.* (2007), Kim *et al.* (2011), Kim *et al.* (2012), Kug and Ahn (2013)
Taipei, Taiwan	Chen *et al.* (2007)
Europe	
London, England	Atkinson (1968, 1969, 1971), Hand (2005)
Hamburg, Germany	Schlünzen *et al.* (2010)
Bucharest, Romania	Tumanov *et al.* (1999)
Moscow, Russia	Romanov (1999)
North America	
Windsor, Canada	Sanderson and Gorski (1978)
Mexico City, Mexico	Jauregui and Romales (1996)
Atlanta, United States	Bornstein and Lin (2000), Shepherd *et al.* (2002), Dixon and Mote (2003), Diem and Mote (2005), Mote *et al.* (2007), Rose *et al.* (2008)
Chicago, United States	Changnon (1968, 1980b, 2001), Huff and Changnon (1973), Westcott (1995), Changnon and Westcott (2002)
Houston, United States	Huff and Changnon (1973), Orville *et al.* (2001), Steiger *et al.* (2002), Shepherd and Burian (2003), Burian and Shepherd (2005)
St. Louis, United States	Huff and Changnon (1973, 1986), Changnon *et al.* (1977, 1991), Ackerman *et al.* (1978), Changnon (1981), Westcott (1995)
South America	
São Paulo, Brazil	Naccarato *et al.* (2003), Farias *et al.* (2009), Pinto *et al.* (2013)

the METROMEX data indicate increased cloudiness (up to 10%), increased total rainfall (up to 30%), and increased severe storm activity (up to 100%) over and 15 to 40 km downwind of St. Louis in summer. The main focus of the METROMEX effort was summer season precipitation, but some studies (e.g., Huff and Changnon, 1986; Changnon *et al.*, 1991) analyzed the METROMEX data for other seasons to ascertain the presence of urban effects on the transition seasons (spring and fall) and winter precipitation. Using a statistical approach, Changnon *et al.* (1991) revealed that an urban effect in the St. Louis area, leading to increased downwind precipitation, exists in fall (+17%) but is negligible in spring (+4%) and not present in winter.

Shepherd *et al.* (2002) and Shepherd and Burian (2003) established the possibility of utilizing satellite-based rainfall estimates to identify the modification of rainfall by urban areas on a global scale and over longer time periods. Their results corroborate early METROMEX findings and other ground-based observational and modeling studies that show rainfall maxima over and/or downwind of major cities (see the example of Houston in Fig. 2).

Urban-related changes in convective phenomena have been detected over and around major cities in the United States and globally, as listed in Table 1. For example, observational studies show an increase in the cloud-to-ground flash density (lightning activity) and a decrease in the percentage of positive flashes over and/or downwind of Houston (Orville *et al.*, 2001; Steiger *et al.*, 2002), three large metropolitan areas in southeastern Brazil (São Paulo, Campinas, and São José dos Campos) (Naccarato *et al.*, 2003; see Fig. 3), and Seoul (Kar *et al.*, 2007). Several case studies show that the structure and movement of cloud systems can be influenced by urban areas. A radar observation study of cloud systems crossing the city of Bucharest shows the disruption of a frontal system passing over the city and the reshaping of the frontal system after crossing it (Tumanov *et al.*, 1999). Bornstein and LeRoy (1990) found that moving thunderstorms with strong regional flows tend to bifurcate and move around the city due to the urban barrier effect in the New York City area. By analyzing surface meteorological data in the Atlanta area, Bornstein and Lin (2000) documented convective thunderstorms that were initiated in urban heat island-induced convergence zones. The rapid growth of moving storms passing over cities was observed in some major urban areas, such as in the London area (Atkinson, 1971) and the Chicago area (Changnon and Westcott, 2002). Recent studies by Kug and Ahn (2013) and Pinto *et al.* (2013), respectively, show that precipitation enhancement in Korean cities and a significant increase in

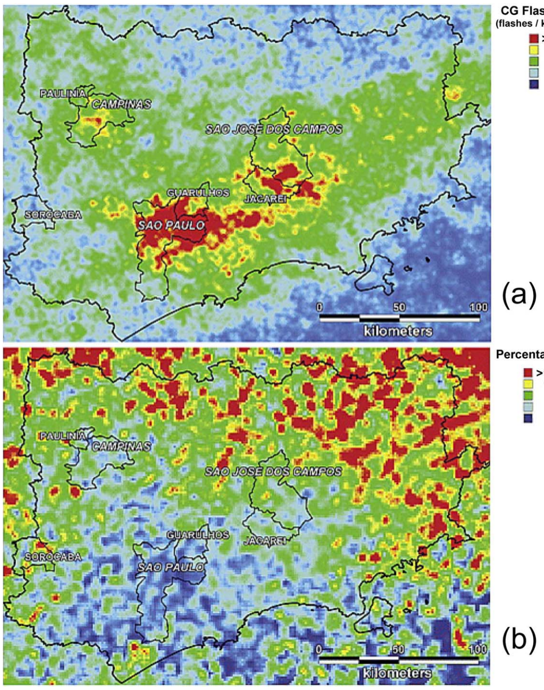


Fig. 3. (a) Cloud-to-ground flash density (flashes per km^2) averaged over three summer seasons from 2000 to 2002 and (b) percentage of positive cloud-to-ground flashes in southeastern Brazil. The outlined area in both figures is located between latitude 22.19°S and 24.25°S, and longitude 44.62°W and 47.62°W. [after Naccarato *et al.* (2003).]

thunderstorm days in large cities in southeastern Brazil are related to the population growth of the cities. More extensive reviews of the observational studies of urban-induced and/or urban-modified precipitation are given in Garstang *et al.* (1975), Lowry (1998), and Shepherd (2005).

3. Causes and mechanisms

Three causative factors (urban heat island, large surface roughness, and higher aerosol concentration) and a number of mechanisms have been proposed to explain observed urban precipitation anomalies. This section reviews the proposed causes and mechanisms.

a. Urban heat island

Heat sources (e.g., latent heating due to cumulus convection) or sinks (e.g., evaporative cooling of falling raindrops) in the atmosphere dynamically induce flow/circulation. The urban heat island, which is regarded as a low-level heat source, induces flow. The urban heat island-induced flow can be theoretically investigated in the context of the response of a stably stratified atmosphere to specified surface or low-level heating. A number of linear, theoretical studies have been performed following this line of research. Olfe and Lee (1971) carried out two-dimensional, steady-state flow calculations in a uniform basic-state flow. In their study, the urban heat island is represented by various surface temperature distributions and for turbulent heat transfer the turbulent diffusion term is added in the thermodynamic energy equation. They showed downward motion directly over the upwind portion of the urban heat island and upward motion on the downwind side (Fig. 4). They also showed positive temperature perturbations near the ground and negative temperature perturbations aloft. The three-dimensional solution for temperature perturbations was also analyzed, which was obtained by the superposition of the two-dimensional solutions at varying angles to the uniform basic-state flow direction. A two-dimensional, time-dependent problem was solved by Lin and Smith (1986) to examine the transient dynamics of airflow near a heat source in a uniform basic-state flow, with applications to several problems including the heat island problem. It was found that air parcels descend over a heat island and ascend on the downwind side. Importantly, through an analysis of the time-dependent solution, they provided an explanation for the curious negative phase relationship between heating and induced vertical displacement in the vicinity of the heat source.

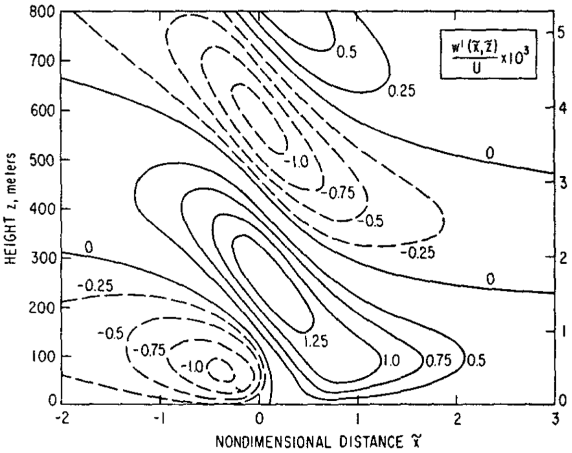


Fig. 4. Field of the urban heat island-induced vertical velocity calculated using a linear theory. The vertical velocity is normalized by the basic-state flow. [after Olfe and Lee (1971).]

Baik (1992) analytically solved a two-dimensional, steady-state problem to investigate the characteristics of airflow past an urban heat island in a basic-state flow with shear. The urban heat island is specified as low-level heating that has a bell shape in the horizontal and decreases linearly with height, roughly imitating real urban heat islands. The turbulent diffusion term was not considered because the low-level heating can be to some or a large extent regarded as a consequence of the turbulent heat transfer from near the surface where the heat source is located. He found that there exists upward motion downwind of the urban heat island and that the magnitude of the perturbation vertical velocity is larger in the shear flow case than in the uniform flow case. Han and Baik (2008) solved a three-dimensional, time-dependent problem for airflow past an urban heat island in a uniform basic-state flow. The urban heat island is specified as steady-state low-level heating in three dimensions. They also confirmed upward motion downwind of the heating center. The dispersion of gravity wave energy into an additional dimension was shown to result in a faster approach to a quasi-steady state and a weaker quasi-steady flow in three dimensions.

The linear, theoretical studies mentioned above highlight that upward motion is induced on the downwind side in the presence of an urban heat island. Lin and Smith (1986), Baik (1992), and Han and Baik (2008) suggested that the urban heat island-induced upward motion on the downwind side is responsible for the precipitation enhancement observed downwind of urban areas. It is noteworthy that gravity waves are generated by heating in a stably stratified atmosphere, so the velocity perturbations induced by an urban heat island in the linear, theoretical studies are essentially gravity waves.

Baik and Chun (1997) extended the previous linear, theoretical studies by solving a weakly nonlinear problem in two dimensions using the perturbation method. They showed that the linear solution part exhibits upward motion downwind, while the weakly nonlinear solution part exhibits downward or upward motion downwind depending on the inverse Froude number that is proportional to the buoyancy frequency and heating depth and inversely proportional to the basic-state wind speed. When the inverse Froude number is large within a valid range of the perturbation expansion, the linear and weakly nonlinear effects constructively work together to produce enhanced upward motion downwind. They proposed that this explains to a greater extent precipitation enhancement downwind of urban areas than is possible from the linear effect alone.

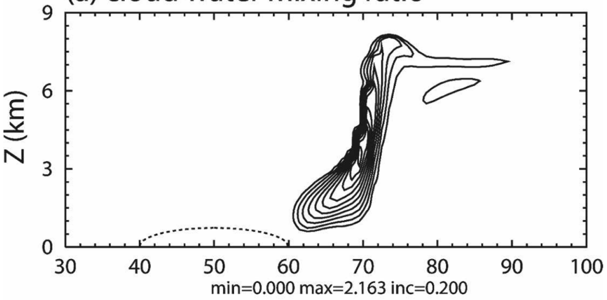
Nonlinear numerical models have been used to investigate urban heat island-induced flow and convection, with specified low-level heating representing an urban heat island under idealized environmental conditions. Using a simple two-dimensional model, Baik (1992) examined nonlinear effects on the flow field. He found that for small heating amplitude (hence, small nonlinearity factor) the flow field is similar to that in the previous linear studies, while for large heating amplitude (thus, large nonlinearity factor) two distinct flow features are observed: a linear gravity-wave-type response field on the upwind side and a strong updraft cell on the downwind side. The strong updraft cell was suggested to be responsible for the observed downwind precipitation enhancement. Atmospheric stability plays an important role in enhancing or suppressing updrafts or convection. Baik *et al.* (2007) examined the effects of atmospheric boundary-layer stability on urban heat island-induced circulation using a two-dimensional, dry mesoscale model. They showed that as the boundary layer becomes less stable, the downwind updraft cell induced by an urban heat island strengthens and the vertical extent of the downwind updraft cell increases. This result implies that in the daytime, with a nearly neutral or less stable boundary layer, the urban heat island-induced circulation can become strong. They suggested that the finding explains urban-induced thunderstorms observed in the late afternoon or evening with a nearly neutral or less stable boundary layer.

Using a two-dimensional mesoscale model with bulk cloud microphysics, Baik *et al.* (2001) demonstrated that the downwind updraft cell induced by an urban heat island can dynamically initiate moist convection and result in surface precipitation in the downwind region under favorable thermodynamic conditions. It was shown that for the same basic-state wind speed and heat island intensity a stronger dynamic forcing (that is, a stronger downwind updraft) is required to trigger moist convection under less favorable thermodynamic conditions. The two-dimensional numerical study of Baik *et al.* (2001) was extended to a three-dimensional numerical study by Han and Baik (2008). In addition to demonstrating in three dimensions the initiation of moist convection by the downwind updraft cell induced by an urban heat island and the subsequent downwind surface precipitation (Fig. 5), they showed that the intensity and horizontal structure of an urban heat island affect the amount and distribution of surface precipitation downwind of the urban heat island.

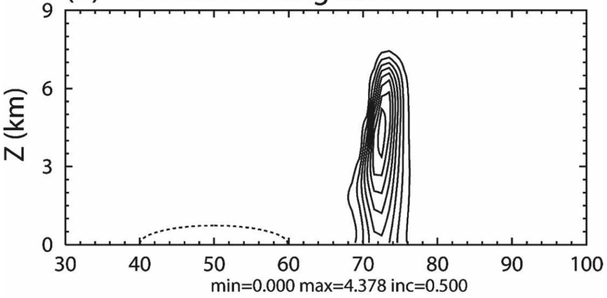
The above idealized, nonlinear numerical studies propose the urban heat island as a cause and mechanism of the observed downwind precipitation enhancement by showing that the urban heat island induces a downwind updraft cell under the conditions of strong urban heat island, weak atmospheric stability or weak basic-state wind and that the downwind updraft cell initiates moist convection downwind under favorable thermodynamic conditions, thus producing surface precipitation downwind. It is noted that the nonlinearity factor for thermally induced finite-amplitude waves is proportional to the heating amplitude and inversely proportional to the buoyancy frequency and the square of the basic-state wind speed (Chun, 1991; Lin and Chun, 1991). Therefore, the conditions of strong urban heat island, weak atmospheric stability or weak basic-state wind correspond to relatively large nonlinearity factors (relatively high nonlinear flow systems).

There are case modeling studies that emphasize the key role of the urban heat island in enhancing precipitation over and/or downwind of cities. Using a three-dimensional mesoscale model, Craig and Bornstein (2002) simulated summertime convective precipitation over Atlanta. In their study, the urban area is roughly represented using the flat-sandbox urbanization approach. By comparing simulations with and without the city of Atlanta, they demonstrated that the urban heat island produces a confluence region, which then leads to convergence, upward motion, and cumulus convection, resulting in precipitation around the eastern boundaries of the city. Their case modeling study provides a link of urban heat island forcing to precipitation. Rozoff *et al.* (2003) conducted numerical experiments of summertime thunderstorms over St. Louis using a three-dimensional mesoscale model that includes an urban canopy model [TEB: Town Energy Budget, Masson (2000)] and examined urban-enhanced precipitation, with focus on surface-driven low-level convergence mechanisms. The inclusion of an urban canopy model in a mesoscale model is necessary to better represent various physical processes occurring at and near the urban surface. Their sensitivity experiments show that the urban heat island plays the largest

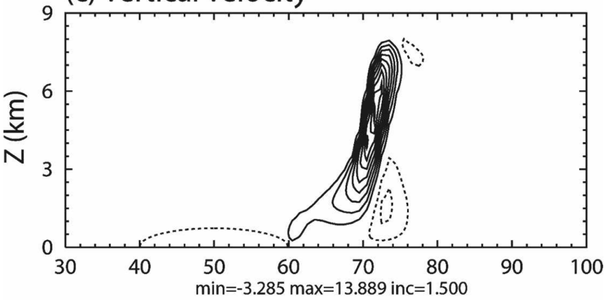
(a) cloud water mixing ratio



(b) rainwater mixing ratio



(c) vertical velocity



(d) temperature

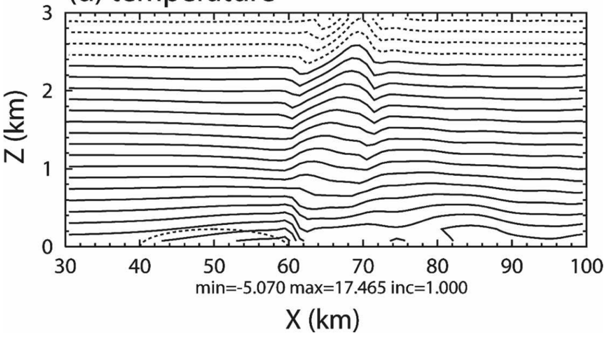


Fig. 5. Fields of the (a) cloud water mixing ratio (g kg^{-1}), (b) rainwater mixing ratio (g kg^{-1}), (c) vertical velocity (m s^{-1}), and (d) temperature (^{o}C) in a three-dimensional, moist simulation. The center of the urban heat island is located at $x = 50$ km, and the concentrated heating region is outlined by dashed line between $x = 40$ and 60 km. [after Han and Baik (2008).]

role in initiating deep, moist convection downwind of the city. Shem and Shepherd (2009) performed two case studies on summertime thunderstorms over Atlanta using a three-dimensional mesoscale model. The simple urban land-cover parameterization is utilized. Precipitation amounts downwind of the city were found to be higher by 10-13% in the simulations with the city of Atlanta than in the simulations in which the city is removed and replaced by the dominant land-cover type of the surrounding rural area. They stated that the increase in precipitation amount is possibly attributed to intensified activity within the planetary boundary layer resulting from the urban heat island effect. The urban heat island effect on summertime precipitation over a complex geographic environment in northern Taiwan including the city of Taipei was examined through a case modeling study by Lin *et al.* (2011). They employed a three-dimensional mesoscale model that includes the urban canopy model of Kusaka *et al.* (2001). The simulation results show that not only the rainfall system is enhanced downwind of the city over the mountainous area, but also it occurs in the upwind plain area. In the above case modeling studies, convection is explicitly resolved using bulk cloud microphysics.

The work of Thielen *et al.* (2000) is of note, as it addresses the question of the extent of influence of urban surfaces on the development of precipitation using a two-dimensional mesoscale model with bulk cloud microphysics. The model is initialized with a single profile of temperature, dew point temperature, and wind speed based on the summertime midday sounding observed upwind of Paris. Among spatially varying surface sensible heat flux, surface latent heat flux, and roughness length, on a time scale of less than 4 h the surface sensible heat flux variations were found to have the most significant impact on the development of precipitation. This result implies that the urban heat island is the most influential factor because the (much) larger surface sensible heat flux in urban areas than in surrounding rural areas greatly contributes to increasing near-surface air temperature in urban areas, thus exhibiting enhanced urban heat island. The inclusion of urban heat islands was found to result in increased precipitation over the urban heat island and at a certain distance downwind of it.

In observational studies, it is inherently difficult to isolate and understand the effects of the individual factors that influence a phenomenon and also find the relative importance of each individual factor. However, in numerical modeling studies, isolation is possible and relative importance can be found through a series of well-designed simulations. The above idealized and case modeling studies confirm that the urban heat island-induced strong updrafts can produce clouds/thunderstorms on the downwind side, resulting in downwind precipitation enhancement. This mechanism works, particularly well when the urban surface sensible heat flux is large and the atmospheric boundary layer is almost neutral. The urban heat island and the mechanism largely explain observations of thunderstorms often occurring downwind of cities in the afternoon or in the early evening in summer.

b. Large surface roughness

Spatial changes in surface roughness can lead to changes in airflow. Larger surface roughness in a city than in its surrounding rural area causes air approaching the city to slow

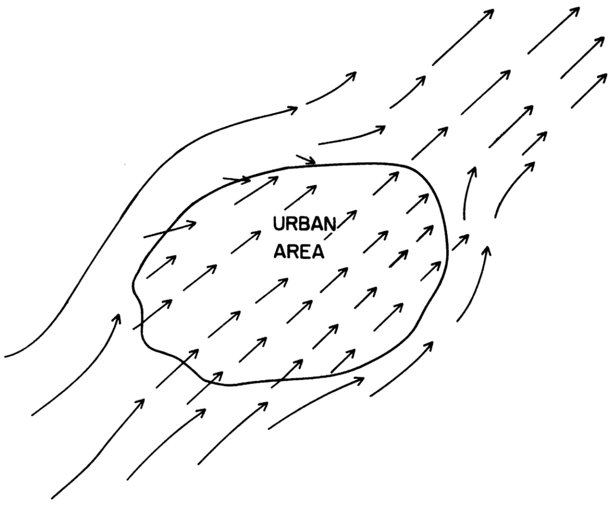


Fig. 6. Schematic of low-level airflow over and around an urban area due to changes in surface roughness. [after Cotton and Pielke (1995).]

down near the upwind city boundary and/or over the city. In addition, the air approaching a city tends to divert around it and the diverted air can converge on the downwind side of the city, yielding upward motion there (Cotton and Pielke, 1995). These two features that can appear due to rougher urban surface are schematically depicted in Fig. 6.

The question arises as to whether the upward motion near the upwind urban boundary and/or over an urban area that results from rougher urban surface is strong enough to initiate moist convection in that area. Some studies have produced relevant answers to this question. A two-dimensional modeling study of Thielen *et al.* (2000) indicates that precipitation is enhanced with increased roughness. They speculated that the effect of roughness changes on the precipitation intensity could be substantially reduced because the airflow can go around the urban area. A case modeling study for St. Louis indicates that the increased urban momentum drag induces convergence on the windward side of the city, but this convergence is not strong enough to initiate storms (Rozoff *et al.*, 2003). If the results of Thielen *et al.* (2000) and Rozoff *et al.* (2003) are considered together, two inferences can be made. First, the upward motion induced by rougher urban surface will be stronger in two dimensions than in three dimensions. In terms of dimensions, this is similar to the result of Han and Baik (2008) that shows that the urban heat island-induced upward motion is stronger in two dimensions than in three dimensions. Second, in three dimensions, the upward motion will become strong with increasing urban roughness. Due to the lack of extensive previous studies, it is not confirmed that roughness alone can initiate moist convection (or the roughness can play an important role in initiating moist convection) in reality and thus can explain to some extent observed precipitation enhancement over and/or downwind of cities. There is, of course, a possibility that updrafts produced by high-rise buildings in highly built-up urban areas can initiate moist convection, although not studied yet. To make any conclusions related to the problem in question, case modeling studies for many cities, together with idealized modeling studies, are needed in three dimensions. We add here that there are no existing systematic studies that investigate a possible connection between the convergence of the diverted airflow on the downwind side of a city and the initiation of moist convection. This is an interesting research topic, necessitating investigation.

As described in section 2, observational studies show that precipitating convective systems can be disrupted or bifurcated while passing over cities (Bornstein and LeRoy, 1990; Tumanov *et al.*, 1999). These observed phenomena are attributed to larger urban roughness. Miao *et al.* (2011) conducted a case study of the effects of urban processes on summer precipitation over Beijing using a three-dimensional mesoscale model that includes the urban canopy model of Kusaka *et al.* (2001). They indicated that the presence of the city leads to the breaking of the squall line into convective cells over the urban area. Previous observational and case modeling studies demonstrate that cities affect precipitating convective systems that pass over them. However, it is not clear whether disrupted or bifurcated convective systems produce more precipitation over and/or downwind of cities. Precipitation can either increase or decrease depending on factors such as water vapor supply and the degree of urban roughness. Idealized and further case modeling studies would help understand the mechanism involved in the impacts of rougher urban surface on precipitating convective systems passing over the urban area and find under what conditions precipitation can increase/decrease.

c. Higher aerosol concentration

Aerosols can significantly affect the development of clouds and precipitation by acting as cloud condensation nuclei (CCN) or ice nuclei as well as by absorbing and scattering solar radiation. There is a general agreement that an increased aerosol (number) concentration suppresses precipitation from warm shallow clouds by producing a narrow drop size distribution that is inefficient in the collision-coalescence process (e.g., Rosenfeld, 1999). However, the role of aerosols in suppressing or enhancing precipitation from mixed-phase clouds and the mechanism involved are still under debate.

From observations taken from the Tropical Rainfall Measuring Mission (TRMM) satellite, Rosenfeld (2000) found evidence that both warm-rain and cold-rain processes are inhibited in polluted clouds. He suggested that the lack of primary and secondary ice production resulting from reduced cloud droplet size could be the reason for the suppression of ice precipitation formation. Combining remote sensing and in-situ mountaintop measurements, Borys *et al.* (2003) showed that a pollution-induced decrease in cloud droplet size causes a decrease in snowfall rate from mixed-phase clouds in mountainous regions by inhibiting the riming process. Givati and Rosenfeld (2004) observed a downwind shift of precipitation from relatively short-lived orographic clouds in polluted urban areas in the United States and Israel, and suggested that this is due to the effect of aerosols that slow down the conversion of cloud water to precipitation. This observation is supported by Lynn *et al.* (2007), who investigated the effects of aerosols on orographic precipitation in the Sierra Nevada of California by performing simulations under maritime and continental aerosol conditions using a two-dimensional mesoscale model with bin cloud microphysics. They showed that a downwind shift of precipitation results from the fact that anthropogenic aerosols suppress the warm rain process and therefore produce more cloud ice and snow, which can be advected farther downwind because of their lower sedimentation velocities. By analyzing the weekly cycles of pollution and precipitation, Svoma and Balling (2009) found that the aerosol concentration is inversely related to the winter precipitation frequency in the Phoenix metropolitan area. Based on this observation, they suggested that human activity influences precipitation primarily by the suppressing effect of aerosols.

On the other hand, some observational studies that analyze the relation between the weekly cycles of air pollutants and summertime precipitation show evidence of enhanced rainfall on high aerosol concentration days in the southeast United States (e.g., Bell *et al.*, 2008; Lacke *et al.*, 2009). A positive correlation between the aerosol concentration and the cloud-to-ground lightning activity is found in many urban areas, for example, in Spain (Soriano and Pablo, 2002), Brazil (Naccarato *et al.*, 2003; Farias *et al.*, 2009), the United States (Steiger and Orville, 2003), and Korea (Kar *et al.*, 2007, 2009). By analyzing both surface and satellite observations, Choi *et al.* (2008) found that higher aerosol concentrations are significantly correlated with an increase in moderate rainfall events and with an increase in mid-level ice or mixed clouds in China. They suggested that on the time scale of a few days the increase in aerosol concentration results in an increase of summer rainfall frequency via enhanced ice nucleation in the mid-troposphere. Several studies explain the observed precipitation enhancement in polluted areas by a mechanism that the delayed onset of precipitation in deep convection allows updrafts to accelerate and transport more cloud water to upper levels where it can release the additional latent heat of freezing (e.g., Andreae *et al.*, 2004; Rosenfeld *et al.*, 2008; Carrió *et al.*, 2010; Carrió and Cotton, 2011). A more detailed explanation of how increased aerosol concentration in urban areas affects convection induced by the urban heat island is provided in a recent numerical study of Han *et al.* (2012) using a two-dimensional cloud model with bin microphysics. The simulation results show that the development of stronger convective cloud under higher aerosol concentrations is mainly due to the release of an increased amount of latent heat resulting from the enhanced condensation process. The low collision efficiency of smaller cloud droplets and the resulting stronger updraft under higher aerosol concentrations result in larger liquid water content (LWC) at higher levels, leading to the enhanced riming process, which produces large ice particles. The melting of a larger amount of hail leads to precipitation enhancement downwind of the urban area with increasing urban aerosol concentration. These urban aerosol impacts on deep convective cloud and precipitation are summarized in a schematic diagram (Fig. 7).

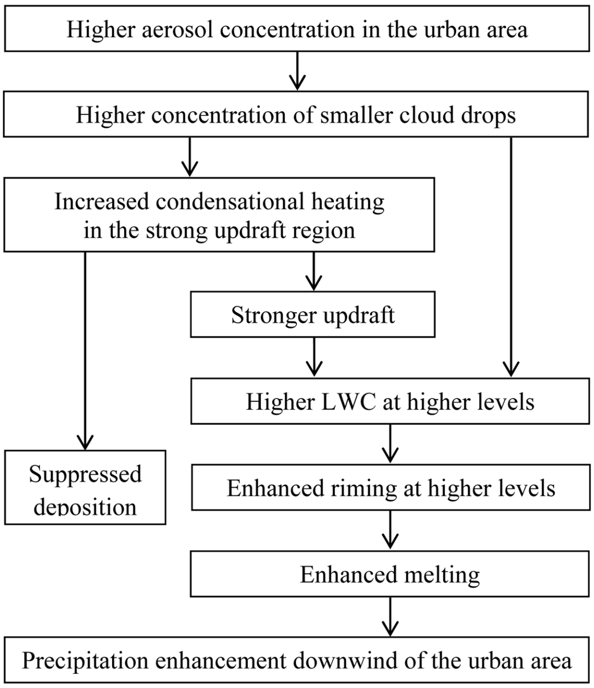


Fig. 7. Schematic diagram that shows how increased aerosol concentration in the urban area affects deep convective cloud and precipitation. [after Han *et al.* (2012).]

Several observational and numerical studies indicate that anthropogenic air pollution can inhibit or enhance convective activity depending on cloud type (as discussed above), environmental conditions, and size and concentration of aerosol particles. For example, Khain *et al.* (2008) and Khain (2009) indicated that aerosols usually decrease precipitation in stratocumulus clouds or in isolated cumulus clouds developing in a dry environment, while aerosols usually increase precipitation in cloud ensembles or in clouds developing in a moist environment (Fig. 8). By analyzing the trends of orographic winter precipitation and aerosols in the western United States, Rosenfeld and Givati (2006) suggested that a decreasing trend in orographic precipitation during the last two decades is likely to be the result of decreasing concentrations of coarse aerosols which may enhance precipitation by acting as giant CCN, in conjunction with the stable or increasing concentrations of fine aerosols which may suppress precipitation.

Using a three-dimensional mesoscale model that incorporates sophisticated surface and bulk microphysics processes, van den Heever and Cotton (2007) examined the impacts of urban-enhanced aerosols on convective storms that develop over and downwind of St. Louis, focusing on the dependence of cloud-aerosol interactions on the size and concentration of background aerosols. Their sensitivity experiments show that when giant CCN are enhanced, the rapid formation of liquid water and ice species leads initially to stronger updrafts, which in

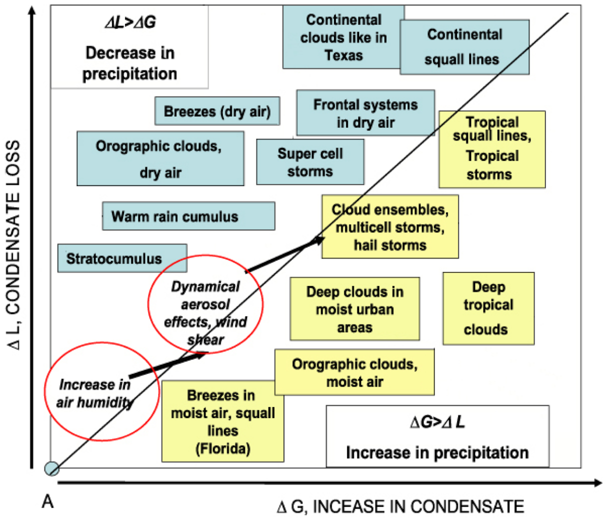


Fig. 8. A schematic diagram of the aerosol effects on clouds and cloud systems of different types under different environmental conditions. The zone above (below) the diagonal corresponds to a decrease (an increase) in precipitation with an increase in the aerosol concentration. [after Khain (2009).]

turn enhances surface precipitation. However, this generates stronger downdrafts and more intense cold pools earlier, causing the earlier demise of the storm and the absence of new storm development. On the contrary, when CCN alone (without giant CCN) are enhanced, although the updrafts develop later in association with the delayed hydrometeor formation, they are eventually stronger. The storms last longer and new storm development occurs. They stated that complex, nonlinear relationships between the microphysics and dynamics make it difficult to make definitive statements about the impacts of urban aerosols on downwind convection and precipitation. They also showed that urban aerosol effects decrease with increasing background aerosol concentration. Different cloud-aerosol interactions with varying aerosol concentrations are indicated in case modeling studies of Carrió *et al.* (2010) and Carrió and Cotton (2011), which examine the effects of urban growth and associated aerosols sources on convection over Houston using a three-dimensional cloud-resolving model with detailed treatments of land surface processes and aerosol microphysics. In their simulations, precipitation first increases and then decreases with increasing aerosol concentration. With the highest aerosol concentration, riming of ice particles becomes so inefficient that a greater fraction of condensate is transported into the storm anvil, causing a decrease in precipitation efficiency. They also showed that higher pollution levels are required to reach maximum precipitation efficiency for more unstable environments. By analyzing the cloud-to-ground lightning data and pollution data over the metropolitan area of São Paulo, Farias *et al.* (2014) also found that lightning activity first tends to increase and then to decrease with increasing pollutant concentration.

Previous modeling studies seem to suggest that surface precipitation can increase further under higher aerosol concentrations if the air humidity is high and deep and strong convection occurs. However, the relation between the aerosol concentration and surface precipitation amount is, as indicated by many observational and modeling studies, varies depending on many factors. For example, a three-dimensional mesoscale modeling study for the northeastern United States including New York City (Ntelekos *et al.*, 2009) shows that increasing aerosol concentration can lead to either enhancement or suppression of precipitation in intense convective storms, which depends on convective available potential energy (CAPE), relative humidity, and wind shear. High CAPE, high relative humidity, and strong wind shear were found to result in precipitation enhancement with increasing aerosol concentration. Systematic modeling studies are required to find under what conditions the surface precipitation increases/decreases with increasing urban aerosol concentration and understand mechanisms involved. Also, the effects of the size distribution of aerosols need to be investigated. Comprehensive reviews of the complexity of cloud-aerosol interactions, which do not focus on the impacts of urban aerosols, are given in Levin and Cotton (2009), Khain (2009), and Tao *et al.* (2012).

d. Urban vs. no-urban simulation studies

A simple approach that is used to examine the bulk effect of urban areas or urbanization on precipitation using numerical models is to perform two simulations (an urban simulation and a no-urban simulation) and compare the simulation results. In the no-urban simulation, the urban area is replaced by the land use/land cover of the surrounding rural area or before urbanization. Both simulations utilize the same initial and boundary conditions. In addition, simulations using a variety of urbanization scenarios can be performed. Numerous modeling studies have taken this line of research using mesoscale models or regional climate models. In the models used, the increase in aerosol concentration due to urban air pollution and its effects on cloud and precipitation processes are not treated, so precipitation changes are caused by the combined effect of the urban heat island and the larger urban surface roughness.

A large number of modeling studies indicate precipitation enhancement over and/or downwind of cities (e.g., Rozoff *et al.*, 2003; Shem and Shepherd, 2009; Shepherd *et al.*, 2010; Lin *et al.*, 2011; Wan *et al.*, 2013). Interestingly, some modeling studies indicate that cities can decrease precipitation (e.g., Trusilova *et al.*, 2008; Zhang *et al.*, 2009). A modeling study of Trusilova *et al.* (2008) shows that summer precipitation increases in the eastern region of Europe, but decreases in the central and southern regions of Europe and that the reduction in summer precipitation is distinct downwind of cities in the central and southern regions of Europe. They explained these regional differences in summer precipitation with the climatic differences of the regions. For example, the central region of Europe has a mild climate and precipitation in the region is frequent in summers. Thus, the summer precipitation reduction is explained by the reduction in surface

Table 2. Three-dimensional numerical modeling studies of urban-related changes in precipitation over and around cities.

City	References
Asia	
Beijing, China	Guo *et al*. (2006), Jiang and Liu (2007), Zhang *et al*. (2009), Miao *et al*. (2011)
Eastern and Southern China	Shao *et al*. (2013)
Nanjing, China	Yang *et al*. (2012)
Pearl River Delta, China	Lin *et al*. (2009)
Yangtze River Delta, China	Wan *et al*. (2013)
Mumbai, Bangalore, and Chennai, India	Goswami *et al*. (2010)
Jerusalem, Israel	Shafir and Alpert (1990)
Kanto area, Japan	Yang *et al*. (2000)
Seoul and surrounding area, Korea	Eun *et al*. (2011)
Taipei, Taiwan	Lin *et al*. (2011)
Western Plain, Taiwan	Lin *et al*. (2008)
Europe	
Brussels, Begium	Hamdi *et al*. (2012)
Vilnius, Lithuania	Mažeikis (2013)
Whole Europe	Trusilova *et al*. (2008)
North America	
San Juan, Puerto Rico	Comarazamy *et al*. (2006)
Atlanta, United States	Craig and Bornstein (2002), Shem and Shepherd (2009)
Baltimore-Washington, United States	Ntelekos *et al*. (2008), Li *et al*. (2013)
Fairbanks, United States	Mölders and Olson (2004)
Houston, United States	Li *et al*. (2008), Carrió *et al*. (2010), Shepherd *et al*. (2010), Carrió and Cotton (2011)
Indianapolis, United States	Niyogi *et al*. (2011)
New York City, United States	Ntelekos *et al*. (2009)
St. Louis, United States	Rozoff *et al*. (2003), van den Heever and Cotton (2007)
Oceania	
Sydney, Australia	Gero and Pitman (2006)

water availability in the extensive urban areas of the region. Through numerical simulations, Zhang *et al.* (2009) suggested that the observed reduction in summer precipitation in the northeast area of Beijing is due to the urban expansion and showed that the reduction in evaporation in the urban area and the subsequent decrease in CAPE are responsible for the summer precipitation reduction. Previous studies show that in many regions of the world urbanization acts to increase precipitation over and/or downwind of cities, but in some regions the precipitation reduction occurs. Further in-depth modeling studies are necessary to find the causes and processes that lead to such differences.

Table 2 lists three-dimensional numerical modeling studies of urban-related changes in precipitation over and around cities.

4. Summary and conclusions

In this article, we have reviewed urban impacts on precipitation. Observational studies show that cities do affect the spatial distribution and amount of precipitation and that precipitation tends to increase over and/or downwind of cities. Causative factors and mechanisms involved have been proposed to explain, in particular, the observed downwind precipitation enhancement. Here, we present a universal mechanism of urban-induced precipitation based on the results of previous studies. The urban heat island can lead to a near-surface convergence zone and consequently updrafts on the leeward or downwind side of cities. Under thermodynamic conditions that are conducive to moist convection, the urban heat island-induced updrafts act as dynamic forcing to initiate moist convection and produce surface precipitation. Surface precipitation is likely to further increase under higher aerosol concentrations if the air humidity is high and deep and strong convection occurs. Larger surface roughness does not appear to play a major role in urban-induced precipitation. Observational studies indicate that precipitating convective systems are influenced (disrupted or bifurcated) by cities while passing over them. This is attributed to the larger urban surface roughness. The urban-modified precipitating systems can, however, either increase or decrease precipitation over and/or downwind of cities depending on many factors such as topography and local/regional water vapor supply. It cannot be definitely stated that urban-modified precipitation systems produce more precipitation downwind of cities than upwind of cities.

As reviewed in this study, numerical models have been extensively used for studying urban impacts on precipitation. To better simulate and predict urban-related weather and climate, numerical models need to be further developed, with focus on the interactions of urban surfaces with the overlying atmosphere (urban parameterization: e.g., Masson, 2000; Kusaka *et al.*, 2001; Martilli *et al.*, 2002) and cloud microphysics. To more reliably and intensively study the effects of urban air pollution on precipitation and aerosol-cloud-precipitation interactions, it is necessary to couple meteorological models with aerosol/chemistry models. In addition, the bin cloud microphysics would be better to be included in cloud-resolving mesoscale models because it relaxes some constraints imposed on bulk cloud microphysics and contains higher-level cloud microphysical processes, although it requires much longer computing times. Such advanced coupled models would offer the possibility of in-depth or new understandings of individual physical processes and complex interactions among the processes. Together with model development and modeling studies, a greater number of observational studies for major global cities using all available data are necessary. In particular, the analyses of long-term radar data would be greatly beneficial because of its high spatiotemporal resolution and wide spatial coverage. Such research would lead to a better understanding of urban impacts on precipitation.

If urbanization continues in the future, cities are likely to exert greater influences on local and regional weather and climate. It would be interesting to conduct research on how the spatial pattern and amount of precipitation change with future urbanization. Intensive studies are required to further understand and reliably predict urban precipitation anomalies.

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