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Review

A Systematic Review of the Potential Influence of Urbanization on the Regional Thunderstorm Process and Lightning Activity

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Abstract: In the context of global climate change, lightning disasters have emerged as a serious environmental factor that restricts the sustainable development of megacities. This paper provides a review of the research on the impact of urbanization on thunderstorm processes and lightning activity, exploring various aspects, such as aerosols, urban thermal effects, urban dynamic effects, and building morphology. Despite numerous significant achievements in the study of the impact of air pollutants on lightning activity, there is no consensus on whether aerosols serve to enhance or inhibit lightning activity. The temperature difference between the urban underlying surface and the natural underlying surface could sustain and promote the occurrence and development of convective systems, thus enhancing lightning activity. In terms of urban dynamics, the barrier effect has led to the maximum center of lightning appearing at the edge of a built-up area, which might be associated with factors, such as urban heat island (UHI) intensity, wind speed, synoptic background, and city size. Additionally, the size of a city and the height of the buildings was also an influencing factor on lightning activity. In summary, scholars have made progress in understanding the characteristics and drivers of urban lightning activity in recent years, but there are still some urgent problems that need to be solved: (1) How to analyze, comprehensively, the spatiotemporal patterns of urban lightning activity under different thunderstorm intensity backgrounds? (2) How to conduct analysis to investigate the influence of alterations in the boundary layer structure, water–heat energy balance, and water vapor circulation processes on urban lightning activity in the context of urbanization? (3) How to couple numerical models of different scales to enhance the understanding of the impact of complex underlying surfaces on urban lightning activity? Future studies could investigate the relationship between urbanization and thunderstorm/lightning activity using a combination of observational data, numerical modeling, and laboratory experiments, which holds promise for providing valuable theoretical insights and technical support to enhance the prediction, nowcasting, early warning, and risk assessment of thunderstorms and lightning in urban areas.

Keywords: urbanization; lightning activity; aerosol; urban thermal effect; urban dynamic effect; building height

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1. Introduction

With the increasing frequency of extreme global events and the continuous advancement of urbanization, lightning events have emerged as a major obstacle to the safe operation of cities and social–economic development. The advancement of lightning detection technology has facilitated in-depth analysis of the characteristics and causes of urban lightning activity, highlighting its significant scientific significance and practical application value [1–3].

During the process of urbanization, the population continues to gather in urban areas, leading to the expansion of the scale of the built-up areas. The urban underlying surface can alter the heat and momentum exchange in the boundary layer, and human activities emit air pollutants, ultimately shaping the local urban climate. The mechanisms by which urbanization impacts lightning activity primarily involve air pollutants, the urban thermal effect, the urban dynamic effect, and building morphology [4–10]. Some studies have found that air pollutants can enhance lightning activity by influencing the formation of ice particles and the development of convection [11,12]. However, some scholars have concluded that there is no significant correlation between air pollutants and urban lightning activity [5,13]. Research has even suggested that air pollutants can weaken lightning activity through radiation effects [14]. Further exploration may be necessary to establish whether aerosols play a role in either promoting or mitigating lightning activity.

With regard to the urban thermal effect, numerous scholars have made valuable discoveries [15,16]. Westcott et al. [17] were the first to note that the UHI effect can modulate lightning activity. Simulation results from a mesoscale model (MM5) in the Atlanta area showed that the urban heat island (UHI) can trigger and enhance thunderstorms, with thunderstorms primarily concentrated in the urban center [18]. Thielen et al. [19] conducted sensitivity tests on urban surface parameters and found that as the UHI intensity weakens, there are significant changes in the center of thunderstorm activity. Under the influence of weak synoptic backgrounds, the UHI effect causes disturbance in the city, which plays a dominant role in triggering local convection [20]. Scholars have concluded that the urban thermal effect can promote the development of a mixed boundary layer and assist in triggering thunderstorms [12]. However, some scholars have acknowledged that the contribution of the UHI effect to thunderstorm development is not evident [21,22].

The urban underlying surface, with its roughness, can alter the structure and motion of the near-surface atmospheric layer in cities through dynamic interactions [23,24], which then has a significant impact on weather processes within the urban area and the surrounding regions [25,26]. A limited number of scholars have emphasized that the barrier effect can facilitate the bifurcation and detouring of thunderstorms [27], leading to the concentration of lightning activity at the periphery of built-up areas [28]. Preliminary investigations into the causes of the urban barrier effect have been conducted from a climatological perspective [17,29]. During periods when the urban heat island (UHI) is weak, summer thunderstorms are observed to bifurcate and bypass the city [30]. Moreover, when ground wind speeds are high, the urban barrier effect on thunderstorms becomes particularly pronounced [29]. The development of thunderstorm systems is also closely linked to larger-scale synoptic conditions [31]. When thunderstorms with strong frontal synoptic backgrounds pass through the city, the central city density of cloud-to-ground (CG) lightning flashes tends to be lower [28]. However, some studies have observed the opposite, finding that even under weak synoptic conditions, thunderstorms passing through urban areas can bifurcate [26]. Previous research has emphasized the significance of urban morphology in influencing lightning activity and thunderstorm processes [32–34]. The evolving urban landscape, marked by expanding city sizes, plays a crucial role in shaping thunderstorm systems [34]. The type of urban land use has been observed to alter the spatial patterns of lightning activity [28]. Additionally, building heights within urban areas can also impact lightning activity [35]. However, a comprehensive understanding of the influence of the urban underlying surface on lightning activity and thunderstorm processes remains elusive, lacking a systematic description and mechanistic explanation [6,8].

The impact of urbanization on lightning activity and thunderstorm processes has been a long-standing and challenging research topic, serving as a crucial scientific foundation for the precise forecasting of intense local thunderstorms in terms of timing, location, and magnitude [36–40]. With the continuous expansion of the urban scale, the impact of various factors, such as the air pollutant concentration, heat island intensity, rough underlying surface, and high plot ratio of built-up areas, on lightning activity cannot be overlooked. This paper poses the following pivotal questions: What are the distinct features of lightning activity within built-up areas? How can we systematically delineate the predominant influence of urbanization on lightning activity and thunderstorm processes? And what is the mechanism driving these observed patterns? In addressing these concerns, this paper reviews the research on the impact of urbanization on thunderstorm processes and lightning activity from various perspectives, including aerosols, urban thermal effects, urban dynamic effects, and building morphology. The aim is to provide a valuable theoretical basis and technical support for potential urban lightning prediction, early warning, and risk assessment.

2. The Method Involving the Lighting Location and Experimentation

During the occurrence of lightning, electromagnetic waves are emitted outward, primarily within the frequency range of 1 Hz to 300 MHz [41]. As illustrated in Figure 1, ground-based lightning detection networks utilize captured electromagnetic wave signals to compute crucial parameters, such as the time of arrival (TOA) and directional finder (DF), based on the unique characteristics of these radiation signals [42,43]. The DF method, although requiring fewer observation stations, tends to exhibit relatively larger measurement errors. Conversely, the TOA method offers high positioning accuracy, but necessitates a substantial number of observation stations. Scholars have employed magnetic field sensors and audio sensors for synchronous measurements, aiming to determine the distance of lightning strikes, based on the significant disparities between acoustic and magnetic propagation speeds [44].

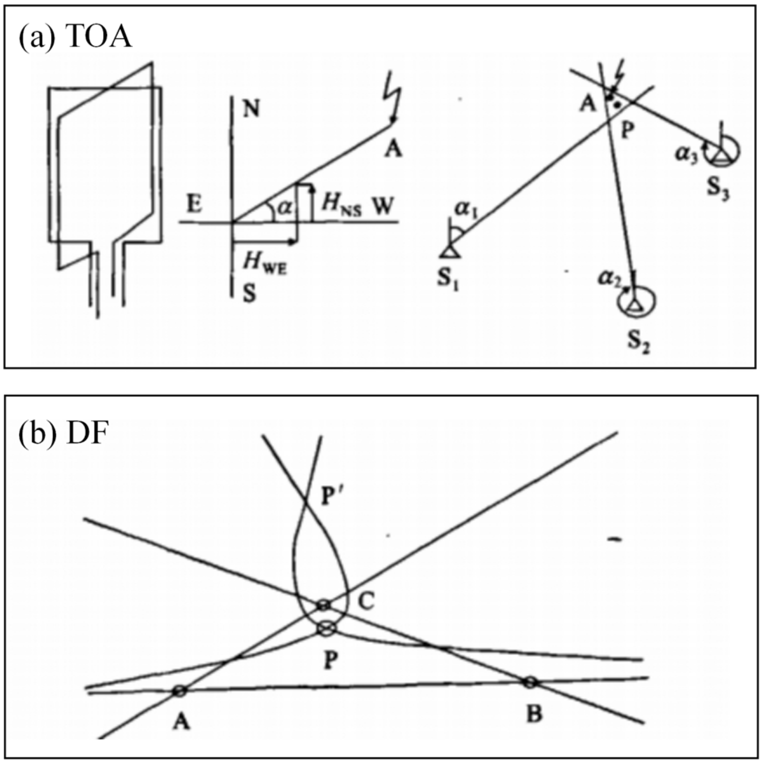

Figure 1. The lightning location method, based on the time of arrival (TOA) and directional finder (DF) [43].

Ground-based lightning detection technology has undergone extensive exploration and application over an extended period [2,45,46]. Currently, large-scale ground-based lightning detection networks include the National Lightning Detection Network (NLDN) in the United States, the World Wide Lightning Location Network (WWLLN), the Global Lightning Detection System (GLD360), and the Advanced Direction Finding and Time Difference (ADTD) established by China's Meteorological Administration, and the State

Grid Lightning Network (SGLNET), constructed by the State Grid Corporation of China. Taking SGLNET as an example, it presents a fully automated and precision-oriented lightning monitoring system, capable of capturing crucial lightning parameters, including the time, position, peak current, polarity, and numerous others. Since the early 1990s, the State Grid began to establish a provincial lightning monitoring system in China. By the end of 2015, SGLNET had built 45 central stations and 776 detection stations, achieving full coverage in the whole country (as shown in Figure 2). The technical level and scale of the SGLNET station network has reached a leading level internationally [47]. The datasets on the lightning location contain information such as the time, longitude, latitude, peak current, and polarity of the CG strokes [7]. Scholars have compared the results from artificially triggered lightning experiments and the Guangzhou high-tower observation station with the location of SGLNET, indicating that the location error and detection efficiency of SGLNET is 710 m and 94%, respectively [48].

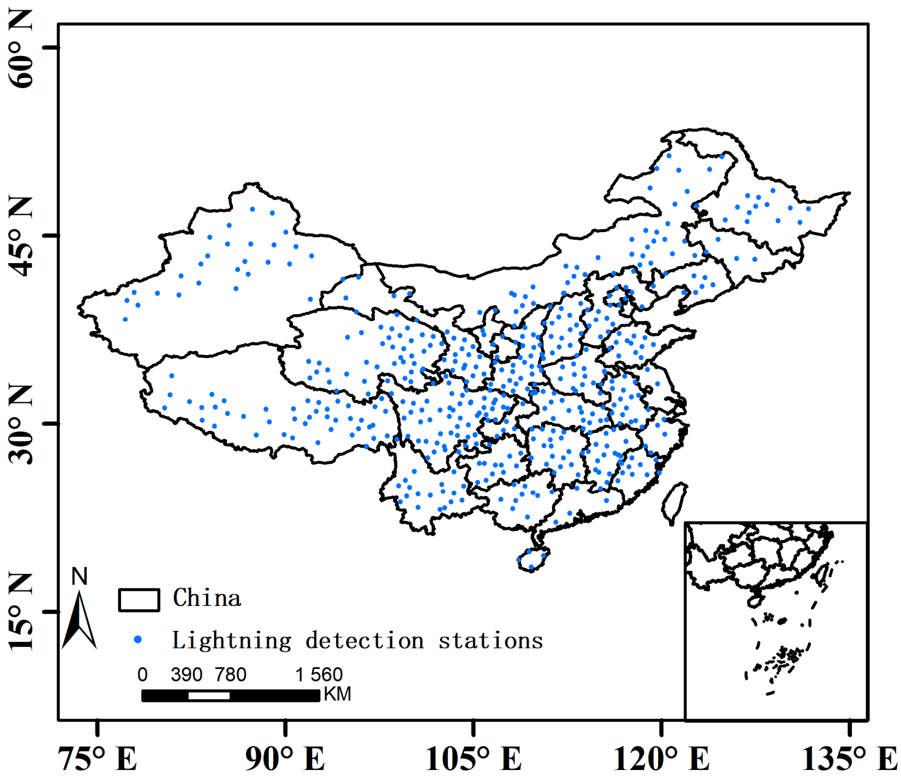

Figure 2. Distribution of detection stations in SGLNET, constructed by the State Grid Corporation of China [47].

As a highly controllable lightning measurement method, rocket-triggered lightning has been used to study the physical processes and discharging mechanism of natural lightning flashes [49–58]. Figure 3 provides a sketch of the experiment setup for the triggered lightning experiment related to the Field Experiment Base on Lightning Sciences, by the China Meteorological Administration (CMA-FEBLS), in the summer of 2019. The whole experimental field consisted of a rocket launching point, control room, close observation site, and far observation site. The distance from the close site and far site to the rocket launching site was 79 m and 1.9 km, respectively. Under vigorous thunderstorm conditions when the surface E-field reaches a certain threshold (e.g., 4.0 kV/m), the operator turned on the power switch of the ignition box in advance, and when the conditions were suitable, the wired rocket was launched into the bottom of the thundercloud. A high-speed video camera, slow and fast antenna, surface E-field, and other equipment were installed at the trigger site, and the main site was able to be used for simultaneous observation and study of the lightning discharge process by optical, electrical, and magnetic means [52]. The output signal of the current sensing device was connected to the transmitting end of a fiber optic system with high-voltage isolation, transmitted via the signal transmission fiber to the receiving end in the control room; the current data were recorded by a DL750 digital oscilloscope.

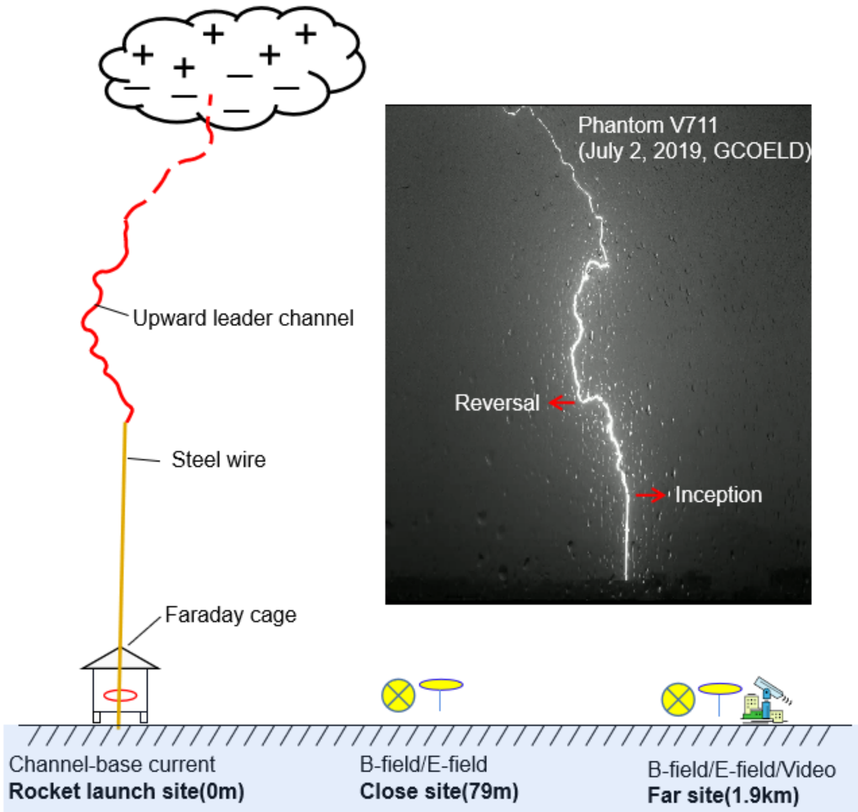

Figure 3. Schematic diagram of the initial process of triggering lightning with a wired rocket during the triggered lightning experiment: Field Experiment Base on Lightning Sciences, China Meteorological Administration [44]. The symbol + represents positive charge, and the symbol − represents negative charge.

3. The Lightning Hazard and Its Spatial and Temporal Activity Characteristics

When lightning strikes, it generates a range of intense physical phenomena, including powerful electrical currents, potent electromagnetic radiation, severe shockwaves, and extreme heat. These effects have the potential to instantaneously inflict harm on people and property, ultimately culminating in adverse societal consequences [59]. Lightning can generally be divided into two categories. Cloud-to-ground (CG) lightening refers to lightning that hits the ground from thunderstorm clouds, while intra-cloud (IC) lightening refers to lightning that occurs in or between clouds, that is, all lightning that does not hit the ground. In particular, the CG lightning that occurs between clouds and the ground poses the most serious threat to ground objects and human beings. When utilizing lightning location data for the research of cloud-to-ground (CG) lightning, it is imperative to account for the contamination caused by intra-cloud (IC) discharges on the CG lightning detection network. A peak current threshold of <10 kA can be effectively employed as a screening criterion to mitigate the interference from IC discharges [60,61]. This approach helps ensure more accurate and reliable results from the lightning detection network. Scholars have analyzed the spatiotemporal distribution patterns of IC and CG flashes in Beijing and the surrounding areas using an SAFIR3000 device, a device capable of observing total lightning flashes (Figure 4). The results indicate that CG lightning is primarily concentrated in the northeastern part of Beijing, northern Tianjin. The maximum density of CG flashes is approximately 30 flashes/km^2·a. The spatial distribution of CG flashes is generally similar to that of cloud IC flashes, yet the maximum density of CG flashes is significantly lower, reaching only about 5 flashes/km^2·a [62].

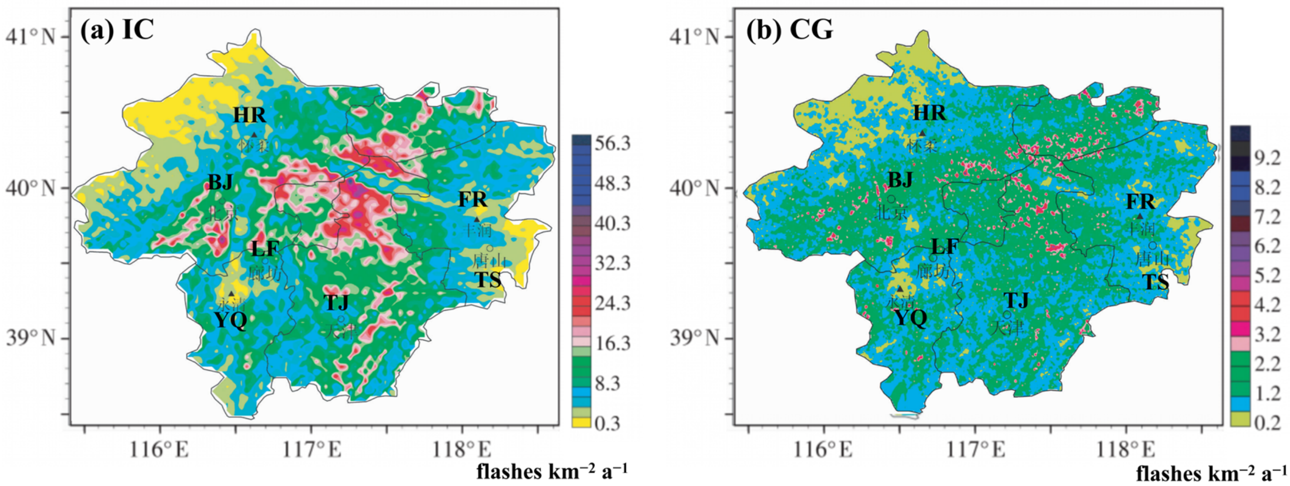

Figure 4. The spatial distribution of IC density (**a**), and CG density (**b**), in Beijing and the surrounding areas from 2005 to 2007. HR, BJ, LF, YQ, TJ, FR, TS represent Huairou, Beijing, Langfagn, Yongqing, Tianjin, Fengrun, and Tangshan, respectively [62].

Overall, current research primarily focuses on analyzing the spatiotemporal characteristics of cloud-to-ground (CG) lightning flashes [36,37,39,63–68]. The lightning location data collected by the lightning detection network installed at the Korean Meteorological Administration (KMA) have been used to study the CG lightning activity over and around Seoul, the largest metropolitan city in South Korea, for the period of 1989–1999 [63]. Hu et al. [65] selected the lightning location data in Beijing from 2007 to 2008 to calculate the distribution of lightning density, and used the geographic information system (GIS) to assess the risk of lightning disasters in Beijing. The results showed that the risk of lightning disasters in urban areas in Beijing was generally high. Ntelekos et al. [66] selected Baltimore, as a representative of large cities in the United States, to conduct detailed research on the characteristics of lightning activity in the vicinity of the city. Given the complex and diverse terrain in China, there are significant regional differences in the characteristics of lightning activity [36,37]. Scholars have found that the Taihang Mountains in the west and the Yanshan Mountains in the north are areas with high concentrations of CG lightning, by analyzing lightning detection data [67]. The location data of lightning in Beijing from 1995 to 1997 was analyzed and it was found that lightning was mainly distributed in the east, south, southeast, north, northwest, and other directions [36]. Cheng et al. [68] utilized the data from the China Meteorological Administration lightning location network to delve into the temporal and spatial patterns of ground lightning activity in Beijing. Their findings indicated that the diurnal variations in positive and negative ground lightning exhibit distinct patterns: a single peak for positive lightning and a double peak for negative lightning. As shown in Figure 5, Wang et al. [39] employed data from the Beijing lightning location network to classify thunderstorms based on their frequency and duration. This allowed for deeper analysis of the temporal and spatial distribution characteristics of lightning in Beijing. In conclusion, while the temporal and spatial patterns of urban lightning activity have garnered significant interest, current research remains limited by a lack of consistent and long-term ground-based lightning detection data.

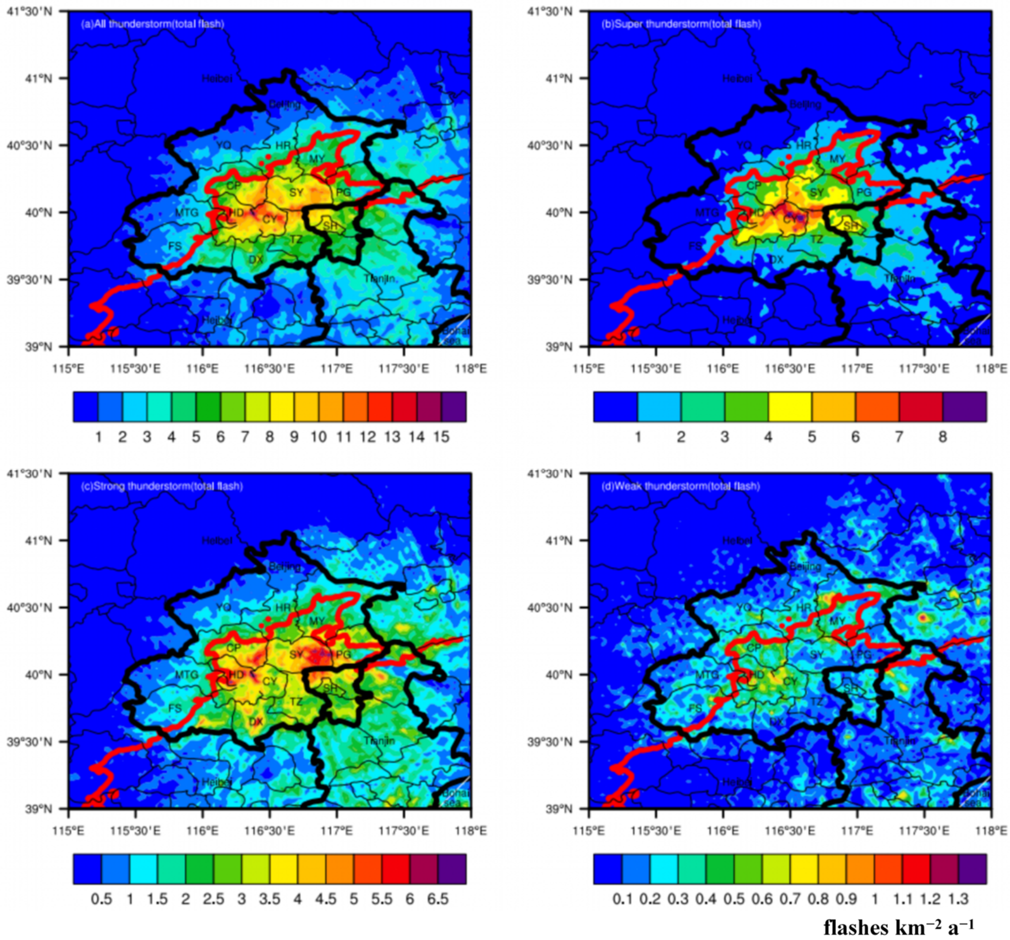

Figure 5. CG flash density of a total thunderstorm (**a**), super thunderstorm (**b**), strong thunderstorm (**c**), and weak thunderstorm (**d**), in Beijing. The color code at the bottom represents the CG flash density (unit: flashes km^{-2} a^{-1}) [39].

4. Impact of Aerosols on Thunderstorm Processes and Lightning Activity

Social production activities and daily life are heavily concentrated in urban areas [69]. As urban construction operations proceed, significant amounts of energy are consumed, leading to the emission of air pollutants and anthropogenic heat into the atmosphere. This alters the composition and structure of the near-surface atmosphere [21], ultimately shaping the local climate of the city [70,71]. The primary air pollutants emitted by vehicles and industrial activities in urban areas include sulfur dioxide (SO_2), particulate matter (PM), and other air pollutants [72].

Scholars have conducted comprehensive research on the influence of aerosols on lightning activity, exploring the intricate relationship between these atmospheric components and their role in modulating lightning occurrence [11,32,43,73–80]. Soriano and de Pablo [43] utilized lightning detection data to analyze the lightning activities in various Spanish cities and found that higher concentrations of SO_2 correlate with an increase in CG flashes. Farias et al. [75] discovered by analyzing air pollutant data that aerosols can extend the duration of thunderstorms and increase lightning frequency. Lal and Pawar [76] observed an increase in lightning activity in the southern Indian city of Bangalore and attributed this trend to increasing aerosol concentrations. Kar et al. [63] concluded that a higher concentration of SO_2 contributes to the enhancement of CG lightning flashes, and the contribution of the PM_{10} concentration did not appear in this study to be as significant as SO_2 in the enhancement of CG lightning flashes. Rosenfeld and Woodley [77] found that aerosols can impact the microphysical processes of thunderstorms, promoting the electrification process within thunderstorm clouds, ultimately leading to an increase in lightning activity. Tan et al. [11] postulated that air pollutants can delay the initial discharge from thunderstorm clouds, prolonging the duration of lightning and, ultimately, increasing its frequency. Conversely, some scholars have suggested that aerosols can inhibit lightning activity. Orville et al. [79] and Wang et al. [5] propose that air pollutants in the boundary layer can increase the concentration of cloud condensation nuclei and inhibit the average droplet size, thereby influencing the electrification and lightning activity within the cloud (as illustrated in Figure 6). Therefore, while numerous significant advancements have been made in the study of the impact of air pollutants on lightning activity, there is no consensus on the role of aerosols in this regard.

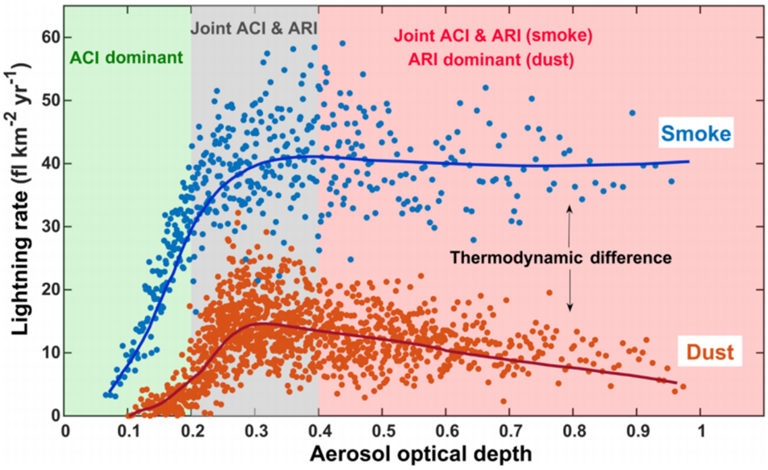

Figure 6. Lightning flash rate as a function of the aerosol optical depth (AOD) in the dust-dominant (orange dots) and smoke-dominant regions (blue dots). ACI and ARI represent the aerosol–cloud interactions and aerosol–radiation interactions, respectively [78].

5. Influence of Urban Thermal Effect on Thunderstorm Processes and Lightning Activity

During the mid-1970s, some scholars conducted the Metropolitan Meteorological Experiment in Saint Louis, revealing that the city significantly increased the frequency and duration of thunderstorms [81,82]. When Westcott et al. [17] studied lightning activity in Chicago, they were the first to note the impact of cities on lightning frequency. Shepherd et al. [83] discovered by analyzing lightning detection data that the peak lightning activity in Houston occurs in the afternoon and attributed this to the diurnal variation in the UHI effect.

Scholars have utilized lightning location data to investigate the thunderstorm activity characteristics of the Pearl River Delta urban agglomeration and observed that the lightning frequency is significantly higher compared to other regions [84]. Meng et al. [23] postulated that the UHI effect enhances the instability of stratification within a city, thereby facilitating thunderstorm formation. The UHI effect not only alters the thermal field and boundary layer structure within urban areas, but also impacts the development of convective systems through local circulation. The vertical movement of airflow within a city is intricately correlated with the stability of the boundary layer. When the boundary layer is less stable, the vertical velocity and ascending height within the city increase, favoring the initiation and intensification of thunderstorms [85]. Luo et al. [20] posited that under weak synoptic conditions, the UHI effect can trigger local convergence and convection by causing disturbances. Sun et al. [12] contended that the urban thermal effect promotes the development of a mixed boundary layer and, ultimately, leads to thunderstorm system activation (as demonstrated in Figure 7).

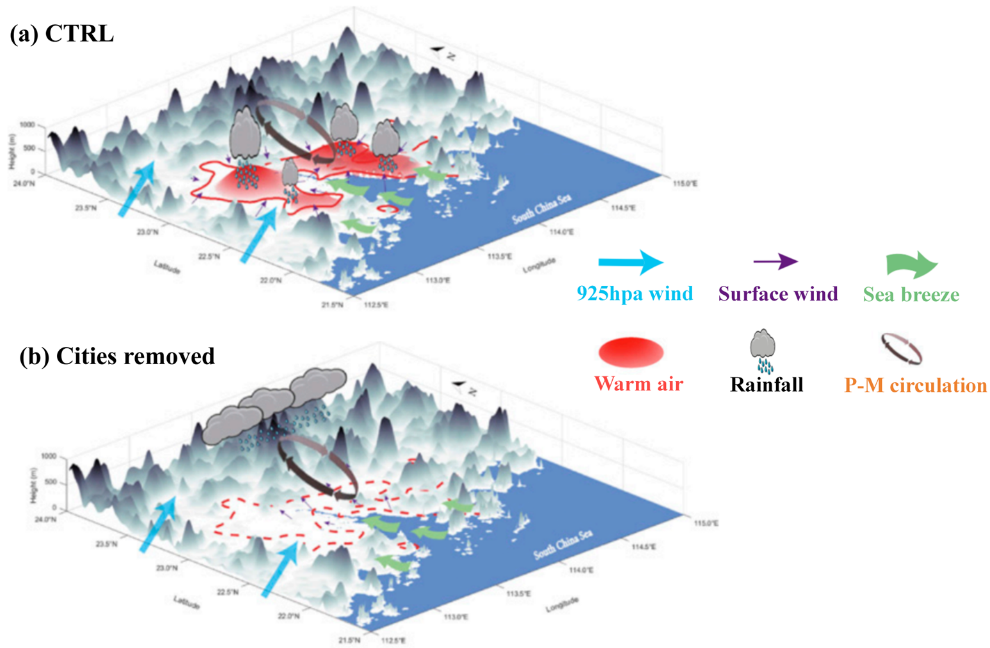

Figure 7. Schematic diagrams of urban-related thermodynamic disturbances associated with an afternoon thunderstorm over the Great Bay Area in South China [12].

Unstable conditions, water vapor conditions, and vertical shear are important environmental factors that affect the development of thunderstorm systems [86,87]. Vertical shear, in particular, can cause air masses with diverse properties to undergo vertical mixing, and its strength in the middle and lower layers has a direct impact on the intensity of thunderstorms [88]. Additionally, Sun et al. [89] examined how the cold pool outflow from thunderstorms affects the vertical shear due to thermal differences as it passes through cities, without considering the influence of the Coriolis force. Assuming the incoming flow direction of the thunderstorm system is the x-axis (from northwest to southeast), the Boussinesq approximation equation can be expressed as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \omega\frac{\partial u}{\partial z} = -\frac{\partial \pi}{\partial x} + k\frac{\partial^2 u}{\partial z^2} \quad (1)$$

$$\frac{\partial \theta}{\partial t} + u\frac{\partial \theta}{\partial x} + \omega\frac{\partial \theta}{\partial z} = k\frac{\partial^2 \theta}{\partial z^2} \quad (2)$$

$$\frac{\partial \pi}{\partial z} = \lambda\theta \quad (3)$$

$$\frac{\partial u}{\partial x} + \omega\frac{\partial \omega}{\partial z} = 0 \quad (4)$$

Taking the partial derivatives of z for Equations (1) and (3), respectively, we can obtain:

$$\frac{\partial}{\partial t}(\frac{\partial u}{\partial z}) = -\frac{\partial}{\partial z}(u\frac{\partial u}{\partial x} + \omega\frac{\partial u}{\partial z}) - \frac{\partial}{\partial x}(\frac{\partial \pi}{\partial z}) + k\frac{\partial^3 u}{\partial z^3} \quad (5)$$

$$\frac{\partial}{\partial x}(\frac{\partial \pi}{\partial z}) = \lambda\frac{\partial \theta}{\partial x} \quad (6)$$

By omitting the influence of $\frac{\partial}{\partial z}(u\frac{\partial u}{\partial x} + \omega\frac{\partial u}{\partial z})$ and $\frac{\partial^3 u}{\partial z^3}$, it can be concluded from Equations (5) and (6) that:

$$\frac{\partial}{\partial t}(\frac{\partial u}{\partial z}) \cong -\lambda\frac{\partial \theta}{\partial x} \quad (7)$$

It is evident from the provided equation that when a thunderstorm system passes through a built-up area, the horizontal temperature gradient between the cold pool outflow and the urban underlying surface exerts a force that enhances the vertical shear of the wind speed. A strong horizontal wind speed vertical shear can significantly enhance vertical airflow movements [90]. When the upwelling airflow enters the city, it is propelled forward in the upper atmosphere due to the force of environmental winds, leading to a tilt in the main body of the thunderstorm. This ensures the continuous upwelling of the airflow [91]. Consequently, the enhanced vertical wind shear resulting from the thermal differences on the underlying surface plays a crucial role in maintaining and intensifying the thunderstorm system.

The distinct physical differences in the properties between urban underlying surfaces and suburban areas result in a faster temperature rise in built-up areas. The phenomenon of surface wind fields converging toward urban areas can impact the vertical structural characteristics of the entire boundary layer flow field, facilitating an elevation in the boundary layer height and an increase in the vertical mixing height [15,92]. This maintains a strong upward movement in the thunderstorm center. However, some scholars have suggested that the impact of the UHI effect on thunderstorms is not significant [21,22], and that it may actually accelerate raindrop evaporation within clouds and alter water vapor exchange between the ground surface and the atmosphere, potentially inhibiting urban thunderstorm activities [93,94]. Overall, the UHI effect has a certain enhancing effect on thunderstorm processes and lightning activity.

6. Influence of Urban Dynamic Effect on Thunderstorm Processes and Lightning Activity

In addition to the urban air pollution and thermal effect, scholars have also recognized the driving force of the urban dynamic effect on lightning activity [8,27,95]. Compared to natural underlying surfaces, the roughness of urban surfaces is significant. Urban buildings have a strong drag effect on the horizontal flow field, and the wind field converges, rises, and flows around in the windward direction of the city [96]. Yin et al. [24] posited that the friction of the urban underlying surface increases the momentum flux in the urban near-surface layer, leading to enhanced atmospheric convergence, which contributes to the development of thunderstorm systems. However, compared to the urban thermal effect, the vertical motion intensity when urban airflow "climbs" is minimal [97], which is insufficient to trigger convective activities.

As shown in Figure 8, the urban barrier effect refers to the phenomenon where the amount of lightning or precipitation in the center of the city is significantly lower than that in the periphery of the city. This effect can lead to the bifurcation of thunderstorms, which move around cities [27,98], with the peak area of the lightning and rainfall generated by the thunderstorm system concentrated in the periphery of cities [28,30]. Niyogi et al. [99] analyzed 91 thunderstorm systems in Indianapolis from the summer of 2000–2009 and found that thunderstorms with large horizontal scales split over the city and merge downstream of the urban area. Miao et al. [100] posited that the increase in the buildings in the urban area of Beijing may break the squall line into convective cells and promote the bifurcation of rainfall clouds, but the barrier effect of the urban canopy is less than its thermal effect on strong convection. Yue et al. [6] conducted a systematic review of the research progress on the impact of the urban barrier effect on strong convection processes, concluding that current research on the barrier effect is not yet comprehensive.

Currently, scholars have explored the impact of the urban barrier effect on thunderstorms from a climatological perspective [29,30,101]. During weak UHI periods, summer thunderstorms with strong synoptic backgrounds bifurcate and detour through the city [30], and the flash density shows a low value trend in the city center [28]. The synoptic backgrounds of thunderstorms in Beijing are classified into weak synoptic backgrounds and strong synoptic backgrounds (Figure 9). After statistical analysis, it was found that over 60% of CG flashes in built-up areas were produced by the strong weather system, which was also an important cause of the occurrence of the barrier effect [102]. So, a strong synoptic background may be an important condition for the barrier effect on the spatial patterns of a long series of CG lightning in the built-up areas in Beijing. Additionally, some scholars believe that when the wind speed near the surface exceeds 4–6 m/s, the urban barrier effect is significant [29]. However, some scholars have observed the opposite phenomenon [26], where thunderstorm systems under weak synoptic conditions also bifurcate at the junctions of urban and rural areas. Therefore, the synoptic hypothesis proposed by previous studies cannot fully explain the formation mechanism of the barrier effect.

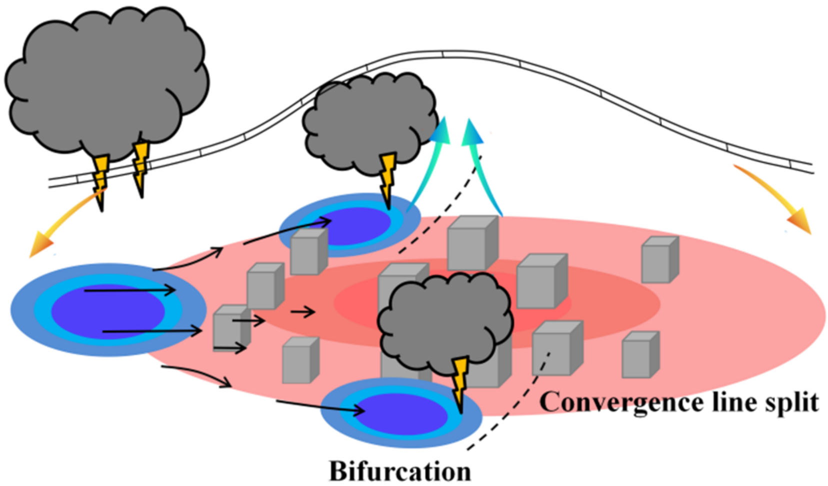

Figure 8. The influence mechanism of the barrier effect that alters the CG lightning activity and thunderstorm processes (self-drawing).

The characteristics of urban morphology include the size of the city and the spatial configuration of urban building groups. The city size is considered to be an important factor affecting thunderstorm activities. Kingfield et al. [34] used radar echo data to study the impact of four cities in the Central Plains of the United States on thunderstorm frequency and intensity and found that larger cities may increase the incidence and intensity of downwind thunderstorms in such cities. Additionally, the spatial configuration of urban agglomerations also has a tendency to alter thunderstorm activities. Stallins and Bentley [28] used GIS technology to analyze the distribution characteristics of lightning in Atlanta and found that the lightning density in high-density building areas was low (Figure 10). Dai et al. [95] believe that the buildings in the urban area of Shanghai lead to the detouring of near-ground airflow, the divergence of the airflow in the upwind direction of the city was not conducive to the occurrence of convection, and the convergence of the airflow in the downwind direction was conducive to the strengthening of convection. Yi et al. [103] found that the rough urban underlying surface blocked and lifted the airflow at the middle and low levels, resulting in the concentration of lightning activity centers in the west and south of Guangzhou. Zhang et al. [104] found that buildings have drag and blocking roles on the flow field using a three-dimensional model, with airflow clearly bypassing and weakening when passing through buildings [101]. In the context of urbanization, the size of cities and the density of buildings are increasing, necessitating continued exploration of the mechanism of the dynamic effect of urban underlying surfaces on thunderstorm processes and lightning activity.

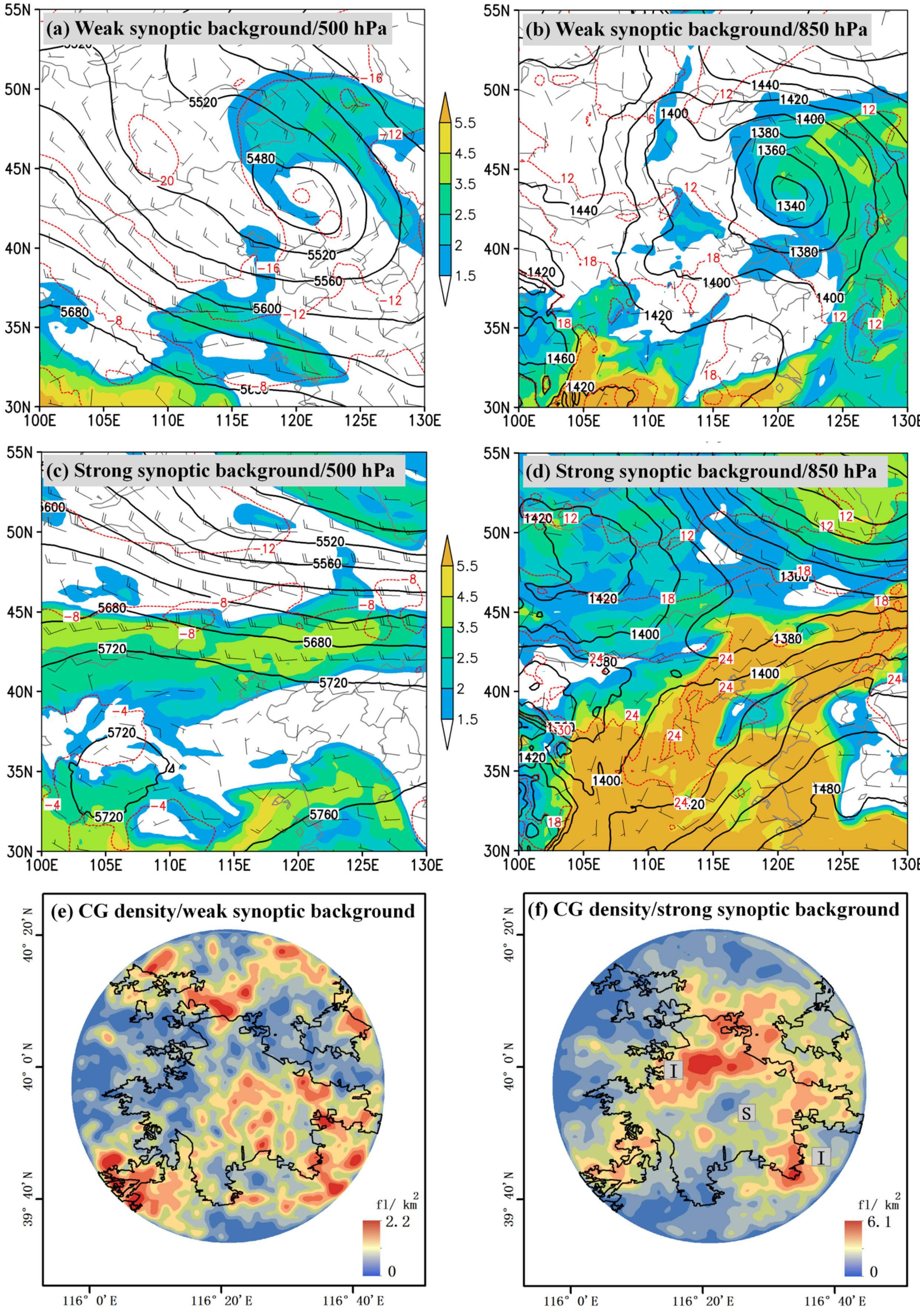

Figure 9. Weak synoptic background (**a**,**b**), strong synoptic background (**c**,**d**), and spatial patterns of CG density (**e**,**f**) [73].

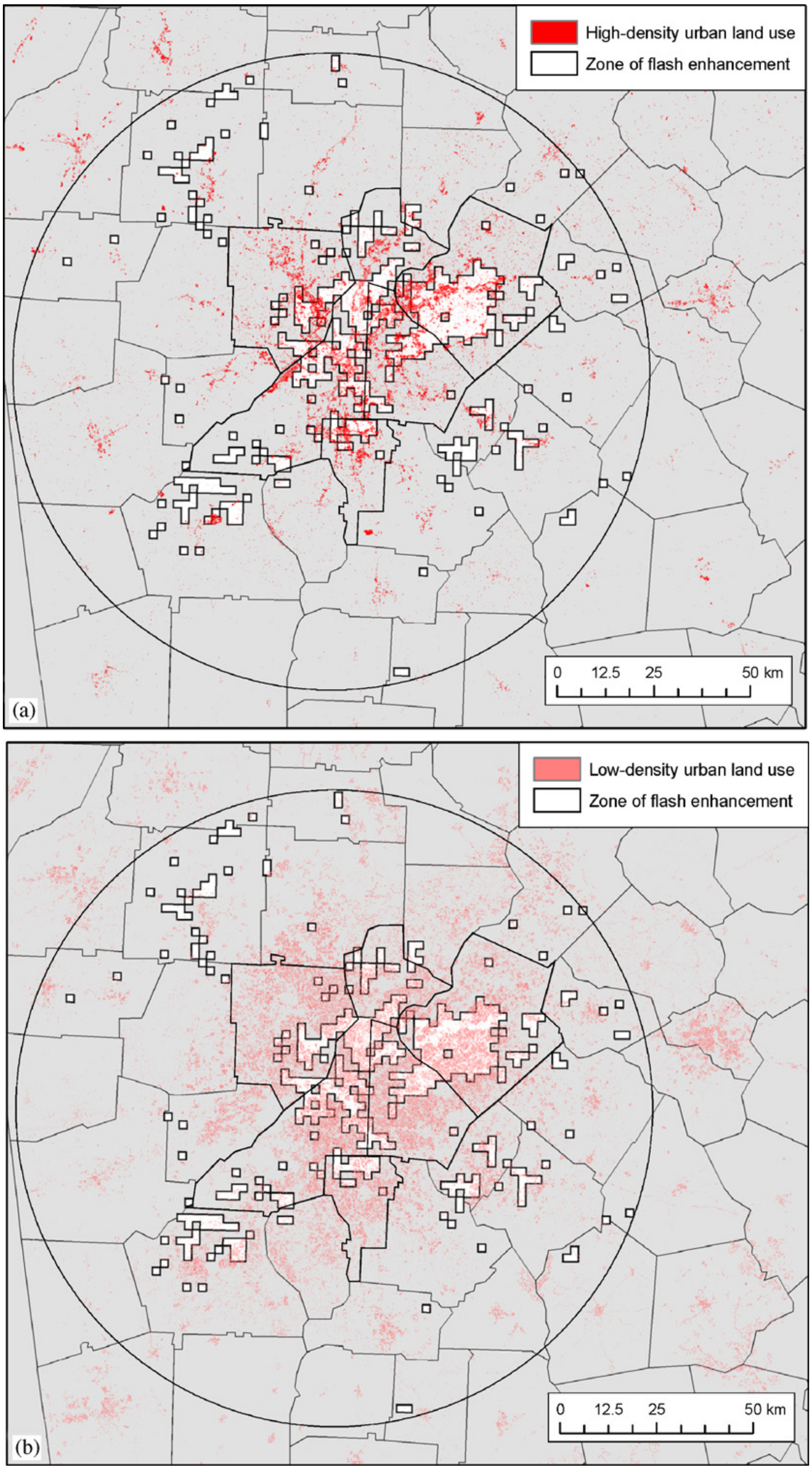

Figure 10. Characteristics of lightning activity in high-density building areas (**a**), characteristics of lightning activity in low-density building areas (**b**) [28].

7. Influence of Tall Structures on Atmospheric Electrical Activity

Modern cities are increasingly dotted with towering structures, which not only attract nearby downward CG flashes, but also initiate upward CG flashes at their summits, influencing lightning discharge characteristics. Since the 1930s, various research teams across the globe have installed optical, electromagnetic, or current detection equipment on or adjacent to prominent high-rise structures, such as the Empire State Building in the United States, Canada's National Tower (CN Tower), the Ostankino TV Tower in Russia, the Säntis Tower in Switzerland, the iron tower in Mt. San Salvatore, the Meteorological Tower in Beijing, China, and the Guangzhou Tower in China. These locations have facilitated observations and research on lightning strikes to high buildings [105–112].

During the passage of a thunderstorm cloud overhead, the local electric field at the tips or corners of tall buildings is enhanced, making them more susceptible to lightning strikes, while the probability of lightning strikes to surrounding low-rise buildings or flat surfaces decreases relatively. Armstrong and Whitehead [113] proposed a method to calculate the flash-to-ground distance based on the characteristics of negative polarity long-gap discharges and established the electrical geometric model, which led to the development of the rolling ball method for analyzing the shielding performance of buildings. However, the rolling ball method's criteria are not applicable to taller buildings, whose height exceeds the radius of the rolling ball [114]. Some scholars have evaluated the impact of tall buildings on nearby CG flash activity by analyzing the CG flash densities around them. Ngqungqa [115] used CG flash localization data to analyze the lightning activity around two iron towers in South Africa, which were 250 m and 220 m tall and separated by a distance of 5.2 km. The study found that the lightning density within a 2.5 km radius of the towers was higher than that in the annular region between 2.5 km and 10 km, suggesting that the towers have an attraction effect on lightning. With a total height of 600 m, Guangzhou Tower is the tallest tower in China. Lv et al. [116] compared the location of the lightning return stroke within 1 km of the Guangzhou Tower before and after its completion, concluding that the number of CG flashes around the Guangzhou Tower increased significantly after its completion (Figure 11). The process of initiating and developing the upward leader is a key factor influencing the location of lightning strike points. Therefore, research on this process is crucial for understanding the physical processes of lightning and disaster prevention [117]. However, in natural lightning, the upward leader is usually triggered when the downward leader approaches the ground. The luminous intensity and electromagnetic radiation of the upward leader are weaker than that of the downward leader, making optical observation and radiation source localization difficult. As a result, it is currently challenging to directly detect the upward leader in natural lightning.

With its controllable location, predictable occurrence time, and the ability to measure the current, the artificial triggering lightning experiment has become a vital tool for studying natural lightning. The initial phase of this experiment, where the upward leader is initiated and the initial continuous current is generated, parallels the process seen in lightning strikes triggered by tall buildings [51,52]. Prior research has shown that when the experimental rocket reaches a height of several hundred meters, a breakdown at the top of the conductor produces an upward leader. The upward leader in artificial lightning is self-triggered and develops upward from the ground. It is relatively easy to locate its radiation source, through electrical detection, and optical detection [35,44,118]. Figure 12 depicts the electromagnetic signals captured during the initial phase of the artificial lightning experiment. According to the statistical analysis, the peak current of precursors ranges between 10 and 35 A, with an average value of 25.4 A, and the waveform duration averages approximately 2.1 µs. The peak current of the upward leader (UPL), on the other hand, falls between 18 and 45 A, with an average value of 32.7 A, and its waveform duration averages about 3.7 µs. Both currents are greater than those of the precursors. These observed results align closely with previous research findings [49,119].

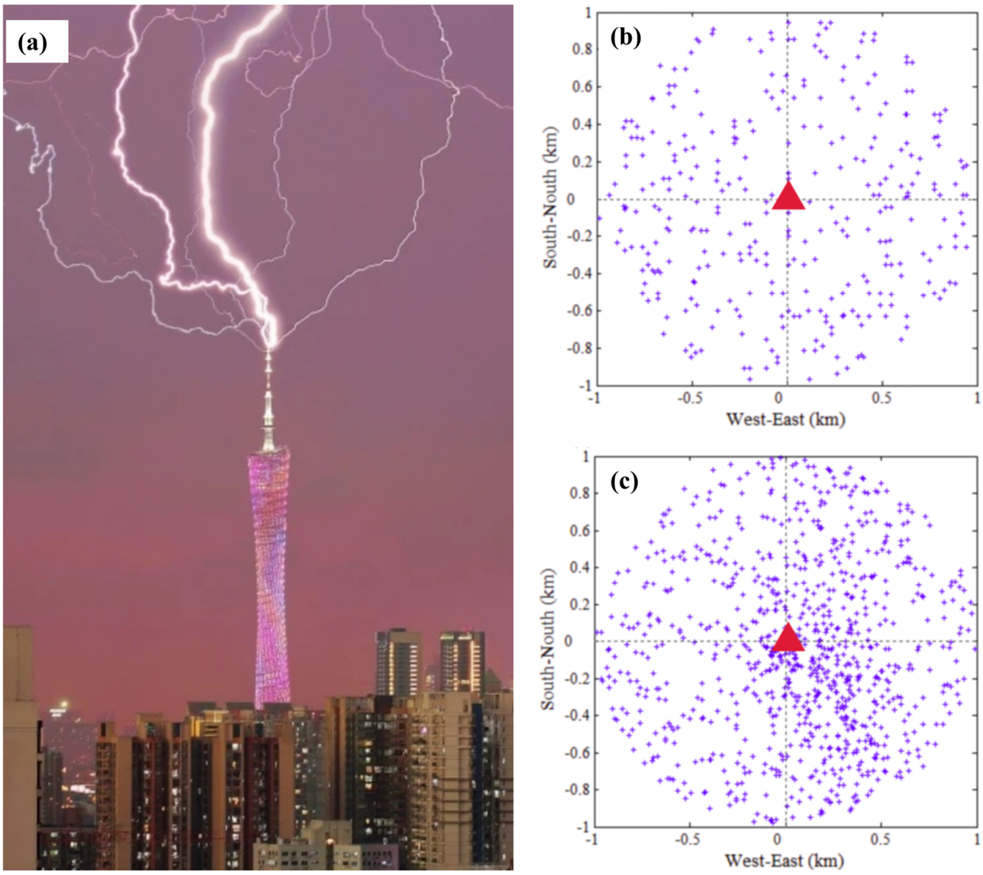

Figure 11. Guangzhou Tower was struck by lightning from the network (**a**). Before the completion of Guangzhou Tower (**b**), and after the completion (**c**), the lightning distribution within 1 km of Guangzhou Tower, and the red triangle represents the location of Guangzhou Tower [116].

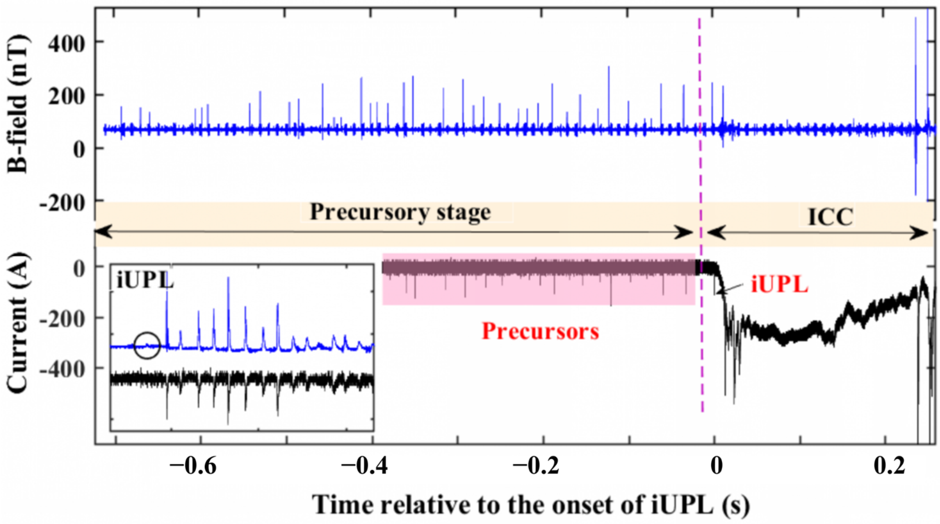

Figure 12. Channel-base current waveform (black line) and close B-field signals (blue line) at the triggered site, during the precursory stage of negative rocket-triggered lightning flashes (self-drawing).

According to the leader model [53–56], a heightened environmental electric field facilitates the ability of the upward leader to initiate. Conversely, a space charge with a higher density increases the likelihood of leader development failure. Furthermore, a space charge region with a smaller radius enhances the propensity of the upward leader to initiate. Among these parameters, the environmental electric field is the most significant factor [120].

Lalande et al. [121] used the physical model of the leader to calculate the minimum environmental electric field (E_{stab}) at different heights and established a functional relationship between E_{stab} and height through nonlinear fitting:

$$E_{stab+}(H) = [\frac{306.7}{1 + H/6.1} + \frac{21.6}{1 + H/132.7}]\delta \quad (8)$$

$$E_{stab-}(H) = [\frac{723}{1 + H/10} + 4]\delta \quad (9)$$

$$\delta = (P/P_0)(T_0/T) \quad (10)$$

In the above formulas, P_0 and T_0 represent the standard atmospheric pressure and the standard atmospheric temperature, respectively, while P and T represent the ambient pressure and ambient temperature. By applying these formulas, the minimum environmental electric fields required for the UPL at different heights can be determined. These values are plotted in Figure 13.

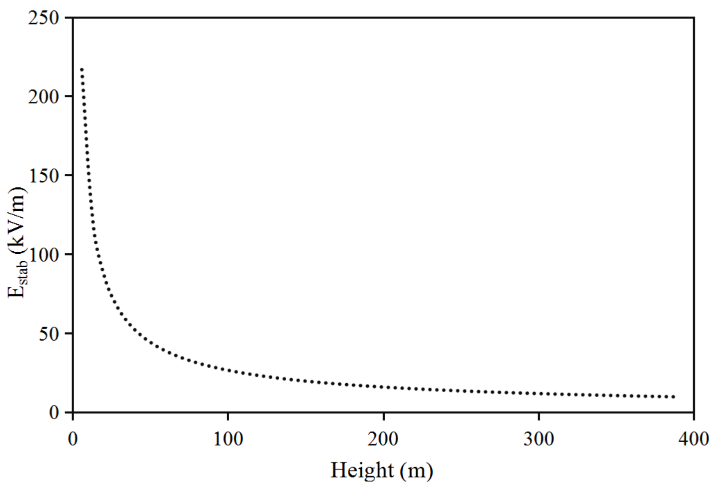

Figure 13. Functional relationship between E_{stab} and height [85].

It can be observed that as the height increases, the E_{stab} required by the UPL decreases significantly. Specifically, at a height of 20 m, the E_{stab} is approximately 160 kV/m, while at 50 m, it rapidly drops to 49 kV/m. Therefore, whether the upward leader can develop continuously is primarily determined by the environmental electric field and the height of the building. In other words, taller buildings are more susceptible to lightning strikes. This finding provides valuable insights for the study of urban lightning activity characteristics and the lightning protection of buildings.

8. Conclusions

The evolution of temporal and spatial characteristics of urban lightning activity has always been a research focus and challenge. It is also an essential scientific foundation for conducting local severe thunderstorm forecasting, including timing, fixed-point, quantitative, and refined predictions. This paper reviewed the research results on the impact of urbanization on the regional thunderstorm process and lightning activity in recent years and summarized the existing research deficiencies and future research directions in regard to aerosols, the urban thermal effect, the urban dynamic effect, building forms, and so on. Currently, research on the temporal and spatial characteristics of urban lightning lacks support from stable and long-term, ground-based lightning detection data. In terms of the role of air pollutants, there is no consensus on whether aerosols serve to enhance or inhibit lightning activity. With respect to the urban thermal effect, the UHI effect has a certain enhancement effect on thunderstorm processes and lightning activity. Additionally, the urban dynamic effect results in the peak center of lightning appearing at the edge of a built-up area. Furthermore, the building height is also a factor that affects thunderstorm processes and lightning activity. In summary, scholars have made progress in understanding the characteristics and drivers of urban lightning activity in recent years, yet there remain several shortcomings:

(1) How to analyze comprehensively the spatiotemporal patterns of urban lightning activity under different thunderstorm intensity backgrounds?

To address this knowledge gap, future research could categorize thunderstorm intensity based on parameters such as the lightning frequency, radar echo intensity, and thunderstorm duration. Subsequently, these distinct categories of thunderstorms could be subjected to further statistical analysis to elucidate the spatiotemporal characteristics of urban lightning activity within each intensity level.

(2) How to conduct analysis to investigate the influence of alterations in the boundary layer structure, water–heat energy balance, and water vapor circulation processes on urban lightning activity in the context of urbanization?

The existing observation data for urban lightning research are primarily from conventional data sources, such as surface automatic stations, Doppler radars, and wind profilers, etc. With the continuous advancement of technology, the detection of the urban boundary layer has entered a new period. Taking a phased-array radar as an example, it has a flexible beam control capability and can greatly enhance the observation ability of the vertical structure. In the future, it is necessary to expand the utilization of unconventional data sources to conduct in-depth analysis on the impact of the boundary layer structure, the water and heat energy balance, as well as changes in water vapor circulation processes on lightning activity in the context of urbanization.

(3) How to couple numerical models of different scales to enhance the understanding of the impact of complex underlying surfaces on urban lightning activity?

Except for comprehensive observations, numerical simulation has also been utilized by numerous scholars to analyze the impact of cities on thunderstorm processes. Researchers have investigated the evolution mechanism of urban thunderstorms by coupling the weather research and forecasting model (WRF) with the urban canopy model (UCM). Computational fluid dynamics (CFD) is suitable for local and block scales in numerical models and can be utilized to explore the relationship between the near-surface thermal dynamic field and the morphological characteristics of the underlying surface. In the future, the CFD model, driven by the meteorological element field output from the WRF model, will simulate the thermal dynamic field of the urban underlying surface, and sensitivity tests will be conducted by modifying the shape and orientation of the city, enabling a comprehensive and in-depth understanding of the influence mechanism of urbanization on thunderstorm processes and lightning activity.

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