

Article

Urbanization Effect on Local Summer Climate in Arid Region City of Urumqi: A Numerical Case Study

Aerzuna Abulimiti ¹, Yongqiang Liu ¹, Qing He ^{2,3,4} , Ali Mamtimin ^{2,4,5,6,7} , Junqiang Yao ^{2,4,5,6}, Yong Zeng ^{2,8,9}  and Abuduwaili Abulikemu ^{1,*} 

- ¹ Xinjiang Key Laboratory of Oasis Ecology, College of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi 830017, China; aerzuna@stu.xju.edu.cn (A.A.); liuyq@xju.edu.cn (Y.L.)
- ² Institute of Desert Meteorology, China Meteorological Administration (CMA), Urumqi 830002, China; qinghe@idm.cn (Q.H.); ali@idm.cn (A.M.); yaojq@idm.cn (J.Y.); zengyong@idm.cn (Y.Z.)
- ³ Wulanwusu Ecology and Agrometeorology Observation Research Station of Xinjiang, Urumqi 830002, China
- ⁴ Xinjiang Key Laboratory of Desert Meteorology and Sandstorm, Urumqi 830002, China
- ⁵ National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang, Urumqi 830002, China
- ⁶ Taklimakan Desert Meteorology Field Experiment Station of China Meteorological Administration, Urumqi 830002, China
- ⁷ Dabancheng National Special Test Field for Comprehensive Meteorological Observation, Urumqi 830002, China
- ⁸ Field Scientific Observation Base of Cloud Precipitation Physics in West Tianshan Mountains, Urumqi 830002, China
- ⁹ Xinjiang Cloud Precipitation Physics and Cloud Water Resources Development Laboratory, Urumqi 830002, China
- * Correspondence: abduwaly@xju.edu.cn

Abstract: The urbanization effect (UE) on local or regional climate is a prominent research topic in the research field of urban climates. However, there is little research on the UE of Urumqi, a typical arid region city, concerning various climatic factors and their spatio-temporal characteristics. This study quantitatively investigates the UE of Urumqi on multiple climatic factors in summer based on a decade-long period of WRF-UCM (Weather Research and Forecasting model coupled with the Urban Canopy Model) simulation data. The findings reveal that the UE of Urumqi has resulted in a reduction in the diurnal temperature range (DTR) within the urban area by causing an increase in night-time minimum temperatures, with the maximum decrease reaching -2.5°C . Additionally, the UE has also led to a decrease in the water vapor mixing ratio (WVMR) and relative humidity (RH) at 2 m, with the maximum reductions being 0.45 g kg^{-1} and -6.5% , respectively. Furthermore, the UE of Urumqi has led to an increase in planetary boundary layer height (PBLH), with a more pronounced effect in the central part of the city than in its surroundings, reaching a maximum increase of over 750 m at 19:00 Local Solar Time (LST, i.e., UTC + 6). The UE has also resulted in an increase in precipitation in the northern part of the city by up to 7.5 mm while inhibiting precipitation in the southern part by more than 6 mm. Moreover, the UE of Urumqi has enhanced precipitation both upstream and downstream of the city, with a maximum increase of 7.9 mm. The UE of Urumqi has also suppressed precipitation during summer mornings while enhancing it in summer afternoons. The UE has exerted certain influences on the aforementioned climatic factors, with the UE varying across different directions for each factor. Except for precipitation and PBLH, the UE on the remaining factors exhibit a greater magnitude in the northern region compared to the southern region of Urumqi.

Keywords: urbanization effect; numerical simulation; arid region; Urumqi; multiple climatic factors



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1. Introduction

The urbanization effect (UE) on the local or regional climate is one of the research hotspots in the research field of urban climates [1–5]. The IPCC Sixth Assessment Report (AR6) specifically emphasized the evidence of human-induced impacts within the broader evidence base of climate change [6]. With the progression of urbanization, the exchanges of energy, momentum, and water vapor in urban areas are gradually altered by the unique physical characteristics of urban areas, leading to increasingly pronounced UE on local climate and weather, such as exacerbating extreme precipitation, droughts, and heatwaves [7,8].

Each city has unique urbanization characteristics, geographical locations, and climatic backgrounds, resulting in distinct UEs [9–13]. The changes due to the UE also impact urban infrastructure, resident health, and safety. Consequently, it is imperative to conduct appropriate descriptions and simulations, as well as comprehensive and detailed research, focusing on the UE [14]. Temperature is one of the most extensively studied urban climate components over an extended period [15–18]. In most cities worldwide, scholars have observed a significant urban heat island (UHI) effect [19,20]. In arid regions, however, several researchers have identified the urban cool island (UCI) phenomenon [21,22]. The notable differences in urban–rural climates have increasingly focused attention on the impact of multiple urban climate factors.

The numerical simulations offer advantages over remote sensing and observations by allowing for the study of urban climates at high spatio–temporal resolutions and quantitatively isolating the UE on multiple regional climate factors through sensitivity experiments when studying the UE of individual cities [9]. In contrast to physical simulation methods that require specialized facilities and are expensive, as well as observational methods that do not permit sensitivity testing, numerical simulation offers many experimental controls, enables a variety of sensitivity tests, produces higher resolution outputs, and provides predictions of practical value [9]. Consequently, a growing number of scholars are utilizing the WRF–UCM (Weather Research and Forecasting model coupled with the Urban Canopy Model) to investigate the UE on climate factors beyond temperature. Yao et al. [23] used the WRF–UCM model to investigate the UE on climate in Chengdu and found that urbanization decreased the relative humidity (RH) at 2 m. Zhou et al. [24] conducted sensitivity experiments using the WRF–UCM model and discovered that urbanization in Kunming increased the planetary boundary layer height (PBLH) by approximately 102 m.

Some previous research [25] shows that surface warming in global arid regions has reached 1.2 °C to 1.3 °C, which is 20% to 40% higher than in the humid regions (about 0.8 °C to 1.0 °C) over the past century. However, arid regions produce about 230 Gt of anthropogenic carbon dioxide emissions, with only 30% of emissions from humid regions. It is estimated that when global warming reaches 2 °C, arid regions may warm by 3.2 °C to 4.0 °C, while wet regions will warm by only 2.4 °C to 2.6 °C [25]. Therefore, arid regions will encounter more severe risks associated with climate change [25]. Previous studies [26–28] on the UE on the local climate in Urumqi have primarily focused on land surface temperature and daily mean temperature at 2 m; however, there was no previous research on the UE in Urumqi on other climatic factors such as diurnal temperature range (DTR), RH, water vapor mixing ratio (WVMR), and PBLH.

Detecting the influence of anthropogenic activities on precipitation changes has always been a key area of geoscience research [29,30]. For arid regions, precipitation-related research is particularly important. Zhong et al. [31] used the WRF–UCM to simulate a summer rainfall event in Beijing. Their numerical experimental results, which replaced the urban underlying surface with farmland, showed that there was more rainfall in the southwest of Beijing and less in the northeast, indicating that urbanization significantly

affects the spatio-temporal characteristics of precipitation. Some other studies [32] have also shown that urbanization can influence precipitation intensity and frequency in the specific directions of a city, such as reducing the probability of light rain and increasing the probability of heavy rain in downwind areas. Furthermore, other previous research [33] indicated that the urban underlying surface in Paris, France, significantly impacts winter monthly average precipitation and extreme daily precipitation in winter, increasing precipitation in the northeastern part of the city.

However, most studies on the UE on precipitation have been conducted in humid and semi-humid regions with substantial precipitation, and such studies are rare in arid regions with scarce water resources and low precipitation. In an earlier period, Han et al. [34] used historical meteorological data from two meteorological stations in Urumqi's urban and rural areas over nearly 40 years to study the UE on local precipitation. They found that precipitation in the urban area was 3.93 times that of the rural areas, and the growth rate was 3.98 times that of the rural areas. Subsequent studies on the UE on precipitation in Urumqi were still conducted using urban–rural comparisons (i.e., Urban minus Rural—the UMR method) [35,36]. However, meteorological stations in Urumqi are relatively sparse, and the city is encircled by mountains on its three sides, featuring a relatively complex terrain (Figure 1a). Therefore, using the urban–rural comparison method to explore the UE on precipitation may bring about uncertainties, and it is difficult to quantitatively analyze the spatio-temporal distribution characteristics of UE on precipitation. Therefore, a numerical simulation method with high spatio-temporal resolution is a good way to investigate the impact of the UE on local or regional climate in arid region cities, such as Urumqi, in order to obtain more reliable conclusions.

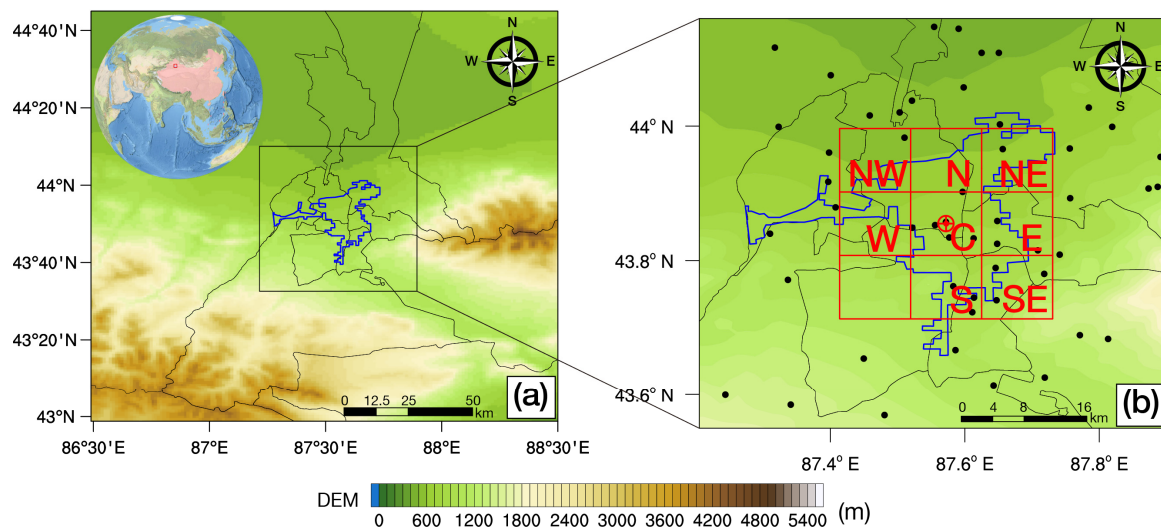


Figure 1. (a) Geographical locations and terrain altitude (colorful shading, units: m) of the study area; the boundary of the major urban and built-up area of Urumqi is indicated by the closed irregular area with a thick blue solid line, and the gray solid lines indicate the administrative boundaries of Urumqi and its districts. The location of the study area is also indicated by the small red box from a broader perspective in the little globe in the upper left corner of this panel. (b) Terrain altitude (colorful shading, units: m) from an enlarged scope of the study area, showing the locations of the 51 weather stations (pointed out by black dots) selected in this present study to verify the results of the numerical simulation. Further, the small red target symbol with a cross and dot in the central area indicates the location of the central point of the urban area. The red square areas indicate the immediate areas in various orientations around the central point of the urban and built-up area, i.e., NW (northwestern), N (northern), NE (northeastern), W (western), C (central), E (eastern), S (southern), and SE (southeastern) areas, respectively. The outline of the urban area is indicated by the closed irregular area with a thick blue solid line.

Urumqi, as the provincial capital city of Xinjiang, located at the core region of the Silk Road Economic Belt, is an important economic hub in Western China with a strong radiating effect on the region of Central Asia. By the end of 2023, the permanent population of Urumqi had reached 4.0848 million, with an urbanization rate of 96.1%. The economy of Urumqi has been growing rapidly, with a regional gross domestic product (GDP) of CNY 389.322 billion in 2022. However, Urumqi is situated near the edge of the Gurbantunggut Desert, and being the city furthest from the ocean globally, maritime moisture has difficulty reaching this area. Consequently, the ecological environment of Urumqi and its surrounding areas is extremely fragile, with high-intensity anthropogenic activities bringing a certain threat to the ecological environment in Urumqi. Some research indicates that [36] Xinjiang is a sensitive and vulnerable area affected by climate change, with a noticeable increase in temperature and precipitation over recent decades, exhibiting characteristics of “warm-wet” changes and an increase in extreme disaster events. Therefore, as the largest and fastest-growing city in Xinjiang, Urumqi not only faces the dual pressures of global climate change and rapid urbanization but also has a unique urban climate effect due to its special climatic background and relatively fragile ecological environment. However, there are few in-depth studies on the UE on local climate in Urumqi, especially regarding the UE on water vapor, precipitation, and their spatio-temporal characteristics. Therefore, considering the frequent occurrence of heavy summer precipitation and corresponding meteorological disasters in Urumqi, this study aims to comprehensively investigate and explore the UE on local climate in summer based on a decade-long period (from 2012 to 2021) of numerical simulation data. This study can be considered a good attempt to address the deficiencies and gaps in numerical simulation studies of the UE on local climate in arid region cities of northwest China and improve the understanding of the impact of human activities on the local climate in Urumqi, and it may provide important references and insights for other arid region cities worldwide.

The rest of this present paper is organized as follows: The data and methods are introduced in Section 2, and Section 3 delivers a specific elaboration of the results. Then, the conclusions and discussions are provided in Sections 4 and 5.

2. Data and Methods

2.1. Data

In this study, the China Land Cover Dataset (CLCD) [37] with a spatial resolution of 30 m is employed to update the land surface (land use) categories in the WRF–UCM model to improve the accuracy of numerical simulation. The CLCD is a type of remote sensing data, and it was produced based on the platform of Google Earth Engine (GEE), which includes annual land cover and its dynamics with 30 m resolution in China (from 1990 to 2023). The CLCD was derived from interpreting samples of satellite time-series data, as well as from Google Earth and Google Maps. Utilizing 335,709 Landsat images on the GEE, several temporal metrics were constructed and then fed into a random forest (RF) classifier to achieve classification results for the CLCD. Subsequently, the data developers proposed a method of post-processing that incorporates spatio-temporal filtering and logical reasoning to enhance the spatio-temporal consistency of the dataset. In addition, three climatic elements including daily maximum air temperature (T_{max}), daily minimum air temperature (T_{min}), and precipitation observed by 51 stations (including 47 automatic weather stations and four conventional weather stations) were used to verify the results of numerical simulation according to data quality and integrity. All of the observation data were derived from the National Meteorological Center of the China Meteorological Administration (CMA). In addition, the 5th generation of global atmospheric reanalysis dataset produced by the European Center for Medium-Range Weather Forecasts (ECMWF) (ERA5 data) is utilized

in this study. The ERA5 data can offer atmospheric circulation fields and initial static data (e.g., soil temperature, soil water, and moisture) for the WRF–UCM simulation.

2.2. Methods

The numerical simulations are performed utilizing the Weather Research and Forecasting (WRF) model (version 4.2.2) in this present study. It is a popular meso-scale numerical model developed for meso-scale numerical weather prediction (NWP) and in the related field of atmospheric science [38–44]. In this present study, the WRF model coupled with the single-layer Urban Canopy Model (UCM) is used [45], abbreviated as the WRF–UCM model (Figure 2). The Urban Canopy (UC) scheme includes the effect of the building drag, radiation trapping (and shading), and the influence of the Urban Canopy on local turbulence [46]. When using the WRF coupled with the UCM, it is possible to freely change the land use and parameter details such as urban morphology, heat capacity, building surface albedo, and anthropogenic heat [47]. The WRF–UCM is an important model for urban climate-related research, and its flexibility creates suitable conditions for the design of experimental scenarios. Many studies have used the WRF–UCM to perform scenario experiments to explore the numerous urbanization effects on local weather and climate across the globe [48–51]. Detailed information and descriptions of the WRF–UCM model, as well as its applications, can be referred to in the works of Kusaka et al. [45].

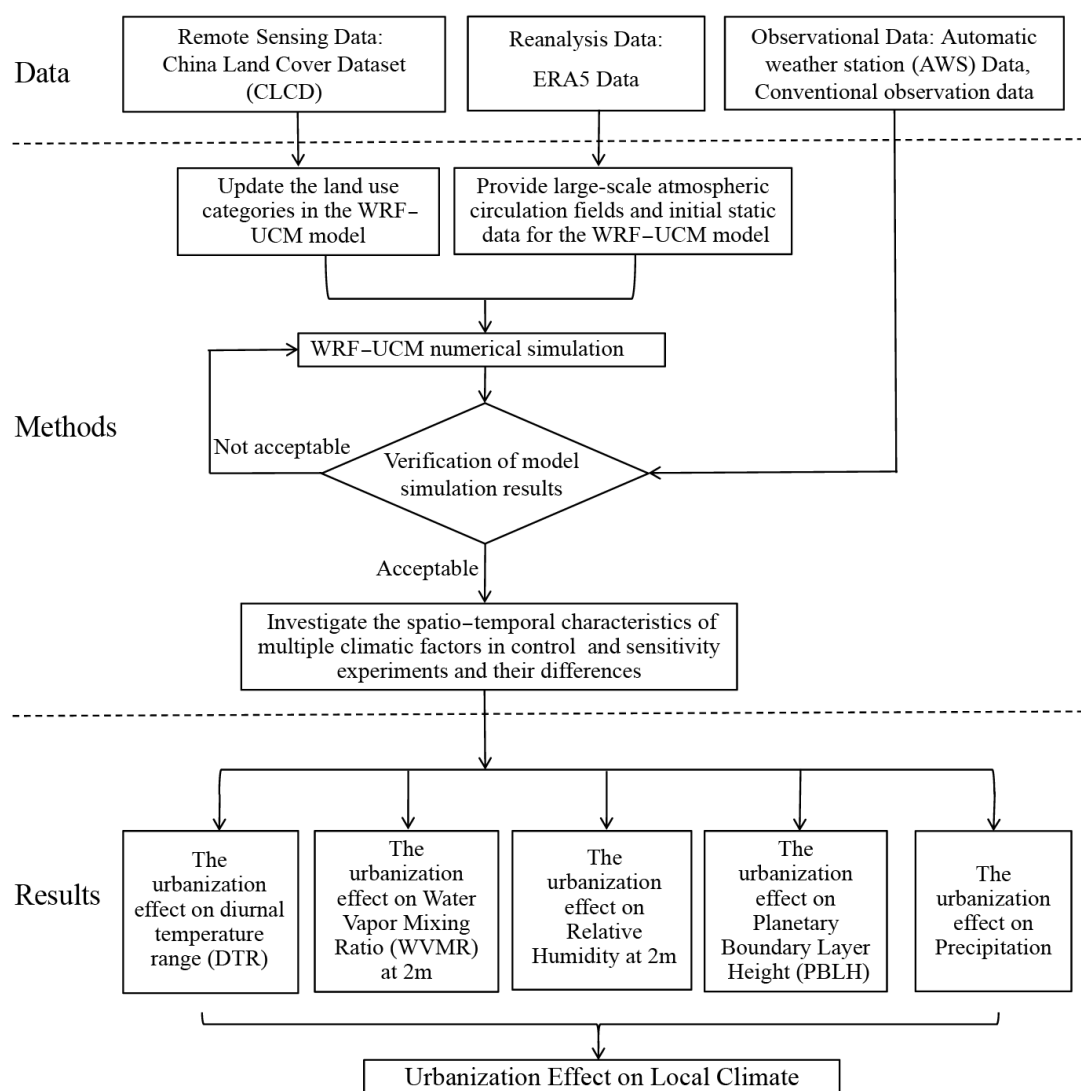


Figure 2. The technical flow chart regarding the data, methods, and results of this study.

In this study, the WRF–UCM simulation was conducted in two-level domains with two-way nested domains including a decade-long period (2012–2021). The time resolution of the numerical data is 1 h, with a horizontal spatial resolution of 1 km, enabling us to examine the variation characteristics of the climatic factors in an hourly time scale. This simulation consists of two domains, with the outermost domain (d01) featuring 201×201 grid points in the east–west direction, and the south–north direction with a horizontal resolution of 3 km, covering almost the whole region of northern Xinjiang. The innermost domain (d02) contains 221×221 grid points, with a 1 km horizontal spatial resolution, encompassing the whole city of Urumqi. Further, there are 35 vertical (eta) levels, and the highest eta level reaches 50 hPa. The microphysics parameterization adopted the New Thompson scheme [52], which included ice, snow, and graupel processes suitable for high-resolution simulations. The cumulus parameterization was turned off as recommended in other previous studies [39–43]. Both the longwave and shortwave radiation schemes selected the RRTMG scheme [53], and the planetary boundary layer scheme used the Yonsei University (YSU) scheme [54]. The land surface processes utilized the Noah Land Surface scheme [55], and the surface layer parameterization used the Revised MM5 surface layer scheme [54].

In this study, two sets of simulation experiments, i.e., the urban (control) experiment and non-urban (sensitivity) experiment, were designed. The land surface (land use) categories derived from the CLCD dataset were used in both domains in the urban experiment (Figure 3a), indicating the real urban land use conditions. In the non-urban experiment, the land surface (land use) categories where the original urban and built-up area in the city of Urumqi were substituted by grassland (Figure 3b), and all the other options are consistent with the control (urban) experiment. Given that the extent of built-up areas may have continuously evolved over the period from 2012 to 2021, with grid points that once belonged to rural areas becoming urban in subsequent years, it would be inconsistent to replace the underlying surface types with the CLCD data from each individual year. Otherwise, when spatially averaging the values of climatic factors, the inconsistency in the urban attributes of some grid points could lead to confusion or chaos. Therefore, we had to select land use data from a single year to replace the underlying surface types throughout the entire decade. Consequently, we further considered that the larger the built-up area, the more pronounced the urbanization effects might be. Thus, we chose the surface type data from the year with the largest built-up area within this decade, which is the most recent year in this period (i.e., 2021), namely the CLCD data from 2021.

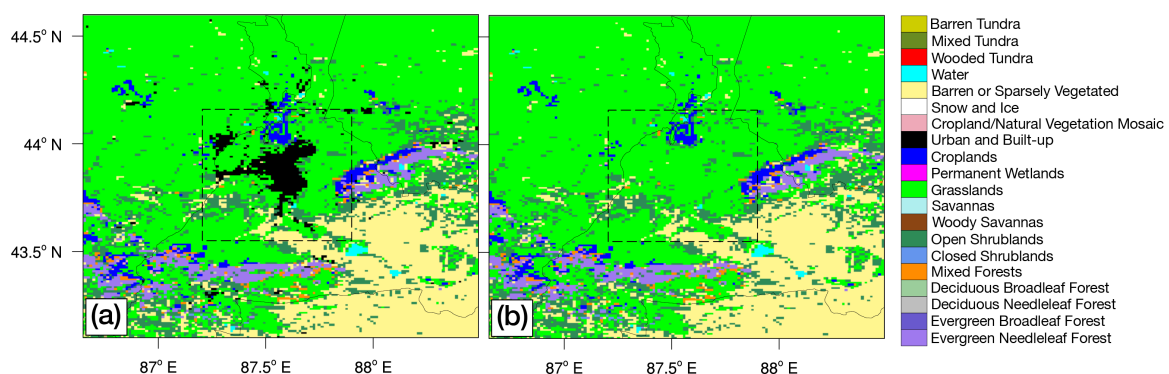


Figure 3. (a) The land surface (land use) categories (colorful shading) obtained from the CLCD dataset of the urban (control) experiment of the WRF–UCM simulation. Here, (b) is the same as (a) but for the non-urban (sensitivity) experiment of the simulation in which the urban areas are substituted by grasslands. The dashed line boxes indicate the area of the plane figure showing spatial distribution of the climatic factors which will be shown in the following.

In some previous similar numerical studies [31,50,56], when conducting similar sensitivity experiments (i.e., urban and non-urban experiments), it is common to replace the urban underlying surface with the most prevalent land use type surrounding the urban area within the study area, using it as the underlying surface type for the non-urban scenario. Therefore, the urban land surface is replaced with grassland because the predominant land use type in the suburban areas surrounding the urban area of Urumqi is grassland. Therefore, substituting the urban underlying surface with grassland allows for a clearer manifestation of the urbanization effect on the local climate in the simulation results, leading to more reliable simulation results.

Urumqi is located at the northern foot of the middle section of the Tian Shan Mountains and on the southeastern edge of the Junggar Basin, characterized by substantial topographic relief and is encircled by mountains on three sides: west, east, and south. The northern suburbs of Urumqi are predominantly characterized by farmland as the primary land use type, while the western, eastern, and southern suburbs are covered by extensive grassland areas. The urban area of Urumqi has been continuously expanding, accompanied by a rapid pace of urbanization, and the intensity of land use development within the urban has progressively increased [57].

To investigate the spatio-temporal distribution features of the UE on various climate factors in Urumqi, the urban central point of the urban area of the city of Urumqi (denoted by a red dot in the center of the area in Figure 1b) was calculated, and eight square areas (marked with different capital letters) were divided over the area in various orientations to the central point. The size of each square area is $10 \text{ km} \times 10 \text{ km}$, without including the southwestern area, almost without any urban and built-up area in it.

3. Results

3.1. Verification of Simulation Results

To establish the credibility of the WRF-UCM simulation, its simulation results are verified in regard to three basic climatic factors (i.e., $T_{\max}$, $T_{\min}$, and precipitation). Given that this study focuses on the UE of Urumqi on local summer climate, the observational data and simulated data for July were utilized to validate the model results. Figure 4 shows the scatter plots and their fitting lines comparing the monthly averaged values (2012–2021) of the three factors observed from the 51 weather stations (Figure 1b) and the results of the WRF-UCM simulation from the same points (locations) of these 51 weather stations in July. As shown in Figure 4, the correlation coefficient between the numerical simulation results of air temperature in this study and the corresponding observational data is relatively high (i.e., 0.948 and 0.752 for $T_{\max}$ and $T_{\min}$, respectively), indicating that the model demonstrates a relatively high level of accuracy in simulating air temperature. There were plenty of numerical simulation studies [38–43,58–63] on precipitation events that stated that there were timing and positioning biases of the precipitation in their studies because the initiation and development mechanisms of the weather systems are very complex. Moreover, the WRF model's capability to simulate precipitation can be affected by complex underlying surfaces and various parameterization schemes [64–66]. Consequently, the values of r and R^2 for the precipitation are not high in this study. Given that the primary focus of this study is to explore the urbanization effect in Urumqi on multiple climatic factors, along with their spatial distribution characteristics and diurnal variation patterns, rather than for precipitation forecasting, this bias in precipitation is deemed acceptable. In future research, we will focus more on the application evaluation and enhancement of the WRF model's simulation capabilities in the complex underlying the surface areas of Xinjiang.

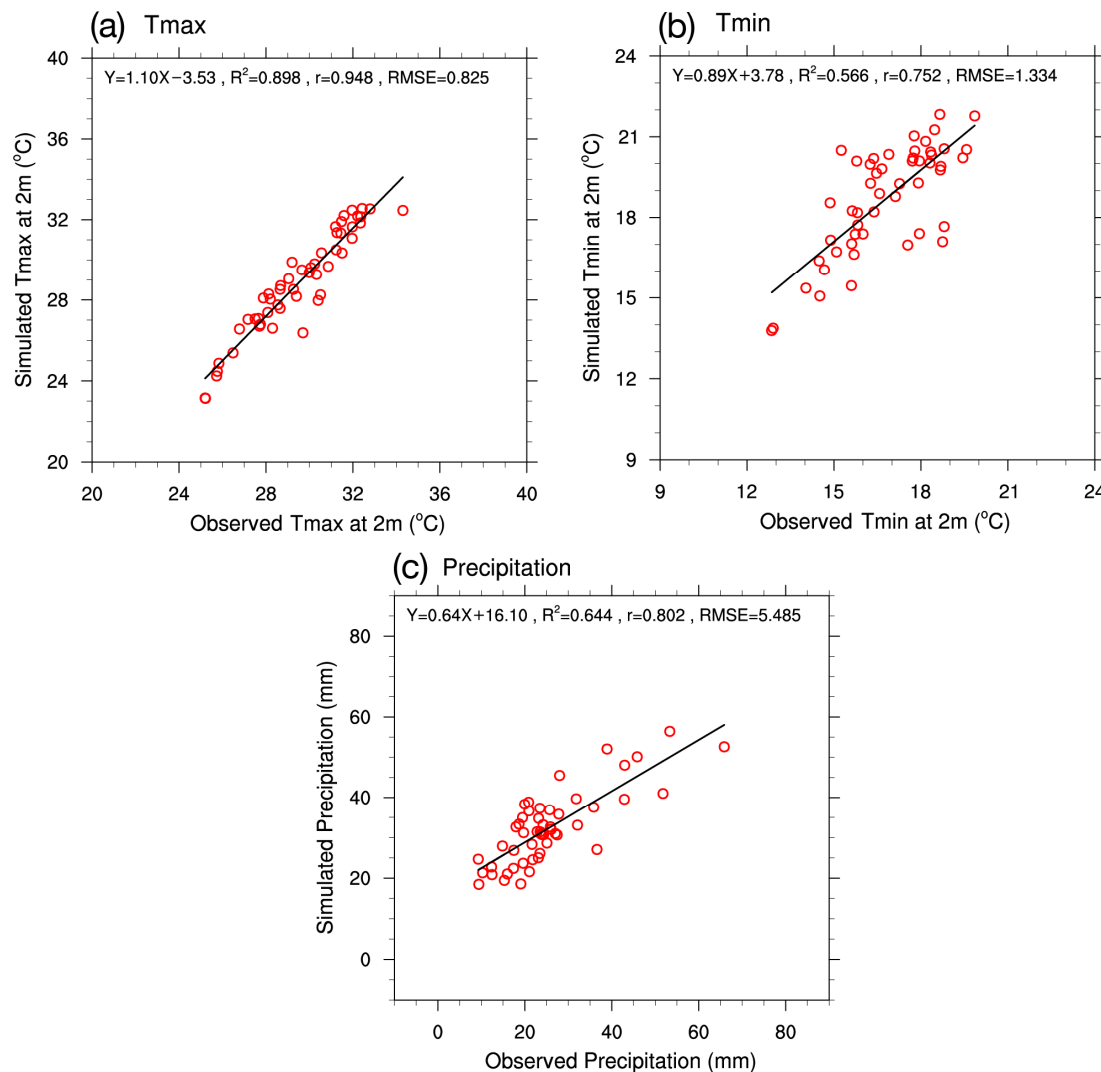


Figure 4. Scatter plots with linear regression fitting lines and regression equations and Pearson's correlation coefficient (r), as well as the root mean square error (RMSE) depicted at the top of each panel, indicating the corresponding simulation results (monthly average value at the 51 meteorological stations shown in Figure 1b) with corresponding observational data in July (2012–2021). Here, (a), (b), and (c) indicate the Tmax, Tmin, and precipitation, respectively.

3.2. The UE on DTR

Our previous research [26] demonstrated that the urbanization in Urumqi imposes a significant effect on the daily mean temperature at 2 m (Tmean), with the maximum summer canopy layer urban heat island (UHI) effect reaching 2.6 °C at approximately 05:00 LST, with a slight urban cool island (UCI) effect emerging during summer in the daytime. In this study, we further explore the average value of UE (calculated during the summer in the consecutive decade-long period from 2012 to 2021) of Urumqi on the Tmax, Tmin, and DTR in summer. As illustrated in Figure 5a,b, the DTR in the urban area gradually decreases from north to south, with the DTR reaching approximately 10 °C in the northeastern part of the city and around 8 °C in some southern districts of Urumqi. Figure 5c,d displays the spatial distribution of the UE on summer DTR, revealing that UE leads to a reduction in DTR across all areas within the urban area. The average UE is approximately −1.55 °C, with a greater decrease in the north than in the south. The maximum UE on DTR occurs in the northern part of the city, reaching approximately −2.5 °C. Previous studies [67] have indicated that the difference in DTR between the urban and suburban area are primarily attributed to the differing responses of urban temperatures

to the urban underlying surface during daytime and night-time. Due to its superior heat storage capacity, urban areas are more prone to accumulating warm air at night compared to suburbs. During the daytime, the warming effect caused by the urban underlying surface can be transported to the suburbs with the assistance of boundary layer turbulence. Therefore, it results in a weakened DTR in urban areas, whereas it increases in suburbs and rural regions.

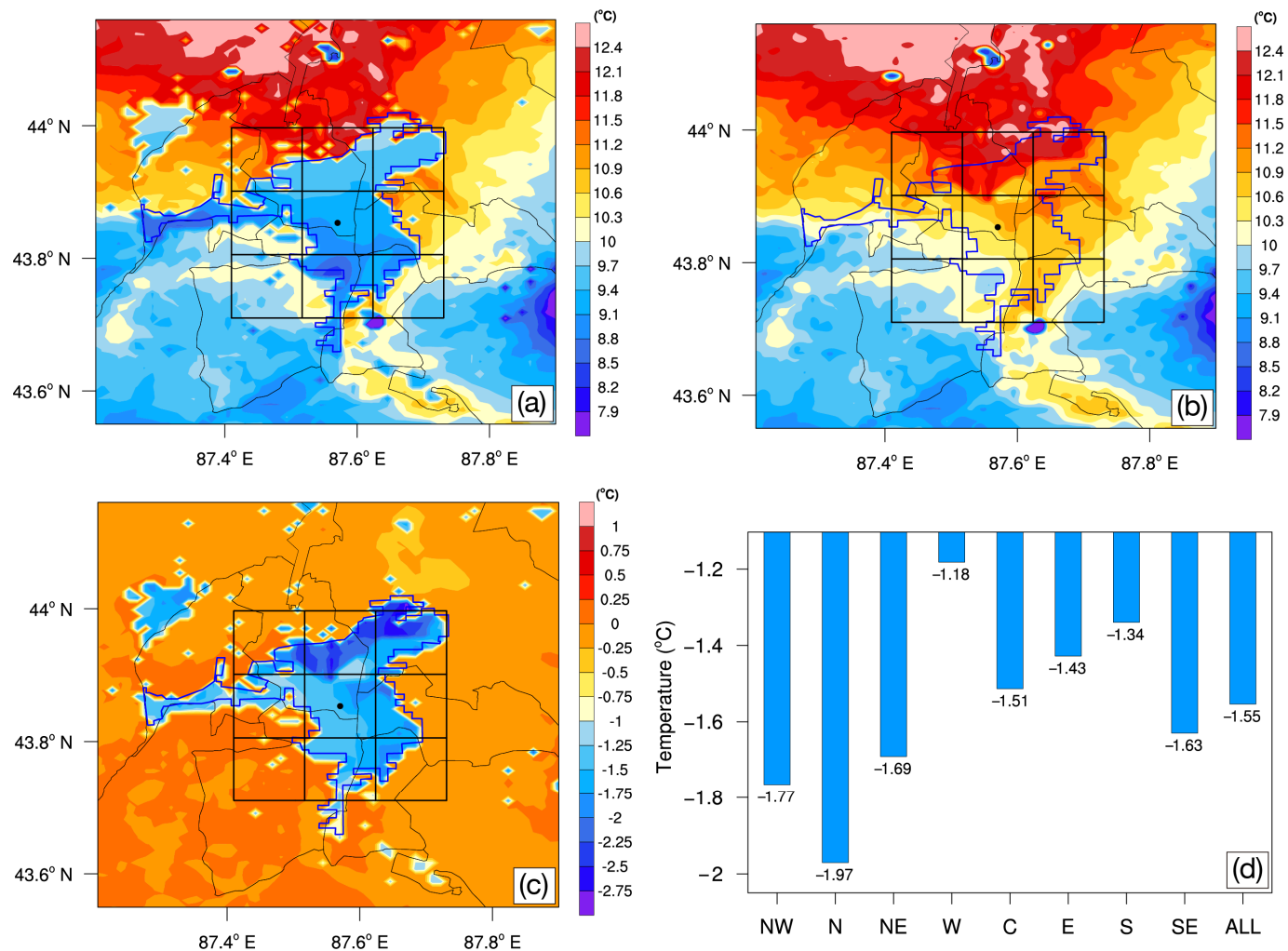


Figure 5. (a–c) Spatial distribution of the averaged diurnal temperature range (DTR) (colorful shading, unit: °C) in summer from 2012 to 2021 in Urumqi in the urban and non-urban experiments and UE (i.e., values of urban–non-urban) on the Tmean, respectively. The closed irregular area with a thick blue solid line represent the outline of the urban area, and the thinner black lines show the boundaries of districts in Urumqi. The black square areas show the immediate areas in the various orientations of the urban central point of Urumqi, which are also depicted in Figure 1b. (d) The average values of the averaged Tmean in summer over the eight immediate areas (calculated over the urban area) in the various orientations of the urban central point. The capital letters on the horizontal axis indicate the eight square areas illustrated in Figure 1b, and ALL denotes the average value of all of the urban areas (i.e., the mean value of all eight square areas).

To further investigate the UE of Urumqi on night-time and daytime temperatures, this study also focused on the spatial distribution features of the UE on Tmax and Tmin. As shown in Figure 6, the UE of Urumqi results in a decrease in Tmax within the urban area, with a reduction of 0.06 °C in the northern part of Urumqi, which is three times the decrease found in the southern part. The cooling effect of urbanization on temperatures is more pronounced in the suburban areas. As illustrated in Figure 7, the UE of Urumqi on the

Tmin is more significant than on the Tmax, with an increase in Tmin reaching 1.91 °C in the northern region of Urumqi. It can be concluded that the UE of Urumqi primarily induces the urban heat island (UHI) effect through nocturnal warming. Some previous research [68] had indicated that the northern, northwestern, and northeastern regions of the Urumqi contain a higher concentration of industrial parks, potentially contributing to atmospheric warming through increased anthropogenic emissions. Additionally, the northern part of the Urumqi comprises a newly developed urban area, where surface albedo is lower compared to the older urban areas. Consequently, surface temperatures (Ts) in the newly generated urban areas are typically larger than those in the older urban areas [9]. As the surface transfers heat to the atmosphere, the air temperature exhibits a spatial distribution characteristic of decreasing from north to south. By comparing the high-value regions in Figure 6c with those in Figure 7c, it is found that the maximum increase in Tmin due to the UE reaches above 2.4 °C, while the maximum decrease in Tmax caused by the UE drops below −0.12 °C. It suggests that urbanization resulted in a decrease in the DTR owing to the increase in night-time Tmin.

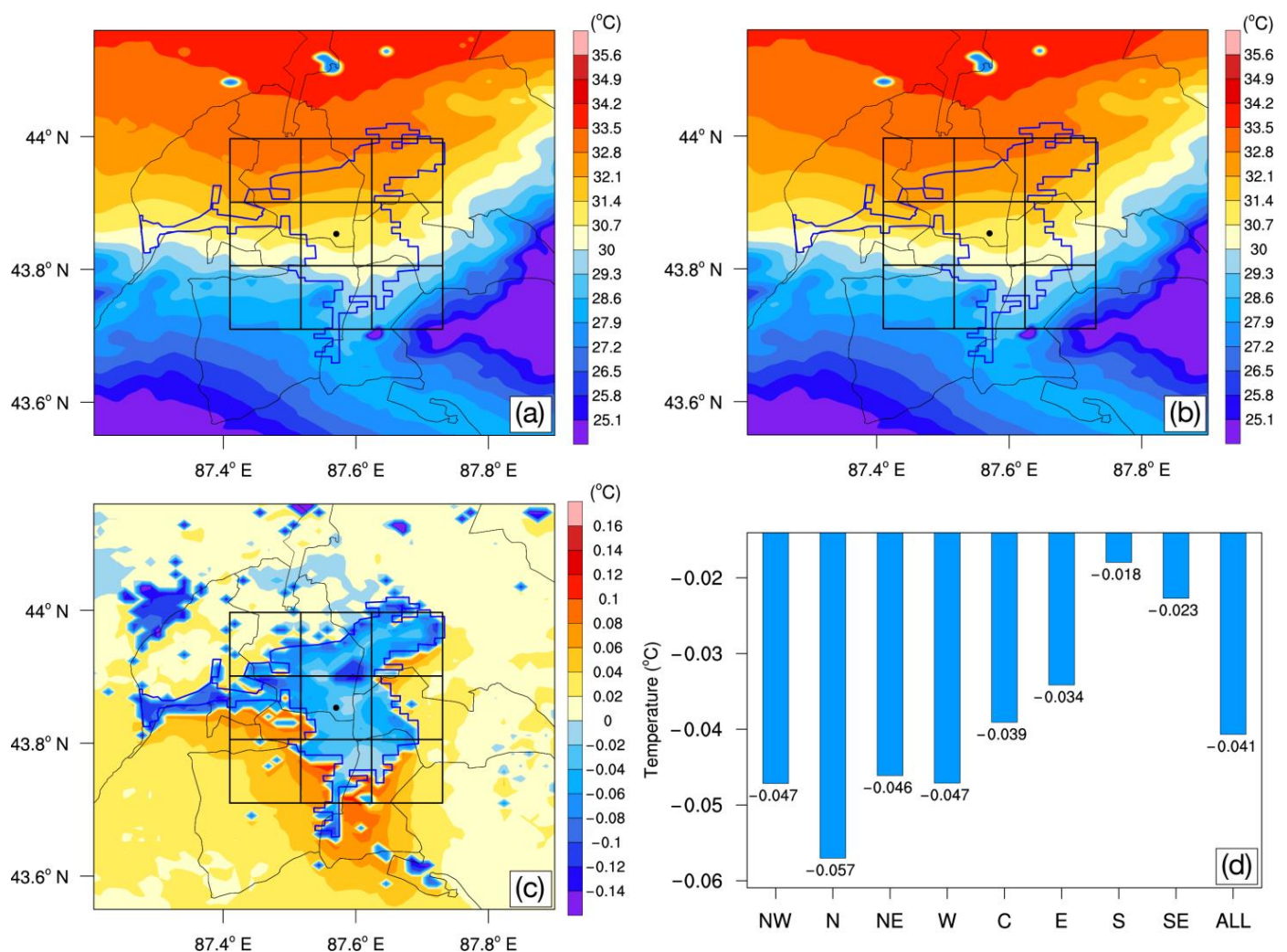


Figure 6. Here, (a–c) are the same as in Figure 5a–c, but for the spatial distribution of the averaged Tmax (colorful shading, unit: °C) in summer from 2012 to 2021 in Urumqi in the urban and non-urban experiments and UE (i.e., values of urban–non-urban) on the Tmax, respectively. Here, (d) is the same as in Figure 5d, but for the average values of the averaged Tmax in summer over the nine areas.

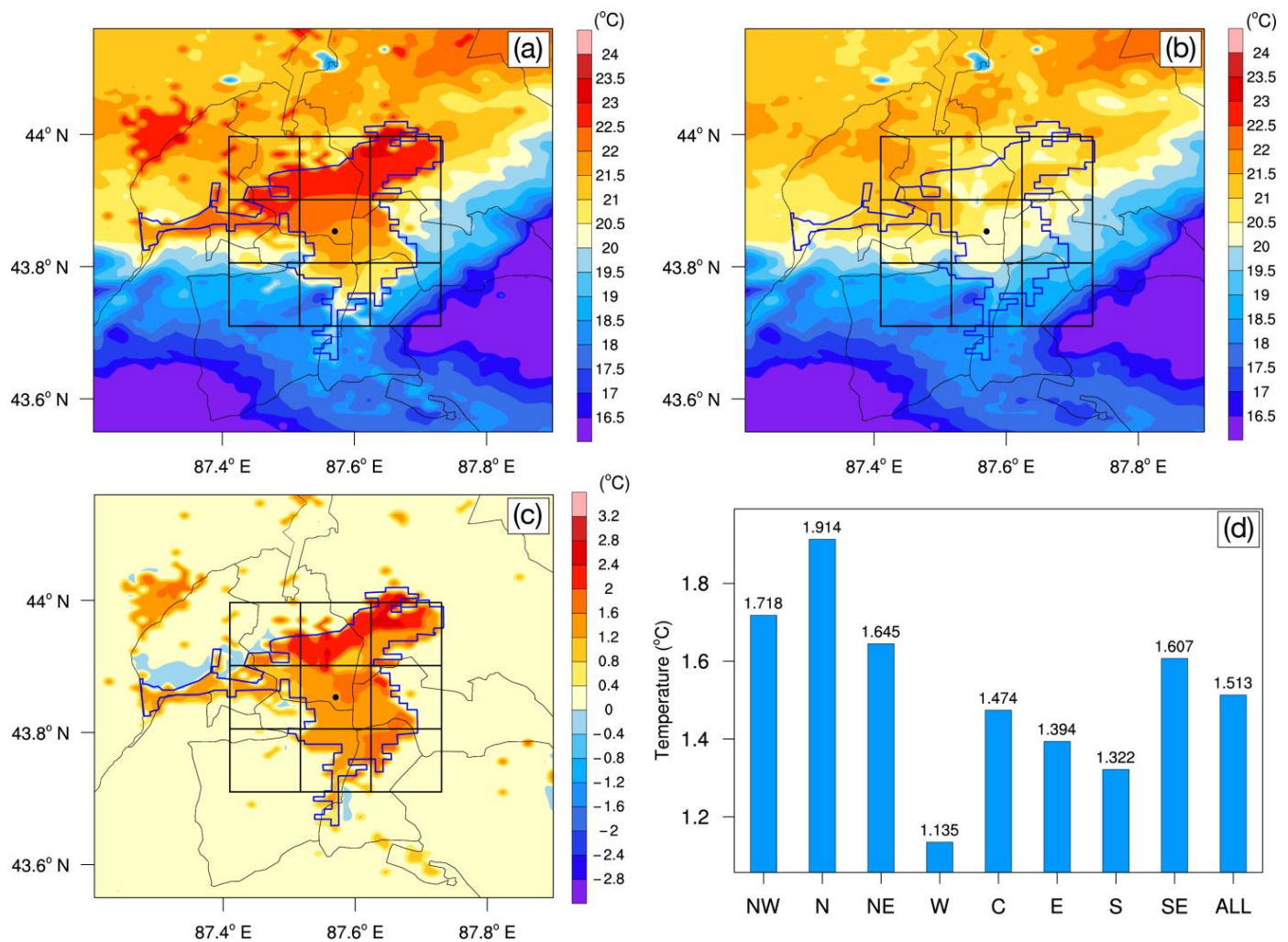


Figure 7. Here, (a–c) are the same as in Figure 5a–c but for the spatial distribution of the averaged Tmin (colorful shading, unit: °C) in summer from 2012 to 2021 in Urumqi in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the Tmin, respectively. Here, (d) is the same as in Figure 5d, but for the average values of the averaged Tmin in summer over the nine areas.

3.3. The UE on Water Vapor Mixing Ratio (WVMR) at 2 m

The WVMR can be defined as the mass ratio of water vapor to dry air within moist air. Figure 8a illustrates the WVMR at 2 m above ground level (AGL) in the urban experiment, showing that the urban area generally has lower values than the surrounding suburbs, with a distinct pattern of lower values in the north and larger values in the southern part of Urumqi. In contrast, the non-urban experiment (Figure 8b) exhibits a pattern of larger values in the south compared to the north of Urumqi. According to Figure 8c,d, the UE of Urumqi results in a decrease in the WVMR at 2 m in the urban area during summer, with an average UE on the WVMR reaching -0.27 g kg^{-1} . The magnitude of this decrease is relatively uniform across all orientations. The primary reason for the reduction in the WVMR at 2 m due to urbanization in summer is the abundance of surface runoff and green vegetation in the suburbs (non-urban experiment), which leads to high evaporation and a greater amount of water vapor in the air. Conversely, in urban areas (urban experiment), there is less runoff and green vegetation available for evaporation or transpiration compared to the suburbs. Additionally, the UHI intensity is not strong in summer, and an UCI-effect even occurs in the daytime, causing a decrease in urban temperatures. Therefore, evaporation in urban areas is much weaker than in rural areas (suburbs), resulting in the WVMR at 2 m in the urban area compared to the suburbs.

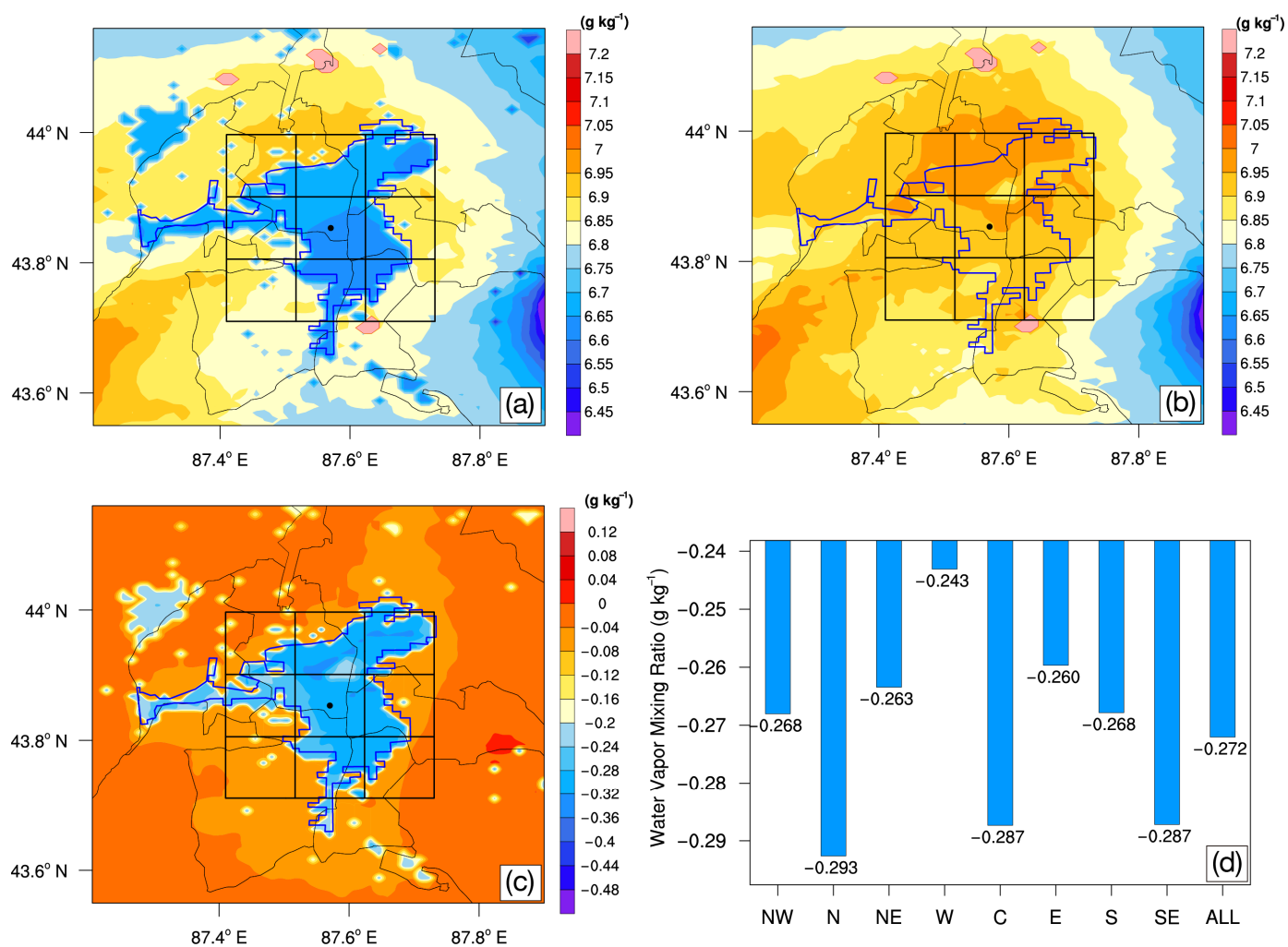


Figure 8. Here, (a–c) are the same as in Figure 5a–c, but for the spatial distribution of the averaged WVMR (colorful shading, unit: g kg^{-1}) at 2 m in summer from 2012 to 2021 in Urumqi in the urban and non-urban experiments and UE (i.e., values of urban–non-urban) on the WVMR at 2 m, respectively. Here, (d) is the same as in Figure 5d, but for the average values of the averaged WVMR at 2 m in summer over the nine areas.

Regarding diurnal variation characteristics of the WVMR at 2 m (Figure 9), the maximum value of the UE on the WVMR at 2 m occurs at around 07:00 LST and 19:00 LST. This is primarily due to the impervious urban surface leading to lower evaporation and a significant reduction in the WVMR at 2 m in the daytime. In contrast, the UHI effect is stronger at night, leading to increased evaporation due to a relatively higher temperature resulting from the relatively strong UHI effect. Thus, the decrease in the WVMR at 2 m due to the UE of Urumqi is less pronounced at night compared to the daytime. The maximum reduction in the WVMR at 2 m due to the UE occurs in the northern part of the Urumqi at around 07:00 LST, with a decreased magnitude reaching 0.45 g kg^{-1} . Furthermore, the stronger UHI effect at night reduces the condensation of moisture in the air, increasing the amount of moisture in the atmosphere, which also contributes to a decrease in the WVMR at 2 m.

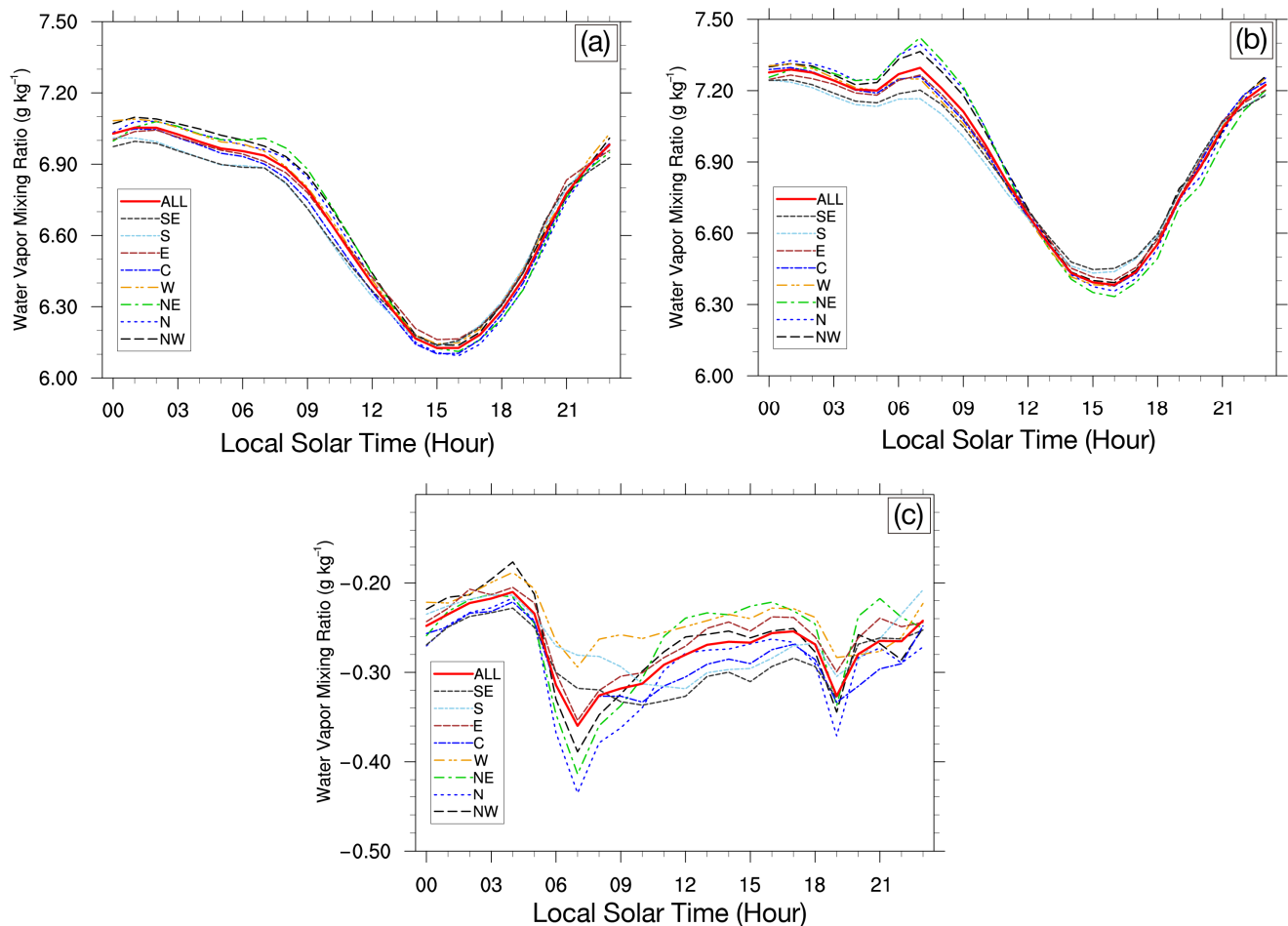


Figure 9. (a–c) Diurnal variation features of the averaged water vapor mixing ratio (WVMR, unit: g kg^{-1}) at 2 m in summer from 2012 to 2021 in different square areas in various orientations of the urban central point of Urumqi in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the WVMR at 2 m, respectively. The capital letters indicate the corresponding values of WVMR at 2 m calculated in these eight square areas shown in Figure 1b, and ALL shows the averaged value of all urban areas.

3.4. The UE on Relative Humidity (RH) at 2 m

In general, dense urban landscapes are characterized as “dry” [13] due to impervious surface-dominated land cover and a relative lack of vegetation, which implies a limited amount of water available for natural evaporation [8]. The RH at 2 m is one of the crucial climatic factors that significantly impacts human comfort. It is clear in Figure 10a,b that the RH at 2 m in the urban area is lower than those in the suburbs. Figure 10c demonstrates that the UE in Urumqi leads to a decrease in RH in the urban area, indicating the existence of an “urban dry island” effect. The decrease in the RH at 2 m in the northern urban area due to UE reaches 2.76%. This is primarily because, although urbanization has a similar impact on the WVMR at 2 m in both the southern part and northern part of the urban area, the air temperature at 2 m in the northern urban area is higher than that in the southern urban area due to urbanization, leading to a slightly greater decrease in RH at 2 m in the north compared to the southern urban area.

The special distribution characteristics of the UE on the RH at 2 m are similar to that of Tmean and WVMR at 2 m, exhibiting higher values in the north and around the periphery compared to the south and central regions of the urban area. The diurnal variation features of the RH at 2 m (Figure 11) indicate that the UE on the RH at 2 m is negative both during the day and at night. Further, the maximum decrease in the RH at 2 m attributable to the UE

occurs in the northern part of the Urumqi approximately in the early morning (05:00 LST), with a magnitude of reduction exceeding 6.5%. The UE on RH at 2 m exhibits a pattern of being smaller during the daytime and larger at night, which is similar to the UE on the air temperature at 2 m.

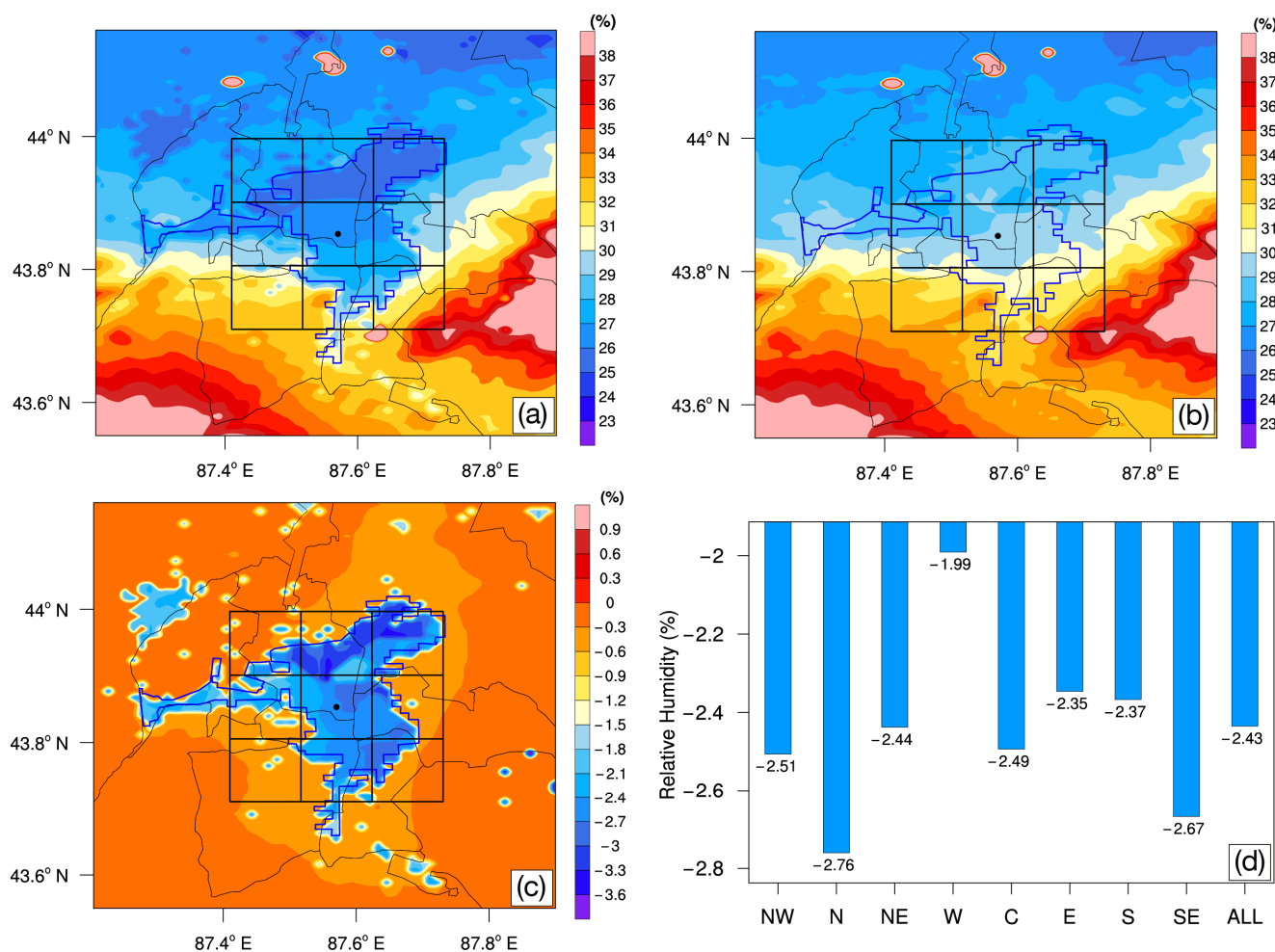


Figure 10. Here, (a–c) are the same as in Figure 5a–c, but for the spatial distribution of the averaged RH (colorful shading, unit: %) at 2 m in summer from 2012 to 2021 in Urumqi in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the RH at 2 m, respectively. Here, (d) is the same as in Figure 5d, but for the average values of the averaged RH at 2 m in summer over the nine areas.

3.5. The UE on Planetary Boundary Layer Height (PBLH)

The urban boundary layer is a type of atmospheric planetary boundary layer that develops as an internal boundary downwind of the urban frontier when air currents flow from rural areas to cities. The structure of the PBLH significantly influences the accumulation and transport of atmospheric pollution, playing a crucial role in regional atmospheric environmental quality [9]. Consequently, the PBLH above the area of the urban area is also one of the crucial factors of urban climate. It can be found in Figure 12a,b that the PBLH in the urban experiment is more complex than that in the non-urban experiment, with greater spatial variability and significantly higher values in the urban area compared to its surrounding suburban areas. Figure 12c,d demonstrates that the UE leads to a notable increase in the summer PBLH in Urumqi, with the UE on PBLH exhibiting higher values over the central urban area and lower values around its periphery. Due to urbanization, the PBLH near the urban centroid increases by more than 120 m.

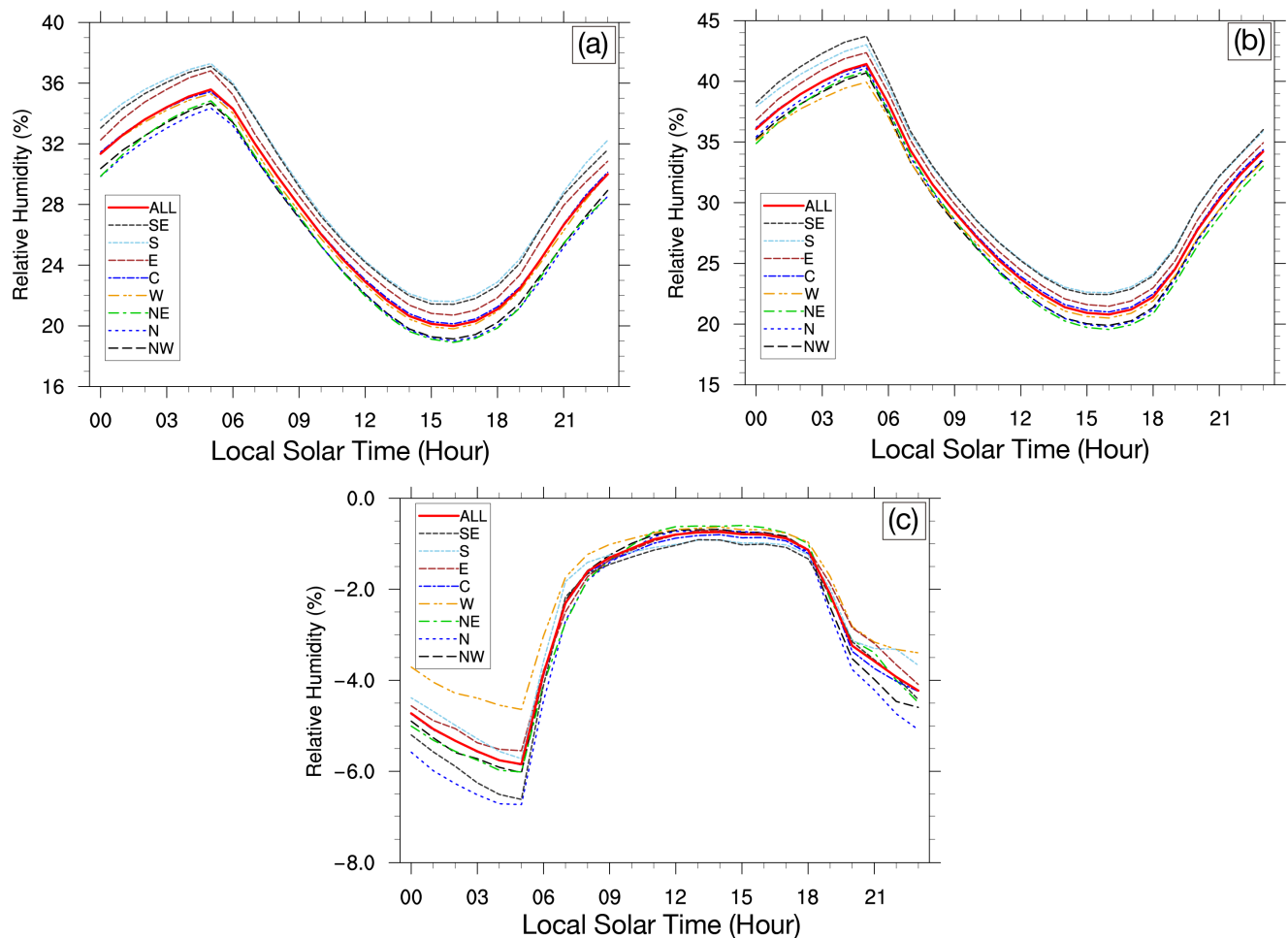


Figure 11. Here, (a–c) is the same as in Figure 9a–c but for the averaged RH (unit: %) at 2 m in summer from 2012 to 2021 in different square areas in various orientations of the urban central point of Urumqi in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the RH at 2 m, respectively.

The diurnal variation characteristics of the PBLH (Figure 13) indicate that the UE on PBLH is significant, ranging from 0 to 750 m. The PBLH caused by urbanization rapidly rises around 18:00 LST and reaches its daily maximum value at about 19:00 LST, which aligns well with the UHI intensification trend. After 19:00 LST, the PBLH caused by the UE of Urumqi decreases rapidly, similar to the diurnal variation pattern of the RH at 2 m caused by the UE. This suggests that the UE of Urumqi may primarily increase the PBLH by elevating the air temperature at 2 m and enhancing atmospheric thermal capacity. However, urbanization also decreases the atmospheric humidity in urban areas, resulting in a decrease in the PBLH.

3.6. The UE on Precipitation

Research on the UE on precipitation has persisted for over a century [4,69], confirming that the UE on precipitation remains one of the least understood and most controversial fields of urban climatology [9]. As evident in Figure 14a,b, precipitation in the Urumqi exhibits a gradual increase from north to south in both urban and non-urban experiments. Further, it is found that the UE on precipitation shows significant spatial variance in Urumqi. The UE in summer resulted in an increase in precipitation in north (2.73 mm) and northeast (1.85 mm) Urumqi, while it decreased in the southern (−3.95 mm) and southeastern (−2.17 mm) regions. The precipitation increase in the northern part of Urumqi

due to the UE reached about 7.5 mm, a considerable amount for the arid climate of Xinjiang. Meanwhile, the UE suppresses precipitation in the southern part of Urumqi by more than 6 mm. Considering the generally low precipitation levels in Xinjiang and referring to the precipitation grade standards for Xinjiang [70], it can be deduced that the UE on summer precipitation in Urumqi cannot be ignored.

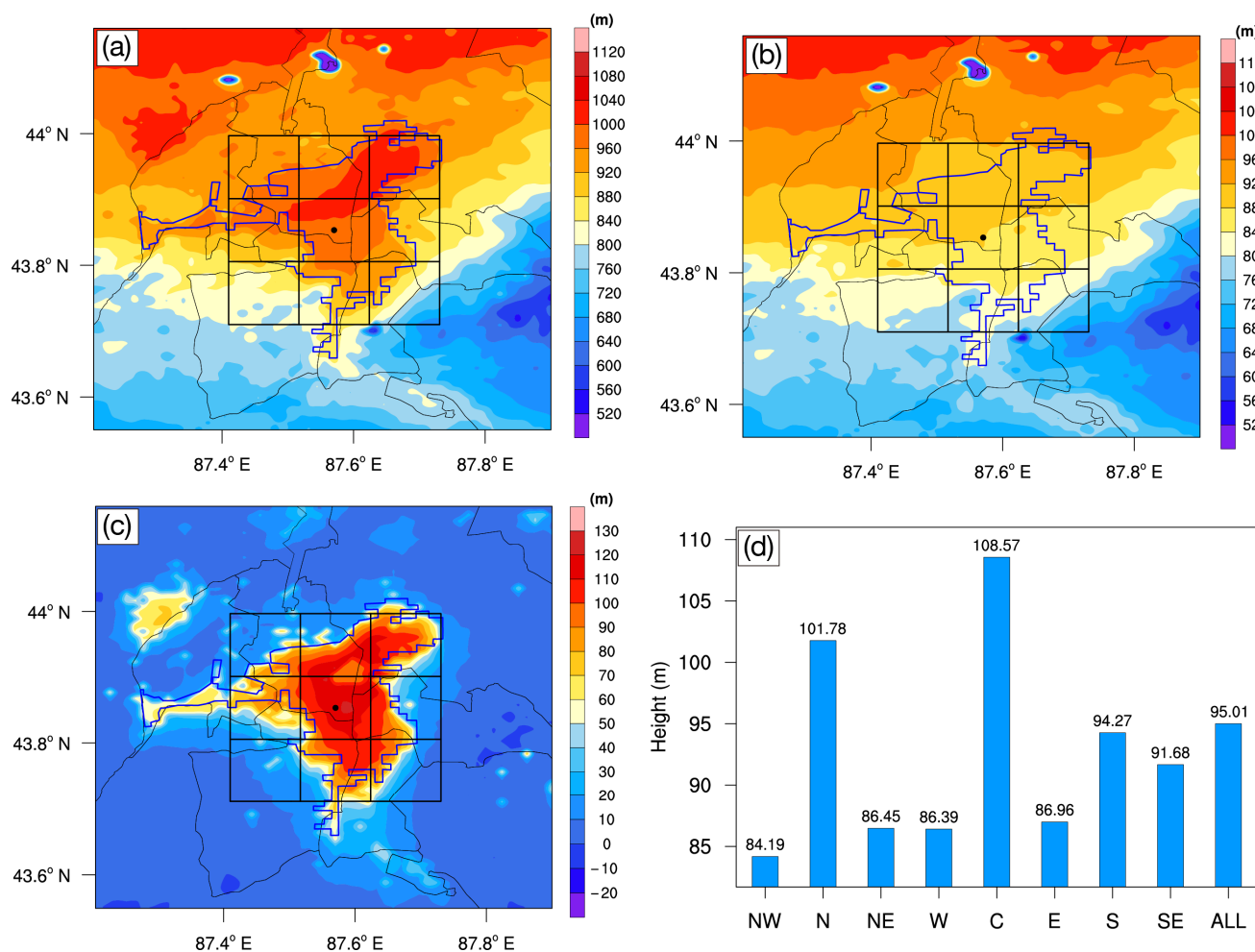


Figure 12. Here, (a–c) are the same as in Figure 5a–c, but for the spatial distribution of the averaged PBLH (colorful shading, unit: m) in summer from 2012 to 2021 in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the PBLH, respectively. Here, (d) is the same as in Figure 5d, but for the average values of the averaged PBLH in summer over the nine areas.

Some previous studies [32,71] indicate that the promoting or inhibiting effects of urbanization on precipitation mostly occur in the upwind or downwind areas of cities, rather than in their centers. To investigate the UE on precipitation in different wind direction areas, this study also examined the wind field at 10 m AGL in Urumqi, finding that northwesterlies are predominant in summer. The UE leads to an increase in precipitation in the downwind direction of the city (as depicted by the dashed black rectangular area in Figure 14c), with the maximum increase reaching 7.9 mm. This is probably due to the changes in humidity over the urban area and thermodynamic processes caused by urbanization; for example, alterations in the urban surface energy balance that result in the UHI effect and the formation of thermally driven circulations, which in turn induce atmospheric convection and wind convergence in urban areas and their downwind regions, leading to more precipitation. This study also found a precipitation center in the northern suburbs of Urumqi, which may be related to the circulation due to the UHI effect in this

area (indicated by red rectangular area in Figure 14c). Since urbanization has the most significant warming effect on the air temperature at 2 m in the northern part of the Urumqi during summer, and the ambient wind field in this region is weak, it is prone to forming an urban heat island circulation. This circulation involves flow convergence in a low-level and upward motion, all contributing to increased precipitation.

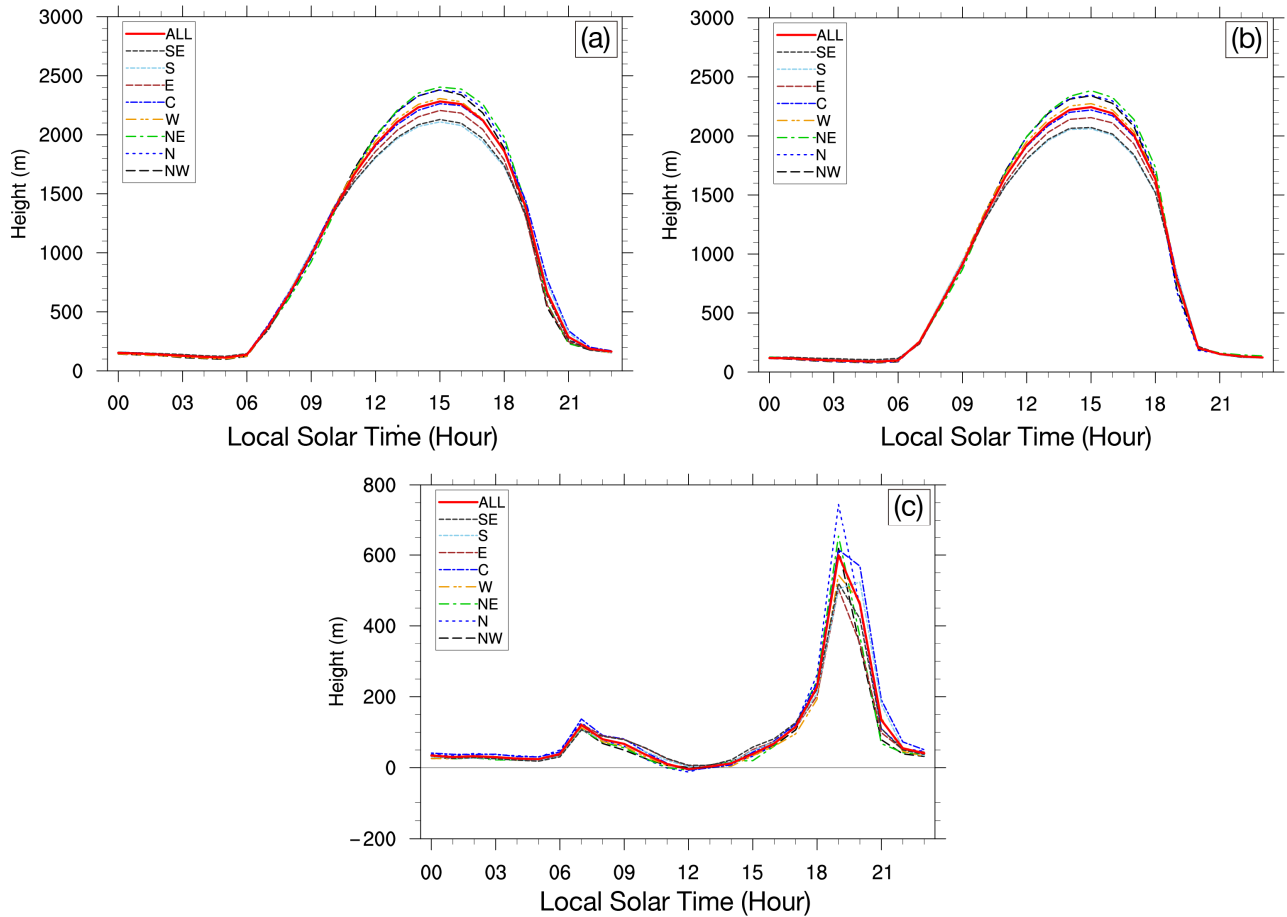


Figure 13. Here, (a–c) is the same as in Figure 9a–c, but for the averaged planetary boundary layer height (PBLH, unit: m) in summer from 2012 to 2021 in different square areas in the various orientations of the central point of urban area in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the PBLH, respectively.

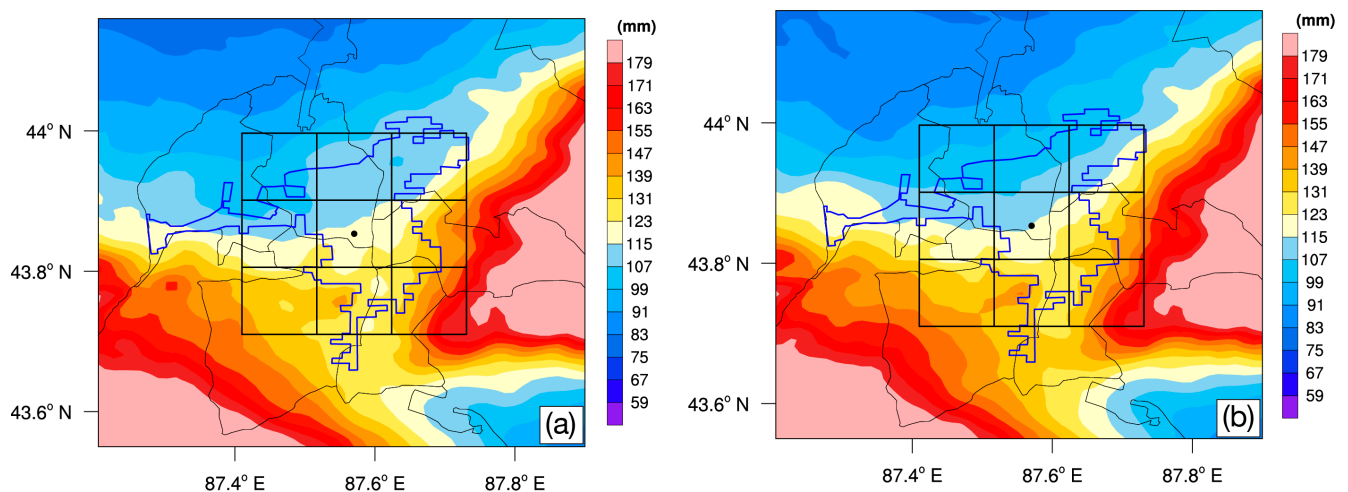


Figure 14. Cont.

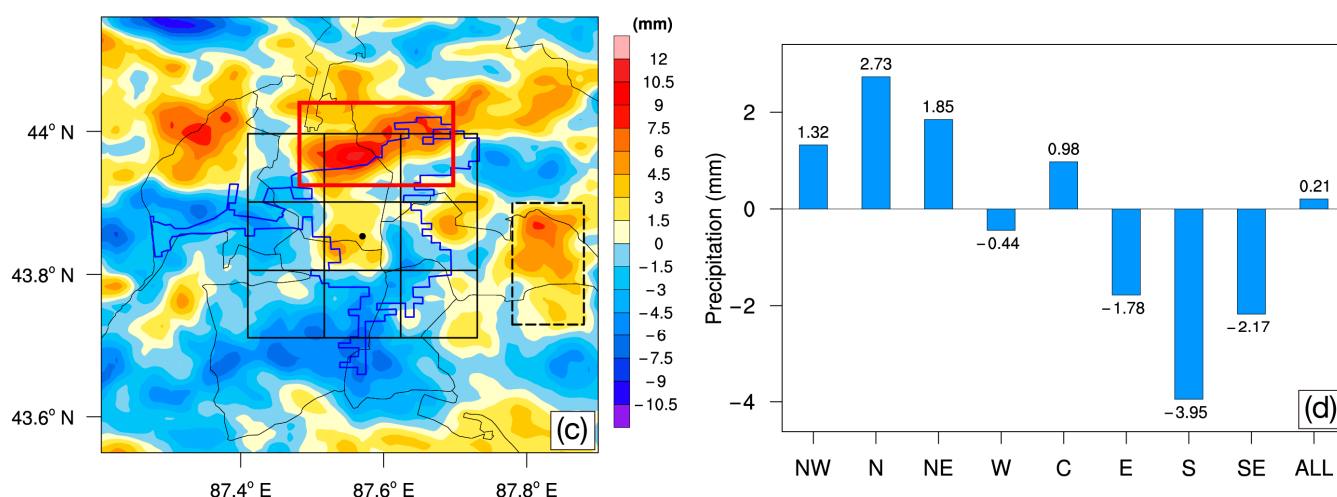


Figure 14. Here, (a–c) are the same as in Figure 5a–c, but for the spatial distribution of the average precipitation (colorful shading, unit: mm) in summer from 2012 to 2021 in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the precipitation, respectively. Here, (d) is the same as in Figure 5d, but for the average values of the average precipitation in summer over the nine areas. The two rectangular areas, delineated by red solid lines and black dashed lines, indicate the northern and eastern suburbs of Urumqi, respectively, where the UE has increased the precipitation.

The diurnal variation characteristics of precipitation (Figure 15a) indicate that, under the urban experiment, the peak summer precipitation in the urban area of Urumqi occurs around 23:00 LST, with a peak appearing around 08:00 LST, similar to the non-urban experiment, indicating that urbanization does not significantly affect the timing of the peak precipitation. The variation characteristics of the UE on summer precipitation in the diurnal scale (Figure 15c) reflected that urbanization mainly suppresses precipitation during the night-time (00:00–06:00 LST), but promotes precipitation at other times, reaching a maximum promotional effect around 16:00 LST in the afternoon.

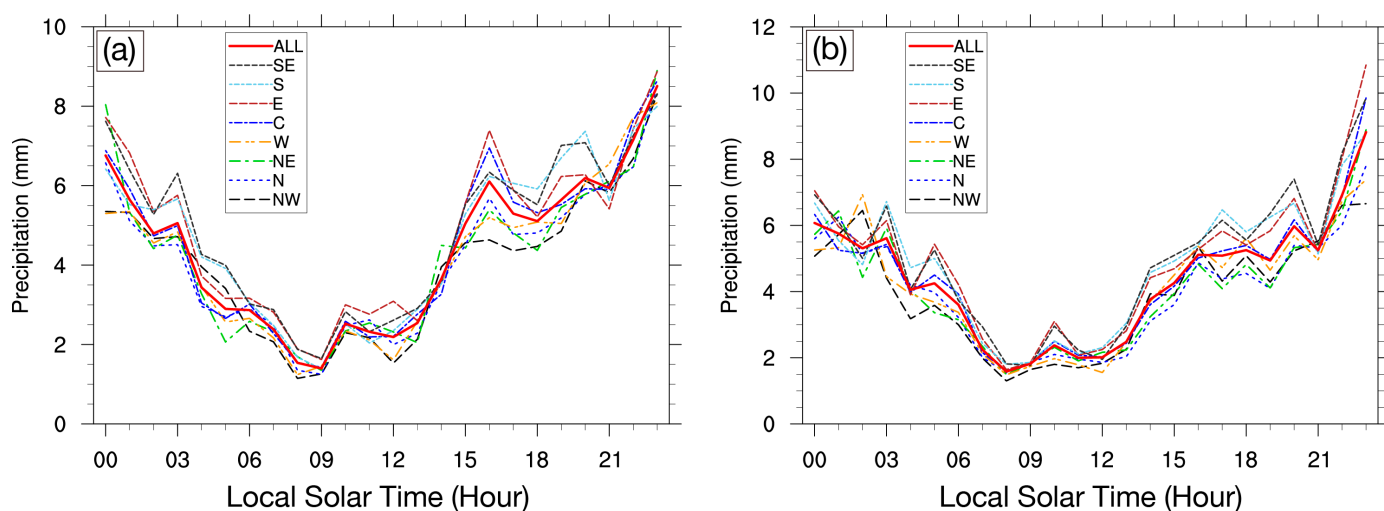


Figure 15. Cont.

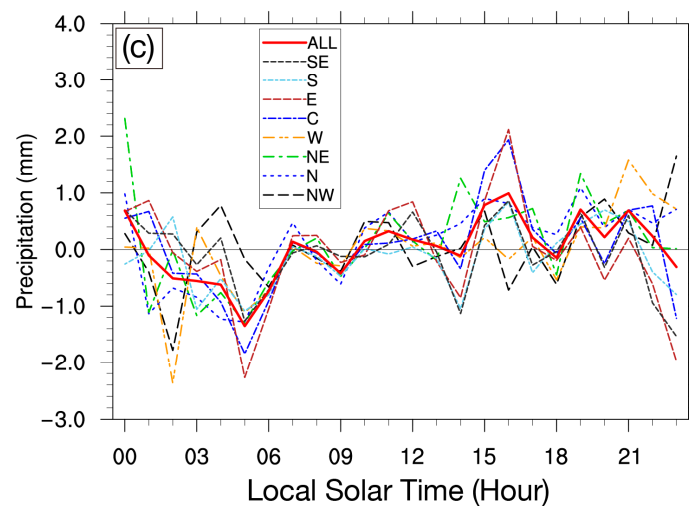


Figure 15. Here, (a–c) is the same as in Figure 9a–c, but for the averaged precipitation (unit: mm) in summer from 2012 to 2021 in various square areas in various orientations of the urban central point of Urumqi in the urban and non-urban experiment and UE (i.e., values of urban–non-urban) on the precipitation, respectively.

4. Discussion

(1) Some previous research [72–74] has indicated that the UE on regional climate is significantly associated with the urban background climate. Table 1 presents the comparison of the UE on the DTR, PBLH, WVMR, and RH at 2 m, as well as precipitation in Urumqi (a dry region) and Chengdu (a humid region). It is evident that the decrease in the DTR in Urumqi owing to the UE is notably higher than that in the city of Chengdu. It is probably because of the lower moisture in the soil in Urumqi as an arid region city, which leads to an intensified UHI effect at night, resulting in a more substantial increase in the night-time T_{min} . Additionally, Urumqi experiences a slight daytime UCI effect, causing a decrease in the daytime T_{max} . Consequently, the magnitude of DTR reduction due to the UE in Urumqi in summer is notably larger than that in Chengdu. In addition, the increase in summer PBLH due to the UE in Urumqi is substantially smaller than that in Chengdu. This is probably attributed to the fact that temperature and humidity are the most fundamental meteorological conditions that directly influence the height of the PBLH. The climate in Chengdu is wetter than that of Urumqi, possessing both high-temperature and high-humidity conditions, which enhance turbulence and cause the PBLH to rise, resulting in a greater increase in summer PBLH compared to Urumqi. Furthermore, urbanization in both Urumqi and Chengdu has resulted in a reduction in the summer WVMR and RH at 2 m, but the magnitude of this decrease in Chengdu is 3 to 4 times greater than that in Urumqi. This could also be due to the fact that the climate in Chengdu is wetter, with more water vapor in the atmosphere than in Urumqi, and thus the decrease caused by the UE is also larger in Chengdu. Both urbanization in Chengdu and Urumqi have caused a strengthening of the precipitation amount in upwind and downwind regions of the urban area. However, the mechanisms by which urbanization influences precipitation may vary between arid and humid regions [9,75]. Further research is therefore required to delve into these mechanisms and understand the climatic effects of urbanization in both arid and humid environments, as well as the differences between them.

Table 1. Comparison of the UE on climatic factors in summer between Urumqi and Chengdu.

	Urumqi (This Study)	Chengdu (Yao, et al. [23])
The UE on the DTR	−1.55 °C	0.85 °C
The UE on the PBLH	95.01 m	150 m
The UE on the WVMR at 2 m	−0.27 g·kg ^{−1}	−0.8 g·kg ^{−1}
The UE on RH at 2 m	−2.43%	−11%
The UE on precipitation	−1.55 °C/ −0.44 °C	0.85 °C/0.6 °C

(2) Precipitation has consistently been a key point of research in meteorology and climatology, posing an even greater challenge in arid regions such as Xinjiang due to the sparsity of observation stations and the complexity of the underlying surfaces and terrains. However, this study did not specifically address the UE on the extreme precipitation in Urumqi. Previous research [35,36] on UE on the extreme precipitation in the city of Urumqi has primarily been confined to comparisons between urban and suburban extreme precipitation events. However, factors such as terrain elevation, wind, and circulation conditions at urban and suburban stations may influence precipitation amount and intensity [75]. Consequently, there are potential uncertainties to some extent in conclusions drawn about the UE on extreme precipitation. Future research must employ numerical simulation techniques, utilizing rigorous variable control methods, to investigate the UE on extreme precipitation in arid regions. This will enable a deeper exploration of the influence of anthropogenic activities, exemplified by urbanization, on the precipitation in arid areas. Additionally, the driving factors and formation mechanisms of precipitation in arid regions are highly complex. Therefore, a comprehensive analysis of the characteristics and mechanisms through which urbanization affects precipitation can be conducted from various perspectives, including multi-year simulations and case studies of individual extreme (or heavy) precipitation events. Such efforts are crucial for effectively addressing the urgent need to understand the precipitation in arid regions.

(3) In this study, the UE on the diurnal temperature range (DTR) in the northern part of the city is significantly greater than that in the southern part. Potential reasons for this phenomenon may be related to the north–south difference in the urban heat island (UHI) effect intensity in Urumqi, as well as topographical differences between the north and south. Our previous research [26] has demonstrated that Urumqi exhibits a pronounced UHI effect at night, with the intensity of the UHI being greater in the northern part than in the southern part. Urbanization has led to a larger increase in the T_{min} at night-time in the northern part compared to the southern part of the city, while the difference in the UE on the daytime T_{max} between the north and south is relatively small. Consequently, the decrease in DTR caused by urbanization also exhibits a notable north–south difference. Furthermore, the northern part of Urumqi has a lower elevation compared to the southern part. Generally, turbulent energy diffusion in the near-surface atmosphere is slower or weaker in lower-elevation areas than in higher-elevation areas. Therefore, energy turbulent diffusion in the northern part of the city is weaker, making it more susceptible to higher temperatures in the north. The stronger UHI effect and weaker energy dissipation in the northern part lead to a greater increase in T_{min} at night, with a smaller decrease in daytime T_{max} due to the UCI effect, compared to the southern part, resulting in a larger decrease in DTR in the northern part. We will conduct more detailed investigations about this issue in the future.

(4) In our previous study [26], the UE on the urban thermal environment in Urumqi and associated possible mechanisms in all four seasons were explored from the perspective of a surface energy budget (e.g., sensible heat, latent heat, ground heat flux, long-wave

radiation, short-wave radiation). It was found that the UE on the thermal environment varies significantly among different seasons. Further, it is found that Urumqi experiences a strong UHI effect at night, while a weak UCI effect occurs during the day, and a detailed analysis of their spatio-temporal distribution characteristics was conducted. However, in contrast, we found in our present study that urbanization in Urumqi leads to a decrease in DTR, which is caused by raising the T_{min} at night and lowering the T_{max} during the day, thus considering UCI and UHI effects as potential primary contributors to the reduction in DTR. Furthermore, we found in our present study that urbanization results in increased precipitation in the downwind areas of the urban area, consistent with the previously mentioned viewpoint regarding UE on precipitation (Oke et al. [9]). It can be speculated that changes in the urban surface energy balance led to the UHI effect and the formation of thermally driven circulation, subsequently causing atmospheric convection and wind field convergence in the downwind areas of the urban area. Additionally, this study identified another area of increased precipitation due to urbanization located to the north of the urban area. In conjunction with our previous research [26], which found the strongest UHI intensity and weakest wind field in the northern region of urban area, it is plausible to suspect the presence of an UHI circulation in this area. The region of increased precipitation caused by urbanization coincides with this area, and thus UHI may be a primary factor affecting precipitation. Of course, further investigation into the interrelationships between these phenomena will be investigated in the future.

(5) Previous research has revealed that urban expansion and population growth exert a notable influence on urban climates, with a particularly significant impact on surface temperatures [76]. This study conducted a detailed investigation of the UE of Urumqi on various local climatic factors and their diurnal variation characteristics through a comparison of urban and non-urban experiments based on a decade-long numerical simulation. However, it has not yet addressed the influence of urban area expansion, as well as population growth on local or regional climates. Therefore, greater attention will be paid to the influence of the “urbanization process” on regional or local climates in our future research. For example, we will examine the impact of the urbanization process on climatic elements by conducting numerical simulations over broader time spans, such as those for the years 1990, 2000, 2010, and 2020, and utilizing the differences between simulation results from different years. Furthermore, the urbanization process will be disaggregated into multiple dimensions including urban expansion, population increase, and economic growth, allowing for a detailed exploration of how these urbanization factors affect regional or local climates. Additionally, future studies will further investigate the influence of anticipated urban expansion on local and regional climates by forecasting urban expansion trends over several decades.

(6) This study examines the UE on summer climate (based on several certain climatic factors) in Urumqi. However, Urumqi is surrounded by mountains on three sides, and its climate is highly susceptible to the influences of topography and large-scale circulation patterns. Consequently, the conclusions drawn from this study may possess greater regional characteristics. The majority of global research on the UE centers around large cities with humid climates, while studies related to arid region urban climates have a relatively late start. Nevertheless, cities in arid regions with fragile ecosystems face greater risks and threats from climate change, underscoring the need for further research. Shepherd [77] analyzed urbanization in Phoenix, a city in the arid region of the United States, and identified it as a primary cause of increased suburban precipitation. Castro et al. [78] examined the UE of Phoenix regarding storms using a WRF model simulation and found that the UE reduced rainfall over the urban core while increasing it around the city’s periphery. In our present study, the areas of increased precipitation due to UE are also located in

the suburbs; however, unlike Phoenix, the UE on precipitation in the built-up areas of Urumqi exhibits distinct north–south differences. Furthermore, Svoma and Balling [79] found that human activities in Phoenix primarily influence winter precipitation through the suppression of PM_{2.5}, with PM_{2.5} concentration inversely related to the precipitation frequency, indicating that the UE on precipitation also shows certain seasonal variations. In our previous research [26], we analyzed the UE on the urban thermal environment (e.g., surface temperature and 2 m air temperature) and its possible mechanisms in Urumqi from the perspective of surface energy budget and found significant variations in the UE on the thermal environment across different seasons. Consequently, this study further investigates the UE on climatic factors such as WVMR, RH, PBLH, and precipitation, focusing on the summer season, which experiences higher precipitation, with the aim of thoroughly examining the UE during summer. Our future research will also focus on the UE on winter blizzards, temperature inversions, valley winds, and other meteorological elements influenced by anthropogenic emissions.

5. Conclusions

As the first study on the urbanization effect (UE) on multiple climatological factors in summer in Urumqi, one of the biggest cities in the arid region in northwest China, based on a consecutive decade-long period (2012–2021) of numerical simulation data, this study quantitatively investigates the spatio-temporal characteristics of the UE on several basic climatic factors. The conclusions are as follows:

(1) The UE of Urumqi has resulted in considerable variations in multiple climatic factors in summer. It has led to decreases in the DTR mainly by increasing T_{min} . Meanwhile, it has caused reductions in the WVMR and RH at 2 m. The maximum value of the UE in Urumqi on these climatic factors reached $-0.12\text{ }^{\circ}\text{C}$, $2.4\text{ }^{\circ}\text{C}$, $-2.5\text{ }^{\circ}\text{C}$, -0.45 g kg^{-1} , and -6.5% , respectively. Furthermore, urbanization has also resulted in the occurrence of the “dry island effect” throughout the day within the urban area. In addition, the UE of Urumqi further influences the PBLH through the UHI effect, resulting in a significant increase in the PBLH. The maximum increase in the PBLH due to the UE occurs in the central part of the Urumqi around 19:00 LST, with an increase of 750 m.

(2) The UE of Urumqi has caused an increase in precipitation in the northern part of the city, with the maximum increase reaching 7.5 mm. In addition, it has suppressed precipitation in the southern part of the city, with the maximum suppression exceeding 6 mm. The UE has also brought about an increase in the precipitation amount in the upwind and downwind areas of the city, with the maximum increase in precipitation reaching 7.9 mm. The UE on the diurnal variation of precipitation is relatively small, mainly suppressing precipitation in the early morning and increasing it in the afternoon.

(3) The UE on various climatic factors exhibits different spatio-temporal characteristics. The UE on the DTR, T_{max} , and T_{min} , as well as the RH at 2 m, indicates a pattern of higher (lower) values in the northern (southern) part of Urumqi. In contrast, the UE on the PBLH depicts a pattern of higher (lower) values in the central part (surrounding area), while the UE on precipitation is relatively complex, generally exhibiting a pattern where the southern part of Urumqi exhibits a higher effect compared to the northern part.

Author Contributions: Data curation: A.A. (Aerzuna Abulimiti); formal analysis: A.A. (Aerzuna Abulimiti) and Y.L.; investigation: A.A. (Aerzuna Abulimiti), Q.H. and A.A. (Abuduwaili Abulikemu); methodology: A.A. (Aerzuna Abulimiti), Q.H., Y.L. and A.A. (Abuduwaili Abulikemu); project administration: Q.H.; resources: Q.H., A.A. (Abuduwaili Abulikemu), A.M., Q.H., J.Y. and Y.Z.; software: A.A. (Aerzuna Abulimiti), Q.H. and A.A. (Abuduwaili Abulikemu); supervision: A.A. (Abuduwaili Abulikemu) and Y.L.; validation: A.A. (Aerzuna Abulimiti) and A.A. (Abuduwaili Abulikemu); writing—original draft: A.A. (Aerzuna Abulimiti); writing—review and editing: A.A.

(Aierzuna Abulimiti), Q.H. and A.A. (Abuduwaili Abulikemu). All authors have read and agreed to the published version of the manuscript.

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