Research Article

Effects on Local Temperature and Energy of Oasis City Expansion in Arid Area of Northwest China

Miao Zhang¹, Geping Luo², Peng Cai² and Rafiq Hamdi³

¹Northwest Land and Resources Research Center, Shaanxi Normal University, No. 620, West Chang'an Avenue, Chang'an District, Xi'an 710119, China

²State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, No. 818 South Beijing Road, Urumqi, 830011 Xinjiang, China

³Royal Meteorological Institute, Avenue Circulaire 3, B-1180 Brussels, Belgium

Correspondence should be addressed to Geping Luo; luogp@ms.xjb.ac.cn

Received 16 July 2019; Revised 29 October 2019; Accepted 10 January 2020; Published 1 February 2020

Guest Editor: Jingwei Wang

Copyright © 2020 Miao Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The land surface model SURFEX 7.3 was used to study climate effect of urban expansion located in oasis in arid area of Northwest China by surface and 2 m urban heat island (UHI) intensity and available energy ratio (B). We performed a true regional development scenario and three assumed scenario simulations in 1978, 1993, 2004, and 2014, respectively. The results show that 2 m UHI always displays positive twin peaks during whole day, while surface UHI only displays a positive single peak with several hours during daytime at four seasons in the four years. Moreover, 2 m UHI intensity during night is higher than that during daytime, indicating that UHI intensity is contributed more by “trap effect” from urban complex geometry or anthropogenic heat and that surface UHI according to land surface temperature cannot reflect UHI comprehensively. The oasis-urban development resulted in local warming and increasing of B , and compared with the original undeveloped environment, local climate in the study area was in a relatively balanced state in 1978 and 1993 due to the “heating effect” of urban area and the “cooling effect” of oasis, but the offsetting effect from oasis would become weaker after 1993.

1. Introduction

Research on local climate change caused by urban expansion has received increasing interest due to the fact that it is closely related to the living quality for humans in the past few years [1–6]. But studies with respect to the climate effect of urban expansion in the oasis-desert system in arid area is relatively rare [7, 8]. Northwest China has a special mountain-basin geomorphology, and urban are in this region is usually converted from surrounding oasis area, while oasis is usually from a difficult reclamation in the surrounding desert. Both urban and oasis development in this region are greatly limited by local water and soil resources in the basin [9, 10], since the main water resource is from the limited melting of snow and glaciers and the precipitation in tall mountain ranges and the desert background also makes oasis and urban compete for the limited fertile soil on alluvial fan out of the mountains [11]. Urban expansion

on such oasis will inevitably increase instability of oasis and the integrated ecosystem [12, 13]. Based on our previous studies, the oasis plays a role of wet-cold island compared with the surrounding desert and drives local atmospheric circulation between oasis and desert, which plays an important role in maintaining the existence of oases [14, 15]. However, what we do not know is whether this urban expansion will affect the wet-cold island effects of oasis and local climate and how? Thus, exploring climate effects of urban expansion in this region will provide beneficial information to regional sustainable development [16].

Expansion of impervious surface area (ISA) is a representative of urban development [17], and the urban heat island (UHI) has been considered as the most obvious feature that resulted from the ISA expansion [18]. However, we found that the understanding for UHI and the relation with the increasing of ISA in previous studies are incomplete, unilateral, and controversial. For example, some researchers

determined that city center is sometimes cooler than the rural environment, such as in the morning in the summer [19]. Others believed that the city center was always warmer than rural area in whole year [20]. Except for difference in urban scale and urban geometry description [21], one possible important reason for these controversial conclusions is from the different UHI definitions. As we all know, the UHI is defined as the temperature difference between urban and rural areas. But some researchers calculated the UHI using air temperature difference between the urban and rural areas [2, 19, 22–24], while others calculated the UHI from land surface temperature (LST) difference between urban and rural areas [1, 20, 25].

Therefore, in this paper, we compared the two different UHI intensities at hour scale with the increasing of ISA in a typical middle-scale oasis-urban Fukang (FK for short) in the north slope of Tianshan Mountains. The vertical temperature difference between land surface and its over and available energy ratio in the urban center were also studied for understanding further the mechanism of UHI.

2. Method

2.1. Study Area. The particularity of the study area was mainly that such urban area expanded on artificial oases [9, 10], while the formation of these oases rely on the geomorphic characteristics of high mountain-basin systems. The limited water resources from melting of snow and glaciers and the precipitation in mountain ranges maintain oasis and urban survival in these mountain-basin systems. Water resources are scarce for both human livelihoods and ecosystems here, and urban development will certainly increase the instability of regional sustainable development.

We selected FK in SanGong River Basin (SGRB) in the north slope of the Tianshan Mountains as the study area, which has an area of 304 km². The FK with central latitude and longitude of 44°09′ and 87°58′. The SGRB has a gentle slope from the southeast to the northwest with the average altitude of 575 m, and the famous Gurbantonggut desert is located in the northern areas. Before the year 1958, FK is just a small village, and the dominant plant species of the SGRB were desert shrubs, grassland, and saline [26]. The area and population of FK have dramatically increased approximately to 60.87 km² and 220,000 (population density of oasis reached 71 persons/km²) in the past 60 years. The dominant plant species become crops such as wheat, cotton, and surrounding sparse desert shrubs. The SGRB belongs to continental arid and semiarid climate with average evapotranspiration of 2292 mm and average precipitation of 145 mm. The average annual temperature is 6.7°C, and there had been the historical extreme highest temperature of 41.5°C and the lowest temperature -37°C.

2.2. Model. The externalized surface scheme SURFEX 7.3 was used in this paper. The SURFEX actually includes various modules to describe the exchanges of water, momentum, and energy over four universal surface area titles: sea, lake, vegetation, and town [27]. In this paper, we used the Town Energy Balance (TEB) [28] scheme to parameterize the local

scale energy and water exchanges between urban surfaces and the atmosphere and simultaneously coupled with the Interactions between Soil, Biosphere, and Atmosphere (ISBA) scheme [29, 30] to simulate the energy and water budget of soil and vegetation. TEB simulates the urban energy and water exchange over three generic and comprehensive surfaces (road, roof, and wall). Although TEB is a single-layer canopy module with simplification hypotheses on the canopy shape and direction, it is enough to accurately describe the change trend of surface energy, canyon air temperature, and surface temperature. The coupling of ISBA and TEB was run in offline mode.

2.3. Input Data

2.3.1. Impervious Surface Area Estimation. In this study, both aviation photos and satellite images were used to access the fraction of impervious surface area (ISA): scanned aviation photos in 1958 and 1978, Landsat 5 TM in 1993 (30 m), SPOT 4 in 2004 (10 m), and Landsat 8 in 2014 (15 m). All of the satellite images were acquired from July to September. Since vegetation grows vigorously in this period, it is easy to distinguish different land cover types on the basis of obvious spectral difference. The images in 1993, 2004, and 2014 were first radiometrically and atmospherically corrected using the ENVI/FLAASH module, and geometric corrections were also performed. The projection of all images was projected using the Universal Transverse Mercator with WGS-84 coordinate system. The main method to extract ISA is referenced from the studies [17, 31–33]. First of all, water was masked according to the Normalized Difference Water Index. Three abundant spectral information bands were extracted by minimum noise fraction, which were used to select the four quite different and classical endmembers (vegetation, low albedo, high albedo composition, and soil composition). Finally, ISA fractions were obtained using the Decision Tree classification. For the photos in 1958 and 1978, the ISA was extracted by sketching city boundaries digitally and calculating the ISA by the grayscale difference of aviation photos and referenced to the FK yearbook. The ISA expansion can be seen in Figure 1.

2.3.2. Forcing and Observed Data. Reanalysis Modern-Era Retrospective Analysis for Research and Applications (MERRA) was selected as forcing data. This product is produced at one-hour intervals, and the full spatial resolution is 1/2 degrees (latitude) × 2/3 degrees (longitude), which were downloaded from the Goddard Earth Sciences Data and Information Services Center (MERRA). MERRA was generated with version 5.2.0 of the Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system (DAS). The MERRA used the ensemble assimilation methods [34] and had high quality [35]. The forcing variables consist of hourly downward direct shortwave radiation, downward longwave radiation, rainfall rate, 10 m air temperature, northward wind and eastward wind at 10 m above displacement height, surface pressure, specific humidity at 10 m above the displacement height for the years of 1978 and 1993, but at 50 m in the years of 2004 and 2014, and equivalent

FIGURE 1: Impervious surface area (ISA) in 1958, 1978, 1993, 2004, and 2014.

FIGURE 2: Location of FK station and SanGong River Basin (SGRB).

density of CO_2 (350 ppm) during the simulation. In situ observations from a meteorological station FK are used to validate the simulated hourly temperature (Figure 2). The original underlying surface of the FK station is irrigated crop, but with the expansion of FK, the observation is influenced more by the urban area.

2.4. Simulation Scenarios. Because there is smaller ISA (Figure 1) and a lack of forcing data in 1958, we performed a true control scenario and three assumed scenario simu-

lations only in 1978, 1993, 2004, and 2014, respectively. Table 1 displays the land use change in different scenarios and explains the details of different scenarios. CDISA scenario represented the true evolution of land cover in the historical four years. CDC scenario assumed that the ISA in the true scenario was converted from surrounding oasis and the desert was still the same with CDISA scenario. Thus, the difference between CDISA and CDC can explain the contribution of ISA on local climate when urban area developed at the expense of oasis. CDD referred that the ISA in CDISA

TABLE 1: Simulation scenarios.

	ISA	Oasis	Desert
CDISA	True	True	True
CDC	No	Original oasis+ISA area	True
CDD	No	True	Original desert+ISA area
D	No	No	Original desert+ISA+oasis
CDISA-CDC	The effect on local climate of ISA expansion when the ISA area was converted from oasis		
CDISA-CDD	The effect on local climate of ISA expansion when the ISA area was converted from desert		
CDISA-D	The effect on local climate when both oasis and ISA developed (true regional development)		
CDC-D	The effect on local climate when oasis only developed		

was converted from the desert, and the difference between CDISA and CDD can explain the ISA effect when urban area developed from the surrounding desert. We also assumed that there is no urban and oasis expansion in the past (D scenario) and the climate from the D scenario represented assumed climatic environment of the undeveloped state. Thus, the difference between CDC and D will give climate effect when the oasis only developed, and the difference between CDISA and D gives climate effect of true development. Because of the same forcing data and parameters used in the different simulation scenarios, we can deduce that the local climate difference between different scenarios at the same year resulted from regional development.

2.5. Model Parameters. The dominant crop types of the SGRB were cotton and wheat according to fieldwork ([36]). The leaf area index (LAI) values in 12 months were set as 0, 0, 0.5, 1.06, 2.38, 3.4, 4.2, 4.3, 3, 1.33, 0, and 0 based on the average of MERRA LAI data (MERRA), dominant crop phenology [37–39], and fieldwork. Road in oasis city generally can be divided into surface layer, base layer, and the cushion. According to survey, the thickness of the surface layer is about 3–15 cm and the layer is composed of the combination of asphalt and concrete layer. The thickness of base layer approaches to 50 cm, and the layer is mainly composed of concrete to keep the stability of road. The cushion is the layer between the base layer and soil and is also mainly composed of concrete. Wall in oasis city can be composed of plaster and layer on both sides and internal insulation and adiabatic layer (200–300 cm) of hollow brick, aerated concrete, or benzene board. Roof in oasis city can be divided into surface waterproof layer, insulation and adiabatic layer, and reinforced concrete layer [40, 41]. In this study, parameters of roof, wall, and road were set as three layers referenced from fieldwork and papers [3, 23, 40–43]. The details can be seen in Table 2.

3. Results

3.1. Simulation Evaluation. We used Pearson correlation coefficient (r), index of agreement (d), mean bias (Bias), root mean square error (RMSE), standard deviations (SDT), and proportions of systematic and unsystematic error (S/U) to comprehensively evaluate the simulation result. These measures describe the direction of the error bias and indicate the average error magnitude. Table 3 shows SURFEX perfor-

mance in simulating 2 m daily average temperature from the true (CDISA) simulation at the FK station. A strong linear relationship is obtained at all seasons in the three years from simulation with coefficients of determination (d) larger than 0.74 ($p < 0.05$) and Pearson correlation coefficient (r) larger than 0.66 ($p < 0.05$) (Table 3). Simulation in warm seasons (summer and autumn) was better than that in cold seasons (spring and winter). The proportions of systematic and unsystematic errors were much less than 30%; this means that physical processes that the model routinely simulate are relatively well [44]. The 2 m temperatures simulated using the SURFEX in three years were well consistent with observation. Considering that the UHI intensity is different between urban center and rural area, the simulated errors were counteracted to some extent, and acceptable bias and mean absolute error were obtained except for the spring and winter in the years 1993 and 2004.

3.2. The 2 m and Surface UHI and Energy Partition in the True Scenario. The hourly and yearly intensity of UHI in 1978, 1993, 2004, and 2014 was calculated at a height of 2 m (T2MD for short) and land surface (TSD for short). T2MD refers to the 2 m air temperature difference between the city center and the rural area, and TSD means the difference of average temperature of three urban surfaces (road, roof, and wall) and the rural surface temperature. At the same time, we also computed the vertical temperature difference at 2 m from the city surface to its over (TUD) and from rural area to its over (TVD) in these four years with the purpose of further understanding the reasons and physical process of UHI.

From Figure 3, the following rules can be obviously obtained. (1) T2MD always displays positive twin peaks during whole day at four seasons in the four years, and the twin peak in the winter becomes weaker than the other three seasons (Figure 3 solid line), while the TSD displays a single peak and the temperature of the city surface is higher than that of the rural surface several hours during daytime in the four seasons in the four years, but displaying a cooler surface during deep night (Figure 3 dotted line). This means that 2 m air temperature of city environment is indeed warmer than that in rural environment in whole day, but surface temperature of the city is not always warmer than that of the rural area. The UHI defined by air temperature difference has different rules with UHI calculated by land surface temperature

TABLE 2: Morphometric parameters and the physical properties of city elements in the modelling.

	1978	1993	2004	2014
Land cover fraction				
C3 crop	47.09	59.46	46.51	44.00
Sparse desert plant	49.99	20.43	13.58	10.45
ISA	2.92	20.11	39.91	45.55
Morphometric parameters				
Mean building height	10	10	20	30
Height/width	1	1	2	3
Road properties				
Main materials	Asphalt, concrete	Asphalt, concrete	Asphalt, concrete	Asphalt, concrete
Albedo	0.08	0.08	0.08	0.08
Emissivity	0.94	0.94	0.94	0.94
Roughness length	0.05 m	0.05 m	0.05 m	0.05 m
Roof properties				
Main materials	Asphalt, mortar, concrete	Asphalt, mortar, concrete	Asphalt, mortar, concrete	Asphalt, mortar, concrete
Albedo	0.14	0.14	0.14	0.14
Emissivity	0.90	0.90	0.90	0.90
Roughness length	0.15 m	0.15 m	0.15 m	0.15 m
Wall properties				
Main materials	Plaster, concrete, brick	Plaster, concrete, brick	Plaster, concrete, brick	Plaster, concrete, brick
Albedo	0.14	0.14	0.14	0.14
Emissivity	0.90	0.90	0.90	0.90

TABLE 3: The Pearson correlation coefficient (r), index of agreement (d), mean bias error (Bias), and root mean square error (RMSE) between the simulated and observed for winter (DJF), spring (MAM), summer (JJA), and fall (SON) in 1978, 1993, and 2004.

Year		r	d	Bias (°C)	RMSE (°C)	S/U
1978	Spring	0.95	0.97	-0.562	2.46	21%
	Summer	0.67	0.82	-0.046	2.27	32%
	Autumn	0.98	0.99	0.2286	1.84	23%
	Winter	0.96	0.97	0.7246	1.94	25%
1993	Spring	0.92	0.95	-1.1652	3.14	24%
	Summer	0.86	0.90	-0.8438	1.8	29%
	Autumn	0.95	0.97	0.3199	3.25	21%
	Winter	0.66	0.74	2.216	5.04	26%
2004	Spring	0.98	0.98	-1.608	2.38	31%
	Summer	0.91	0.94	-0.903	1.98	28%
	Autumn	0.97	0.97	-0.0811	2.75	11%
	Winter	0.92	0.95	1.2073	2.98	25%

*S/U means proportions of systematic and unsystematic errors.

difference. Some researchers think that remotely sensed UHIs are usually stronger and exhibit the greatest spatial variability of UHIs [45]. However, why do 2 m UHI and surface UHI have different diurnal variation patterns rather than just quantity differences in this study? The main reason is that UHI is not only from the difference of specific heat capacity

for the averaged urban surface and rural area surface, which results in larger difference between surface and its over air evidenced by the greater range of TUD than TVD (Figure 4), but is also closely related with the complex and heterogeneous three-dimensional structure, which makes it difficult for energy to spread out. Anthropogenic heat is a major contributor to the formation of the UHI. Sources include heat generated by the combustion process in vehicles, heat created by industrial processes, the conduction of heat through building walls or emitted directly into the atmosphere by air-conditioning systems, and the metabolic heat produced by humans [46]. Therefore, surface UHI can only reflect responsibility of land surface to energy, while 2 m UHI reflected land-atmosphere interaction status including effects of atmospheric pollution on absorption and scattering of longwave shortwave radiation, anthropogenic heating, “trap effect” from urban complex geometry, and energy interaction between surface and over air. This further implies that the main reason of UHI resulted from “trap effect” of urban complex geometry or anthropogenic heat and also implies that surface UHI according to the inversion temperature from remote sensing data cannot reflect UHI comprehensively. (2) T2MD during night is higher than that during the day, which indicates that the intensity of 2 m UHI during the night is stronger than that during the day. The reason might be that 2 m air temperature in both city environment and rural environment is increasing and the difference of the increasing rate between the two environments is relatively less during daytime. While the 2 m air temperature in both

FIGURE 3: Comparison of daily and yearly T2MD (solid lines reference to the left axis) and TSD (dotted lines reference to the right axis) in 1978, 1993, 2004, and 2014.

city environment and rural environment is decreasing after sunset, the decreasing rate of 2m air temperature in rural environment is much quick than that in city environment (the slow release due to “trap effect” from urban complex geometry), which makes the temperature difference between the city and the rural environment continue to increase. These indicate that the intensity of 2m UHI during daytime mainly resulted from the difference of energy absorption rate of the city and rural area, while the UHI intensity during night is decided by energy release rate of these two environments. This further confirms the above conclusion that the UHI intensity is determined more by “trap effect” from

urban complex geometry or anthropogenic heat after urban expansion. (3) Both T2MD and TSD at sun rising time are the lowest in a day, which illustrates that the UHI is the weakest at sun rising time. (4) The intensity of 2m UHI in the whole year displays similar twin peak trends. The strongest period of 2m UHI is April, September, and October in this region and relatively weaker during July, when it is the warmest period in the study area. The reason is that the evapotranspiration difference between the rural area and the urban area in July significantly decreased, thereby the temperature difference between them also decreased. The range of hourly and yearly averaged surface UHI is from

FIGURE 4: Comparison of daily and yearly TUD (solid lines) and TVD (dotted lines) with the increasing of ISA in 1978, 1993, 2004, and 2014.

-4°C to 7°C and from -3°C to 3°C, respectively, which were greater than that of 2 m UHI, with the range from 0°C to 3.5°C and 0°C to 2°C, respectively.

3.3. Effects on Local Climate Resulted from Increasing of ISA. 2 m temperature difference between the true scenario and the three assumed scenarios can quantitatively reveal the contribution to local climate of regional land use change. The red and green dotted lines in Figure 5 represented the change of 2 m temperature that resulted from the expansion of ISA in the four years at the expense of crop and desert, respectively. And black solid line and dark-green dotted line in Figure 5 represented the change of 2 m temperature that resulted from true regional development and without urban development, respectively. No matter if ISA was converted from oasis or desert, this conversion would increase local temperature in this region (red and green dotted lines in Figure 5), and increased magnitude of annual temperature

that resulted from crop to ISA conversion from 1978 to 2014 was 0.02°C, 0.16°C, 0.23°C, and 0.31°C, which was more than desert-ISA conversion directly. This confirms that urban development in the past 60 years resulted in the increasing of local temperature. Moreover, according to the true regional development, both urban and city are expanded in the past 60 years, but the “cooling effect” caused by expansion of oasis to local climate in the study region (dark-green dotted lines) was counteracted by the effect from urban expansion.

Bowen ratio (B) difference is important to understand the local climate change of land use change from the view point of available energy. If B is greater than 1, a greater proportion of the available energy at the surface is passed to the atmosphere as sensible heat than as latent heat, vice versa [47]. Figure 6 displays B in the true scenario and the B differences between the true and the three assumed scenarios in 1978, 1993, 2004, and 2014. No matter if the ISA was converted

FIGURE 5: 2 m mean temperature difference in simulation area between the true and assumed scenarios in 1978, 1993, 2004, and 2014.

from land cover of crop or desert, there is no doubt that city development resulted in the increasing of B in a year (red and green dotted lines). The reason might be from the double effects of rising in sensible heat and declining in latent heat. Increased sensible heat flux was caused by more heat storage due to “trap effect” which resulted from rough three-dimensional shape of urban area, relatively smaller reflectivity and heat capacity, and decreased latent heat flux was due to rare vegetation in the city. Thus, the increasing of B was a positive correlation with the increasing of ISA, which implies that B can also be an indicator of urbanization. Oasis development can lead to decreased B in a year except for the growing peak season, which can be seen from the different comparison between CDC and D scenario (dotted dark-green line in Figure 6). Compared with the original undeveloped environment, local thermal environment was in a relatively balanced state based on equivalent increased sensible heat and decreased latent heat in 1978 and 1993 due to combined effects of urban and oasis expansion, but local climate becomes warmer due to dominant increased sensible heat after 1993.

In order to explore the quantitative effects of oasis and urban expansion on the local climate, 2 m averaged temperature and B difference between true scenario (CDISA) and undeveloped environment (D) were compared in the years 1978, 1993, 2004, and 2014 (Figures 7(a) and 7(b)). B difference is almost greater than zero in the four years (Figure 7(a)); both B and local temperature increased from 1978 to 2014 (Figures 7(a) and 7(b)). The relation between both annual B and temperature with extended ISA is a positive correlation (see Figure 7(c)), the conclusion that regional land development in the study area, especially the growth of ISA, resulted in the increased B and local temperature.

4. Discussion

In this study, the effects of oasis-urban (regional) development on local climate in arid area of Northwest China from viewpoints of surface and 2 m UHI intensity and the change of available energy partition, using SURFEX land surface model, were discussed.

FIGURE 6: Bowen ratio (B) and its differences between the true and assumed scenarios in 1978, 1993, 2004, and 2014.

Our study also contributes certain new findings. The differences between surface and 2 m UHI show different diurnal variation patterns, rather than just quantity differences in this study. This conclusion is different from papers [1, 20, 25]; they indicate that surface and 2 m UHI have similar diurnal variations and differ only in magnitude. In addition, compared with the original undeveloped environment, local thermal environment was in a relatively balanced state in 1978 and 1993 due to the combined effects of urban and oasis expansion, but local climate becomes warmer due to the dominant increased sensible heat after 1993. This result is consistent with the findings reported in previous investigation [48], in which the author considered that the urbanization of most cities in northwestern China resulted in considerable negative warming effects before 1978, but in evidently positive effects after this year.

However, the report is only partly supplementary to the effects of urban development in the arid area; there are still many aspects that need to be studied or explored in depth, such as modelling uncertainty. Although we think it is feasible to use a grid forcing data in plain area, we plan that the

further research focus on the sensitivity analysis for uncertainty of different forcing data and model parameters and larger ISA, to explore the response of oasis-urban heat island to these parameters. As we all know, the poor choice of parameter values can cause a large drop in performance for models [49]; if better observed information about FK city such as annual air pollution, average building height, building materials, and larger cities are available in this study, then the simulated accuracy of this model can be improved and the conclusions in this study are more convincing. In addition, the simulations in this paper are unidirectional, not bidirectional, and these will bring some unpredictable uncertainty.

5. Conclusion

The SURFEX 7.3 was used to simulate effects of oasis-urban development on local climate in arid area of Northwest China from viewpoints of surface and 2 m UHI intensity and available energy partition. We performed a true scenario and four assumed scenario simulations in each year of 1978,

FIGURE 7: Local thermal environment change with the increasing of ISA.

1993, 2004, and 2014 and obtained the following conclusions. (1) 2 m UHI always displays positive twin peaks during whole day, while surface UHI displays a positive single peak during daytime at the four seasons in the four years, displaying a cooler surface during deep night. Surface UHI can only reflect responsibility of land surface to energy, while 2 m UHI reflects a comprehensive and three-dimensional land-atmosphere interaction after urban development. The UHI is determined more by “trap effect” from urban complex geometry or anthropogenic heat after urban expansion and that surface UHI according to the inversion temperature from remote sensing data cannot reflect UHI truly and comprehensively. (2) The urban development increased local temperature and available energy ratio (B) no matter if the ISA was converted by oasis or desert. Compared with the original undeveloped environment, local climate was in a relatively balanced state in 1978 and 1993 due to “heating effect” of urban and “cooling effect” of oasis, but the offsetting effect from oasis would become weaker

with the increasing of ISA. We hope the report can not only be beneficial to local planners but be helpful to regional climate researchers.

Data Availability

The data including validating data, forcing data for land surface model, code for processing output from land surface model, et al. used to support the findings of this study have been deposited in the “GitHub” repository (<https://github.com/mmzpb/Urban-in-arid-area>).

Additional Points

Highlights. 2 m urban heat island (UHI) intensity during night is higher than that during the day. UHI intensity is contributed more by “trap effect” from urban complex geometry or anthropogenic heat. Surface UHI according to land surface temperature from remote sensing data cannot reflect

UHI truly and comprehensively. Local climate in the study area was in a relatively balanced state in 1978 and 1993 due to “heating effect” of urban and “cooling effect” of oasis.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant Nos. 41801095 and 4167112) and the Fundamental Research Funds for the Central Universities (Grant No. GK201903117).

References

- [1] M. V. K. Aparna Dwivedi and B. K. Mohan, “Estimation of land surface temperature to study urban heat island effect in Mumbai using Landsat ETM+ image,” *International Journal of Remote Sensing and GIS*, vol. 4, no. 1, pp. 8–16, 2015.
- [2] S. Grossman-Clarke, J. A. Zehnder, T. Loridan, and C. S. B. Grimmond, “Contribution of land use changes to near-surface air temperatures during recent summer extreme heat events in the Phoenix metropolitan area,” *Journal of Applied Meteorology and Climatology*, vol. 49, no. 8, pp. 1649–1664, 2010.
- [3] R. Hamdi, A. Deckmyn, P. Termonia et al., “Effects of historical urbanization in the Brussels capital region on surface air temperature time series: a model study,” *Journal of Applied Meteorology and Climatology*, vol. 48, no. 10, pp. 2181–2196, 2009.
- [4] R. Hamdi, O. Giot, R. De Troch, A. Deckmyn, and P. Termonia, “Future climate of Brussels and Paris for the 2050s under the A1B scenario,” *Urban Climate*, vol. 12, pp. 160–182, 2015.
- [5] D. Li, T. Sun, M. Liu, L. Yang, L. Wang, and Z. Gao, “Contrasting responses of urban and rural surface energy budgets to heat waves explain synergies between urban heat islands and heat waves,” *Environmental Research Letters*, vol. 10, no. 5, 2015.
- [6] T. Loridan, F. Lindberg, O. Jorba, S. Kotthaus, S. Grossman-Clarke, and C. S. B. Grimmond, “High resolution simulation of the variability of surface energy balance fluxes across Central London with urban zones for energy partitioning,” *Boundary-Layer Meteorology*, vol. 147, no. 3, pp. 493–523, 2013.
- [7] Z. Hu, C. Zhang, Q. Hu, and H. Tian, “Temperature changes in Central Asia from 1979 to 2011 based on multiple datasets,” *Journal of Climate*, vol. 27, no. 3, pp. 1143–1167, 2014.
- [8] C. Li, C. Zhang, G. Luo et al., “Carbon stock and its responses to climate change in Central Asia,” *Global Change Biology*, vol. 21, no. 5, pp. 1951–1967, 2015.
- [9] C. Gao, J. Lei, and F. Jin, “The classification and assessment of vulnerability of man-land system of oasis city in arid area,” *Frontiers of Earth Science*, vol. 7, no. 4, pp. 406–416, 2013.
- [10] Y. Yang and Y. Liu, “Spatio-temporal analysis of urbanization and land and water resources efficiency of oasis cities in Tarim River Basin,” *Journal of Geographical Sciences*, vol. 24, no. 3, pp. 509–525, 2014.
- [11] G. Luo, Y. Feng, B. Zhang, and W. Cheng, “Sustainable land-use patterns for arid lands: a case study in the northern slope areas of the Tianshan Mountains,” *Journal of Geographical Sciences*, vol. 20, no. 4, pp. 510–524, 2010.
- [12] B. Lamptey, E. Barron, and D. Pollard, “Impacts of agriculture and urbanization on the climate of the northeastern United States,” *Global and Planetary Change*, vol. 49, no. 3–4, pp. 203–221, 2005.
- [13] S. Z. Qi, X. Y. Li, and H. P. Duan, “Oasis land-use change and its environmental impact in Jinta Oasis, arid northwestern China,” *Environmental Monitoring and Assessment*, vol. 134, no. 1–3, pp. 313–320, 2007.
- [14] M. Zhang, G. Luo, P. De Maeyer, P. Cai, and A. Kurban, “Improved atmospheric modelling of the oasis-desert system in Central Asia using WRF with actual satellite products,” *Remote Sensing*, vol. 9, no. 12, p. 1273, 2017.
- [15] M. Zhang, G. Luo, R. Hamdi et al., “Numerical simulations of the impacts of mountain on oasis effects in arid Central Asia,” *Atmosphere*, vol. 8, no. 12, p. 212, 2017.
- [16] J. W. Yan, J. Y. Liu, B. Z. Chen et al., “Changes in the land surface energy budget in eastern China over the past three decades: contributions of land-cover change and climate change,” *Journal of Climate*, vol. 27, no. 24, pp. 9233–9252, 2014.
- [17] D. S. Lu, G. Y. Li, E. Moran, M. Batistella, and C. C. Freitas, “Mapping impervious surfaces with the integrated use of Landsat Thematic Mapper and radar data: a case study in an urban-rural landscape in the Brazilian Amazon,” *Isprs Journal of Photogrammetry and Remote Sensing*, vol. 66, no. 6, pp. 798–808, 2011.
- [18] F. Yuan and M. E. Bauer, “Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery,” *Remote Sensing of Environment*, vol. 106, no. 3, pp. 375–386, 2007.
- [19] E. Vardoulakis, D. Karamanis, A. Fotiadis, and G. Mihalakakou, “The urban heat island effect in a small Mediterranean city of high summer temperatures and cooling energy demands,” *Solar Energy*, vol. 94, pp. 128–144, 2013.
- [20] M. L. Imhoff, P. Zhang, R. E. Wolfe, and L. Bounoua, “Remote sensing of the urban heat island effect across biomes in the continental USA,” *Remote Sensing of Environment*, vol. 114, no. 3, pp. 504–513, 2010.
- [21] P. A. Mirzaei, “Recent challenges in modeling of urban heat island,” *Sustainable Cities and Society*, vol. 19, pp. 200–206, 2015.
- [22] E. M. Fischer, K. W. Oleson, and D. M. Lawrence, “Contrasting urban and rural heat stress responses to climate change,” *Geophysical Research Letters*, vol. 39, no. 3, 2012.
- [23] R. Hamdi and G. Schayes, “Sensitivity study of the urban heat island intensity to urban characteristics,” *International Journal of Climatology*, vol. 28, no. 7, pp. 973–982, 2008.
- [24] L. Wang, Z. Gao, S. Miao et al., “Contrasting characteristics of the surface energy balance between the urban and rural areas of Beijing,” *Advances in Atmospheric Sciences*, vol. 32, p. 10, 2015.
- [25] R. Hamdi, “Estimating urban heat island effects on the temperature series of Uccle (Brussels, Belgium) using remote sensing data and a land surface scheme,” *Remote Sensing*, vol. 2, no. 12, pp. 2773–2784, 2010.
- [26] G. Luo, C. Zhou, and X. Chen, “Process of land use/land cover change in the oasis of arid region,” *Acta Geographica Sinica Chinese Edition*, vol. 58, pp. 63–72, 2003.

- [27] P. Le Moigne, A. Boone, J. Calvet, B. Decharme, S. Faroux, and A. Gibelin, "SURFEX scientific documentation," in *Note de centre (CNRM/GMME)*, Météo-France, Toulouse, France, 2009.
- [28] V. Masson, C. S. B. Grimmond, and T. R. Oke, "Evaluation of the town energy balance (TEB) scheme with direct measurements from dry districts in two cities," *Journal of Applied Meteorology*, vol. 41, pp. 1011–1026, 2002.
- [29] V. Masson, P. Le Moigne, E. Martin et al., "The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of earth surface variables and fluxes," *Geoscientific Model Development*, vol. 6, no. 4, pp. 929–960, 2013.
- [30] J. Noilhan and J. F. Mahfouf, "The ISBA land surface parameterisation scheme," *Global and Planetary Change*, vol. 13, no. 1–4, pp. 145–159, 1996.
- [31] C. Deng and C. Wu, "A spatially adaptive spectral mixture analysis for mapping subpixel urban impervious surface distribution," *Remote Sensing of Environment*, vol. 133, pp. 62–70, 2013.
- [32] D. Lu and Q. Weng, "Use of impervious surface in urban land-use classification," *Remote Sensing of Environment*, vol. 102, no. 1–2, pp. 146–160, 2006.
- [33] D. S. Lu and Q. H. Weng, "Spectral mixture analysis of ASTER images for examining the relationship between urban thermal features and biophysical descriptors in Indianapolis, Indiana, USA," *Remote Sensing of Environment*, vol. 104, no. 2, pp. 157–167, 2006.
- [34] M. M. Rienecker, M. J. Suarez, R. Gelaro et al., "MERRA: NASA's modern-era retrospective analysis for research and applications," *Journal of Climate*, vol. 24, no. 14, pp. 3624–3648, 2011.
- [35] Z. Hu, Q. Hu, C. Zhang, X. Chen, and Q. Li, "Evaluation of reanalysis, spatially interpolated and satellite remotely sensed precipitation data sets in Central Asia," *Journal of Geophysical Research: Atmospheres*, vol. 121, no. 10, pp. 5648–5663, 2016.
- [36] Y. Shen, S. Li, Y. Chen, Y. Qi, and S. Zhang, "Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989–2010," *Agricultural Water Management*, vol. 128, pp. 55–64, 2013.
- [37] N. Dağdelen, E. Yılmaz, F. Sezgin, and T. Gürbüz, "Water-yield relation and water use efficiency of cotton (*Gossypium hirsutum*) and second crop corn (*Zea mays* L.) in western Turkey," *Agricultural Water Management*, vol. 82, no. 1–2, pp. 63–85, 2006.
- [38] D. Haboudane, "Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: modeling and validation in the context of precision agriculture," *Remote Sensing of Environment*, vol. 90, no. 3, pp. 337–352, 2004.
- [39] S. K. Hicks and R. J. Lascano, "Estimation of leaf area index for cotton canopies using the LI-COR LAI-2000 plant canopy analyzer," *Agronomy Journal*, vol. 87, no. 3, pp. 458–464, 1995.
- [40] C. Romeo and M. Zinzi, "Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study," *Energy and Buildings*, vol. 67, pp. 647–657, 2013.
- [41] A. Takano, S. K. Pal, M. Kuittinen, K. Alanne, M. Hughes, and S. Winter, "The effect of material selection on life cycle energy balance: a case study on a hypothetical building model in Finland," *Building and Environment*, vol. 89, pp. 192–202, 2015.
- [42] J. S. Golden and K. E. Kaloush, "Mesoscale and microscale evaluation of surface pavement impacts on the urban heat island effects," *International Journal of Pavement Engineering*, vol. 7, no. 1, pp. 37–52, 2006.
- [43] R. Hamdi and V. Masson, "Inclusion of a drag approach in the town energy balance (TEB) scheme: offline 1D evaluation in a street canyon," *Journal of Applied Meteorology and Climatology*, vol. 47, no. 10, pp. 2627–2644, 2008.
- [44] C. J. Willmott, "Some comments on the evaluation of model performance," *Bulletin of the American Meteorological Society*, vol. 63, no. 11, pp. 1309–1313, 1982.
- [45] A. J. Arnfield, "Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island," *International Journal of Climatology*, vol. 23, no. 1, pp. 1–26, 2003.
- [46] L. Allen, F. Lindberg, and C. S. B. Grimmond, "Global to city scale urban anthropogenic heat flux: model and variability," *International Journal of Climatology*, vol. 31, no. 13, pp. 1990–2005, 2011.
- [47] R. Khatun, M. Farukh, A. Miyata, and M. Baten, "Bowen ratio measurements of energy budget components over various ecosystems in Mymensingh, Bangladesh," *Journal of Environmental Science and Natural Resources*, vol. 7, no. 1, p. 4, 2015.
- [48] F. Fang, J. Guo, L. Sun, J. Wang, and X. Wang, "The effects of urbanization on temperature trends in different economic periods and geographical environments in northwestern China," *Theoretical and Applied Climatology*, vol. 116, no. 1–2, pp. 227–241, 2013.
- [49] C. S. B. Grimmond, M. Blackett, M. J. Best et al., "Initial results from phase 2 of the international urban energy balance model comparison," *International Journal of Climatology*, vol. 31, no. 2, pp. 244–272, 2011.