ARTICLE OPEN

Seasonal variation of dry and wet islands in Beijing considering urban artificial water dissipation

Zhuoran Luo^{1,2}, Jiahong Liu^{1,2,3}✉, Yongxiang Zhang¹, Jinjun Zhou¹, Weiwei Shao², Yingdong Yu² and Ruitao Jia¹

Urbanization has resulted in dry/wet island effects in built-up areas. Compared to the limited number of observational datasets, simulations can provide data with richer spatial distribution, thereby proving to be more helpful for revealing the spatial distribution of dry/wet islands. This study simulated dry/wet island effects during typical summer and winter conditions in Beijing by coupling the Artificial Water Dissipation Urban Canopy Model with the Weather Research and Forecasting model. Observations of relative humidity, absolute humidity, and temperature from weather stations in Beijing were used to verify the model. The results showed that in 2020, Beijing was prone to be a dry island during summer, with the relative humidity approximately 5–10% lower than the surrounding suburbs. The dry island effect was not obvious in winter, and Beijing tended to be a wet island. The influence of artificial water dissipation on dry/wet islands is higher in winter than in summer. By considering the water vapor from artificial water dissipation, humidity in urban areas can be simulated more accurately.

npj Climate and Atmospheric Science (2021)4:58; <https://doi.org/10.1038/s41612-021-00216-4>

INTRODUCTION

Human activities have been found to impact hydrological processes and the atmospheric moisture content in urban areas^{1–4}. With rapid urbanization and the corresponding intensification of human activities^{5–7}, artificial surfaces such as roads, buildings, and paved areas have replaced natural surfaces such as farmland, vegetation, and wetlands^{8–10}. Consequently, vegetation transpiration has reduced in urban areas, causing urban dry island effects. At the same time, urban population growth has markedly increased the flux of artificial urban water circulation and the intensity of water dissipation in urban areas^{11–13}. If the water vapor from artificial water dissipation is higher than vegetation transpiration, then urban areas are prone to wet island effects^{14,15}.

Urbanization changes both the natural underlying surface and hydrological processes^{16–18}, having a significant impact on dry/wet island effects and the balance of water supply and demand^{19,20}. Therefore, urban surface humidity changes have been a research focus in recent years^{21–25}. The anthropogenic influence on meteorological elements in urban areas is well supported by observations^{26,27}. Urbanization has a significant and complex impact on humidity, and due to the influence of the underlying surface and human factors in urban areas, dry/wet island effects can vary greatly in different seasons. Consequently, accurate simulations of urban dry/wet island effects are important for understanding urban hydrological processes²⁸.

Comparing the water vapor pressure and relative humidity at different meteorological stations in urban and suburban areas can provide a basic analysis of the impact of urbanization on dry/wet islands^{29–32}. For example, Wang et al.³³ used air temperature and relative humidity data in Beijing from 1940 to 2010 to show that the intensity of heat and dry islands increased year by year, and relative humidity was decreased by 10% in urban areas. Numerical simulations provide a means to study dry/wet islands that can quantitatively identify the influence of different factors. The Urban Canopy Model (UCM) coupled with the Weather Research and

Forecasting Model (WRF) is a commonly used tool for this. Because the UCM can account for the influence of complex underlying surfaces and the urban canopy on atmospheric movement, numerical simulations have become the primary tool for studying urban meteorology^{34,35}. Wang et al.³⁶ established the water evaporation model of urban ground vegetation and pavement, which coupled the transport of water and energy in the UCM. Ryu et al.³⁷ introduced trees into the urban canopy, in addition to urban underlying surfaces and hydrological processes with different material properties, considerably improving the simulation of latent heat flux in the UCM. To date, research on urban dry/wet islands has focused on the comparative analysis of long-term and large-scale meteorological observation data, while the numerical simulation of dry/wet islands on a regional scale^{38,39} and the influence of artificial water dissipation on urban dry/wet islands⁴⁰ have received limited attention. In particular, the numerical simulation of non-uniform urban underlying surfaces and the atmospheric boundary layer remains challenging.

Evapotranspiration is a critical process for maintaining the land surface water-energy balance^{41–44}. Zhou et al.⁴⁵ classified urban underlying surfaces as buildings, hardened ground, soil, and vegetation, and used different artificial water dissipation calculation models to estimate evapotranspiration in urban areas. They concluded that higher degrees of urbanization resulted in a greater proportion of artificial water dissipation, which refers to various forms of water vapor dissipation from human water use activities⁴⁶. The built-up land area^{47,48} and population density are important factors influencing the intensity of artificial water dissipation. In 2015, artificial water dissipation accounted for 45.33–65.92% of the total water dissipation in the main urban area of Beijing, and only 12.67–25.62% in the surrounding suburban areas. These data indicate that artificial water dissipation has a considerable impact on urban air humidity (absolute humidity). Relative humidity (RH) is the ratio of absolute humidity to the absolute humidity of saturated air at the same temperature.

¹Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing 100124, China. ²State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China. ³School of Transportation and Civil Engineering & Architecture, Foshan University, Guangdong 528000, China. ✉email: liujh@iwhr.com

Thus, differences in the RH of urban and suburban areas can describe dry/wet islands. If urban relative humidity is lower (higher) compared to the surrounding suburbs, it will be defined as dry (wet) island.

In this study, we weight and summarize the evapotranspiration of different underlying surfaces induced by artificial water use based on the results of previous studies to obtain the total evapotranspiration due to artificial water dissipation in urban areas. Then, we incorporate these classifications into an artificial water dissipation urban canopy model (AWDUCM) and couple the model with WRF to study the seasonal and spatial distribution of urban dry/wet islands. By analyzing the causes of dry/wet islands in the context of artificial water dissipation and heat island effects, we strengthen our understanding of urban hydrological processes. Finally, we verify the accuracy of dry/wet island simulations by comparing them with observations from urban and suburban areas of Beijing⁴⁹. The results of this study will provide a basis for enhancing the sustainable management of urban areas.

RESULTS

Study area

Beijing, China, (39.35–41.15 °N 115.25–117.65 °E) was chosen as the study area (Fig. 1a). Beijing is a world-class city experiencing rapid urbanization and population growth. Located on the northern reaches of the North China Plain in the warm temperate semi-humid and semiarid monsoon climate zone, the city is dry (humid) during winter (summer). The area of Beijing is approximately 16,410 km^{2,50}, and land use types include forests and shrublands in the western and northern mountainous areas, and

croplands and built-up land to the east and south. By default, the geogrid program in WRF will interpolate land use categories from Moderate-Resolution Imaging Spectroradiometer International Geosphere-Biosphere Programme (MODIS IGBP) 21-category data. Therefore, we used MODIS 30s high-resolution underlying surface data, downloaded from the WRF official website (https://www2.mmm.ucar.edu/wrf/users/download/get_sources_wps_geog.html)²⁹. These data are shown in Fig. 1b, and dots represent the locations and numbers of meteorological stations in the study area. The UCM was invoked for the model grid incorporating urban and built-up land types.

Beijing is typical of cities experiencing rapid urbanization and population growth; hence, research results from the region will have relevance for other large cities in developing countries^{51–53}. Urban and built-up land is mainly distributed in six core districts of Beijing, where the degree of urbanization is much higher compared to that of the surrounding areas. Hence, we considered that these core districts were urban areas and the surrounding areas were classified as suburban.

Summer simulation

Figure 2 shows the mean 2 m relative humidity, specific humidity, and temperature for the summer simulation (1:00 UTC, August 5, 2020–24:00 UTC, August 6, 2020) over Beijing. According to observations, 13.7 mm of precipitation occurred during the simulation period. The 2 m relative humidity ranges from 65–70% in urban areas, 70–75% in the southern suburbs, and 70–80% in the western suburbs, indicating that relative humidity is generally lower in urban areas by approximately 5–10%.

Fig. 1 Study area and land use distribution. **a** Study area and nested domains of the WRF simulation area; **b** land use distribution and location of meteorological stations.

Fig. 2 Beijing experiences a dry island effect during summer. Average summer simulation results (48 h average values) for **(a)** 2 m relative humidity (%), **(b)** 2 m air specific humidity (g kg^{-1}), and **(c)** 2 m air temperature ($^{\circ}\text{C}$).

Fig. 3 Beijing experiences a wet island effect during winter. Average winter simulation results (48 h average values) for (a) 2 m relative humidity (%), (b) 2 m air specific humidity (g kg^{-1}), and (c) 2 m air temperature ($^{\circ}\text{C}$).

Figure 2b shows that the specific humidity is approximately 16 g kg^{-1} in urban areas, which is generally higher compared to that of the northwest suburbs (14 g kg^{-1}). Specific humidity shows a decreasing trend from the southeast (cities) to the northwest (suburbs). Following urbanization, the underlying surface is generally impervious, allowing only a small amount of rainwater to be absorbed by the underlying surface. Instead the majority of rainwater is discharged through urban sewer pipes. Furthermore, vegetation coverage is generally smaller, consequently, transpiration is lower in urban areas compared to that of the suburbs. Therefore, the natural water content of the urban underlying surface should be lower than that in the suburbs. Urban water dissipation consists of natural water dissipation and artificial water dissipation. When evaporation due to artificial water is considered, the overall urban evapotranspiration is higher than the suburban evapotranspiration during summer, indicating that the artificial water content of cities is higher compared to that of the suburbs. The water vapor content of urban areas is affected by both precipitation and artificial water dissipation. During the simulation period, precipitation was low and evapotranspiration due to artificial water was dominant. Artificial water dissipation is larger in the plain areas, and lower in mountainous areas, leading to less water supply. Therefore, urban specific humidity is higher than that in suburban areas. We compared the observed specific humidity from weather stations in urban and suburban areas during the summer simulation period and found that specific humidity in urban areas was 1.8 g kg^{-1} higher compared to the surrounding suburbs. Thus, observations show that the water content in urban areas is higher than the surrounding suburbs and our simulations are representing urban hydrological processes well. Artificial water dissipation plays an important role in the total amount of urban water vapor.

Figure 2c shows that the heat island effect is significant. Temperatures are above 28°C in urban areas, between 22 and 28°C in the surrounding suburbs and generally below 24°C in the mountainous areas to the west. Urban areas are mostly composed of buildings and hardened ground, which have a higher heat absorption rate and smaller specific heat capacity compared to the soil and vegetation in suburbs. Consequently, the temperature in urban areas is generally higher than that in the suburbs. Observations showed that the average temperature in urban areas was 2.0°C higher compared to suburban areas. Warmer air can hold more water than cooler air, therefore, the relative humidity of warmer air is lower for the same water content. Because both the specific humidity and temperature of urban areas are higher than those in the suburbs, differences in relative humidity between urban and suburban areas are smaller compared to specific humidity differences. Under the combined influence of these factors, relative humidity in urban areas is lower than that in the suburbs. Consequently, Beijing experiences a dry island effect

during summer in 2020, which indicates that the temperature plays a dominant role.

Winter simulation

Figure 3 shows the mean 2 m relative humidity, specific humidity, and temperature for the winter simulation (1:00 UTC, December 21, 2020–24:00 UTC, December 22, 2020). There was no snowfall during the simulation period. It is apparent that the spatial distribution of relative humidity is markedly different from that of the summer simulation, ranging from 45–50% in urban areas and 40–45% in the southwest and northeast suburbs (a difference of approximately 5%).

Figure 3b shows that the specific humidity is over 1.9 g kg^{-1} in urban areas, which is higher than that of the surrounding suburbs. Temperatures are low, and vegetation and precipitation are scarce in winter; consequently, artificial water dissipation has become the most important source of near-surface water vapor. Human activities, such as urban industries, burning fuels, and traffic exhausts, discharge water vapor into the atmosphere. This water vapor is mainly concentrated near the ground, increasing the near-surface specific humidity. Observations showed that the specific humidity in urban areas was 0.2 g kg^{-1} higher compared to the surrounding suburbs, indicating that the water content was higher in urban areas.

Figure 3c shows that temperatures in the urban area ($>0^{\circ}\text{C}$) are higher than those of the surrounding suburbs, indicating a significant heat island effect for the same reasons as described in section summer simulation. Observations showed that the average temperature in urban areas was 1.8°C higher than that in the suburbs. The heat island effect increases the saturated water content of urban air, resulting in decreased relative humidity. Based on air humidity and temperature, the relative humidity in urban areas is higher compared to that of some suburban areas during winter in 2020. Consequently, dry island effects are not obvious and urban areas tend to be wet islands, indicating that specific humidity is dominant.

Generally, seasonal differences between urban dry/wet islands in Beijing are influenced by differences in temperature and the underlying surface. The water vapor generated by artificial water dissipation is an important factor impacting urban dry/wet island effects.

Model validation

Figure 4 compares simulated and observed data at an urban and suburban station during winter and summer. The results of numerical simulation experiments without a UCM are added to quantify the improvements made by the AWDUCM. Compared to the marked diurnal variations in temperature and relative humidity, specific humidity remains relatively stable throughout the day. Simulation results reflect the variability of these

Fig. 4 Comparison with observations and simulations. Comparison of observed and simulated (AWDUCM and NON) 2m relative humidity, specific humidity, and temperature at Beijing station (a, e, and i) and Fangshan station (b, f, and j) during summer, and Beijing station (c, g, and k) and Fangshan station (d, h, and l) during winter.

Table 1. Root mean square error of simulated meteorological variables at urban and suburban weather stations.

Simulation	Relative humidity (%)	Specific humidity (g/kg)	Temperature (°C)
Summer			
NON	11.6	1.6	1.6
AWDUCM	9.2	1.3	1.4
Winter			
NON	17.0	0.5	1.8
AWDUCM	9.7	0.2	1.8

meteorological elements well, with low RMSE values (as shown in Table 1). By considering the water vapor due to artificial water dissipation, the simulation can reflect hourly variations in urban temperature and humidity well. Furthermore, it is apparent that the simulation accuracy of the model with the AWDUCM is higher than that of the model without a UCM.

According to the classifications of urban and suburban areas, we also compared urban dry/wet island effects using observed data. Because the altitude in the northwest mountainous region is higher compared to that of the plains area, the temperature is lower and the relative humidity is higher. Furthermore, a few suburban stations in the plains area are located on urban and built-up land. Therefore, we only considered stations located in the plain areas that were not on urban and built-up land as suburban stations and compared them with urban stations to analyze seasonal dry/wet island effects. The average relative humidity in urban areas was 79.2% (50.2%) in summer (winter), and 84.2% (49.7%) in suburban areas during summer (winter). Therefore, the observations reveal a tendency towards dry (wet) island effects during summer (winter). Dou et al.⁵⁴ analyzed data from observation stations in Beijing and concluded that humidity in urban areas during summer was lower compared to the surrounding suburbs (dry island). During winter, they found that the activities of the dense urban population emitted water vapor to the atmosphere, increasing the specific humidity in urban areas compared to the surrounding suburbs (wet island). Furthermore, Zhou et al. proposed that the seasonal difference in urban water dissipation intensity was obvious. They found that natural water dissipation (vegetation transpiration) was the main source of water vapor during summer and autumn, and artificial water dissipation was predominant during winter and spring. The results of our study are consistent with the existing research and provide further evidence to support the role of artificial water dissipation on dry/wet island effects.

DISCUSSION

Artificial water dissipation is the key factor affecting the transformation of urban dry/wet islands, which scientifically explains the reason for the seasonal transformation of urbanization effects. By considering artificial water dissipation, we reveal the mechanisms driving dry/wet island effects in urban areas, thereby helping to build a livable and comfortable environment and promote the sustainable development of the city.

Based on observations from Beijing Station for 2017–2020, 2 m temperature and specific humidity during August and December 2020 were compared to the conditions of the previous three years. Although some differences in temperature and humidity attributed to seasonal variability are apparent, the average temperature and humidity in August and December in 2020 are similar to those of the previous three years. Supplementary Fig. 1 provides a detailed description of the observed daily time series for August and December 2017–2020.

To draw more reliable conclusions, we incorporated longer simulation experiments. The summer (winter) simulation period was expanded to cover the entire month of August (December). We analyzed the monthly mean values of meteorological elements during the extended simulation period to reveal the distribution of dry/wet islands in Beijing. The daily dry/wet island simulation results for the extended summer and winter simulation periods are included in the Supplementary Figs. 2 and 3. We found that the results of the longer-term simulations were consistent with the simulation results described in the results section. Figure 5 shows that Beijing is prone to be a dry island in August and a wet island in December. Therefore, we conclude that the model can accurately simulate the dry/wet islands of Beijing during both summer and winter.

To quantitatively analyze the influence of artificial water dissipation on air humidity, we conducted control simulations during both the summer and winter periods using the default WRF UCM. These control simulations adopted the same parameter settings used in AWDUCM simulations. By comparing differences between the results of the experimental group (accounting for artificial water dissipation) and the control group (not accounting for artificial water dissipation), the influence of artificial water dissipation on urban air humidity can be measured.

Figure 6 shows the differences in the mean 2 m relative humidity, specific humidity, and temperature between the control and AWDUCM simulations during summer and winter. AWDUCM-UCM represents the difference between the experimental and control group. Simulations that considered artificial water dissipation had relative humidity increases of 2–6% in summer, inhibiting dry island effects to some extent (Fig. 6a). Furthermore, the 2 m specific humidity of urban and built-up land increased by approximately $0.5\text{--}1\text{ g kg}^{-1}$ when artificial water dissipation was considered (Fig. 6b). By incorporating artificial water dissipation in urban canopy physical processes, the AWDUCM promotes water vapor transport from the surface to the near-surface atmosphere. Figure 6c shows that artificial water dissipation reduced urban temperatures by approximately $0.2\text{ }^{\circ}\text{C}$. Although artificial water dissipation has increased the air humidity and reduced the temperature to some extent, Beijing still displays dry island effects during summer (Fig. 5a), illustrating the dominant role of the heat island effect during summer.

Figure 6d shows that considering artificial water dissipation increased the relative humidity by 12–18% compared to the control simulations during winter, and the inhibition of dry island effects is much greater than that during summer. Furthermore, artificial water dissipation increased the 2 m specific humidity by $0.2\text{--}0.6\text{ g kg}^{-1}$ (Fig. 6e) and temperatures by approximately $0.2\text{ }^{\circ}\text{C}$ (Fig. 6f) in urban areas, which may be attributed to the fact that the temperature of water vapor produced by artificial water dissipation was higher than the urban temperature in winter. Although the heat island effect is still extremely strong (Fig. 5f), the influence of urban artificial water dissipation is relatively large during winter; hence, the dry island effect is suppressed.

Numerical simulations were conducted during periods of high (low) temperature during summer (winter), and the meteorological conditions were fairly straightforward. In future studies, we will incorporate weather conditions such as haze, strong winds, and snow in our analysis to further explore effects and mechanisms of urban artificial water dissipation.

METHODS

Artificial water dissipation model description

Urban water dissipation incorporates natural evapotranspiration from the underlying surface (hardened ground, soil, vegetation, water surfaces, etc.) and artificial water dissipation, including artificial water from buildings, sprinkler evaporation on hardened ground, and irrigation water for soil and vegetation. Hence, artificial water dissipation and its related hydrological processes need to be considered to accurately simulate urban land surface

Fig. 5 Beijing experiences a dry island effect during summer and a wet island effect during winter. Average (a–c) summer (August average values) and (d–f) winter (December average values) simulation results for 2 m relative humidity (%) (a and d), 2 m air specific humidity (g/kg) (b and e) and 2 m air temperature (°C) (a and f).

Fig. 6 The impact of artificial water dissipation. Differences in mean 2 m relative humidity (a and d), specific humidity (b and e), and temperature (c and f) between simulations that did and did not consider artificial water dissipation during summer (a, b, and c) and winter (d, e, and f).

Table 2. Parameterization schemes and codes used by WRF to simulate different physical processes.

Physical process	Parameterization scheme	Scheme code
Microphysics	WSM 3-class simple ice scheme (WSM 3)	3
Cumulus	None	0
Longwave Radiation	Rapid radiative transfer model scheme (RRTM)	1
Shortwave Radiation	Dudhia scheme	1
Planetary Boundary layer	Yonsei University boundary layer scheme (YSU)	1
Land Surface	Noah land-surface model (Noah)	2
Urban Surface	Water Artificial Dissipation Urban Canopy Model (AWDUCM)	1 ^a

^aRemarks: AWDUCM was used to replace the traditional UCM in WRF.

processes. The urban artificial water dissipation calculation formulas and coupling process with the existing WRF UCM are described in the Supplementary Methods⁵⁵. Artificial water dissipation data comes from the urban water dissipation calculation model and a study on the seasonal characteristics of water dissipation, which provides the theoretical and empirical basis for the WRF simulation.

Definition of dry/wet islands

We use the difference in relative humidity between urban and suburban areas to characterize the intensity of the dry/wet island effect; values less (more) than zero indicate a dry (wet) island. Relative humidity represents the ratio of water vapor mass contained in humid air to water vapor mass contained in saturated air at the same temperature and pressure, which reflects the degree to which unsaturated humid air approaches saturated humid air. Simulations of 2 m air specific humidity and temperature were also evaluated. Specific humidity refers to the ratio of water vapor mass to total air mass (sum of water vapor mass and dry air mass) in humid air, which is an index for recording water vapor content.

WRF-AWDUCM modeling framework

WRF V4.0 was used to conduct numerical simulations with three-layer nesting to obtain high-resolution data (Fig. 1a). The outer, middle, and inner domains had horizontal resolutions of 9, 3, and 1 km, respectively, with 160×160 , 184×184 , and 202×202 grid points, respectively. The center point coordinate of the simulation area was 40.25°N , 116.45°E . The model used a terrain-following mass coordinate with 34 layers in the vertical direction, and the model top was at 150 hPa.

To ensure that the summer simulation period was representative, a period with short duration precipitation (<15 mm) was selected. August 4 and December 20, 2020, were used as the spin-up period for the summer and winter simulations, respectively, and the following two days (1:00 UTC, August 5, 2020—24:00 UTC, August 6, 2020, and 1:00 UTC, December 21, 2020—24:00 UTC, December 22, 2020) were used for analysis. NCEP FNL Operational Model Global Tropospheric Analyses (<https://rda.ucar.edu/datasets/ds083.2/>), with a horizontal resolution of $1^\circ \times 1^\circ$ and a six hourly temporal resolution, was used for the initial and boundary conditions. The model time step was 54 s (six times domain 1), and the output interval was one hour. Meteorological observation data from the hourly datasets of China surface climate data in “The China Meteorological Data Service Center” (URL: <http://data.cma.cn/data/detail/dataCode/A.0012.0001.html>) were used to verify the model data.

The parameterization schemes used in the simulation were based on the results of sensitivity experiments^{56,57} and are listed in Table 2. All three domains used the same parameterizations. The Noah land surface process model was used to couple AWDUCM and WRF to account for the heterogeneity of the urban underlying surface materials and artificial water dissipation. The AWDUCM divides the underlying surface into buildings, hardened ground, soil, vegetation, and water surfaces. Based on these classifications, the water vapor flux was averaged according to the area ratio of the different underlying surfaces, and the overall water vapor flux of the underlying surface was obtained. Convective (cumulus)

parameterization was not used in the model because all domains had a sufficiently high resolution (<10 km) to resolve convection explicitly. Considering the stability of the urban canopy model and its coupling with WRF, we used the single-layer urban canopy model in this study.

Model verification

To evaluate the influence of the AWDUCM on simulation accuracy, three experiments were conducted (from 0:00 UTC, July 23, 2020 to 00:00 UTC, July 25, 2020) before the model was applied. The NON experiment did not use an urban canopy model, the UCM experiment adopted the traditional urban canopy model, and the AWDUCM experiment used the urban canopy model that considered artificial water dissipation. By comparing the results of the three experiments with observations, we determined the impact of the AWDUCM on simulation accuracy.

We compared simulated and observed latent heat flux, 2 m temperature, and 2 m specific humidity. The average urban latent heat flux of NON, UCM, and AWDUCM was $0\text{--}20$, $20\text{--}40$, and $60\text{--}80$ W m^{-2} , respectively, compared to an observed average summer latent heat flux at Beijing station of 62.4 W m^{-2} , indicating that the AWDUCM experiment could simulate latent heat flux more accurately compared to the other simulations. The root mean squared error (RMSE) of air temperature for NON, UCM, and AWDUCM was 1.7, 1.4, and 1.2°C , respectively, and the RMSE of the specific humidity was 2.6, 2.3, and 1.6 g kg^{-1} , respectively. The simulation accuracy of each meteorological element was improved by using AWDUCM.

Observed relative humidity, absolute humidity, and temperature from Beijing (54511; urban) and Fangshan (54596; suburban) stations were used to compare the results from urban and suburban areas. Air pressure sensors at the urban and suburban stations were at heights of 1.2 and 1 m, respectively, therefore, their observations were comparable to the 2 m simulation results. Because WRF does not natively output relative humidity at 2 m, we used 2 m specific humidity and temperature, to calculate 2 m relative humidity as follows:

$$E = 6.112 \times e^{\frac{17.67 \times T}{T + 243.4}} \quad (1)$$

$$q = \frac{RH \times E \times 0.622}{P - RH \times E \times 0.378} \quad (2)$$

where T is air temperature ($^\circ\text{C}$), P is air pressure (hPa), q is specific humidity (g kg^{-1}), and RH is relative humidity (%). The above-mentioned simulation of regional relative humidity has also been modified in this way.

DATA AVAILABILITY

Data are available from NCEP FNL Operational Model Global Tropospheric Analyses (<https://rda.ucar.edu/datasets/ds083.2/>) and “The China Meteorological Data Service Center” (URL: <http://data.cma.cn/data/detail/dataCode/A.0012.0001.html>). The data on social water dissipation (artificial water dissipation) were from indoor and outdoor monitoring experiments and the water dissipation calculation model proposed by Zhou et al.^{14,45}. The area data statistics of different land use types in urban and built-up land are from the Ministry of Housing and Urban-Rural Development of the People’s Republic of China (<http://www.mohurd.gov.cn/>). Details on the social water dissipation calculation model are provided in the supplementary methods.

CODE AVAILABILITY

Code are available on request from the corresponding author.

Received: 23 April 2021; Accepted: 29 October 2021;

Published online: 30 November 2021

REFERENCES

- Hao, L. et al. Ecohdrological processes explain urban dry island effects in a wet region, southern China. *Water Resour. Res.* **54**, 6757–6771 (2018).
- Yan, L., Ting, Z., Aiqing, K., Jianzhu, L. & Xiaohui, L. Research on runoff simulations using deep-learning methods. *Sustainability* **13**, 1336 (2021).
- Seleiman, M. F., Santanen, A. & Mäkelä, P. S. A. Recycling sludge on cropland as fertilizer – advantages and risks. *Resour. Conserv. Recy.* **155**, 104647 (2020).
- Yonghua, Z., Pingping, L., Sheng, Z. & Biao, S. Spatiotemporal analysis of hydrological variations and their impacts on vegetation in semiarid areas from multiple satellite data. *Remote Sens.* **12**, 4177 (2020).

5. Luo, P. et al. Water quality trend assessment in Jakarta: a rapidly growing Asian megacity. *PLoS One* **14**, e0219009 (2019).
6. Lyu, J. et al. A quantitative assessment of hydrological responses to climate change and human activities at spatiotemporal within a typical catchment on the Loess Plateau, China. *Quat. Int.* **527**, 1–11 (2019).
7. Yang, J. & Wang, Z.-H. Physical parameterization and sensitivity of urban hydrological models: application to green roof systems. *Build. Environ.* **75**, 250–263 (2014).
8. Zhou, X. & Chen, H. Impact of urbanization-related land use land cover changes and urban morphology changes on the urban heat island phenomenon. *Sci. Total Environ.* **635**, 1467–1476 (2018).
9. Mooney, H. A., Duraipapp, A. & Larigauderie, A. Evolution of natural and social science interactions in global change research programs. *P. Natl Acad. Sci. Usa.* **110**, 3665–3672 (2013).
10. Sterling, S. M., Ducharme, A. & Polcher, J. The impact of global land-cover change on the terrestrial water cycle. *Nat. Clim. Change* **3**, 385–390 (2013).
11. Foley, J. A. et al. Global consequences of land use. *Science* **309**, 570–574 (2005).
12. Liu, W., You, H. & Dou, J. Urban-rural humidity and temperature differences in the Beijing area. *Theor. Appl. Climatol.* **96**, 201–207 (2009).
13. Varentsov, M., Wouters, H., Platonov, V. & Konstantinov, P. Megacity-Induced mesoclimatic effects in the lower atmosphere: A modeling study for multiple summers over Moscow, Russia. *Atmosphere* **9**, 50 (2018).
14. Zhou, J. et al. Simulation model for urban water dissipation (in Chinese). *Adv. Water Sci.* **28**, 276–284 (2017).
15. Kuang, W. Seasonal variation in air temperature and relative humidity on building areas and in green spaces in Beijing, China. *Chin. Geogr. Sci.* **30**, 75–88 (2020).
16. Aidi, H. et al. Hydrological analysis of loess plateau highland control schemes in Dongzhi Plateau. *Front. Earth Sci.* **8**, 528632 (2020).
17. JinWei, D., WenHui, K. & JiYuan, L. Continuous land cover change monitoring in the remote sensing big data era. *Sci. China Earth Sci.* **60**, 2223–2224 (2017).
18. Kuang, W. et al. What are hot and what are not in an urban landscape: quantifying and explaining the land surface temperature pattern in Beijing, China. *Landsc. Ecol.* **30**, 357–373 (2015).
19. Hao, L. et al. Urbanization dramatically altered the water balances of a paddy field-dominated basin in southern China. *Hydrol. Earth Syst. Sc.* **19**, 3319–3331 (2015).
20. Zhang, Y. et al. Control and remediation methods for eutrophic lakes in the past 30 years. *Water Sci. Technol.* **81**, 1099–1113 (2020).
21. Greve, P. et al. Global assessment of trends in wetting and drying over land. *Nat. Geosci.* **7**, 848 (2014).
22. Aidi, H. et al. Influence of landfill and land use scenario on runoff, evapotranspiration, and sediment yield over the Chinese Loess Plateau. *Ecol. Indic.* **121**, 107208 (2021).
23. Ackerman, B. Climatology of Chicago area urban–rural differences in humidity. *J. Appl. Meteorol.* **26**, 427–432 (1987).
24. Luo, Z. et al. Spatiotemporal characteristics of urban dry/wet islands in China following rapid urbanization. *J. Hydrol.* **601**, 126618 (2021).
25. R., A. P. et al. Land use/land cover changes and climate: modeling analysis and observational evidence. *Wires Clim. Change* **2**, 828–850 (2011).
26. Eugenia, K. & Ming, C. Impact of urbanization and land-use change on climate. *Nature* **423**, 528–531 (2003).
27. Liu, Y. et al. Evapotranspiration and water yield over Chinas landmass from 2000 to 2010. *Hydrol. Earth Syst. Sci.* **17**, 4957–4980 (2013).
28. Vose, J. M. et al. Forest ecohydrological research in the 21st century: what are the critical needs? *Ecohydrology* **4**, 146–158 (2011).
29. Zhao, L., Lee, X., Smith, R. B. & Oleson, K. Strong contributions of local background climate to urban heat islands. *Nature* **511**, 216–219 (2014).
30. Solecki, W. D. et al. Mitigation of the heat island effect in urban New Jersey. *Environ. Hazards* **6**, 39–49 (2005).
31. Tan, C. L., Wong, N. H., Tan, P. Y., Jusuf, S. K. & Chiam, Z. Q. Impact of plant evapotranspiration rate and shrub albedo on temperature reduction in the tropical outdoor environment. *Build. Environ.* **94**, 206–217 (2015).
32. Kong, F. et al. Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation. *Agr. For. Meteorol.* **217**, 22–34 (2016).
33. Wang, X. & Gong, Y. The impact of an urban dry island on the summer heat wave and sultry weather in Beijing city. *Chin. Sci. Bull.* **55**, 1657–1661 (2010).
34. Kusaka, H., Kondo, H., Kikigawa, Y. & Kimura, F. A simple single-layer urban canopy model for atmospheric models: comparison with multi-layer and slab models. *Bound-Layer. Meteorol.* **101**, 329–358 (2001).
35. Kusaka, H. & Kimura, F. Thermal effects of urban canyon structure on the nocturnal heat island: numerical experiment using a mesoscale model coupled with an urban canopy model. *J. Appl. Meteorol.* **43**, 1899–1910 (2004).
36. Wang, Z. H., Bou-Zeid, E. & Smith, J. A. A coupled energy transport and hydrological model for urban canopies evaluated using a wireless sensor network. *Q. J. R. Meteorol. Soc.* **139**, 1643–1657 (2013).
37. Ryu, Y.-H., Bou-Zeid, E., Wang, Z.-H. & Smith, J. A. Realistic representation of trees in an urban canopy model. *Bound. -Layer. Meteorol.* **159**, 193–220 (2016).
38. Ryo, M., Keiko, W. & Kazuyuki, M. Urban dry island phenomenon and its impact on cloud base level. *J. Jsc.* **1**, 521–529 (2013).
39. Yang, Z., Dominguez, F., Gupta, H., Zeng, X. & Norman, L. Urban effects on regional climate: A case study in the Phoenix and Tucson “Sun Corridor”. *Earth Interact.* **20**, 151027111902006 (2016).
40. Liu, J. et al. Review on Urban Hydrology (in Chinese). *Chin. Sci. Bull.* **59**, 3581–3590 (2014).
41. Fall, S., Diffenbaugh, N. S., Niyogi, D., R., A. P. & Rochon, G. Temperature and equivalent temperature over the United States (1979–2005). *Int. J. Climatol.* **30**, 2045–2054 (2010).
42. Fan, Z. & Thomas, A. Decadal changes of reference crop evapotranspiration attribution: Spatial and temporal variability over China 1960–2011. *J. Hydrol.* **560**, 461–470 (2018).
43. Lawrence, P. J. & Chase, T. N. Investigating the climate impacts of global land cover change in the community climate system model. *Int. J. Climatol.* **30**, 2066–2087 (2010).
44. Sun, G. et al. Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. *J. Geophys. Res-Bioge.* **116**, G00J05 (2011).
45. Zhou, J. et al. Dissipation of water in urban area, mechanism and modelling with the consideration of anthropogenic impacts: A case study in Xiamen. *J. Hydrol.* **570**, 356–365 (2019).
46. Zhou, J., Wang, H., Liu, J., Wang, Z. & Zhang, Y. “Nature-Social” dual attribute and seasonal characteristics of urban water dissipation: A case study of Beijing (in Chinese). *J. Hydraul. Eng. -Asce.* **51**, 1325–1334 (2020).
47. Zhou, J., Liu, J., Wang, H., Wang, Z. & Mei, C. Water dissipation mechanism of residential and office buildings in urban areas. *Sci. China-Technol. Sci.* **61**, 1072–1080 (2018).
48. Zhou, J., Liu, J., Wang, H. & Wang, Z. Simulation of water dissipation in urban buildings. *Proc. Inst. Civil. Eng. -Water Manag.* **172**, 312–322 (2019).
49. Sun, T., Bou-Zeid, E., Wang, Z.-H., Zerba, E. & Ni, G.-H. Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport. *Build. Environ.* **60**, 211–224 (2013).
50. Luo, Z. et al. The influence of ecological restoration projects on groundwater in Yongding River Basin in Beijing, China. *Water Sci. Technol. -Water Supply* **19**, 2391–2399 (2019).
51. Luo, P. et al. Flood inundation assessment for the Hanoi Central Area, Vietnam under historical and extreme rainfall conditions. *Sci. Rep.* **8**, 12623 (2018).
52. Dengrui, M. et al. Impact of temporal rainfall patterns on flash floods in Hue City, Vietnam. *J. Flood Risk Manag.* **14**, e12668 (2020).
53. Shasha, X. et al. The relationship between coordination degree of the water–energy–food system and regional economic development. *Sustainability* **13**, 1305 (2021).
54. Dou, J., Wang, Y. & Miao, S. Fine spatial and temporal characteristics of humidity and wind in Beijing urban area (in Chinese). *J. Appl. Meteorol.* **25**, 559–569 (2014).
55. Zhou, J. et al. Mechanisms and empirical modeling of evaporation from hardened surfaces in urban areas. *Int. J. Environ. Res. Public Health* **18**, 1790 (2021).
56. Chen, G., Zhao, L., Mochida, A., Cartalis, C. & Santamouris, M. Urban heat island simulations in Guangzhou, China, using the coupled WRF/UCM model with a land use map extracted from remote sensing data. *Sustainability* **8**, 628 (2016).
57. Wang, J., Huang, B., Fu, D., Atkinson, P. M. & Zhang, X. Response of urban heat island to future urbanexpansion over the Beijing-Tianjin-Hebei metropolitan area). *Appl. Geogr.* **70**, 26–36 (2016).

ACKNOWLEDGEMENTS

This study was supported by the Chinese National Natural Science Foundation (No. 51739011), the National Key Research and Development Program of China (2018YFC1508203), the Research Fund of the State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin (SKL2020ZY03), and the Natural Science Basic Research Program of Shannxi Province (2019JLZ-15).

AUTHOR CONTRIBUTIONS

Conceptualization, Z.L. and J.L.; methodology, Z.L., J.L. and Y.Z.; software, Z.L. and Y.Y.; validation, J.Z. and W.S.; formal analysis, Z.L., J.L. and Y.Z.; investigation, Z.L. and R.J.; resources, J.L.; data curation, Z.L. and J.Z.; writing—original draft preparation, Z.L.; writing—review and editing, J.L., Y.Z. and J.Z.; visualization, Z.L. and J.Z.; supervision, Y.Z. and W.S.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41612-021-00216-4>.

Correspondence and requests for materials should be addressed to Jiahong Liu.

Reprints and permission information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2021