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Optimal water use strategies for mitigating high urban temperatures

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Abstract. Urban irrigation and road sprinkling are methods for mitigating high urban temperatures which are expected to enhance evapotranspiration and affect the urban weather, climate, and environment, and the optimization of limited water supplies is necessary in regions with water shortages. In this study, we implemented urban water usage schemes such as urban irrigation and road sprinkling in the Weather Research and Forecasting (WRF) model, and assessed their effects with different amounts of water in city centers, suburbs, and rural areas by using the WRF model at a resolution of 1-km Beijing, China. In addition, we developed an optimization scheme with a cooling effect as the optimal objective and the total water supply as the constraint condition. Nonlinear relationships were identified between the cooling effect and water consumption for both road sprinkling and urban irrigation, and the cooling effect due to urban irrigation was more effective than that attributed to road sprinkling. Based on the optimal water management scheme and according to the Beijing's 13th Five Year Plan, about 90% of the total water supply should be used for urban irrigation and 10% for road sprinkling as the most effective approach for decreasing urban temperatures by about 1.9°C.

1 Introduction

Throughout the world, the level of urbanization increased from 39% to 55% in the last four decades (Chen et al., 2014). Vast numbers of people have moved from rural to urban areas across the world, thereby increasing greenhouse gas emissions, anthropogenic heat release, and energy consumption in urban areas, as well as causing land use and land cover changes that increase the likelihood of urban high temperature events (McCarthy et al., 2010). The frequency of high temperature events in the first decade of the 21st Century was much higher compared with that in the last 10 years of the 20th Century (WMO, 2013). According to a previous report, the temperature reached a maximum of 42.1°C in Beijing, China on August 3, 2018. In addition, increased temperatures can substantially increase the rate of temperature-related illnesses (Zhang et al., 2014). Applying water can cool urban areas directly by increasing transpiration from vegetation and evaporation from the soil (Coutts et al., 2013). Beijing is a region that lacks adequate water resources and optimal water use strategies can help to

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improve water cooling efficiency. Thus, understanding and quantifying the relationships between the amounts of water applied and the cooling effect are critical for designing and planning better cities.

Urban irrigation includes ecological irrigation in city centers and farmland irrigation in suburban and rural areas. Many previous studies focused on the impacts of urban irrigation on hydrometeorological variables at different scales (Kueppers et al., 2007;Vahmani and Hogue, 2014). Clearly, irrigation is a critical component of the regional water cycle because it enhances evapotranspiration due to the increased soil moisture contents and it contributes substantially to the latent heat flux in land–atmosphere interactions (Coutts et al., 2013;Pei et al., 2016). This so-called phenomenon "oasis effect" is common in arid and semiarid cities. The impacts of irrigation on precipitation depend on the atmospheric circulation, where increasing the soil moisture can increase rainfall (Pei et al., 2016;DeAngelis et al., 2010;Yang et al., 2017;Moore and Rojstaczer, 2001;Alter et al., 2015), whereas it may inhibit rainfall in other cases due to the evaporative cooling effect strengthening the atmospheric stability and weakening deep convection (Ek and Holtslag, 2004;Zeng et al., 2017). In addition, outdoor water use changes the partitioning of the available energy between the sensible and latent heat fluxes. A decrease in the sensible heat flux can reduce the urban air temperature by more than 3°C, which helps to reduce thermal stress in cities during the summer (Lobell et al., 2008;Kueppers et al., 2007;Puma and Cook, 2010;Mueller et al., 2016). However, the cooling effects of different irrigation distributions differ slightly. The reductions in the daily maximum air temperature due to irrigation are evident in all urban land use types, but well vegetated low-intensity residential areas such as suburbs and rural areas exhibit the largest effects (Gao and Santamouris, 2019). The optimal distribution of water supplies to mitigate urban high temperatures in the summer is a problem. Indeed, optimizing water usage is limited by the agricultural water demand, crop production, and water transactions (Amir and Fisher, 1999;Kuschel-Otarola et al., 2018;Feinerman et al., 1985). However, a effective method is not available for determining the distribution of the water supply to achieve the optimal cooling effect while also meeting the minimal requirements for plants.

Sprinkling water on the road can keep roads clean and control air pollution, and it is also an effective method for mitigating urban high temperatures and the urban heat island effect (Yamagata et al., 2008;Hendel et al., 2016;Hendel and Royon, 2015). However, the relationship between the amount of water applied by road sprinkling and the cooling effect in different urban areas has not been investigated. Moreover, urban irrigation and road sprinkling have different role in the water cycle process, where urban irrigation is related to plant and soil processes, whereas road sprinkling responds directly to the atmosphere. Thus, determining the different effects of these two water usage approaches is essential for developing water management strategies to mitigate urban high temperatures.

In this study, we determined the optimal method for distributing water by urban irrigation and road sprinkling in different part of city in order to mitigate urban high temperatures. We elucidated the relationship between the amount of water applied and the cooling effects of urban irrigation and road sprinkling based on simulations with the Weather Research and Forecasting (WRF) model. We then investigate whether the proposed method can be applied to other cities. We also collected water usage data for Beijing based on the water deficit coefficient, water supply, and land use cover in our case

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study, and modified the urban irrigation and road sprinkling schemes in the urban canopy and hydrology modules of the WRF model before conducting the simulations.

The remainder of this paper is organized as follows. In Section 2, we describe the materials and methods employed, including the optimal water management method, development of the model, data, and experiments conducted. In Section 3, we present our results and discussion, including the model validation process, relationships between the amount of water applied and the cooling effect, and the optimal water use strategies. We give our concluding remarks in Section 4.

2 Materials and Methods

2.1 Optimal water usage scheme

The problem of how to distribute the water supply to plants and road in different parts of a city in order to obtain the optimal cooling effect can be solved with an optimization scheme. In this study, we divided the city into three parts according to the population density and urban type as the city center, suburbs, and rural areas. If the relationships between the amount of water applied and the cooling effect are known for the three parts of city, then an optimal water usage scheme can be developed whose optimization objective can be stated as the comprehensive temperature decrease attributable to both road sprinkling and urban irrigation in the city center, suburbs, and rural areas. The optimal water usage scheme can be described as follows:

$$\text{Max: } \sum_{j=1}^{3}\sum_{i=1}^{2} f_{i,j}(w_{i,j}), \quad (1)$$

where i represents road sprinkling and urban irrigation as i equal to 1 or 2, respectively; j represents the city center, suburbs, and rural areas as j equal to 1, 2, and 3, respectively, and $f_{i,j}(w_{i,j})$ is a function of the normalized amount of water applied and the cooling effect, which can be fitted based on the model simulation results presented in Section 3.2.

Considering that the total amount of urban water supplied for road sprinkling and urban irrigation is a fixed value, the water demand for each part of city should be satisfy the minimal needs for the municipal services and plants in terms of ecology, farmland, and roads. Thus, the constraint conditions for optimizing the usage of water are as follows:

$$\text{s.t.} \quad \sum_{j=1}^{3}\sum_{i=1}^{2} w_{i,j} = A, \quad (2)$$

$$b_j \ll w_{1,j} \ll B_j, j = 1,2,3, \quad (3)$$

$$c_j \ll w_{2,j} \ll C_j, j = 1,2,3. \quad (4)$$

where A represents the total water supplied for road sprinkling and urban irrigation; j represents the city center, suburbs, and rural area as j equal to 1, 2, and 3, respectively; b_j represents the minimal water demand for road sprinkling, B_j represents the maximum water supply for road sprinkling, c_j represents the minimal water demand for urban irrigation, and C_j represents the maximum water supply for urban irrigation. In addition, other water restrictions applied in each part of the city can be expressed as another equality or inequality among this optimal water usage scheme.

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2.2. Model development

The WRF model is a limited area, nonhydrostatic, mesoscale modeling system with a terrain-following eta coordinate, which is coupled with land surface models and the Urban Canopy Model (UCM) to provide a better representation of the physical processes related to the exchange of heat, momentum, and water vapor in an urban environment. The land surface model nonmatter Noah-MP or Community Land model (CLM) describes the physical soil hydrological processes explicitly, including infiltration, storage, redistribution, drainage, and evaporation. The UCM is a single-layer model with a simplified urban geometry, where its features include shadowing from buildings, reflection of short and long-wave radiation, the wind profile in the canopy layer, and multi-layer heat transfer equations for roof, wall, and road surfaces (Tewari et al., 2007). The impervious roads lack soil hydrological processes but the evaporation of liquid water above the road still occurs which can change urban weather, climate and environment.

A simple urban water usage scheme including urban irrigation and road sprinkling was incorporated into the WRF model based on the scheme of Zeng et al. (2017). Here, ecological and farmland irrigation were both treated as urban irrigation and implemented the same in the model. The soil hydrological processes were changed and the water balance between the land surface and atmosphere was disturbed provided that the irrigation water was added to the first layer of the soil and it was regarded as the available liquid water in the model, where this process was conducted for farmland and urban land use types, also to keep water balance the added water from surface soil should be remove from the water table of ground. The road sprinkling scheme was activated in the night during the summer when water was applied to the impervious road layer to accelerate evaporation. The flow chart of urban water usage scheme including irrigation and road sprinkling in model can be seen in Figure 1, and he specific scheme is represented by Eqs (5)–(8). The advanced water usage scheme mentioned above was coupled into the WRF model. Water from urban irrigation with a specific spatial distribution was entered as an input for the model via a data interface with the WRF model. The program was initialized for the real three-dimensional case study and the amount of water applied for road sprinkling was no more than the maximum water-holding capacity of the urban impervious layer.

$$\mathrm{w}_{i,j,t} = \begin{cases} wi_{i,j,t} & ,pervious\ layer \\ a \times pondmax_{urban} & ,impervious\ layer \\ 0 & ,otherwise \end{cases} \tag{5}$$

$$\mathrm{W}_{i,j,t} = \mathrm{W}_{i,j,t-1} + \mathrm{w}_{i,j,t} \tag{6}$$

$$\mathrm{wo}_{i,j,t} = \begin{cases} wi_{i,j,t} & ,pervious\ layer \\ 0 & ,otherwise \end{cases} \tag{7}$$

$$\mathrm{zwt}_{i,j,t} = \mathrm{zwt}_{i,j,t-1} - \mathrm{wo}_{i,j,t} \tag{8}$$

where the subscript i, j, t represent the latitude, longitude and time; $wi_{i,j,t}$ represent the water amount of urban irrigation , a is a coefficient from 0 to 1, $pondmax_{urban}$ represent the maximum water-holding capacity of the urban impervious layer, $\mathrm{W}_{i,j,t}$ is the surface liquid water enter into the first layer soil or impervious layer, $\mathrm{W}_{i,j,t-1}$ is previous timestep of $\mathrm{W}_{i,j,t}$, $\mathrm{wo}_{i,j,t}$ represents the water amount that need to be removed from water table of the ground, $\mathrm{zwt}_{i,j,t}$ represents the water table of time t, and $\mathrm{zwt}_{i,j,t-1}$ represents the previous timestep of $\mathrm{zwt}_{i,j,t}$.

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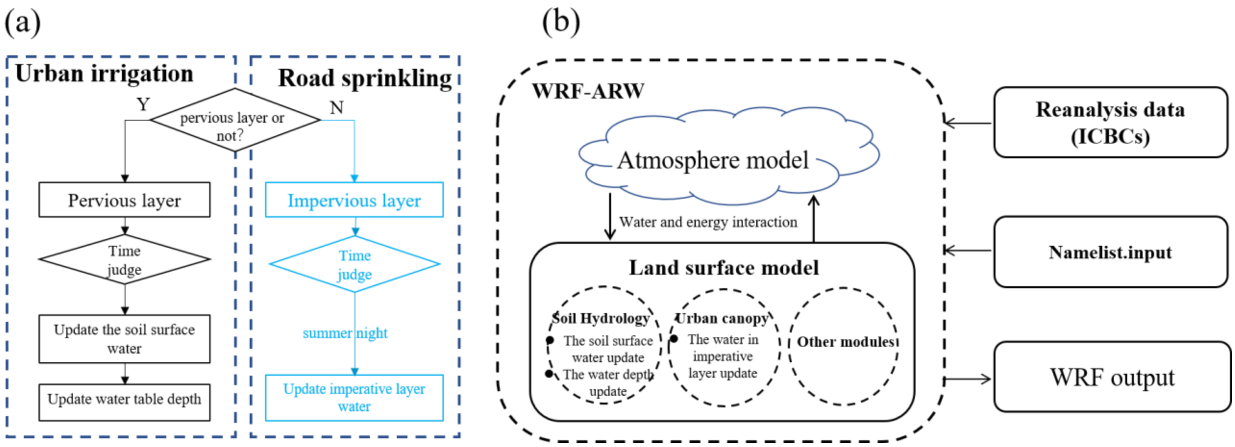

Figure 1. Water usage scheme and it's coupling with Weather Research and Forecasting (WRF) model. (a) Flow chart of water usage scheme including urban irrigation and road sprinkling, (b) schematic showing the Weather Research and Forecasting (WRF) model coupled with the water usage scheme.

2.3. Data and experiments

Air temperatures obtained from reanalysis data and in-situ data were used to validate WRF model output. in-situ data were obtained from 20 national meteorological stations in Beijing, and the regional reanalysis data came from the China Meteorological Administration Land Data Assimilation System (CLDAS) as hourly outputs with a resolution of 0.0625° × 0.0625°. more detail data descriptions can see Table 1. In addition, these data were also collected to verify the effectiveness of the WRF physical schemes.

Table 1. Data set descriptions

Site/Regional	Resource	Other details
Site	National meteorological stations	20 observation sites; hourly; 2001–2017
	Flux station	140 meters high in 39.9° N,116.38° E, July to August in 2012
Regional	CLDAS	0.0625° ×0.0625°; hourly; 2008–2014

CLDAS: China Meteorological Administration Land Data Assimilation System (Shi et al., 2011)

The gridded water usage data was derived from the total water consumption in Beijing and distributed according to the gridded population density, GDP and water deficit efficiency. The downscaling method employed was reported previously (Zeng et al., 2017). The spatial distribution of water usage amounts for the sum of irrigation and ecological water are shown in Figure 2. Farmland irrigation was mainly located in the south of Beijing and the ecological water consumption occurred mainly in the center of the city. A primeval forest with little human influence is located to the north of Beijing and the water consumption was low in this area. The urban plan for Beijing can be divided into urban, suburban and rural areas divided by the fifth and sixth ring roads. The area within the fifth ring road was treated as the urban area inhabited by the majority of the

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population. The population declined from the fifth to the sixth ring road in the so-called suburban transition area. The rural areas were located outside the sixth ring road, where they mainly comprised farmland with few building and factories.

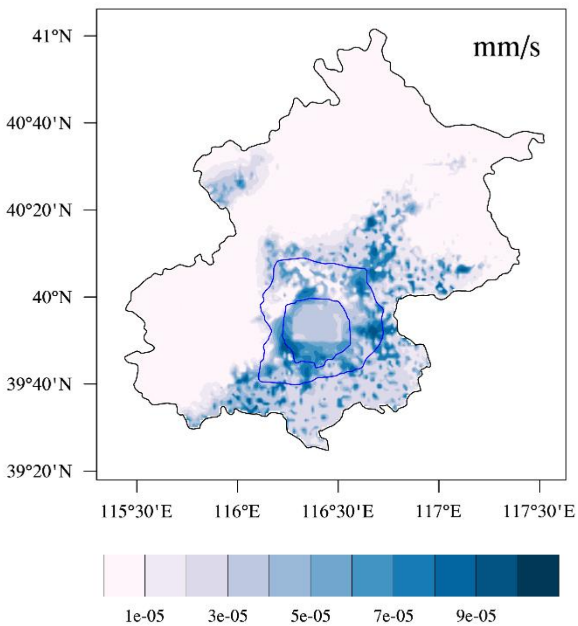

Figure 2. Estimated urban irrigation water use in Beijing.

We used the WRF model (Skamarock WC, 2008) with the Advanced Research WRF Dynamic Core version 3.9.1 coupled with a single-layer UCM in the experiments. Three experiments were conducted to consider no water usage, urban irrigation and road sprinkling. In the urban irrigation experiment, the gridded water usage data range from 0.1 to 1.9 times of the estimated urban irrigation in city center, suburbs and rural areas were regarded as new input variables and added to the model initial input files with the same spatial resolution as the model when WRF model was running. In the road sprinkling experiment, the water amount of road sprinkling was ranged from 0.2 to 1 times of the maximum water-holding capacity of impervious layer in three parts of city showing different urban sprinkling frequency and strength.

Three-layer nested domains with horizontal resolutions of 15 km (d01; mesh size 95 × 121, most of northern China), 5 km (d02; mesh size 135 × 185; almost all of the Jing-Jin-Ji metropolitan area), and 1 km (d03; mesh size 205 × 270; Beijing as the area of interest) were designed for the experiments (Figure 3). The National Centers for Environmental Prediction Global Final Analysis 6-h data (soil water, moisture, and temperature) were used for the first-guess initial field and lateral boundary conditions. The terrestrial and United States Geological Survey (USGS) land-use data provided in the WRF model described the real terrestrial and land-cover characteristics of the regions of interest, and the default static data were used in the experiments. A climate summer time periods from 2000 to 2017 were averaged to 4 days which represent the climatic May, June, July and August. And the first day was considered as the spin up period. The schemes in terms of the physical options are presented in Table 2.

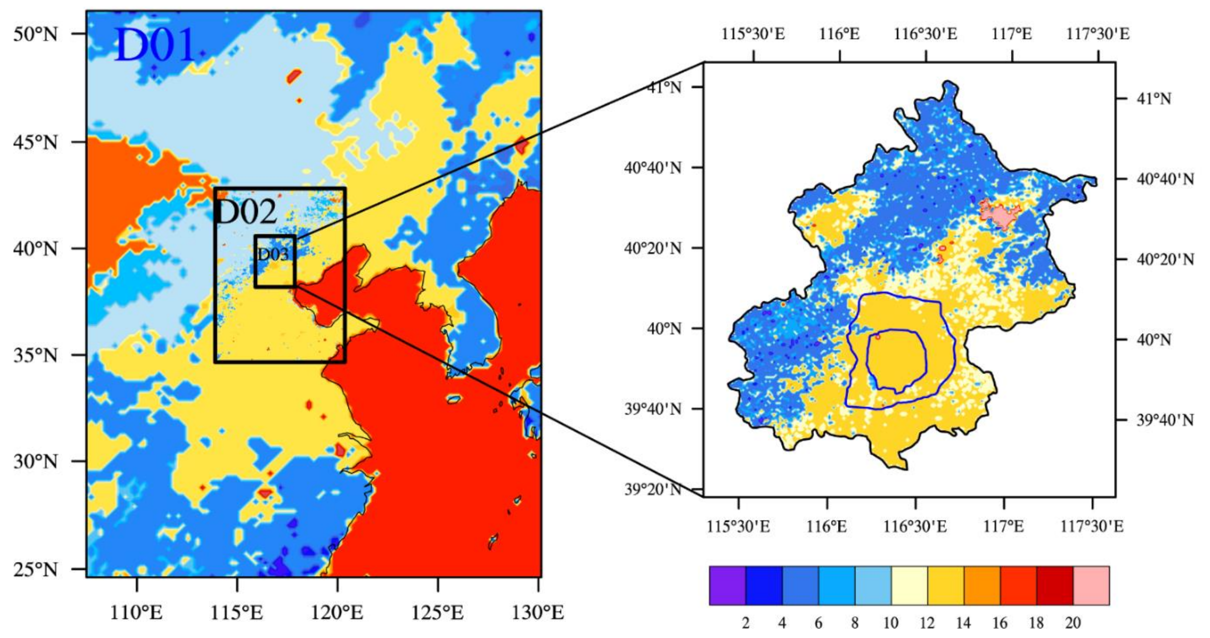

Figure 3. Simulated area and land use and land cover in Beijing.

Table 2. Physical parameterization schemes

Physical scheme	Selected scheme option
Microphysics	Kessler scheme
Longwave	RRTM scheme
Shortwave	MM5 shortwave scheme
Cumulus	Grell-Devenyi
Planetary boundary physics	ACM2 PBL scheme
Land surface model	CLM/NOAH-MP
Urban model	SLUCM

3 Results and Discussion

3.1 Model Validation

Considering that atmospheric stochastic processes may lead to the uncertainty of cooling effect, offline comparison experiments were conducted to illustrate the cooling effect of urban irrigation and road sprinkling. These experiments were raw simulation without urban water usage, urban irrigation and road sprinkling with community land model(CLM4.5). The simulations were driven by ITP atmosphere forcing data (June to August of year 2012) which was obtained from the Data Assimilation and Modeling Center for Tibetan Multi-spheres, Institute of Tibetan Plateau Research, Chinese Academy of Science(Yang et al., 2010a). The simulation results showed that urban irrigation decreased the water table depth due to

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groundwater extraction which is similar to the research of Yang et al. (2010b), and increased the surface soil moister (Figure 4). There was no change of water table depth and surface soil moister for road sprinkling because of lacking underground water process under the impervious layer. Evapotranspiration were strengthened when more water was irrigated to soil or farmland, and heat from ground and air were taken away. This phenomenon was quite similar for road sprinkling but has slightly different physical process. As a result, both two schemes decrease the sensible heat flux, ground temperature, air temperature and wind speed, and increased the latent heat flux (Figure 5). Besides, The impact to land surface variables are limited to the areas where water applied, because offline simulations had no climate effect between atmosphere and land surface. So, Cooling effect was quite obvious for urban irrigation and road sprinkling. And they were also confirmed by other researches (Wang et al., 2019;Hendel and Royon, 2015). Moreover, road sprinkling has been carried out in Beijing and Tokyo. In addition, the results of sensible heat flux(SH) and latent heat flux(LH) from urban water usage simulations (including both urban irrigation and road sprinkling) are better than the raw model results (Figure 6). Flux station observations were from July to August in year 2012 and the station simulation results are interpolated from a regional simulation results of year 2012. Comparing those two data, it showed that the correlation coefficient increased slightly, and root mean square error for SH and LH were decrease 4.69 and 6.94w/m^2. And the absolute error for SH and LH decreased 7.3 and 9.62 w/m^2 respectively. This means that urban water usage including both urban irrigation and road sprinkling should be taken into consideration when conducting weather and climate simulations.

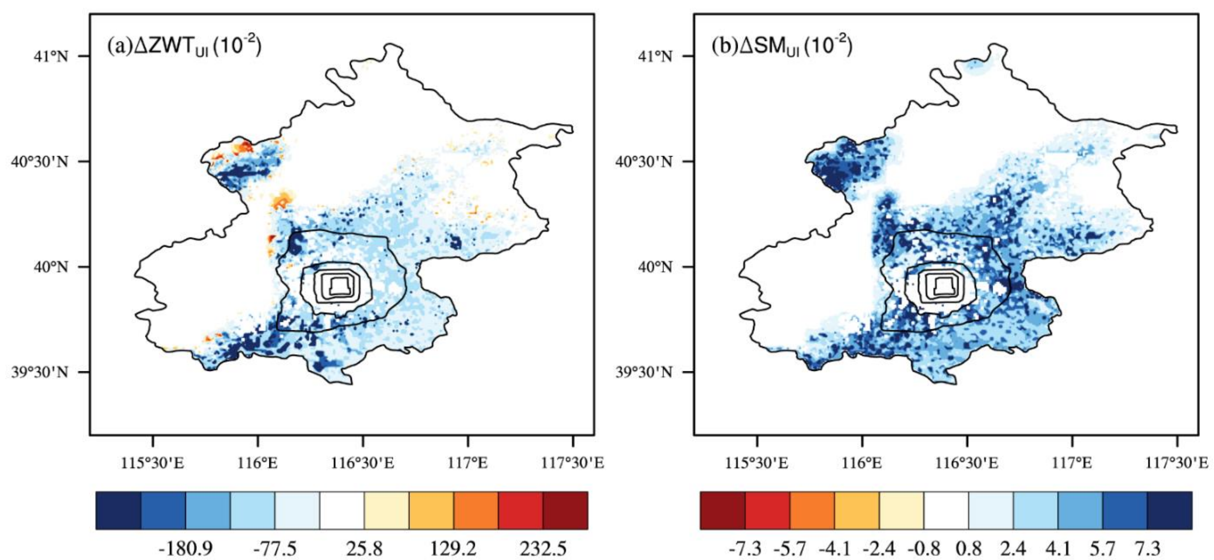

Figure 4. **Changes of (a) water table depth and (b)surface soil moister due to urban irrigation(UI) (unit:10-2)**

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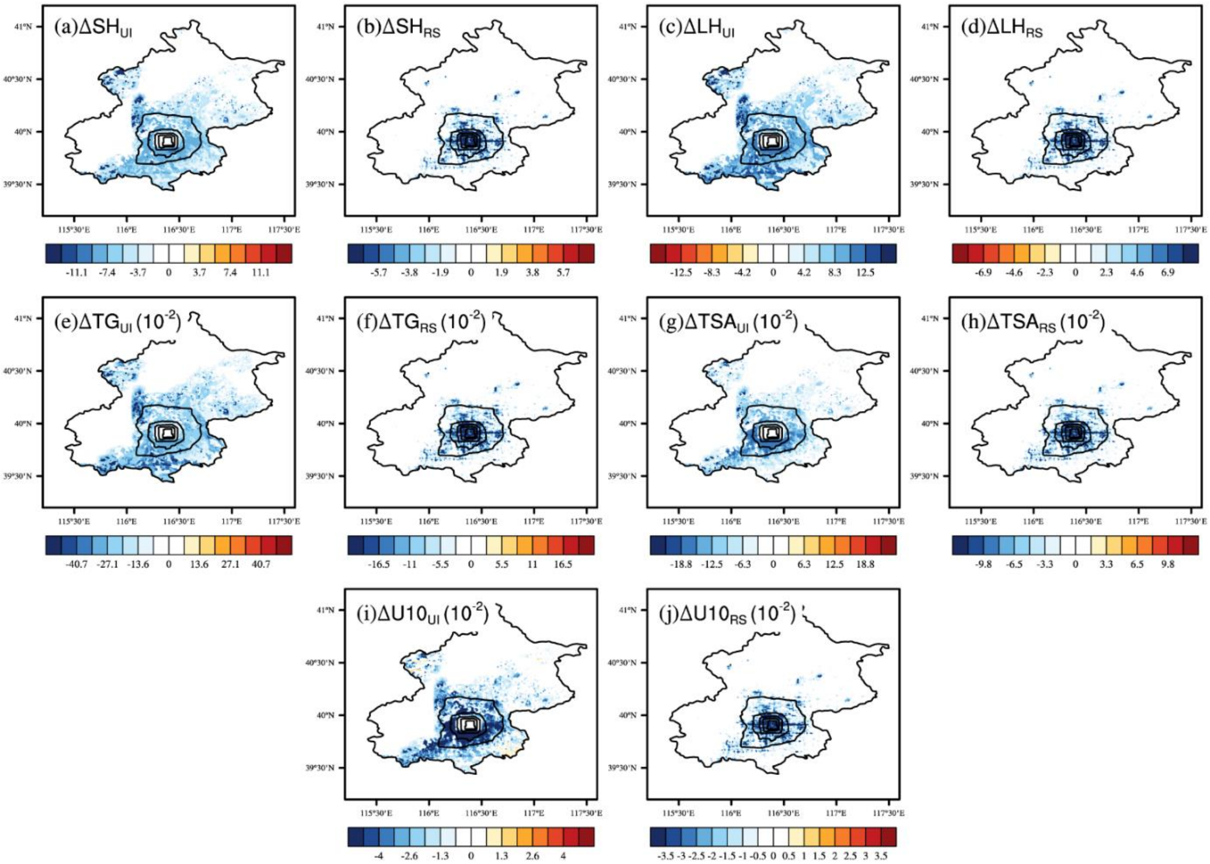

200 **Figure 5. Changes of land surface variables due to urban irrigation(UI) and road sprinkling(RS). (a) sensible heat flux of UI, (b) sensible heat flux of RS, (c) latent hear flux of UI, (d) latent heat flux of RS, (e) ground temperature of UI, (f)ground temperature of RS, (g)air temperature of UI, (h)air temperature of RS, (h)10 meter wind speed of UI, (j)10 meter wind speed of RS.**

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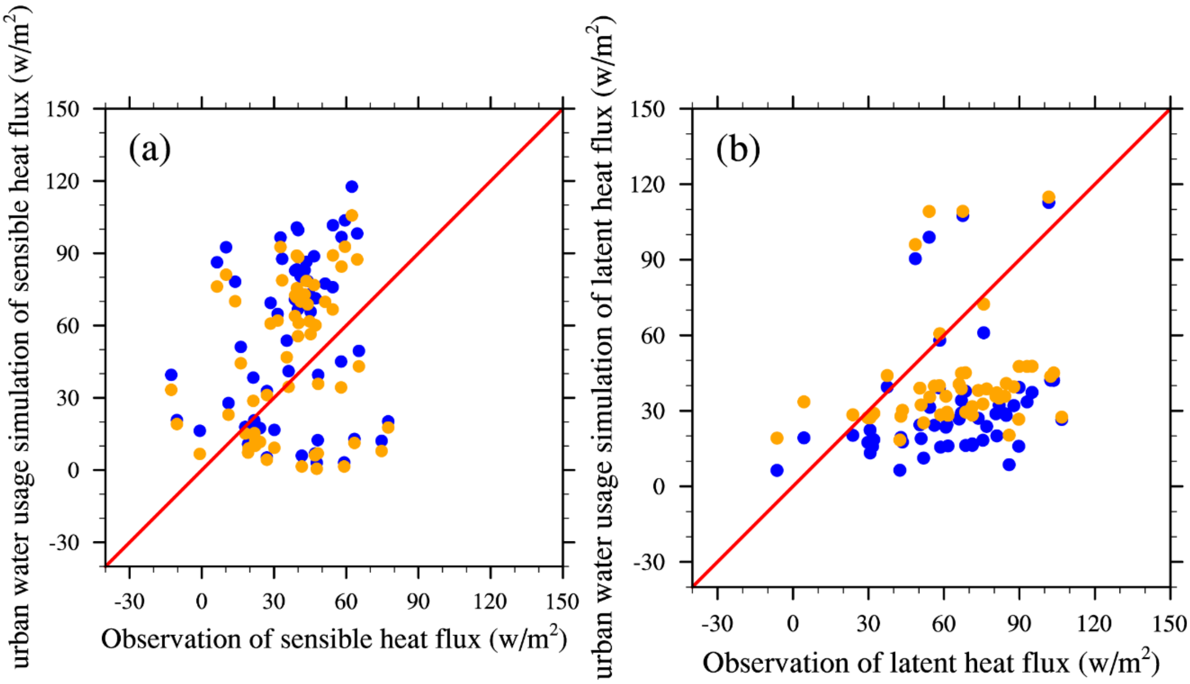

Figure 6. Sensible heat flux(a) and latent hear flux (b) comparisons between station observations and water usage simulations (including water irrigation and road sprinkling).The blue dots are raw simulation results and the orange dots are water usage simulation results.

In addition to the comparisons between station observations and offline model simulations, Comparisons between 7-year summer average temperatures in the CLDAS and WRF simulation has also been done to show the simulation ability of the raw WRF model , the temperatures were higher in the city center than the suburbs. The similar spatial distributions showed that the WRF physical scheme was reasonable. The correlation coefficients between the CLDAS temperatures and WRF simulation results were generally close to one, and the average root mean square error (RMSE) for the two data sets was 0.8°C. The gridded model results were interpolated to the sites according to the coordinates of the stations in urban and suburban areas, and comparisons of the site observations and WRF simulation results also showed that the temperature simulation results were in good agreement with the observations (see in Figure 7). It showed that the WRF model simulation results were reasonable, where the simulated temperatures were slightly higher than the observations and RMSE was mostly less than 2.5°C. So WRF model can be a good tool to start out research.

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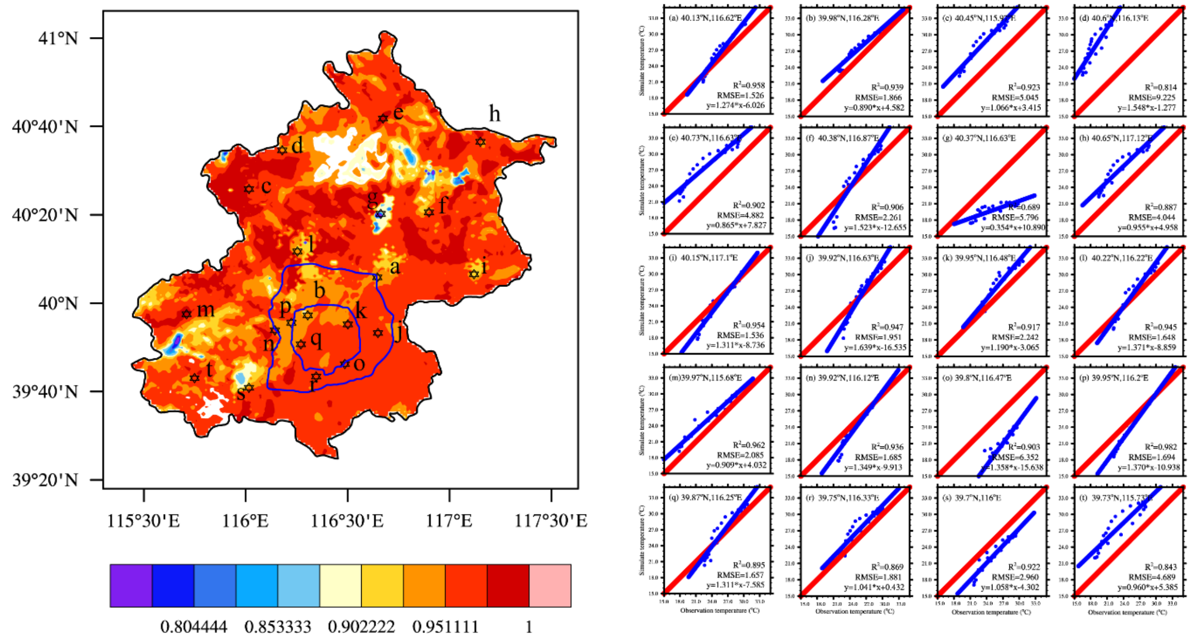

Figure 7. Temperature validation between simulations and reanalysis or in-situ data. Left figure is spatial distribution of correlation coefficients between simulations and CLDAS reanalysis data, right figure form (a)-(t) are regression line, RMSE and coefficient coefficients between simulations and in-situ data.

3.2 Relationships between the amounts of water applied and the cooling effect

Figure 8 shows that road sprinkling and urban irrigation both decreased air temperature. Road sprinkling was mainly conducted at night to avoid disturbing traffic. The simulation results in Figure 8 show that the temperature decreased by a maximum of around 0.5–1°C in the city center where most roads were found, whereas there were no significant decreases in the temperature in rural areas where the lowest amount of road sprinkling occurred due to the low quantity of road surfaces in these areas. However, urban irrigation during the daytime decreased the temperatures in the day and night. Figure 9 shows that urban irrigation in the city center decreased the temperature by more than 1°C when large volumes of water were applied. In the rural areas, the water applied for farmland irrigation had a reasonable cooling effect in the daytime, and the cooling effect continued but smaller in the nighttime due to the evaporation from farmland crops and urban plants after irrigating in the daytime. This effect was much more significant in the rural areas than the city center and suburbs. In addition, localized water usage could influence all of the areas, where road sprinkling or urban irrigation in the city center could decrease the temperatures in the suburbs or rural areas, and this effect may also occur in other locations. In general, the cooling effect of urban irrigation was stronger than that of road sprinkling because the amount of water applied for urban irrigation was greater than that for road sprinkling.

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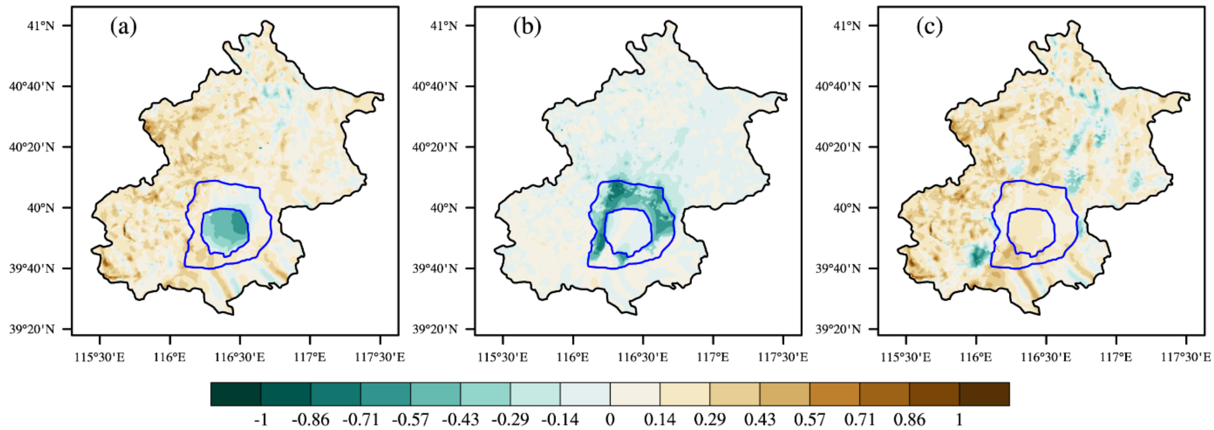

Figure 8. Cooling effects in the city center (a), suburbs (b), and rural areas (c) caused by road sprinkling in the night. Here, the water amount is half of the maximum water-holding capacity of the urban impervious layer.

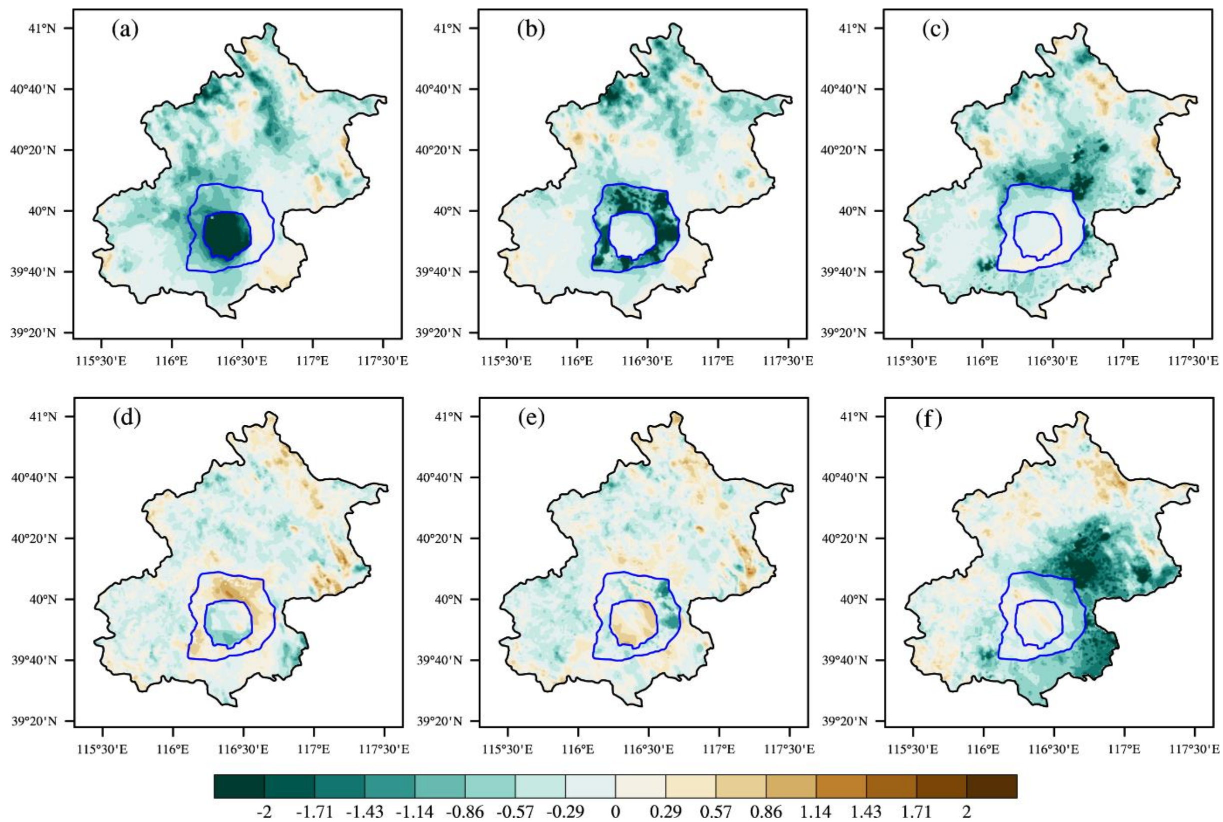

Figure 9. Cooling effects in the city center, suburbs, and rural areas caused by urban irrigation in the day and night. (a) cooling effect of urban irrigation in city center in the day (b) cooling effect of urban irrigation in suburbs in the day, (c) cooling effect of urban irrigation in rural areas in the day, (d) cooling effect of urban irrigation in city center in the night, (e) cooling effect of urban irrigation in the suburbs in the night, (f) cooling effect of urban irrigation in rural areas in the night. Here, the water amount is as the estimated urban irrigation.

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The application of water in urban areas could change the energy cycles and dynamic processes. Figure 10 shows that the changes in these variables were most significant in the areas where road sprinkling or urban irrigation were conducted and it may weak the atmospheric dynamic processes. The application of water by road sprinkling or urban irrigation increased the latent heat flux, decreased the sensible heat flux, and lowered the boundary layer heights locally. However, changes could be more general throughout the whole region. For example, urban irrigation in the city center not only lowered the boundary layer height in the city center, but also have impact in the suburbs and rural areas. Similar results were found for the latent heat flux and sensible heat flux, but they were not as significant.

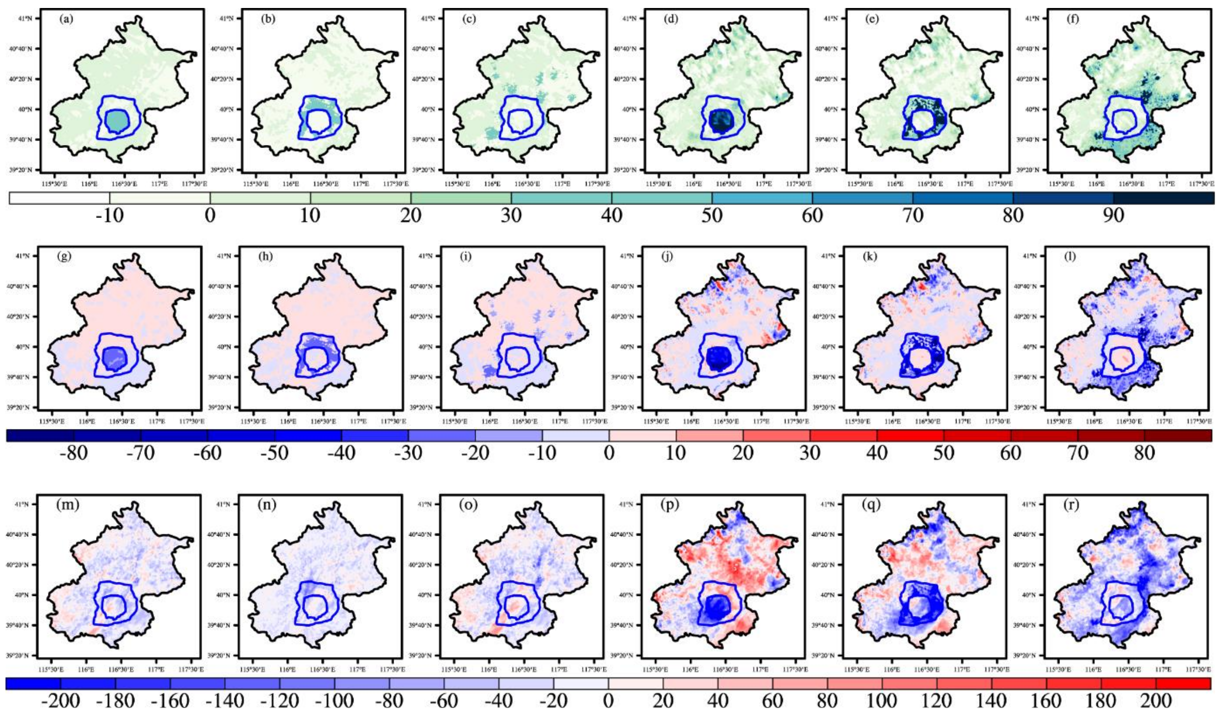

Figure 10. Changes in the latent heat flux, sensible heat flux, and boundary layer height due to road sprinkling and urban irrigation. (a) change in latent heat flux (LH) due to road sprinkling in the city center, (b) change in LH due to road sprinkling in the suburbs, (c) change in LH due to road sprinkling in rural areas, (d) change in LH due to urban irrigation in the city center, (e) change in the LH due to urban irrigation in suburbs, (f) change in LH due to urban irrigation in rural areas, (g)-(l) change in sensible heat flux, similar to (a)-(f), (m)-(r) change in the boundary layer height, similar to (a)-(f).

The quadratic functions fitted to the relationships between the amounts of water applied and the cooling effects in the simulations are shown in Figure 11 and Table 3. The normalized amounts of water applied in the city center, suburbs, and rural areas for road sprinkling and urban irrigation were 0.528×10^8, 0.2868×10^8, and 0.039×10^8, and 0.81×10^8, 1.72×10^8, and $4.45 \times 10^8 m^3/month$, respectively. The actual amounts of water applied can be determined by multiplying the values on the x-axis and those given above. The results showed that the cooling effects of road sprinkling were similar in three parts of city, where the temperature decreased by a maximum of about 0.55°C, and the cooling effects kept steady when more water was sprinkled on the roads in suburbs and rural areas. Sprinkling the roads in the city center changed the regional temperature more quickly compared with sprinkling water in the suburbs and rural areas. However, the cooling

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efficiency did not increase according to the amount of water applied (for each normalized amount of water applied, the water sprinkling in the city center was twice as many as that in the suburbs and 10 times than that in the rural areas, but the cooling effect was similar, so that the cooling efficiency in city center is lower than suburb and rural areas), possibly because the water sprinkled in the city center was concentrated in a smaller area where the wind was reduced and this decreased the cooling efficiency. The cooling effect of urban irrigation was generally greater than that of road sprinkling and it was most significant in rural areas. However, the cooling efficiency of urban irrigation in rural area was less than city center and suburbs, for the reason that applying the same normalized amount of water for irrigation, the actual water amount in rural areas was almost five times more than the city center and two times more than that in the suburbs; but the temperature decrease in the rural areas was only 1.5 times higher than those in the city center and suburbs. Thus, the effect of urban irrigation was most efficient in the city center. The cooling effects in the city center and suburbs increased as the amount of water applied increased, which was a little bit different from the effect of road sprinkling.

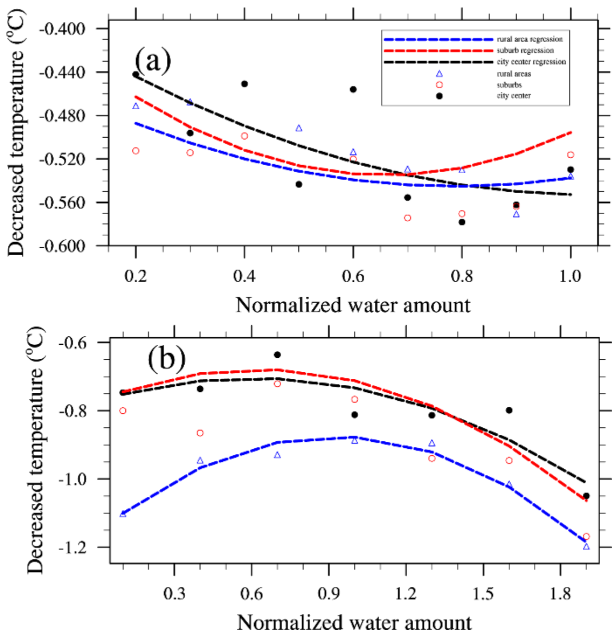

Figure 11. Relationships between the amount of water applied and the cooling effect. (a) for road sprinkling and (b) for urban irrigation. the black dot is the cooling effect of water applied in city center from model simulations, red circle is the cooling effect of water applied in suburbs from model simulations, blue triangle is cooling effect of water applied in rural areas from model simulations; the lines are polynomial regression curves, and the black, red and blue colors represent the city center, suburbs and rural areas.

Table 3. Relationships between the amounts of water applied and the cooling effects

	Road sprinkling	Urban irrigation
City center	$f = 0.15 * w^2 - 0.32 * w - 0.39$	$f = -0.18 * w^2 + 0.22 * w - 0.77$
Suburb	$f = 0.34 * w^2 - 0.45 * w - 0.42$	$f = -0.23 * w^2 + 0.30 * w - 0.86$
Rural area	$f = 0.16 * w^2 - 0.26 * w - 0.44$	$f = -0.33 * w^2 + 0.61 * w - 1.16$

3.3 Optimal water use strategies.

Based on the historical water demand and supply for municipal services described in the Water Resources Bulletin of Beijing, Quality Standards for Road Cleaning (NO: DB11/T 353-2006), and the text entitled "Water Supply Engineering" we set the constraint conditions given in Table 4. In addition, according to the Beijing's 13th Five Year Plan, the water supply for the whole city was set as $43 \times 10^8\ m^3$/year and the total amount of water for road sprinkling and urban irrigation was set as about $17 \times 10^8\ m^3$/year which mainly consumed in summer periods, excluding the water usage by industry and residents. After 24 loop iterations using the Optimization Toolbox in MATLAB, the results showed that the normalized amounts of water applied for road sprinkling from the city center to the rural areas were 0.4, 0.2 and 0.1 (the actual amounts of water applied were 0.21×10^8, 0.06×10^8,$0.04 \times 10^7\ m^3/month$, and road sprinkling for whole city is almost 10% of the total water supply) and the normalized amounts of water applied from urban irrigation from the city center to the rural areas were 0.43, 0.36 and 0.40 (the actual amounts of water applied were 0.35×10^8, 0.62×10^8, $1.78 \times 10^8\ m^3/month$, respectively; and urban irrigation for whole city is almost 90% of the total water supply) to obtain the greater cooling effect with a temperature decrease of 1.9°C. These results are reasonable because the enhanced cooling effect of road sprinkling decreased as the amount of water applied increased, so the lowest water demand was similar when more water was applied by road sprinkling. Urban irrigation in rural areas accounted for a large proportion of the total water supply in order to satisfy the needs of crop growth and environmental cooling.

Table 4. Constraint conditions for water usage in urban, suburban, and rural areas

	RS-urban	RS-suburb	RS-rural	UI-urban	UI-suburb	UI-rural
units （10^8 m^3/month）	0.528	0.2868	0.039	0.81	1.72	4.45
The lowest water demand	0.4	0.2	0.1	0.1	0.1	0.1
The highest water supply	1	1	1	2	2	2

RS means road sprinkling, UI means urban irrigation

The optimized results may be slightly higher than the actual requirements because the water usage in one part of a city will affect the cooling effects in other parts. The uncertainties related to the constraint conditions will also affect the results. The total amount of water applied for road sprinkling and urban irrigation (A in Eq. (2)) must be considered among these uncertainties. Thus, we conducted sensitivity based on proportions ranging from 0.7 to 1.5 relative to $17\times 10^8\ m^3$/year for the total amount of water applied. The results showed that the relationship between the total amount of water applied (A) and

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the cooling effect was nonlinear, where the temperature decreased sharply as the total amount of water applied (A) increased (see Figure 12).

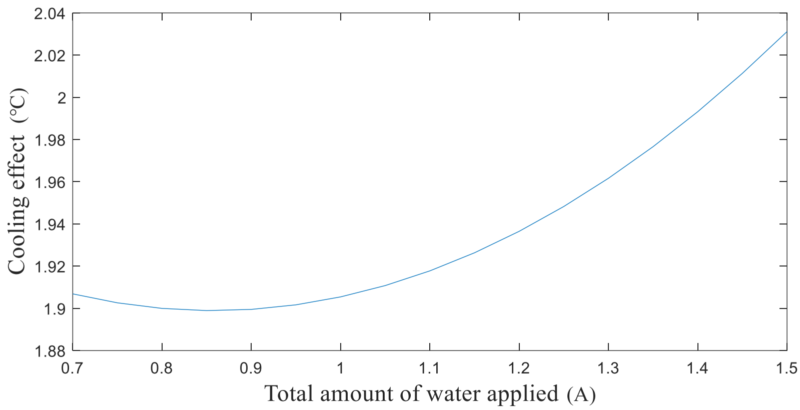

Figure 12. Sensitivity analysis based on the total amount of water applied and the cooling effect.

4 Conclusions

In this study, we coupled improved water usage schemes for road sprinkling and urban irrigation in the WRF model. The soil hydrological and urban canopy modules were modified for this study. Simulations were then conducted at a resolution of 1 km where different amounts of water were applied via road sprinkling and urban irrigation in a case study set in Beijing, China. We determined the relationships between the amounts of water applied and the cooling effects in different parts of the city. The efficiency of the cooling effect due to road sprinkling decreased as the amount of water applied increased, where the city center cooled the most because more roads were present in a small area, whereas sprinkling had no significant effect in rural areas. Urban irrigation in the daytime cooled the city during the day and night because evapotranspiration from the plants and soil was enhanced. The cooling effect was more general throughout the region and not limited to local areas. In addition, urban water usage locally increased the latent heat flux, but decreased the sensible heat flux and the boundary layer height.

We also conducted an optimization process to determine the appropriate amounts of water for application by urban irrigation and road sprinkling in different parts of city, where we treated decreasing the temperature as the optimization objective and the total water supply, highest water supply in different parts of the city, and lowest water demands in the city center, suburbs, and rural areas as the constraint conditions. The optimization results showed that the temperature could be reduced by 1.9°C using road sprinkling and urban irrigation in the city center, suburbs, and rural areas when the normalized amounts of water are applied (i.e., 0.4, 0.2, and 0.1 for road sprinkling, and 0.43, 0.36, and 0.40 for urban irrigation, respectively). Sensitivity analysis based on the total water supply for the whole city (A) detected a nonlinear relationship between the total water supply (A) and the optimized decrease in the temperature, where the cooling effect increased sharply as the amount of water applied increased. Considering the Beijing's 13th Five Year Plan, allocating about 90% of the total water to urban irrigation and 10% to road sprinkling is the most effective approach for mitigating high urban temperatures.

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Besides, other big cities like Tokyo, London, Phoenix and so on are facing the threat of high temperature in summer, too. There, urban water use managements are important part in municipal planning, it makes balance of both water demand and supply, as well as improve urban climate. Although road sprinkling may not a common solution to mitigate high temperature in other countries, the optimal water usage scheme in this study is still applicable to other cities and road sprinkling supply can set to zero if no road sprinkling occurs.

***Code availability*.** Model code can be obtained from the corresponding author, and the data of this manuscript is available in 4TU.Centre for Research Data (http://doi.org/10.4121/uuid:01621202-7ec4-4643-84b5-5f9ec2966004)

***Author contributions*.** Bin Liu completed the simulation analysis and manuscript. Zhenghui Xie aided with manuscript preparation and editing. ChunXiang Shi provided the validation data. Shuang Liu and Yujing Zeng did the initial model development. Ruichao Li, Longhuan Wang, Yan Wang and Si Chen helps in data analysis. Binghao Jia, Peihua Qin and Jinbo Xie offered valuable suggestions.

Competing interests. The authors declare that they have no conflict of interest.

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