Urban Heat Island Mitigation Effectiveness under Extreme Heat Conditions in the Suzhou–Wuxi–Changzhou Metropolitan Area, China

YAN CHEN
Jiangsu Climate Center, Nanjing, China

NING ZHANG
China Meteorological Administration–Nanjing University Joint Laboratory for Climate Prediction Studies, Institute for Climate and Global Change Research, School of Atmospheric Sciences, Nanjing University, and Jiangsu Collaborative Innovation Center for Climate Change, Nanjing, China

(Manuscript received 11 April 2017, in final form 9 November 2017)

ABSTRACT

Cool roofs and green roofs are two important methods used to mitigate the urban heat island (UHI) effect. The Weather Research and Forecasting Model was used to investigate the UHI effect and the effectiveness of cool and green roof mitigation strategies in the Suzhou–Wuxi–Changzhou metropolitan area during an extreme heat wave episode in the summer of 2013. Both urban land-cover change and anthropogenic heat releases exacerbated high temperatures in the urban area. Notably, urban land-cover change and anthropogenic heat release were responsible for 64% and 36% of the UHI intensity, respectively. Both cool and green roofs decreased near-surface air temperatures. The most dramatic decrease in near-surface air temperature occurred in the late morning; nocturnal air temperature decreased slightly because of the decrease in urban heat storage associated with the cool roof strategy. In addition, the UHI mitigation strategies affected the entire urban boundary layer. The decrease in the potential temperature and static stability created a stable urban boundary layer in which turbulent kinetic energy (TKE) decreased simultaneously. Analysis of an urban belt near a large water body showed that the decrease in the surface skin temperature difference between land and the water body weakened the daytime lake breeze. This effect was observed in both the inflow in the boundary layer and the return flow above the boundary layer, and it decreased the heat and moisture exchange between the lake and land boundary layers.

1. Introduction

Although urban areas cover only a tiny fraction of Earth’s surface, more than half of the global population lives in cities, and another 2.5 billion people are projected to move to cities by 2050 (United Nations World Population Prospects 2014, https://esa.un.org/unpd/wup/). In China, the urban area tripled and the urban population doubled from 1978 to 2010 (Schneider and Mertes 2014); these changes are ongoing. With the rapid increase in the urban population and the expansion of cities, the urban climate is becoming increasingly important in the context of human health and sustainable development. During an urban expansion, the underlying soils or vegetated surfaces (e.g., forest, grassland, and cropland) are replaced by artificial impervious materials. The changes in the underlying surface modify the dynamic, radiative, and thermal features of the land surface, and human activities release waste heat and air pollutants. These changes also alter the exchange of heat and moisture between the urban surface and atmosphere and form special meteorological phenomena in cities (Arnfield 2003). One of the most important phenomena is the formation of urban heat islands (UHIs), which are the result of air temperature differences between urban and rural areas. A UHI directly impairs the human thermal environment in cities, especially during heat wave episodes (Zhang et al. 2011; Wang et al. 2017; Ramamurthy et al. 2017). While heat waves are typically synoptic-scale processes (Meehl and Tebaldi 2004; Loikith and Broccoli 2012), UHIs often exacerbate heat waves in urban areas because of the lack of vegetative cover and soil moisture in cities (Basara et al. 2010; Tan et al. 2010; Zhang et al. 2011; Li and Bou-Zeid 2013; Wang et al. 2017; Ramamurthy et al. 2017).
In addition to affecting the microclimatic conditions of the surface, UHIs cause air temperature differences between urban and rural areas. These differences can create horizontal heterogeneities in air pressure and form horizontal pressure gradients, which can lead to the convergence of near-surface wind flows and the formation of mesoscale circulations (UHI circulation). A UHI circulation directly influences the boundary layer structure and turbulent characteristics of urban areas (Miao and Chen 2008; Wang 2009; Ryu et al. 2013; Zhang et al. 2014). In addition, this type of circulation can potentially influence urban cloud and precipitation processes (Miao and Chen 2008; Dou et al. 2015), as well as air pollution transport (Demirci and Cuhadaroglu 2000; Martilli 2003).

For cities located in coastal areas or near large lakes, a UHI circulation can interact with mesoscale flows such as sea or lake breezes (Freitas et al. 2007; Lemonsu et al. 2006; Thompson et al. 2007; Lin et al. 2008; Lu et al. 2010; Chen et al. 2011a; Zhang et al. 2011; Meir et al. 2013; M. Li et al. 2014; Hu and Xue 2016). Notably, a UHI circulation typically enhances daytime sea/lake breezes and may also influence chemical processes in the atmosphere (Lo et al. 2006; Wagner et al. 2012).

Mitigating the UHI effect is an efficient method of reducing the health and environmental risks of heat waves and improving the urban microclimate (Aflaki et al. 2016). In cities, materials such as stone, concrete, and asphalt tend to absorb more solar radiation, and low vegetation coverage and soil moisture can lead to a high surface sensible heat flux, which directly heats near-surface air. The typical methods of mitigating UHIs are 1) to reduce the absorbed solar radiation using high-albedo building materials and 2) to increase surface evapotranspiration by greening the urban surface (Rosenfeld et al. 1995). Cool roofs and green roofs are two UHI mitigation methods used to replace conventional roofs with high-albedo materials or vegetation. These methods have been extensively investigated with both in situ observations and numerical modeling at different scales, including the building and neighborhood scales (Susca et al. 2011; Sun et al. 2013, 2014; Kong et al. 2016). The development of numerical mesoscale/regional climate models has allowed researchers to implement sophisticated urban canopy models to represent the complicated thermal and hydrological processes in urban areas (Masson 2000; Kusaka et al. 2001; Martilli et al. 2002; Kusaka and Kimura 2004; Kondo et al. 2005; Chen et al. 2011b; Gutiérrez et al. 2015; Vázquez Morales et al. 2016). Green roof and cool roof schemes have also been implemented in urban canopy models (D. Li et al. 2014; Jiachuan Yang et al. 2015) to assess the upscaling effects of green and cool roofs at the city scale (Silva et al. 2010; Sharma et al. 2016; Wang et al. 2016). In addition, the global effects of cool roofs were investigated using an Earth system model, which showed that statistically significant reductions in urban surface air temperatures occurred in the urbanized regions of China and the United States, while global changes were negligible (J. Zhang et al. 2016). Most previous studies have focused on the impacts of UHI mitigation on near-surface air temperatures and pedestrian comfort, but little attention has been paid to its effects on the boundary layer structure and UHI circulation. Using the Weather Research and Forecasting (WRF) Model, Sharma et al. (2016) evaluated the effects of green and cool roof mitigation on the UHI in the Chicago metropolitan area, as well as its effects on UHI and lake breeze interactions. Few studies have been conducted in China, where the three largest urban metropolitan areas (the Beijing–Tianjin–Hebei urban belt, the Yangtze
River delta urban belt, and the Pearl River delta urban belt) are located in coastal areas or near large rivers and lakes.

This paper focuses on the Suzhou–Wuxi–Changzhou urban group, which is an important part of the Yangtze River delta urban belt, China’s largest urban belt in terms of population and economic impact. The Suzhou–Wuxi–Changzhou metropolitan area is located in south Jiangsu Province near Tai Lake. In 2014, the total population was 22 million, and the total gross domestic product (GDP) was approximately 2810 billion Chinese yuan (432 billion U.S. dollars). Previous studies have proven that the urbanization in this area modified both the local boundary layer processes and regional climate (Zhang et al. 2010). The heat wave episodes also can exacerbate the UHIs and impair human comfort (Zhang et al. 2011; Kong et al. 2016). The lack of studies on UHI mitigations and their effectiveness is currently a hindrance for urban planning and building design in this area. In this paper, the effectiveness of cool and green roofs is investigated using the WRF Model, and the associated influences on boundary layer structures and lake breezes are analyzed.

2. Numerical model and experimental design

The WRF Model (version 3.8.0, https://www.mmm.ucar.edu/weather-research-and-forecasting-model) was used as the numerical tool in this paper. The model is designed for both meteorological research and numerical weather predictions from the microscale (a horizontal resolution of tens of meters) to the regional/global scales (a horizontal resolution of tens of kilometers). The WRF, which couples a single-layer urban canopy model (SLUCM; Kusaka et al. 2001; Kusaka and Kimura 2004) with the Noah land surface model, has been widely used to investigate the effects of urbanization (Wang et al. 2009; Zhang et al. 2010; Li et al. 2012;
Wei et al. 2013; Liao et al. 2015; Wan et al. 2015). The SLUCM model solves the radiation and energy balance equations of three urban surfaces (roads, walls, and roofs), and each surface has its own thermal and radiative parameters (including albedo, emissivity, conductivity, and heat captivity; Kusaka et al. 2001). In addition, a multilayer green roof system is included in the current version of the SLUCM (Jiachuan Yang et al. 2015). These features make the WRF–Noah–SLUCM model a useful tool for evaluating the performances of cool and green roofs as UHI mitigation methods.

Previous study has documented an increasing trend of heat waves and high-temperature days in the Suzhou–Wuxi–Changzhou metropolitan area (Zheng et al. 2012). In this paper, we focused on three hot-weather days (6, 7, and 8 August 2013). These three hot-weather days
days represent the peak in a monthlong heat wave during the summer of 2013, which is the strongest extreme heat event in the recent six decades in China and in which new, historical near-surface air temperature records were reported in the Suzhou–Wuxi–Changzhou area (40.18°C at Changzhou station on 6 August and 41.0°C at Suzhou station on 7 August) and tens of people were reported dead (http://news.xinhuanet.com/english/indepth/2013-08/13/c_132627590.htm). The heat wave episode in July and August 2013 was caused by anomalies in the northwest Pacific subtropical high in late July and the first half of August. During that period, a strong positive bias in geopotential height at the 500-hPa level occurred over East Asia, and the subtropical high was blocked and stably controlled over southeast China (Fig. 1a). This positive bias lasted until the second half of August, at which point the subtropical high was pushed northeast under the influence of Typhoon Trami and Typhoon Kong-Rey, and the heat wave episode ended (Fig. 1b).

The model configuration consists of a parent domain and two nested domains centered at 31.3°N, 120.4°W, as shown in Fig. 2. The horizontal resolutions of the domains are 18, 6, and 2 km. The horizontal grids have dimensions of 91 × 91 for all domains, and the vertical grid system has 53 levels. The initial and boundary conditions were obtained from the National Centers for Environmental Protection (NCEP) Final (FNL) dataset and had a horizontal resolution of 1° and a temporal resolution of 6 h. The selected integration period in this paper is from 0000 UTC 5 August (0800 LT 5 August) to 0000 UTC 9 August (0800 LT 9 August) 2013, and the results of the latter three days (72 h) were analyzed. The physical parameterization schemes used in the simulations, which are based on those used in previous numerical studies in this area (Zhang et al. 2010, 2011; Zhang and Chen 2014), are shown in Table 1. The SLUCM model was coupled with the Noah model to represent the energy and moisture exchange between the urban surface and the atmospheric boundary layer. The control (CTL) experiment used the default values for the urban surface characteristics, including building albedos, heat capacities, thermal conductivity, emissivity, and so on. The urban land-cover condition was updated using 2012 Landsat observations. The 25-m-resolution Landsat data were used to calculate the urban cover fraction for each model grid as shown in Fig. 2c; and the urban grids were classified into three types—high density, medium density, and low density—based on the urban land-cover fraction (impervious land-cover fraction) as set in the WRF–Noah–SLUCM model. The default urban building parameters of the SLUCM in the WRF release were used in each numerical experiment; however, the building roof albedo was modified in the cool roof experiments. Previous studies have shown that the WRF Model performs well and can capture urban climate characteristics in this area with the SLUCM deployed (Zhang et al. 2011; Zhang and Chen 2014). The roof coverage ratio is an important parameter in the cool roof and green roof mitigation strategies; when the default building parameters are used, the building roof width is the same as the road width over all three urban types, so the building roofs occupied 50% of the total urban area in each urban grid.

The anthropogenic heat release used in this study was estimated using local social and economic data, including population, energy consumption and vehicle data as in Jianbo Yang et al. (2015). In the current SLUCM model, the anthropogenic heat release is determined using fixed diurnal variation profiles over different urban land-cover types that do not interact with the outdoor (canopy level) environment, and the improvement of the urban thermal
environment through the use of UHI mitigation strategies decreases the residential energy demand for room cooling. Although residential anthropogenic heat release levels are much lower than industrial and traffic releases in general, this current anthropogenic heat release scheme in the SLUCM may overestimate urban air temperatures in the UHI mitigation experiments.

Based on the CTL experiment, 18 UHI mitigation sensitivity experiments were conducted to study the influences of different mitigation scenarios on the UHI. The sensitivity experiments were divided into a cool roof (CR) group (8 experiments) and a green roof (GR) group (10 experiments). All of the sensitivity experiments used the same physical schemes and urban canopy model parameters as those used in the CTL experiments, except that in the CR experiments, the building roof albedos (ALBR) varied from 0.10 to 0.90 in increments of 0.1. These experiments were named CR010 through CR090, respectively. Because the default ALBR was 0.20 in the WRF release, the results of the CTL experiment were the same as those of the CR020 experiment. Thus, the CR group comprised only eight experiments. In the GR group, the building roofs were covered by vegetation in different fractions (from 10% to 100% in increments of 10%). These experiments were labeled GR010 through GR100. Two more sensitivity experiments—noAH and noURB—were used to investigate the effects of urbanization on the local urban climate. The anthropogenic heat release parameter was turned off in the noAH experiment, and the urban land cover was replaced by cropland in the noURB experiment. The differences between the CTL, noAH and noURB experiments were used to measure the effects of urbanization following the method proposed by N. Zhang et al. (2016).

3. Results

a. Evaluation of the CTL simulation results

The hourly outputs for air temperature at 2 m ($T_{2m}$), relative humidity at 2 m ($rh_{2m}$), and wind speed at 10 m ($U_{10m}$) were interpolated to the locations of 14 meteorological stations in the domain. The interpolated values were then compared to the respective observations. Next, the mean bias (MB), root-mean-square error (RMSE), and correlation coefficient ($R$) were calculated, as shown in Table 2. The results suggest that when the updated urban land cover and anthropogenic heat release are considered, the model represents the heat wave episode very well. The mean simulated air temperature at the 14 meteorological stations was $34.9^\circ C$, which is similar to the observed mean temperature of $35.3^\circ C$. The RMSE of the near-surface air temperature was $1.10^\circ C$, and $R$ was 0.95. Additionally, the model captured the historical high temperatures at Suzhou and Wuxi stations (Fig. 3). The highest simulated $T_{2m}$ at Suzhou station was $40.8^\circ C$ compared to the $41.0^\circ C$ observed value. The $rh_{2m}$ value simulated by the WRF Model was 51.1%, which is slightly higher than the station observed average of 50.5%, with an MB value of 0.6%. The $R$ of the specific humidity $q_{2m}$ was 0.85, and the RMSE was 1.19 g kg$^{-1}$. The CTL experiments reflected the diurnal variations in $T_{2m}$, $q_{2m}$, and $rh_{2m}$ well. On the three study days, the temperature peaked at approximately 1400 LT, and $q_{2m}$ and $rh_{2m}$ reached minimums at the same time. Both daily $q_{2m}$ and $rh_{2m}$ were lower than those at night because the atmospheric boundary layer and near-surface air temperatures were higher. The model overestimated $U_{10m}$, with an MB of 0.99 m s$^{-1}$, RMSE of 1.24 m s$^{-1}$, and $R$ of 0.51. The observed diurnal variations indicate that...
frequent, calm winds occurred on all three study days; however, the model failed to capture this phenomenon, which led to poor performance in the wind speed simulations.

b. The effects of urban land-cover change and anthropogenic heat on the UHI

Previous studies have demonstrated that urban warming has a direct impact on heat wave episodes in urban areas (Zhang et al. 2011; Wang et al. 2017), and both urban land-cover change and anthropogenic heat releases contribute to the formation of UHIs (Chen et al. 2009; N. Zhang et al. 2016). The meteorological station observations also indicated that UHI might exacerbate heat waves in cities. The averaged UHI intensity calculated with hourly observation in the three days in Suzhou city was 1.7°C (Figs. 3b,g) compared to the 30-yr average of 0.3°C, which was calculated with the conventional four time observations; the 30-yr average UHI intensity 0.1°C at 0800 LT and 0.35°C at 1400 LT, while the maximum UHI intensity for Suzhou city reached 3.2°C during the three study days. Figure 4a shows the simulated diurnal variations of $T_{2m}$ averaged over the high-density urban area (defined as an urban land-cover fraction greater than 90% in this paper) in the CTL, noAH, and noURB experiments. The differences in $T_{2m}$ (Fig. 4b) between these three experiments were used to assess the impacts of urbanization. Both urban land-cover change and anthropogenic heat releases can exacerbate high temperatures in urban areas.
The mean difference in $T_{2m}$ between CTL and noURB (CTL – noURB) was 2.8°C; the mean difference in $T_{2m}$ between CTL and noAH was 1.0°C; and the mean difference between noAH and noURB was 1.8°C. Thus, urban land-cover change and anthropogenic heat releases were responsible for 64% and 36% of the UHI, respectively. These results are similar to those of previous studies conducted in other tropical/subtropical Chinese cities (Chen et al. 2009; N. Zhang et al. 2016). Both urban land-cover change and anthropogenic heat release contributions peaked at night. Notably, the maximum difference in $T_{2m}$ between noAH and noURB occurred just after sunset (approximately 1800 LT), whereas the maximum value between CTL and noAH was observed just before sunrise (approximately 0600 LT).

The urbanization process not only impacts urban areas but also nearby suburban/rural areas (Fig. 5). Figure 4c illustrates the changes in $T_{2m}$ over reference area C (illustrated in Fig. 2c) among different experiments. The differences in $T_{2m}$ indicate a very slight decrease during the day (~0.1°C in the afternoon) and a relatively significant temperature increase at night. This is because the daytime UHI enhanced the lake breeze,
and the flow from the lake surface cooled the lake–coastal area; however, at night, when the UHI intensity was much stronger than during the day, the land breeze brought warm air from the urban area. Previous studies have documented how an UHI-enhanced sea breeze might abate the heat waves over urban area (Sequera et al. 2016); however, this did not occur in our simulations. This may be because the lake breeze in our study area was relatively weak compared to the sea breeze, and during such a subcontinental-scale heat wave episode, the air temperature difference between the lake surface and the land surface was relatively weak.

c. Effectiveness of different mitigation methods

The $T_{2m}$ differences in high-density urban areas between the UHI mitigation sensitivity experiments and the CTL experiments were used to estimate the effectiveness of different mitigation methods in this study. Both cool roofs and green roofs can effectively decrease near-surface temperatures; near-surface temperatures decrease as the ALBR and green roof fractions increase (Fig. 6). The most obvious positive impact of the mitigation variables occurred just before noon at approximately 1000 LT in all sensitivity experiments; this result was similar to the results observed in Chicago (Sharma et al. 2016). Replacing building roofs with a very highly reflective material (albedo equal to 0.9) resulted in the largest improvements, with a decrease in $T_{2m}$ of $-2.2^\circ C$ at 1000 LT 6 August; the temperature decrease in GR100 was approximately $-1.8^\circ C$. In the CTL experiments, the daily maximum temperature over all urban grids was higher than 35$^\circ C$ (the threshold value used in China to define a high-temperature day) on these three days. In the CR090 experiments, 23% of urban grids outputted daily maximum temperatures lower than 35$^\circ C$; this same measure was 17% in the GR100 experiment. The mitigation measures’ effectiveness was also influenced by the synoptic background and changed from day to day. The absolute value decreases in $T_{2m}$ on 6 and 7 August were greater than that on 8 August because the near-surface wind speed in the daytime was strongest on 8 August (the observed $U_{10m}$ reached 5 m s$^{-1}$ at Wuxi station; Fig. 3j). This high wind speed caused strong horizontal transport and turbulent mixing over the urban area and reduced the mitigation measures’ effectiveness. Both cool and green roofs simultaneously increased urban surface wetting both in near-surface specific humidity ($q_{2m}$) and near-surface relative humidity ($rh_{2m}$). The increase in $q_{2m}$ at 1000 LT 6 August was 1.4 g kg$^{-1}$, and the increase in $rh_{2m}$ at the same time was 9.3% in the CR090 experiment. In addition, the respective changes in the GR100 experiment were approximately 1.6 g kg$^{-1}$ and 8.5%. There were two reasons for the $q_{2m}$ increase in the urban area. As shown before in both UHI mitigation strategies, the near-surface air temperature decreased, which led to a more stable atmospheric boundary layer, inhibited turbulent motion, and weakened vertical mixing. These processes increased the vapor concentration in the urban atmospheric boundary layer. At the same time, the decrease in the air temperature in the urban area caused the horizontal pressure gradient and surface wind fields to change, and

![Fig. 8. The mitigation effectiveness of (a) cool roofs and (b) green roofs.](image-url)
convergences occurred in the urban area in all sensitivity experiments (Fig. 7). Furthermore, moisture from the rural area was transported to the urban area, which increased the atmospheric humidity in the urban area. The decrease in $T_{2m}$ decreased the saturation vapor pressure, and both the $T_{2m}$ decrease and the $q_{2m}$ increase caused $r_{h2m}$ to increase. The increase in boundary layer stratification impacted both the near-surface specific humidity (Figs. 6b,f) and the near-surface wind speed in the urban area (Figs. 6d,h).

In both UHI mitigation strategy groups, the near-surface wind speed ($U_{10m}$) decreased in the late morning when the near-surface temperature exhibited the largest decrease because a more stable atmospheric boundary layer weakens the vertical exchanges of moisture and momentum and decreases near-surface wind speeds.

Cool roofs change the surface energy balance by reducing solar radiation, and green roofs change the surface energy balance by providing more soil moisture for evapotranspiration and altering the energy partition between sensible heat flux and latent heat flux. The changes in the surface energy balance decrease the surface skin temperature of building roofs and cause the near-surface air temperature to decrease. These are the key mitigation mechanisms of both cool and green roofs. The changes in the roof surface skin temperature can also alter the temperature difference between a building roof and indoor air and change the heat storage of the urban surface. Previous studies have documented that the release of stored urban heat at night is one of the key factors associated with maintaining a nocturnal UHI; thus, UHI mitigation is also important at night. The diurnal variations in $T_{2m}$ (Fig. 5) show that in all the different sensitivity experiments, the near-surface temperature decreased at night. Compared to the changes in $T_{2m}$ during the day, the nocturnal changes were relatively small, and the results suggest that cool roofs had a more obvious impact on the nocturnal near-surface air temperature than did green roofs. The changes in the average, maximum, and minimum $T_{2m}$ values in the high-density urban area were calculated, and their relationships with the fraction of green roofs and the albedo of cool roofs were analyzed, as shown in Fig. 8. The results show that the average, maximum, and minimum values of $T_{2m}$ decreased linearly as the green roof or ALBR fractions increased, although the changes in the minimum $T_{2m}$ values were negligible in the GR group.

Because both cool and green roof mitigation strategies only change the surface features of building roofs, the modifications of surface features in a simulation grid depend on the urban land-cover types and fractions. Previous studies (e.g., D. Li et al. 2014) assessed the mitigation effectiveness of cool and green roofs over different urban land-cover types (e.g., commercial urban, high-density residential urban, and low-density residential urban areas) and assumed that the impervious surface fractions over different urban types were fixed. In this paper, the urban area was classified into different types based on the impervious surface cover fraction. The mitigation effectiveness ratios of both cool and green roofs were estimated for each urban cover fraction, as shown in Table 3. The results demonstrate that both cool and green roofs lead to large $T_{2m}$ decreases in urban areas where the urban impervious surface fraction is high, and the effect on the maximum $T_{2m}$ is more obvious than that on the average $T_{2m}$. In grids where the impervious cover fraction is greater than 90%, the average $T_{2m}$ decreased by 0.07°C and the maximum $T_{2m}$ decreased by 0.13°C when the vegetation cover fraction of a building roof increased by 10%; nevertheless, the change in

### Table 3. Mitigation effectiveness over different density urban areas.

<table>
<thead>
<tr>
<th>Urban type</th>
<th>Impervious cover fraction (%)</th>
<th>Avg</th>
<th>Cool roof ($^\circ$C per 10%)</th>
<th>Green roof ($^\circ$C per 0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>1</td>
<td>0 ≤ f ≤ 20</td>
<td>−0.03</td>
<td>−0.05</td>
<td>−0.01</td>
</tr>
<tr>
<td>2</td>
<td>20 &lt; f ≤ 30</td>
<td>−0.03</td>
<td>−0.06</td>
<td>−0.01</td>
</tr>
<tr>
<td>3</td>
<td>30 &lt; f ≤ 40</td>
<td>−0.07</td>
<td>−0.15</td>
<td>−0.01</td>
</tr>
<tr>
<td>4</td>
<td>40 &lt; f ≤ 50</td>
<td>−0.08</td>
<td>−0.16</td>
<td>−0.03</td>
</tr>
<tr>
<td>5</td>
<td>50 &lt; f ≤ 60</td>
<td>−0.10</td>
<td>−0.19</td>
<td>−0.03</td>
</tr>
<tr>
<td>6</td>
<td>60 &lt; f ≤ 70</td>
<td>−0.11</td>
<td>−0.19</td>
<td>−0.03</td>
</tr>
<tr>
<td>7</td>
<td>70 &lt; f ≤ 80</td>
<td>−0.13</td>
<td>−0.21</td>
<td>−0.04</td>
</tr>
<tr>
<td>8</td>
<td>80 &lt; f ≤ 90</td>
<td>−0.13</td>
<td>−0.21</td>
<td>−0.04</td>
</tr>
<tr>
<td>9</td>
<td>90 &lt; f ≤ 100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the minimum $T_{2m}$ was nearly zero. In the same grids, average $T_{2m}$ decreased by 0.13°C, maximum $T_{2m}$ decreased by 0.21°C, and minimum $T_{2m}$ decreased by 0.04°C when the albedo of a building roof increased by 0.1. These results indicate that the nocturnal $T_{2m}$ can benefit from the cool roof method because it decreased the daytime urban heat storage. Additionally, the impervious cover fraction changes greater than 70% are very similar, indicating that the effectiveness of cool roof and green roof methods for mitigating near-surface temperature changes might have an upper limit.
d. The mitigation of UHI effects on boundary layer structures

UHI mitigation not only changes the local surface radiation, energy budget, and near-surface meteorological fields, but it also affects the entire urban boundary layer. The spatially averaged diurnal variations in the vertical potential temperature distributions in the sensitivity experiments and the CTL experiment in high-density urban areas (urban land-cover fraction greater than 90%) are shown in Figs. 9 and 10. The decrease in the near-surface potential temperature peaked in the early morning when the planetary boundary layer (PBL) was shallow and started to become weaker after noon (Fig. 9). For example, the potential temperature at the height of 200 m was 33.8°C in the CR090 experiment and 34.2°C in the GR100 experiment compared to 35.1°C in the CTL experiment at 1000 LT 7 August; the values became 37.0°C, 37.2°C, and 37.6°C at 1600 LT. In addition, the influence height increased dramatically as the PBL height increased, and a maximum was reached in the mid-afternoon when the convective PBL was fully developed; the influence height was less than 300 m at 1000 LT and became 1.0 km at 1200 LT. It reached 1.5 km at 1600 LT 7 August. This agreed with the results in Mexico City (Vázquez Morales et al. 2016). In the sensitivity experiments in which the cool roof fraction or green roof fraction was greater than 70%, the potential temperature also decreased at night (Fig. 10). The decrease in the potential temperature caused a stable urban boundary layer. Figure 11 illustrates the differences of the diurnal changes in the static stability among in the sensitivity experiments. The stability increased across the PBL, and the maximum increase occurred in the lower part of the PBL. The increase in the later afternoon reached 0.06 K Pa\(^{-1}\) in the CR090 experiment and 0.05 K Pa\(^{-1}\) in the GR100

---

**Fig. 10.** Differences in the diurnal changes in potential temperature: (a) CR050 – CTL, (b) CR070 – CTL, (c) CR090 – CTL, (d) GR050 – CTL, (e) GR070 – CTL, and (f) GR100 – CTL (°C).
The increase in the stability of the PBL decreased the development of turbulence; the turbulent kinetic energy (TKE) decreased at the same time (Fig. 12). The maximum TKE decrease occurred in the lower part of the boundary layer (approximately 300 m above the ground) in the late morning (approximately 1000–1100 LT), and the absolute value of the maximum decrease, which was observed in the CR090 experiment, was approximately 0.73 m² s⁻². The increase in the stability of the PBL also led to a dramatic decrease in the PBL's height (Fig. 13). The influence on PBL height peaked at noon; the decreases that occurred at 1200 LT 6 and 7 August were −329 and −317 m, respectively, in the CR090 experiment. The decrease that occurred at the same time on 9 August was relatively smaller because of the weaker mitigation effectiveness as discussed in section 3c.

Previous studies have documented that UHIs may interact with sea/lake breezes, and UHIs generally enhance the daytime lake breeze by increasing the surface skin temperature difference between land and the adjacent water body (Yoshikado 1994; Kusaka et al. 2000; Ohashi and Kida 2002; Freitas et al. 2007; Levy et al. 2008; Lin et al. 2008; Lu et al. 2010; Chen et al. 2011a; Sims and Raman 2016). Such observations were also noted in the study area in a previous numerical simulation of a heat wave episode (Zhang et al. 2011). By contrast, when UHI mitigation strategies are implemented, the difference in the surface skin temperature and near-surface air temperature between land and the nearby water body decreases, and the daytime lake breeze weakens. This phenomenon occurs in the surface wind field, as shown in Fig. 7, as well as in the boundary layer wind field. In this paper, a vertical cross-section along the coastline and parallel to the urban belt was selected (line AB, as shown in Fig. 2) to analyze the horizontal exchanges of momentum, moisture and heat between Tai Lake and
the urban area. The horizontally averaged wind velocity, horizontally transported sensible heat flux (HSH; here defined as $\rho C_p \vec{u} \vec{\theta}$, where $\rho$ is the air density, $u$ is the wind velocity and $\theta$ is the potential temperature), and horizontal latent heat flux (HLH; defined as $L_v \vec{u} q$, where $q$ is water vapor) over line AB were calculated. The positive values indicate horizontal transport from Tai Lake to the land area across the AB section, and the negative values reflect the opposite transport process. In the sensitivity experiments, the UHI mitigation strategies reduced the surface temperature difference between the water surface and the land surface and weakened the lake breeze. Furthermore, the heat and moisture transport from the lake area to the land area decreased. The weakening effect occurred mostly in the daytime boundary layer and peaked in the late afternoon, as shown in Fig. 14. The average daytime and PBL (averaged from 0600 to 1800 LT and from Earth’s surface to the top of the PBL) changes in wind velocity, HSH, and HLH were calculated, as shown in Table 4. As the ALBR or green roof fraction increased, the average daytime and PBL wind velocities decreased. The transport of heat and moisture from the lake area to the land surface also decreased. The PBL-averaged daytime wind speed decreased to 0.1 m s$^{-1}$ when ALBR was greater than 0.8 or the green roof fraction was greater than 90%. The changes in HLH were small (less than 5 W m$^{-2}$ in the sensitivity experiments) compared to the changes in HSH. Notably, the HLH in the CR090 experiment changed by only $-3.34$ W m$^{-2}$ compared to the change in HSH of $-61.96$ W m$^{-2}$. Thus, UHI mitigation not only affects the inflow (from the water body to the urban area) of the lake breeze but also weakens the return flow above the boundary layer; however, this effect is small. Even in the CR090 and GR100 experiments, the wind velocity increases above the boundary layer were less than 0.5 m s$^{-1}$.

FIG. 12. As in Fig. 10, but for turbulent kinetic energy (m$^2$ s$^{-2}$).
during the day. Moreover, the HSH and HLH transport from land to the lake area above the boundary layer decreased, and the maximum increases in HSH and HLH above the boundary layer were only 43.3 and 21.7 W m$^{-2}$, respectively.

4. Summary and conclusions

This paper uses the WRF Model, which includes a coupled, physically based urban canopy model, to investigate the urban warming effect and the influence of two UHI mitigation strategies on the Suzhou–Wuxi–Changzhou metropolitan area during an extreme heat wave episode in the summer of 2013. The results demonstrated that both urban land-cover change and anthropogenic heat release exacerbated the high temperatures in the urban study area. Notably, the contributions of urban land-cover change and anthropogenic heat releases to the UHI were 64% and 36%, respectively.

Both cool and green roofs changed the surface radiation and energy budgets over the urban surface. The changes in the surface energy balance decreased the surface skin temperatures of building roofs and caused near-surface air temperatures to decrease. The most dramatic near-surface air temperature decrease occurred in the late morning when the nocturnal air temperature also decreased slightly because of the decrease in urban heat storage associated with the cool roof strategy. The average, maximum, and minimum $T_{2m}$ values linearly decreased as the green roof fraction or the ALBR increased, although the variations in the minimum $T_{2m}$ value were negligible in the GR group. In high-density urban areas where the impervious cover fraction is greater than 70%, the ratios of the $T_{2m}$ decrease to the roof albedo or green roof fraction increase were very similar, indicating that the effectiveness of cool roof and green roof strategies for mitigating near-surface temperature may have an upper limit.

UHI mitigation not only changes local surface meteorological fields but affects the entire urban boundary layer. The decrease in the potential temperature created a stable urban boundary layer, and the TKE decreased simultaneously. Based on our analysis of an urban belt near a large water body, the decrease in the surface skin temperature difference between land and

![Graph of changes in the urban planetary boundary layer height](image-url)

**FIG. 13.** Changes in the urban planetary boundary layer height in the (a) cool roof and (b) green roof experiments.
the water body was weakened the daytime lake breeze. This effect was observed in both the boundary layer inflow and the return flow above the boundary layer, and it decreased the heat and moisture exchange between the lake boundary layer and the land boundary layer.

China has experienced rapid urbanization and economic development in recent decades, and increased

Table 4. Differences in the daytime-averaged boundary layer exchange between lake and land areas.

<table>
<thead>
<tr>
<th>Green roof cover fraction or cool roof albedo</th>
<th>Cool roofs</th>
<th>Cool roofs</th>
<th>Cool roofs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind velocity</td>
<td>HSH</td>
<td>HLH</td>
<td>Wind velocity</td>
</tr>
<tr>
<td>0.1</td>
<td>0.01</td>
<td>8.83</td>
<td>0.44</td>
</tr>
<tr>
<td>0.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>0.3</td>
<td>-0.01</td>
<td>-8.05</td>
<td>-0.39</td>
</tr>
<tr>
<td>0.4</td>
<td>-0.04</td>
<td>-18.36</td>
<td>-1.35</td>
</tr>
<tr>
<td>0.5</td>
<td>-0.05</td>
<td>-27.27</td>
<td>-1.73</td>
</tr>
<tr>
<td>0.6</td>
<td>-0.06</td>
<td>-36.86</td>
<td>-1.97</td>
</tr>
<tr>
<td>0.7</td>
<td>-0.08</td>
<td>-45.88</td>
<td>-2.41</td>
</tr>
<tr>
<td>0.8</td>
<td>-0.10</td>
<td>-51.72</td>
<td>-3.05</td>
</tr>
<tr>
<td>0.9</td>
<td>-0.10</td>
<td>-61.96</td>
<td>-3.34</td>
</tr>
<tr>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
attention has been paid to urbanization-related weather disasters as a result. Furthermore, the improvement of the urban climate and environment is important for the sustainable development of cities. Zheng et al. (2012) analyzed the conventional meteorological observations and documented that summer high-temperature days (daily maximum surface air temperature greater than 35°C) had increased dramatically in the Suzhou–Wuxi–Changzhou metropolitan area because of both the background climate change and local urbanization processes in recent decades. The improvement of the urban thermal environment was a pressing need to reduce the risks on human health and economical loss. The results of this study improve our understanding of the effects of UHI mitigation and can aid in urban building design and planning in the urban belt of east China. Both cool roof and green roof mitigation methods can reduce near-surface air temperatures and improve the thermal environment in cities, and they also lower the energy demand for use in air conditioning, thereby reducing anthropogenic heat releases and the intensity of the UHI further. This is a positive feedback for urban microclimate conditions. The influence on urban air quality is twofold: The reduction in energy consumption decreases air pollutant releases in cities; however, the UHI mitigation strategies increase the urban boundary layer stability, weakening turbulence and decreasing the vertical dispersion of air pollutants. The increasing vegetation coverage in green roof mitigation might reduce aerosol pollution by increasing dry deposition over urban areas; it also might increase the release of volatile organic compounds from plants and exacerbate ozone pollution. Additional studies should be performed to investigate how the changes in the boundary layer structure influence urban air quality to provide an overall evaluation of this topic, especially in Chinese cities that are currently suffering air quality problems.

Acknowledgments. This study was supported by the Chinese National Key R&D Program (2016YFC0200501) and the National Natural Science Foundation of China (Grants 41675008 and 51538005).

REFERENCES


Lemonsu, A., S. Bastin, V. Masson, and P. Drobniski, 2006: Vertical structure of the urban boundary layer over Marseille...


Vázquez Morales, W., A. Jazilevich, A. García Reynoso, E. Caetano, G. Gómez, and R. D. Bornstein, 2016: Influence of green roofs


