Interaction of urban heat islands and heat waves under current and future climate conditions and their mitigation using green and cool roofs in New York City and Phoenix, Arizona

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Abstract

Urban environments and heat waves interact synergistically and aggravate the thermal environment through the urban heat island (UHI) effect. Of concern is the potential for a projected warmer future climate to further compound heat waves in urban environments. The present study investigates the interaction of a 2006 heat wave in North America with two urban environments (Phoenix and New York City (NYC)) in current climate and future climate simulations. The future climate conditions were generated using the pseudo-global warming methodology. Multiple high-resolution (3 km) simulations were performed using the weather research and forecasting (WRF) model coupled with the single-layer urban canopy model to improve representation of urban processes and we explore how irrigated green roofs and cool roofs can mitigate heat wave amplification by UHIs. To quantify heat wave intensity, an analytical model is applied to the WRF model output that considers the urban surface heat and water vapor exchanges with the atmosphere. A future, warmer climate is found to amplify the UHI intensity during heat waves in both Phoenix (21%) and NYC (48%), but the amplification is of great uncertainty as its magnitude is comparable to the temporal variability of temperatures. The increase in urban heat index can be almost completely offset by adopting irrigated green roofs in urban areas, and partially offset by adopting cool roofs.

1. Introduction

In recent decades, significant progress has been made in understanding the relationship between rising greenhouse gas levels and the likelihood or severity of different classes of weather events (Herring et al 2016). Studies have shown that anthropogenic warming has increased the frequency and intensity of heat waves across most continents (Stott et al 2004, 2016, Takahashi et al 2016), and dynamical model projections suggest this trend will continue in this century (Fischer and Schär 2010, Perkins et al 2013). Urban areas, which already suffer from the urban heat island (UHI) effect, will bear the brunt of this trend unless appropriate urban planning strategies are adopted (Georgescu et al 2013, 2014).

Summer heat waves are one of the most high-impact and stressful phenomena for humans (Easterling et al 2000, Meehl and Tebaldi 2004). They can have a devastating impact in both urban and rural environments: the 2003 European heat wave was estimated to have caused 70,000 deaths across the continent (Robine et al 2008), and the 1995 heat wave in Chicago was estimated to be responsible for nearly 800 deaths (Hayhoe et al 2010). Of concern, heat waves are among the many types of extreme weather events projected to become
more frequent in the 21st century (Schär et al 2004, Meehl et al 2009, Kuglitsch et al 2010, Orlowsky and Seneviratne 2012), and the effects in cities, where UHIs aggravate heat stresses, are expected to become more severe (Grimmond 2007, Li and Bou-Zeid 2013).

Experts have strongly encouraged US cities to develop preventative mitigation and responsive adaptation strategies aimed to reduce the vulnerability of urban populations to extreme heat (Hayhoe et al 2010). Here we evaluate the impact of vegetation via green roofs (a roof covered with vegetation), and material via cool roofs (the albedo of a roof is increased) on the UHI effect. This is achieved by employing the single-layer urban canopy model (SLUCM), developed by Kusaka et al (2001).

To examine UHI intensity in a future climate, general circulation models (GCMs) are typically used. Two studies by McCarthy et al (2010) and Oleson et al (2010) coupled a GCM with the SLUCM to examine the influences of urban geometry and anthropogenic heat emissions on UHI intensity. Though such climate models have improved the representation of urban surfaces, their spatial resolution is too coarse to accurately describe urban areas (Kusaka et al 2016). An effective approach to better represent urban areas is to increase the resolution via dynamical downscaling with a regional climate model (RCM).

The present study uses a RCM to examine how the 2006 North American heat wave aggravated the UHIs of Phoenix and New York City (NYC). The RCM was coupled with the SLUCM, in part to quantify how green and cool roofs may alleviate urban heat aggravation. The pseudo-global warming (PGW) method (see section 2.2) is used to project how the 2006 heat wave may evolve in a future climate scenario.

1.1. The 2006 North American heat wave
The 2006 North American heat wave directly affected most of the United States and Canada from mid-July through late August. It was the ‘largest’ heat wave in many parts of the continent (Gershunov et al 2009), contributing to the deaths of over 100 people in California (http://nytimes.com/2006/07/28/us/28heat.html) and 140 people in NYC (http://nytimes.com/2006/11/16/nyregion/16heat.html). The 2006 heat wave was caused by a high-pressure system that covered most of North America for multiple weeks (see figure 1). Hot temperatures and high humidity dominated most of the continent, with almost every state ranking their monthly average temperature as ‘much above normal’ (https://ncdc.noaa.gov/temp-and-precip/us-maps).

Urban areas experienced particularly stifling conditions because of the interaction of the heat wave with UHIs, which is the focus of the present study. Two urban areas are selected for investigation—Phoenix, Arizona (PHX) and NYC to (i) capture the gradual eastward movement of the heat wave across the country; and (ii) ensure our results are somewhat generalizable across urban areas with different characteristics. Indeed, the Köppen–Geiger climate classification for Phoenix is tropical and subtropical desert climate, whereas NYC is humid subtropical climate.

During the 2006 heat wave, Phoenix experienced its hottest day since 1995 (48°C on July 21), while LaGuardia Airport in NYC recorded three consecutive days (1–3 August) above 38°C and very high humidity. Here, we define the heat wave event as a consecutive period when the daily maximum air temperature was greater than 43°C in Phoenix and 35°C in NYC, along with a pre-heat wave, heat wave and post-heat wave date range as (15–20, 21–24 and 25–31 July) for Phoenix and (27–31 July, 1–3 August, 4–6 August) for NYC. Figure 2 shows the 2 m relative humidity (%) and air temperature (°C) at selected observation sites in Phoenix and NYC, respectively. Measurements at an urban vegetation station and an airport station are shown to illustrate the results over heterogeneous urban land use. Temporal variations of humidity and temperature are similar over airport and vegetation stations, with airport stations observing higher temperatures. The PHX region has high temperature during the heat wave but low humidity, whereas NYC has high temperature and medium humidity during the heat wave period.

2. Numerical model setup for current and future climate experiments

2.1. Model setup and numerical experiments
All simulations performed in this study used the advanced research version 3.7.1 of the weather research and forecasting (WRF) model (Skamarock et al 2008). The model is initialized with National Centers for Environmental Prediction (NCEP) final (FNL) data with MODIS land use-land cover data enhanced by NLCD (https://mrlc.gov/nlcd06_leg.php) data for the urban regions of interest, i.e. PHX and NYC.

We used a two-way nested approach to focus on Phoenix and NYC (see figure 3). The outer domain (D01) covered the continental US with a horizontal grid spacing of 15 km. Inset were two nested model domains centered over PHX (D02) and NYC (D03), both with horizontal resolutions of 3 km. Additional details about the setup of WRF are presented in table 1(a). The simulations were performed for 22 continuous days, from 1200 UTC on 15 July 2006 to 1200 UTC on 6 August 2006.

An important benefit of performing these simulations with a 3 km horizontal spatial resolution is a more realistic representation of surface heterogeneity and the associated surface fluxes computed by the SLUCM. SLUCM captures the characteristics and dynamics of heat and moisture fluxes over urban areas
(Chen et al 2011) using a three-category urban land use—low-intensity residential (LIR), high-intensity residential (HIR) and industrial/commercial (COI). The urban parameters used in SLUCM are summarized in table 1(b). We have used the same urban morphological parameters for both PHX and NYC since it is not possible to assign two sets of urban parameters for two different regions in a single WRF simulation. The transition from urban to rural environments can be very sharp, hence a typical climate simulation with \( \sim 20 \) km horizontal spatial resolution will fail to resolve important circulations that develop near the boundaries of these two urban environments (see Kusaka et al 2016 for further discussion).

Four numerical experiments were performed (see table 2). Due to the uncertainty of future urban design projections for Phoenix and NYC, we assumed the urban characteristics of both metropolitan areas would not change for the future climate scenario, with the exception of adoption of green or cool roofs. The impact of projected urban growth is the subject of a future study.

2.2. Data preparation for current and future climate simulations

The outer domain (D01) of the current climate simulation (CTRL) receives initial and boundary conditions from the NCEP FNL reanalysis data (https://rda.ucar.edu/datasets/ds083.2/). The data are available on a \( 1^\circ \times 1^\circ \) grid every 6 h and interpolated in time to provide the boundary conditions for the simulations in this study.

Data for the future climate simulation was prepared following the PGW method (Hara et al 2008, Kawase et al 2009) and using FNL analysis data. The PGW methodology consists of adding a climate perturbation signal to the current climate of the atmosphere (i.e. FNL analysis data) to create a data set for the future period of interest. Both the initial and lateral boundary conditions FNL analysis are perturbed with a time evolving monthly mean fields from the Community Climate System Model (CCSM4). The monthly perturbations are valid at the middle of each month and they are added to the current weather field by linearly interpolating from monthly climatologies to each time period in the FNL analysis. One of the benefits of using this method is that the climate perturbation signal, can be added to the FNL analysis, while the hydrostatic and geostrophic balances were still maintained because the difference of two balanced mean fields retains the linear relationships with the virtual temperature, geopotential height, and horizontal wind perturbation fields. Further details about the approach can be found in Rasmussen et al (2011).

Use of the PGW methodology can also be found in recent studies (Trapp and Hoogewind 2016, Tewari et al 2017).

Figure 1. NCEP Final Analysis valid at 16 July and 3 August 2006 of mean sea level pressure (black contours) and surface temperature (°C; top panels) and surface relative humidity (bottom panels).
In the present study, the climate perturbation is developed by subtracting the current (1985–2005) monthly 21 year climatology from a future (2070–90) monthly 21 year climatology, derived from the CCSM4 RCP8.5 scenario data prepared at National Center for Atmospheric Research. The RCP8.5 scenario incorporates assumptions including high population and slow income growth along with modest rates of technological change and energy intensity improvements through the 21st century (Riahi et al. 2011). These factors lead to long-term higher energy demand and greenhouse gas emissions, which occur in the absence of climate change policies and consequently represents a realistic ‘worst case’ scenario.

The climate perturbation (composed of air temperature, relative humidity, u- and v-component of wind, geopotential height, soil temperature and sea surface temperature) is essentially the difference in the monthly climatology between the current climate and the future RCP8.5 climate projection, as simulated by CCSM4 (Gent et al. 2011). The perturbation is added to the FNL data used in the control simulation as described earlier. To illustrate the impact of this perturbation, figure 4 shows the 2 m temperature difference in D02 and D03 at 12:00Z 15 July 2006, revealing a warming of about 2 °C–3 °C in Phoenix and 4 °C–5 °C in NYC. The projected warming around NYC is relatively homogeneous, with the smallest temperature increase found over the ocean. For Phoenix, the magnitude of the warming shows a general decreasing trend from northeast to southwest.

2.3. Single-layer Urban Canopy Model and setup for green/cool roof experiments

The WRF model is coupled to the SLUCM, with hydrological improvements included since version 3.7 to better capture the urban water budget (see Yang et al. 2015a, 2016a for further information and Brownlee et al. 2017 for its application). We use this latest version for weather simulations in this study. Green roofs and cool roofs are two measures that have gained increasing popularity for UHI mitigation during the past decade (Santamouris 2014, Yang et al. 2016b, Yang and Wang 2017). We tested the effectiveness of green roofs and cool roofs as mitigation strategies for the UHIs of PHX and NYC assuming a 100% areal fraction deployed in each of the metropolitan areas. Our results therefore represent the maximum potential benefit of each strategy. For the green roof implementation, we used short grass as the vegetation type (with a 0.3 m deep loam soil layer and an albedo of 0.3) and assumed they were irrigated daily. In urban areas, potential evapotranspiration of patchy vegetation will be enhanced as compared to that of rural vegetation due
to local advection. Given that building rooftops are isolated from each other, this oasis effect is accounted for when simulating green roofs in this study. A value of 1.5 is used following the previous study (Yang et al 2015a), i.e. potential evapotranspiration of green roofs is multiplied by 1.5. The impact of soil and vegetation type on the performance of green roofs is presented in Yang and Wang (2014). For the cool roofs experiments, the albedo of the urban rooftop was increased to 0.7, following Li et al (2014).

Table 1. (a) Physical parameterization schemes used in the WRF simulations. (b) Canopy parameters over different urban land use in the WRF simulations.

(a)

| Planetary boundary layer | MYJ (Janjic 1994) |
|--------------------------|-------------------|
| Radiation scheme         | RRTMG (Iacono et al 2008) |
| Microphysics scheme      | Thompson (Thompson et al 2008) |
| Land surface model       | Noah (Chen and Dudhia 2001) |
| Urban model              | SLUCM (Kusaka et al 2001) |

(b)

| Urban morphological characteristics | COI | HIR | LIR |
|-------------------------------------|-----|-----|-----|
| Urban fraction                      | 0.95| 0.90| 0.50|
| Building height (m)                 | 10.0| 7.5 | 5.0 |
| Roof/road width (m)                 | 10.0| 9.4 | 8.3 |
| Thermal properties                  |     |     |     |
| Roof                                | 1.0 × 10^6 | 1.0 × 10^6 | 1.4 × 10^6 |
| Wall                                | 0.67 | 0.67 | 0.4004 |
| Road                                | 0.2  | 0.2  | 0.2  |
| Albedo                              | 0.9  | 0.9  | 0.95 |
| Emissivity                          | 0.2  | 0.2  | 0.2  |

Figure 3. WRF domains and land use map (a) all three domains (b) urban land use for a subset D02 and (c) urban land use for a subset D03. LIR, HIR, and COI refer to low-intensity residential, high-intensity residential, and commercial/industrial based on NLCD data. Observations from labeled locations were used to validate the current climate simulation.
2.4. Evaluation of the CTRL simulation using ground-based measurements

To ensure the model simulates the heat wave reasonably well, 2 m temperature and relative humidity from the CTRL simulation are compared to local observations in PHX (at seven locations) and NYC (at eight locations). To illustrate the model performance over different urban land use conditions, figure 5 shows the comparison at one vegetation station and one airport station in Phoenix and NYC, respectively. The CTRL simulation is able to capture the observed 2 m temperature and relative humidity over both stations with a reasonable accuracy. Mean absolute errors (MAEs) over individual stations are computed for pre-heat wave, heat wave and post-heat wave periods. Results are summarized in table 3.

The average 2 m temperature MAEs for the three periods are 1.57 °C, 1.29 °C, and 1.63 °C in Phoenix, and are 1.00 °C, 1.35 °C, and 1.10 °C in NYC. The model performs the best during the heat wave period in Phoenix region, and has the worst prediction during heat wave in NYC. In terms of 2 m relative humidity, MAEs at pre/during/post-heat wave periods are 4.11%, 3.68%, and 6.34% in Phoenix, respectively. For NYC, the MAEs of 2 m humidity are 4.92%, 6.85% and 5.67%. Note that as illustrated in figure 5, maximum errors in 2 m temperature can be up to 4 °C, while maximum errors in 2 m humidity can be as great as 20%.

An earlier study by Li et al (2014) using the WRF and the SLUCM found similar biases in the WRF-simulated 2 m air temperature. They noted the biases had the same sign for urban and suburban/rural sites, hence the UHI is not affected. Given the 2 m temperature biases for the three periods of interest in Phoenix and NYC are comparable to previous studies and are acceptable considering the uncertainty related to mesoscale climate modeling, we then use the WRF with SLUCM to understand the interaction of heat waves and UHI in a future climate.

3. Results

The UHI intensity is hereby quantified in two manners. First, it is computed as simply as the difference in the area-averaged 2 m temperature between urban and rural areas (ΔT₂, urban–rural). To estimate ΔT₂ for NYC and PHX, a circular area with a radius of 0.5° latitude or longitude centered at downtown urban cores is used. Within the circle, mean 2 m temperature is calculated for urban land use types (colored areas in figure 3) and rural land use types (white areas in figure 3). In section 4, the UHI intensity is computed using a more sophisticated method called the urban heat index (ΔT_uh), which also takes into account humidity and wind speed.

Table 2. Numerical experiments performed in this study.

| Scenario | Description of the scenario | Meteorological forcing |
|----------|----------------------------|-----------------------|
| CTRL | Current climate simulation with hydrological improvements (see section 2(c)) | Present climate (NCEP FNL data) |
| Future | Future warm climate conditions (using PGW method) | Future climate (FNL perturbed with CCSM4 data for RCP8.5 scenario) |
| Future_G | Future climate simulation with green roof | Future climate (FNL perturbed with CCSM4 data for RCP8.5 scenario) |
| Future_C | Future climate simulation with cool roof (roof albedo is set to 0.7) | Future climate (FNL perturbed with CCSM4 data for RCP8.5 scenario) |

Figure 4. The 2 m temperature difference (°C) at the model start time between the current and future climates in (a) D02 (Phoenix) and (b) D03 (NYC). Positive values indicate a warmer future climate.

Figure 5. The 2 m temperature difference (°C) at the model start time between the current and future climates in (a) D02 (Phoenix) and (b) D03 (NYC). Positive values indicate a warmer future climate.
3.1. UHI intensity during the 2006 heat wave in current and future climate simulations

The current-day CTRL simulation captures the expected diurnal variation in $\Delta T_2$ in both Phoenix and NYC (figure 6). The $\Delta T_2$ is the strongest in the early morning as urban areas with larger heat capacity cool less rapidly than rural areas, and is the weakest in the afternoon as rural areas heat rapidly from direct solar irradiance. The CTRL simulation also captures the expected differences in $\Delta T_2$ between Phoenix and NYC. Georgescu et al (2011) showed that Phoenix is surrounded by dry desert where evaporation is minimal and rural daytime surface temperatures will be significantly higher than those in urban areas. In contrast, NYC is surrounded by woods and grasslands, as well as being coastal. Hence it follows that the average $\Delta T_2$ is often negative in Phoenix and positive in NYC (figure 6).

Indicative of a synergism between the heat wave and the UHI effect, the daily mean $\Delta T_2$ is larger during the heat wave than the average value of pre- and post-heat wave periods, primarily due to the large nighttime $\Delta T_2$. Under the future climate, daily mean $\Delta T_2$ during the heat wave period increases by 21% in Phoenix and 48% in NYC as compared to current climate. The increase represents a warmer urban environment compared to rural environment in the future warm climate. However, figure 6 shows that the temporal variation in $\Delta T_2$ is large across the simulation period. In Phoenix, the maximum $\Delta T_2$ occurs in the post-heat wave period under both current and future climate. In NYC, though the future climate substantially increases maximum $\Delta T_2$ during the heat wave, the increase is only observed on one day. Considering the large variability in $\Delta T_2$, the interaction between climate warming and UHI during heat waves is of great uncertainty.
Figures 7(a) and (b) shows the change in $\Delta T_z$ from the present day simulation (CTRL) to the future climate simulation (Future). During the heat wave, the Future $\Delta T_z$ can be up to about 2°C higher than the CTRL in Phoenix, and up to about 4°C larger in NYC. Averaged over the diurnal cycle during the heat wave, the mean increase in $\Delta T_z$ under future climate is 0.59°C and 0.42°C in Phoenix and NYC, respectively. In other words, the UHI intensity is exacerbated by the projected future warm climate implying a synergistic interaction exists between the heat wave, the UHI effect and a warming climate. This synergistic interaction is caused by the contrasting responses of surface energy budgets in urban and rural areas to additional incoming energy. The trapping effect by urban canopy and modified thermal properties (lower albedo, larger heat capacity) of engineering materials allow urban areas to retain more heat than rural surfaces (Li et al 2015). We would like to point out that the interaction is not strong in both regions because the projected future warming is only 2°C–4°C, and previous strong interactions between UHI and heat waves were found under the conditions of 10°C abnormally hot. And the large temporal variability under future climate, e.g. $\Delta T_z$ can be 4°C larger in Phoenix during pre- and post-heat wave periods, leaves a large uncertainty on the synergistic interaction between future climate and UHI under heat waves.

Table 3. Summary of MAEs between the CTRL simulation and ground observations.

| Location     | Pre-heat wave | Heat wave | Post-heat wave | Pre-heat wave | Heat wave | Post-heat wave |
|--------------|---------------|-----------|----------------|---------------|-----------|----------------|
| Phoenix      |               |           |                |               |           |                |
| Buckeye      | 1.76          | 1.46      | 1.60           | 5.03          | 3.73      | 6.59           |
| Desert ridge | 1.37          | 1.11      | 1.35           | 3.40          | 3.57      | 6.23           |
| Encanto      | 1.55          | 1.30      | 1.84           | 4.29          | 5.16      | 5.84           |
| Greenway     | 1.40          | 1.21      | 1.55           | 3.45          | 3.70      | 5.61           |
| Mesa         | 1.47          | 1.21      | 1.55           | 3.90          | 2.93      | 6.17           |
| Skyharbor    | 1.75          | 1.51      | 1.79           | 4.48          | 3.28      | 7.40           |
| Waddell      | 1.68          | 1.27      | 1.72           | 4.24          | 3.38      | 6.60           |
| Average      | 1.57          | 1.29      | 1.63           | 4.11          | 3.68      | 6.34           |
| New York City|               |           |                |               |           |                |
| Central park | 1.09          | 1.30      | 1.06           | 5.22          | 6.12      | 5.32           |
| Essex        | 1.23          | 1.48      | 1.27           | 6.36          | 6.47      | 6.40           |
| JFK          | 0.94          | 1.24      | 1.14           | 5.08          | 6.48      | 6.03           |
| LaGuardia    | 0.89          | 1.31      | 1.05           | 4.98          | 7.47      | 5.67           |
| Long island  | 0.93          | 1.35      | 1.07           | 4.18          | 6.15      | 5.40           |
| Newark       | 0.82          | 1.46      | 1.03           | 3.83          | 7.92      | 5.24           |
| Republic     | 1.24          | 1.36      | 1.03           | 4.30          | 7.76      | 5.48           |
| Average      | 1.00          | 1.35      | 1.10           | 4.92          | 6.85      | 5.67           |
A recent study (Scott et al 2018) compared daily minimum air temperatures in 54 US cities for 2000–2015 and suggested that UHI reduces under warmer conditions. It also looked at 15 hottest nights during 2000–2015 and found weaker UHIs during heat waves. Based on the results, Scott et al (2018) suggested that the synergistic interaction between heat wave and UHI found by Li and Bou-Zeid (2013) is atypical. Schatz and Kucharik (2015) showed that in Madison, UHI estimated from daily maximum air temperature shows a much clearer increasing trend than UHI from daily minimum air temperature. Note that land surfaces receive the greatest radiative energy around noontime, then the surface heat is transferred to near-surface air through sensible heat fluxes that maximum air temperature usually occurs in the afternoon. The UHI intensity at daily maximum air temperatures therefore is controlled by how urban and rural surfaces respond to the strong incoming solar radiation. On the other hand, daily minimum air temperature usually happens at early morning shortly before sunrise, as longwave radiation continues to cool land surfaces throughout nighttime. At this time, even effective mitigation strategies during daytime such as green or cool roofs have little impact on UHIs (Li et al 2014). This indicates that the UHI intensity at daily minimum air temperature is likely to be determined by weather patterns, and therefore has a large variability (see figure 10 in Schatz and Kucharik 2015). We suspect the different approaches of utilizing air temperature measurements in Li and Bou-Zeid (2013) and Scott et al (2018) lead to the discrepancy between their findings. Considering the gap in the number of cities in these studies, this contradictory conclusion is worthy of further exploration.

3.2. Effect of irrigated green roofs and cool roofs on UHI intensity in the future climate

The Future simulations with irrigated green roofs and cool roofs (figures 7(c) and (d)) show that $\Delta T_2$ decreases significantly compared to the Future simulation without any mitigation strategy (figures 7(a) and (b)). The green
rooftop adoption almost nullifies the exacerbated UHI intensity $\Delta T_2$ simulated in the Future warm climate, cooling the urban area by around 1.5 °C in Phoenix and about 2.5 °C in NYC during and post-heat wave. The impact of green roofs is more pronounced over the NYC region as compared to Phoenix: In NYC, green roofs are approximately three times more effective than cool roofs whereas in Phoenix green roofs are approximately twice as effective as cool roofs. The stronger cooling benefit of green roofs than cool roofs here is inconsistent with previous studies (Georgescu et al. 2014, Li et al. 2014), primarily owing to the oasis effect and daily irrigation considered in this study. Ma et al. (2018) reported that with daily irrigation, green roofs reduce summertime 2 m air temperature in Sydney more effectively than cool roofs. As potential evapotranspiration of urban vegetation is enhanced by the oasis effect in this study, simulated cooling effect of green roof becomes further larger than that of cool roofs.

Figure 8 shows which strategy is more effective at reducing $\Delta T_2$ during the day (0800–1600 local time) and night (2000–0400 local time, the blue regions indicate where green roofs are more effective). Green roofs are clearly more effective during the day in both Phoenix and NYC. However, in Phoenix, it is isolated to predominantly urban areas. The rural areas tend to be cooler during the day when cool roofs are adopted, exposing the complex (and possibly compensating) flow responses when surface conditions are changed. At night in NYC, the entire region, including rural areas, are cooler when green roofs are adopted.

4. Urban heat index under current and future climate

Quantifying the UHI intensity with only 2 m temperature suffers from its neglect of other meteorological variables, such as humidity and wind speed, which are relevant to how people experience heat (Yang et al. 2015b). As mentioned earlier, a different way for computing the UHI intensity is the urban heat index, $\Delta T_{UH}$. This metric derived by Li and Bou-Zeid (2013) simultaneously solves the coupled heat and water vapor transfer between an urban surface and the atmosphere, and allows the investigation of variance with height. $\Delta T_{UH}$ is defined as:
\[ \Delta T_{\text{UH}}(x, z) = T_i(x, z) - T_r(z) = \left(1 - \frac{\beta_u}{\beta_r}\right) T_r^* f_1(x, z) + g(u_{10}) (Q_u - Q_r) f_2(x, z), \]

where subscripts \( u \) and \( r \) denote the urban and rural areas, \( T_i(x, z) \) is the urban temperature as a function of horizontal distance from the urban center \( (x) \) and height \( (z) \), \( T_r(z) \) is the rural temperature as a function of height, \( \beta \) is the surface moisture availability, \( T_r^* \) is a temperature related to rural temperature and specific humidity, \( u_{10} \) is the mean 10 m wind speed, \( g(u_{10}) \) is a positive function that decreases with \( u_{10} \), \( Q \) is the net radiation at the surface, and \( f_1(x, z) \) and \( f_2(x, z) \) are functions that come from the coupled solution of the advection-diffusion equations. Surface net radiation, 10 m wind speed, 2 m air temperature and 2 m relative humidity from WRF simulations are used as input. 2 m air temperature is used to estimate \( f_1(x, z) \) and \( f_2(x, z) \), and 2 m relative humidity is used as an approximation of surface moisture availability \( \beta_u \) and \( \beta_r \). These variables are averaged over the entire metropolitan area to estimate the value at urban center, and are averaged over the rural area within 0.5° latitude and longitude of the metropolitan center to represent the rural contribution. With the input parameters, the model can solve the growth of the urban thermal boundary layer at a resolution (horizontally and vertically) of 10 m. Detailed derivative processes of the model are referred to Li and Bou-Zeid (2013). \( \Delta T_{\text{UH}} \) accounts for variables related to the main physical processes that impact UHI dynamics.

Figure 9 shows the average daytime (0800–1600 local time) \( \Delta T_{\text{UH}} \) during the heat wave in Phoenix (21–24 July) in each of the four simulations. The horizontal axis shows the normalized distance from the upwind rural area (where \( 0 < x/x_u < 1 \) is the urban region). The vertical axis shows the normalized height above the ground and below one km because the assumed height of the planetary boundary layer is 1 km.

In Phoenix, the daytime average \( \Delta T_{\text{UH}} \) increases slightly (about 0.6°C) in the Future climate simulation (figures 9(a) and (b)). Note that \( \Delta T_{\text{UH}} \) is negative for both current and future climates, indicating a lower temperature in urban areas compared to rural areas. (As described earlier, the daytime urban cool island in Phoenix is caused by the surrounding desert having a smaller heat capacity relative to the built-up urban environment and minimal evaporative cooling.) The impact of built-up terrain on the overlying air layer gradually increases as air travels from upwind from rural areas into the urban region. At the downwind edge \( (x/x_u = 1) \), the daytime average \( \Delta T_{\text{UH}} \) at the
boundary layer height ($z/zh = 1$) is about 3 °C warmer than $\Delta T_{UH}$ near the surface.

In terms of the mitigation strategies, figures 9(c) and (d) show that green roofs are more effective at reducing $\Delta T_{UH}$ than cool roofs during the day in Phoenix. Near the surface, green roofs reduce the average daytime $\Delta T_{UH}$ by more than 10 °C, while cool roofs have a cooling effect of about 5 °C. While the cooling effect by green roofs and cool roofs decreases rapidly with height near the urban center, it is still noticeable at the top of the boundary layer. Note that the cooling impact in this section refers to $\Delta T_{UH}$ instead of air temperature, which accounts for the humidity, wind speed and available energy at the land surface.

At night in Phoenix, when the urban and rural areas reach temperature parity as radiative energy stored by engineering materials is released and warms the cities, the warmer Future climate simulation slightly increases the average $\Delta T_{UH}$ (figures 10(a) and (b)). The variety of $\Delta T_{UH}$ with height is much smaller compared to daytime. Reduction in $\Delta T_{UH}$ at the surface by green roofs and cool roofs (figures 10(c), (d)) is significantly less—approximately 1.4 °C and 0.8 °C, respectively. (Note the different color scales in figures 9 and 10). In other words, the future climate slightly increases $\Delta T_{UH}$ during the heat wave, and green roofs (and cool roofs to a lesser extent) have a significant effect on urban air temperatures during the day only.

In NYC, positive $\Delta T_{UH}$ values indicate a warmer environment in urban areas compared to rural areas (figures 11(a) and 12(a)). Unlike in Phoenix, the daytime $\Delta T_{UH}$ increases significantly under the warmer Future climate simulation in NYC (figure 11(b)). This is related to different vegetation types around NYC (pasture/hay compared to shrubland near Phoenix) providing additional energy for evapotranspiration and thereby evaporative cooling. The urban area has less moisture for evaporation due to its built nature, thus exacerbating $\Delta T_{UH}$. It is noteworthy that the urban surface has a stronger influence on the atmosphere in NYC than in Phoenix. In NYC during daytime, after a short distance into the urban region ($x/xu = 0.2$), air from upwind rural areas is significantly modulated at all heights.

Both green roofs and cool roofs appear effective at almost completely offsetting the future daytime UHI effect in NYC during the heat wave. Green roofs reduce daytime average $\Delta T_{UH}$ by over 5 °C, while cool
roofs reduce daytime $\Delta T_{UH}$ by about 2 °C (figures 11(c) and (d)). Green roofs also more effectively reduce the average $\Delta T_{UH}$ at night (figures 12(c) and (d)), although the UHI effect is not completely offset.

These results reveal an interaction between the UHI intensity and climate change that is strongly dependent on the local climate and environment. For example, the numerical experiments indicate vegetation types in rural areas are critical factors in understanding this interaction. In a warming climate, the UHI intensity is expected to increase notably more for NYC than Phoenix because of the vast dry, urban area in NYC. Fortunately, the green roof and cool roof strategies appear effective measures to offset the UHI effect in NYC, especially during the day.

We note that a warmer future climate and a heat wave serve similar roles in increasing the large-scale background ambient temperature, hence the imposition of a heat wave on a warmer future climate further exacerbates UHI effects. This is consistent with the findings of Li and Bou-Zeid (2013).

5. Summary and conclusions

The interactions between UHIs, heat waves, and a warming climate were investigated using observations and numerical simulations of the 2006 heat wave in the United States. The UHI intensity was amplified during the heat wave in both Phoenix and NYC, the two regions of interest in this study. A key result is that a warming climate was found to intensify the interaction between UHIs and heat waves, though such intensification is of large uncertainty considering the temperature variability. Critically, the exacerbated UHI can be almost completely offset by adopting a widespread green roof strategy.

With the predicted intensification of heat waves under a changing climate, city residents will be at a significantly higher health risk than their rural counterparts. Changes in the heat index metric ($\Delta T_{UH}$), which considers temperature, wind speed and humidity and is therefore more relevant to human comfort, indicate that green roof deployment has a significantly stronger cooling effect than cool roofs on the urban atmosphere. The effectiveness of such mitigation strategies, and others not discussed here, is controlled (in part) by
the size of the urban area and the type of vegetation in surrounding rural areas.

There are some limitations of the present study, which the authors would like to highlight:

1. The effects of future urban expansion are not considered. Georgescu et al. (2013) suggests that the expansion-induced summer warming can be greater than the projected global warming in Arizona. It would be of value to investigate the interactions between UHIs, heat waves, and a warming climate with an expanding metropolitan area. Such studies are planned for future work.

2. The adopted PGW approach provides a first-order estimate of the potential climate warming impact and, in this study, is derived solely on the CCSM4 GCM. It is expected that CCSM4 have its own biases, which propagate into the simulations presented. A standard way to model biases is to use an ensemble of climate projections generated from different GCMs. However, as indicated by Rasmussen et al. (2011), large-scale features of the climate signal are expected to be similar and hence the conclusions derived from the data of a single GCM may not alter the results presented herein.

3. Phoenix and NYC have varied urban morphologies and vegetation. However, identical urban morphological parameters and urban vegetation were used in the SLUCM for both cities. Unfortunately, this limitation was introduced because the simulation of the Phoenix and NYC nested domains occurred within a single parent domain. While the impact of using identical urban parameters and vegetation is unknown, the authors believe that the relative impact of the interaction of the heat wave with the UHIs of Phoenix and NYC under future climate conditions would remain similar. Hence, the conclusions would be unchanged.

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Figure 12. Averaged nighttime (2000–0400 local time) $\Delta T_{UHI}$ for (a) current climate, (b) future climate, (c) future climate with green roofs, and (d) future climate with cool roofs during the heat wave (1–3 August) in New York.
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