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Urban climate effects on extreme temperatures in Madison, Wisconsin, USA

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Abstract

As climate change increases the frequency and intensity of extreme heat, cities and their urban heat island (UHI) effects are growing, as are the urban populations encountering them. These mutually reinforcing trends present a growing risk for urban populations. However, we have limited understanding of urban climates during extreme temperature episodes, when additional heat from the UHI may be most consequential. We observed a historically hot summer and historically cold winter using an array of up to 150 temperature and relative humidity sensors in and around Madison, Wisconsin, an urban area of population 402,000 surrounded by lakes and a rural landscape of agriculture, forests, wetlands, and grasslands. In the summer of 2012 (third hottest since 1869), Madison’s urban areas experienced up to twice as many hours $\geq 32.2\, ^\circ\text{C} (90\, ^\circ\text{F})$, mean July $T_{\text{MAX}}$ up to 1.8 $^\circ\text{C}$ higher, and mean July $T_{\text{MIN}}$ up to 5.3 $^\circ\text{C}$ higher than rural areas. During a record setting heat wave, dense urban areas spent over four consecutive nights above the National Weather Service nighttime heat stress threshold of 26.7 $^\circ\text{C} (80\, ^\circ\text{F})$, while rural areas fell below 26.7 $^\circ\text{C}$ nearly every night. In the winter of 2013–14 (coldest in 35 years), Madison’s most densely built urban areas experienced up to 40% fewer hours $\leq -17.8\, ^\circ\text{C} (0\, ^\circ\text{F})$, mean January $T_{\text{MAX}}$ up to 1 $^\circ\text{C}$ higher, and mean January $T_{\text{MIN}}$ up to 3 $^\circ\text{C}$ higher than rural areas. Spatially, the UHI tended to be most intense in areas with higher population densities. Temporally, both daytime and nighttime UHIs tended to be slightly more intense during more-extreme heat days compared to average summer days. These results help us understand the climates for which cities must prepare in a warming, urbanizing world.

1. Introduction

As Earth’s climate warms, the frequency and intensity of extreme heat is rising both globally (Luber and McGeehin 2008, Seneviratne et al 2014) and in cities (Tan et al 2010, Habeeb et al 2015, Mishra et al 2015), where 54% of the world’s population lives (United Nations, Department of Economic and Social Affairs, Population Division 2015). By 2030, the global urban population is projected to grow from 3.9 to 5 billion (United Nations, Department of Economic and Social Affairs, Population Division 2015), and urban land cover could triple its 2000 extent (Seto et al 2012). The simultaneous global trends of urbanization and climate change present a pressing challenge to create livable cities that are well prepared for future climates.

Extreme heat poses significant risks to Earth’s growing urban population. Heat waves in Chicago in 1995 (Changnon et al 1996), Paris and other European cities in 2003 (Garcia-Herrera et al 2010), and cities across Russia and Eastern Europe in 2010 (Barriopedro et al 2011) caused hundreds, thousands, and even tens of thousands of deaths. Such events have been described as social disasters (Klinenberg 2002) due to the importance of social and demographic vulnerability in explaining patterns of mortality (Semenza et al 1996, Vandentorren et al 2006, Keller 2013). However, cities not only concentrate vulnerable
populations, they also raise temperatures through the urban heat island (UHI) effect. Land surface and air temperatures both experience UHI effects (Arnfield 2003); this study focuses on urban effects on near surface air temperature.

The UHI refers to cities being warmer than their rural surroundings due to the built environment absorbing, retaining, and/or producing more heat than the natural landscape it replaces (Oke 1982). Many studies have reported greater UHI effects during the summer (Arnfield 2003, Schatz and Kucharik 2014, but see other references in Arnfield 2003 reporting other peak seasons), when higher urban temperatures could coincide with summer heat waves. Diurnally, the UHI typically peaks at night, when stored daytime heat prevents cities from cooling as much as rural areas (Oke 1982). During heat waves, this can produce longer, unbroken stretches of stressful temperatures, which pose greater public health risks than isolated hot days (Schwartz 2005, Tan et al 2007, Kalkstein et al 2011).

Under normal temperature conditions, UHIs may not create significant risks to urban communities. During extremes, however, UHIs could have critical impacts by raising already stressful temperatures during heat waves or by providing relief during severe cold. To improve our understanding of UHIs during these conditions, our study describes UHI effects during a historically hot summer, a record setting heat wave, and a historically cold winter in Madison, Wisconsin using one of the densest urban climate networks ever deployed (Schatz and Kucharik 2014).

Our study contributes to a growing body of literature on UHI effects on extreme heat. Several studies have used remotely sensed land surface temperature (e.g., Zaitchik et al 2006, Dousset et al 2011, Laaidi et al 2011, Schwarz et al 2011) or weather research and forecasting model simulations (e.g., Li and Bou-Zeid 2013, Meir et al 2013, Chen et al 2014, Gutiérrez et al 2015) to understand urban effects on extreme heat. Other studies, like ours, use urban sensor arrays to record urban effects on near surface air temperatures during extreme heat events (e.g., Harlan et al 2006, Bornstein and Melford 2009, Basara et al 2010, Kershaw and Millward 2012, Meir et al 2013).

Our study contributes several novel elements to this literature. First, little to no comparable research has been conducted in mid-sized cities like Madison with populations of 100 000–500 000, which together comprise over half of the global urban population (Cohen 2006). Another key element is that we observed not only a record setting heat wave, but also the historically hot summer in which it was nested. This provides a window into the mid- to late-21st century when both average temperatures and episodic extreme heat are projected to increase globally (IPCC 2014) and in Wisconsin (Kucharik et al 2011). Additionally, our temperature and humidity measurements allow us to describe both temperature and apparent temperature (AT) (Steadman 1984). This is one of the first urban studies to report both metrics at such high spatial resolution, providing novel insights into how UHIs affect heat exposure. Finally, to our knowledge, our study is the first to focus on urban effects on extreme cold. Climate change has decreased the incidence of extreme cold over recent decades in many parts of the world (Vavrus et al 2006, Mishra et al 2015), but cold remains a significant health risk factor (Mercer 2003), and we are aware of no other studies describing UHI effects during persistent, regionally extreme cold temperatures.

Using these observations, our objectives are to describe (1) how the UHI affected the intensity and duration of hot and cold conditions, (2) whether the UHI was stronger or weaker during more extreme temperatures, and (3) where UHI effects occurred spatially with respect to where most people lived.

2. Methods

2.1. Data

Madison, Wisconsin is a city of 233 000 in the north-central United States with an urban agglomeration population of 402 000 (US Census Bureau 2012). It has a humid-continental climate (Köppen: Dfa), 1981–2010 mean annual precipitation of 876 mm, and mean temperatures of −7 °C in January and 22 °C in July (NCDC 2014). Madison is surrounded by lakes and a rural landscape of agriculture, forests, wetlands, and grasslands (figure 1).

In March 2012, 135 HOBO® U23 Pro v2 temperature/relative humidity sensors in solar shields (Onset Computing 2010) were installed on streetlight and utility poles across the study area (figure 1). Sensor accuracy is 0.21 °C from 0 to 50 °C for dry bulb temperature and 2.5% from 10 to 90% for humidity (Onset Computing), though errors nearly twice as large have been reported for sensors within shields in field conditions (Nakamura and Mahrt 2005). Additional locations were added in 2012 and 2013 for a total of 150 sensors. The sensors were installed at 3.5 m height to minimize risk of disturbance. This differs from standard meteorological heights of 1.5–2 m, and the possible impacts of this are discussed in our results. Sensors were positioned on the north side of poles except in six cases to avoid the road right-of-way. Instantaneous measurements were recorded every 15 min.

AT reflects the interacting effects of temperature and humidity on physiological heat stress and is commonly used to measure heat exposure in epidemiological studies (Basu 2009). We calculated AT as: \( AT = -1.3 + 0.92 T + 2.2e \) (Steadman 1984), where \( T \) is dry bulb temperature (°C) and \( e \) is vapor pressure (kPa), calculated after Buck (1981). Although our study focuses on temperature and humidity, it is
important to remember that other micro-climatic factors, such as wind and sun exposure, also affect heat stress (Steadman 1984) and are also sensitive to urban development (Landsberg 1981).

Our study describes the summer of 2012 and winter of 2013–14, when 133 and 148 sensors were active, respectively. The summer of 2012 was Madison’s third hottest since 1869 when records began, with temperatures at the Dane County airport (MSN) reaching 32.2 °C (90 °F) on 39 days compared to the 1981–2010 average of nine days (NCDC 2014). In late June and early July, Madison experienced a severe heat wave with seven consecutive days over 35 °C, three consecutive days reaching 38.9 °C, and five consecutive days with record high temperatures (NCDC 2014).

The winter of 2013–14 was Madison’s coldest in 35 years, with 40 days below −17.8 °C (0 °F) compared to the 1981–2010 average of 17 days (NCDC 2014).

2.2. Calculating UHI intensity

UHI intensity (ΔT) is classically defined as the temperature difference between a city and its rural surroundings (Stewart and Oke 2012). However, the degree of urban development varies continuously across landscapes, as will the magnitude of UHI effects. Defining sites as simply urban or rural forces a continuum into a category, oversimplifying both cities and their UHIs. Recently, Stewart and Oke (2012) proposed a wider range of urban and rural land cover categories in order to better describe measurement sites, contextualize UHI intensity, and compare among studies. We offer an alternative definition of ΔT that does not rely on categories, but rather on continuous empirical relationships between temperature and the density of the built environment.

Figure 2 illustrates this definition using simulated data from 20 hypothetical measurement sites. Among
these 20 sites, there is a positive relationship between temperature and percent impervious surface coverage (IMP), with a slope of 0.05. For this paper, we define ΔT as the fitted temperature difference between areas with 0% IMP (i.e., rural) and 100% IMP (i.e., dense urban). In figure 2, ΔT is therefore 5 °C. Urban–rural AT differences (ΔAT) are defined in the same way. This definition puts UHI intensity explicitly in terms of urban development and avoids qualitative urban and rural land cover categories. Other measures of urban physical density, such as height–width ratio or sky view factor (Unger 2004), could be used instead of IMP, but for our study area, IMP consistently provided better model fits than sky view or height–width ratio.

We calculated ΔT on each day of our study period using linear regression models. The response variables were either daily TMAX, TMIN, ΔTMAX, or ΔTMIN at each sensor. The explanatory covariates were average IMP around each sensor (with water masked out), lake proximity, and topographic relief, which all influence temperatures in our study area (Schatz and Kucharik 2014).

Average IMP within circular buffers ranging in radius from 100 to 2000 m (in increments of 100 m) were tested to see which produced the best model fits across the entire study period. Of all radii tested, 600 m provided the best average fit of the temperature and AT data. It was more important to have a consistent set of covariates across the entire study period, enabling direct comparisons of daily ΔT/ATs, than to fit optimal models for each individual day. For lake proximity, we tested various linear and exponential relationships between lake proximity and temperature. The best fitting relationship across the entire study period was $e^{-bd}$, where $d$ is kilometers from the nearest lake shore. Topographic relief was the difference between local elevation and average elevation within a 0.8 km radius on a three meter resolution elevation model.

Daily ΔT/AT models were well behaved for normality, constant variance, and independence of predictors, but significant spatial autocorrelation occurred in 21% of daily models, for which we used spatial regression (Anselin 2002). The spatial models used inverse distance weighted neighbor matrices with maximum neighbor distances of 10 km in either spatial error or spatial lag models, which were selected using Lagrange multiplier tests (Anselin 1988). Using this same method, we explored diurnal UHI patterns during the July 2012 heat wave by calculating ΔT and ΔAT every 30 min.

### 2.3. UHI intensity versus extreme temperature

This analysis addressed two questions. First, did extremely hot or cold days have stronger UHIs? Second, were these relationships due to the extreme temperatures themselves, or to the weather conditions coinciding with extreme temperatures?

To answer the first question, we used linear mixed-effects models to test the relationship between temperature and UHI intensity. To test for extreme heat effects, we used data from the 50 consecutive days of the year with the highest average temperature across our study period (15 June–3 August for 2012–2014; $n = 150$ days) and fit models between daily ΔT and TMAX and between daily ΔAT and ATMAX. To test for extreme cold effects, we used data from the 50 days of the year with the lowest average temperature across our study period (23 December to 13 February for 2012–2014; $n = 100$ days) and fit models between daily ΔT and either minimum temperature or wind chill temperature (WCT). The WCT incorporates the perceived temperature effect of moving air increasing the rate of heat loss from the skin surface, and was calculated as

$$WCT = 13.12 + 0.6215 T - 11.37 V^{-0.16} + 0.3965 TV^{-0.16}$$

where $T$ is temperature (°C) and $V$ is wind speed (km hr$^{-1}$; Osczevski and Bluestein 2005). In all mixed models described in this section, year was included as a fixed effect, and a first order autoregressive correlation structure accounted for serial autocorrelation.

To answer the second question, we used a series of two linear mixed-effects models (Pinheiro et al 2014) on the extreme heat or cold data. The first model controlled for weather effects, with daily ΔT or ΔAT as the response variable. Covariates were daily average wind speed, percent sun, and either soil moisture (warm weather model) or snow depth (cold weather model), which are the primary meteorological determinants of UHI intensity in our study area (Schatz and Kucharik 2014) and elsewhere (Oke 1982, Runnalls and Oke 2000, Malevich and Klink 2011, Smoliak et al 2015). The second model used the residuals from the first model as the response variable, with daily TMAX or TMIN as the explanatory covariate. This series of models allowed us to test whether extreme temperatures had independent effects on UHI intensity beyond their correlation with key weather conditions.

For the weather covariates, temperature, wind speed, and snow depth came from MSN (NCDC 2014). Percent sun was calculated as measured insolation (300–1100 nm; S-LIB-M003 pyranometer, Onset Computing) averaged over three sites in our study area as a percent of potential insolation, which was calculated after Allen et al (1998). Soil moisture was measured at 10 cm depth (EC-5 sensor, Decagon) and also was averaged over three sites in our study area (figure 1).

### 2.4. Interpolations

The intensity and duration of extreme temperatures were visualized on a 400 × 400 m resolution grid using regression kriging, which uses information
about the land surface to inform data interpolation (Hengl et al. 2007). For covariates, IMP, lake proximity, and topographic relief were used (each as described in section 2.2). Lake effect and topography were averaged within each 400 m grid cell; IMP was averaged over a 600 m radius of each grid centroid (with water masked out). Spherical or exponential variogram fits were selected using Akaike Information Criterion. In winter 2013–14, lakes were frozen (Wisconsin State Climatology Office 2015) and there was no significant effect of lake proximity on temperatures, so lake effects were not included.

3. Results

3.1. Urban effects on heat intensity and duration

Madison’s most densely built urban areas are primarily concentrated in the isthmus located between the region’s two largest lakes, near the center of our study region (figure 1). In summer 2012, these densely built urban areas experienced mean July $T_{\text{MAX}}$ up to 1.8 °C higher; mean July $T_{\text{MIN}}$ up to 5.3 °C higher; and up to twice as many hours $\geq 32.2$ °C (90 °F) than rural areas (figures 3(a)–(c)). The physical density of the built environment, represented by IMP, was the primary spatial driver of these differences (table 1, figures 4(a)–(c)). The lakes tended to decrease adjacent temperatures, though these effects were mostly restricted to shoreline locations, as reflected by the rapid exponential decay of lake influence with distance from shore (section 2.2). Local topography was only statistically significant with respect to minimum temperatures (table 1), presumably due to cold air drainage to low lying areas.

The UHI had similar effects on AT as on dry bulb temperature (figures 4(a)–(c)). However, the slope of AT$_{\text{MAX}}$ versus IMP was lower than the slope of $T_{\text{MAX}}$ versus IMP, indicating that the UHI increased AT less than it increased $T$. This may relate to urban areas tending to have drier air, causing the UHI to raise AT$_{\text{MAX}}$ less than it raised $T_{\text{MAX}}$. Calculating urban–rural differences of mean July 2012 maximum dew point confirms this, yielding a ΔDP of −0.5 °C, indicating that urban areas averaged lower dew points.

Our sensors were at 3.5 m height, complicating comparisons with the official NOAA observing station at MSN (figure 1), which is at 2 m. However, comparing observed daily $T_{\text{MAX}}$ at the airport to $T_{\text{MAX}}$ interpolated from our sensors for the same location indicates that at 3.5 m, downtown Madison experienced up to 10 more days $\geq 32.2$ °C than MSN in 2012 (figure S1). If this 10 day difference held at 2 m as well, downtown Madison experienced approximately 49 days over 32.2 °C compared to the 39 days officially
recorded at MSN in 2012. This underscores the impact of urban climates on heat exposure, as well as the potential for rural or semi-rural airport stations to underestimate heat wave severity for nearby urban populations.

3.2. Urban effects during heat wave conditions

During the summer of 2012, Madison also experienced a record setting heat wave. From 1 to 7 July, the densest urban areas, which are near the center of our study region, experienced daily $T_{\text{MAX}}$ from 1.6 to 2.2 °C higher than rural areas, with similar urban effects on $AT_{\text{MAX}}$ (figure 5). Urban effects on nighttime temperatures were particularly striking. Figure 5 shows the growth of each day’s UHI during the evening and nighttime hours, prolonging high temperatures and diminishing nocturnal relief from extreme heat. Minimum temperatures in the densest urban areas averaged 4.4 °C higher than rural areas. This is reflected in the number of consecutive nights without temperatures falling below 26.7 °C (80 °F), which is a heat stress threshold used by the National Weather Service (NWS) (Robinson 2001). While most rural areas cooled below 26.7 °C every night, the densest urban areas spent over four days (temperature) and nearly 7 days (AT) without falling below 26.7 °C (figures 6(a) and (b)).

3.3. UHI intensity during extreme temperatures

Madison’s UHI also affected exposure to cold temperatures. In winter 2013–14, Madison’s most densely built areas experienced a mean January $T_{\text{MAX}}$ up to 1 °C higher and a mean January $T_{\text{MIN}}$ up to 3 °C higher than rural areas (figures 7(a) and (b)). Remarkably, urban areas also experienced up to 40% fewer hours $\leq$−17.8 °C (0 °F) than rural areas, a difference of nearly 200 h (figure 7(c)). The physical density of the built environment, represented by IMP, was the primary spatial driver of these patterns (table 1; figures 8(a)–(c)). Lake proximity was not significant in winter, when the lakes were frozen (Wisconsin State Climatology Office 2015), and local topography was only statistically significant with respect to average January $T_{\text{MIN}}$, presumably due to cold air drainage to low lying areas.

3.4. Population density and the UHI

More densely populated areas tended to experience larger UHI effects. The log of average population density (2010 US Census block group data) within a 1000 m radius of each sensor was linearly related to UHI intensity (figure 9). This was true during both the winter (figures 9(c)–(e)) and summer (figures 9(a), (b) and (f)), with minimum temperatures showing the strongest relationships (figures 9(c) and (d)).
3.5. Was the UHI more intense during more extreme temperatures?
During our warm temperature study period, there was a positive relationship between daily $T_{MAX}$ and $\Delta T$ at $T_{MAX}$ compared to summer average UHI intensity (figure 10(a)) with a similar relationship between $AT_{MAX}$ and $\Delta AT$ (figure 10(b)). Put simply, the daytime UHI tended to be stronger on hotter summer days, with most days over 32.2 °C experiencing above average UHI intensities (figures 10(a) and (b)). There was a weaker positive relationship between $T_{MAX}$ and UHI intensity at $T_{MIN}$ (figure 10(c)), but no significant relationship between $AT_{MAX}$ and $\Delta AT$ at $AT_{MIN}$ (figure 10(d)). Although these are weak relationships, they nonetheless indicate that UHI effects tended to be slightly stronger on hotter summer days. These relationships appeared to be due to hotter summer days coinciding with weather conditions that favor stronger UHIs. After accounting for the variation in $\Delta T$ that was explained by percent sun, wind, and soil moisture, $T_{MAX}$ no longer had significant effects on UHI intensity. Of these weather factors, only percent sun was significant ($p < 0.0001$).

During our cold temperature study period, most of the strongest UHIs occurred at $T_{MIN} \leq -17.8$ °C, while days with a $T_{MIN}$ over −5 °C experienced no above average UHIs (figures 11(a) and (b)). This created a negative relationship between daily $T_{MIN}$ and $\Delta T$, such that colder days and particularly nights tended to have stronger UHI effects. Using WCT, however, rendered these relationships non-significant ($\alpha = 0.01$), presumably because the strong winds that cause low WCTs also tend to weaken UHIs (Oke 1982). As with extreme heat, any significant relationships between $T_{MIN}$ and $\Delta T$ were due to colder days coinciding with weather conditions that favor stronger UHIs. Percent sun and snow depth were each significantly related to both $T_{MIN}$ and $\Delta T$ and accounted for any significant correlations between the two,
though increased anthropogenic heating during very cold conditions could also play a role (Sailor 2011).

4. Discussion

4.1. UHI effects on extreme temperatures

Madison’s UHI substantially increased extreme heat exposure, particularly at night. Heat stress is cumulative, and prolonged heat exposure poses greater risks to public health than isolated hot days (Schwartz 2005, Tan et al 2007, Kalkstein et al 2011). As such, perhaps our most alarming finding was that during the July 2012 heatwave, nearly all rural areas cooled below

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**Figure 7.** Duration and intensity of cold temperatures in Madison, Wisconsin during the winter of 2013–14, interpolated to 400 m resolution using regression kriging. (a) hours $T \leq -17.8\, ^\circ\text{C}$ in winter 2013–14; (b) January 2014 mean $T_{\text{MAX}}$; and (c) January 2014 mean $T_{\text{MIN}}$. Black lines delineate approximate urban extent; filled black polygons represent lakes.

**Figure 8.** Percent impervious surface coverage within a 600 m radius at our sensor locations versus observed (a) January 2014 mean $T_{\text{MAX}}$; and (b) January 2014 mean $T_{\text{MIN}}$; (c) Total hours at $T \leq -17.8\, ^\circ\text{C}$ during winter 2013–14. All relationships were significant at $\alpha < 0.0001$. 

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26.7 °C every night, but the densest urban areas near the center of our study region spent over four days (temperature) and nearly a full week (AT) without falling below 26.7 °C. This exemplifies the power of urban climates to fundamentally alter the severity of heat waves by prolonging and intensifying hot conditions. The UHI had similar effects on AT as on temperature, though during the daytime, urban effects on AT tended to be smaller than urban effects on dry bulb temperature. This is presumably because evapotranspiration from rural soils and vegetation raised rural humidity relative to the urban landscape, particularly during the daytime when evapotranspiration typically peaks.

At the other end of the temperature spectrum, Madison’s UHI reduced exposure to cold temperatures, which can be a significant health risk factor (Mercer 2003). Urban warming during severe cold could save lives and significantly reduce winter heating demand (Kolokotroni et al 2012). In regions susceptible to cold temperatures, it is important to consider these potential cold weather benefits when designing UHI mitigation measures to lower heat risk.

4.2. Extreme heat effects on UHIs

Not only did the UHI increase the severity of extreme heat in Madison, but UHI intensity was greater than the summer average during periods of extreme heat. Several other studies have also reported that UHI intensity is as strong or stronger during heat waves compared to summer background conditions (Harlan et al 2006, Li and Bou-Zeid 2013, Meir et al 2013, Li et al 2015). In Madison, we attributed this to hot summer days coinciding with clearer skies, which favor stronger UHIs (Oke 1982). In Baltimore, Li and Bou-Zeid (2013) attributed the phenomenon to low wind speeds and drier soils during heat waves, which also facilitate stronger UHIs (Oke 1982). In general, heat waves result from stagnant high pressure systems (Loikith and Broccoli 2012) that are associated with clearer skies, calmer winds, and drier soils, all of which favor greater UHI intensity (Oke 1982, Schatz and Kucharik 2014). This suggests that heat wave conditions may generally facilitate stronger UHIs.

Further, Li et al (2015) explored the synergy between heat waves and UHIs using an energy budget approach in Beijing. They found that heat waves increased sensible heat flux relatively more in urban areas and latent heat flux relatively more in rural areas,
leading to greater urban–rural temperature divergence on hotter days. Essentially, heat waves tended to magnify existing differences in urban and rural energy budgets, with more energy partitioned to latent heat in rural areas and more to sensible heat in urban areas. These traits of urban and rural energy budgets are typical of cities (Oke 1982), providing further support for the hypothesis that UHIs strengthen during heat waves. Anthropogenic heating from combustion and air conditioning may also increase during heat waves (Stone 2012), further strengthening UHIs. More research is needed to test these hypotheses, but taken together, this represents a growing body of evidence that UHIs tend to strengthen during extreme heat.

4.3. Population density and UHI intensity

Oke (1973) first described the positive relationship between the log of a city’s population and its maximum UHI intensity. Our study is the first to show a similar relationship within a single urbanized area, such that the most densely populated parts of our study region tended to experience the strongest UHI effects. This does not imply that large concentrations of people create intense UHIs (but see Sailor 2011), but rather that densely built urban areas tend to have both high population density and intense UHI effects. We suspect that this will hold true in many cities, although population density and the physical density of the built environment certainly can be decoupled. People may not live in commercial or industrial areas, for example, and informal urban settlements can have extremely

Figure 10. Daily maximum temperature versus UHI intensity during the period 15 June–03 August from 2012 to 2014. The y-axes represent daily UHI intensity ($\Delta T$ or $\Delta AT$) at each day’s maximum $T$ or AT. The x-axes represent the corresponding daily maximum $T$ or AT at MSN. Horizontal dotted lines represent seasonal mean UHI intensity. ns = not significant at $\alpha = 0.01$ in linear mixed effects models.

Figure 11. Daily minimum temperature versus UHI intensity during the period 23 December–13 February from 2012 to 2014. The y-axes represent UHI intensity ($\Delta T$), as calculated in section 2.2, at each day’s maximum or minimum $T$. The x-axes represent the corresponding daily minimum temperature at MSN. Horizontal dotted lines represent seasonal mean UHI intensity. All relationships are significant at $\alpha = 0.01$ in linear mixed effects models.
high population densities (Streetfield and Karar 2008) without the dense, tall buildings associated with strong UHIs. Nonetheless, urban residents tend to spend much of their time in densely built areas, whether to live or to work, where they may encounter not just urban warming, but relatively strong urban warming.

4.4. The UHI and climate change projections
Climate change projections commonly report future changes in the number of days above high temperature thresholds. For example, Madison currently averages 9 days per year ≥32.2 °C, but this is projected to reach 29–37 days by mid-century and 37–65 days by late century (Kucharik et al 2011), depending on the greenhouse gas emissions scenario (B1, A1B, A2; IPCC 2000). However, these projections do not account for urban climate effects, which is concerning for two reasons. First, cities are where most people will encounter future warming. Second, we observed substantially more time above high temperature thresholds in urban areas compared to rural areas (figures 3, 6, S2), including up to 21 more days ≥32.2 °C in urban versus rural areas in 2012 (figure S1). This suggests that projections failing to account for UHIs could considerably underestimate the amount of heat for which urban communities need to prepare (Fischer et al 2012, Argüeso et al 2015, Oleson et al 2015), with the largest underestimates in the largest cities with the highest populations and strongest UHIs.

5. Conclusion
Using a dense network of temperature and humidity sensors, we recorded UHI effects on historically hot and cold conditions in Madison, Wisconsin. More densely built and populated urban areas experienced significantly greater exposure to extreme heat and lower exposure to severe cold. Further, UHIs tended to be more intense during extreme heat episodes due to hot days coinciding with weather conditions favorable to strong UHIs. These results advance our understanding of urban climates during thermal extremes and help urban communities understand the risks they face in a warming, urbanizing world.

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References
Allen R G, Pereira L S, Raes D and Smith M 1998 Crop evapotranspiration—guidelines for computing crop water requirements FAO Irrigation and Drainage paper 56 (http://fao.org/docrep/X0490E/x0490e00.htm)
Anselin L 1988 Lagrange multiplier test diagnostics for spatial dependence and spatial heterogeneity Geogr. Anal. 20 1–17
Anselin L 2002 Under the hood: issues in the specification and interpretation of spatial regression models Agric. Econ. 27 247–67
Argüeso D, Evans J P, Pitman A J and Di Luca A 2015 Effects of city expansion on heat stress under climate change conditions PLOS ONE 10 e0117066
Arnfield A J 2003 Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island Int. J. Climatol. 23 1–26
Barriopedro D, Fischer E M, Luterbacher J, Trigo R M and Garcia-Herrera R 2011 The hot summer of 2010: redrawing the temperature record map of Europe Science 332 230–4
Basara J B, Basara H G, Illston B G and Crawford K C 2010 The impact of the urban heat island during an intense heat wave in Oklahoma city Adv. Meteorol. 2010 1–10
Basu R 2009 High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008 Environ. Health 8 1–40
Bornstein R and Melford A 2009 UHI and human heat-stress values during the July 2006 Portland, OR heat wave 2nd Int. Conf. UHIs (LBNL, CA, 21–23 September) (http://heatisland2009. lbl.gov/docs/210920-bornstein-doc.pdf)
Buck A L 1981 New equations for computing vapor pressure and enhancement factor J. Appl. Meteorol. 20 1527–32
Changnon S A, Kunkel K E and Reinke B C 1996 Impacts and responses to the 1995 heat wave: a call to action Bull. Am. Meteorol. Soc. 77 1497–506
Chen F, Yang X and Zhou W 2014 WRF simulations of urban heat island under hot-weather synoptic conditions: the case study of Hangzhou city, China China Atmos. Res. 138 364–77
Cohen B 2006 Urbanization in developing countries: current trends, future projections, and key challenges for sustainability Technol. Soc. 28 63–80
Dousset B, Gourmelon F, Laaidi K, Zeghnoun A, Giraudet E, Brelart P, Mauri E and Vandentorren S 2011 Satellite monitoring of summer heat waves in the Paris metropolitan area Int. J. Climatol. 31 313–23
Fischer E M, Oleson K W and Lawrence D M 2012 Contrasting urban and rural heat stress responses to climate change: heat stress response to climate change Geophys. Res. Lett. 39 L13705
Garcia-Herrera R, Diaz J, Trigo R M, Luterbacher J and Fischer E M 2010 A review of the European summer heat wave of 2003 Crit. Rev. Environ. Sci. Technol. 40 267–306
Gutiérrez E, González J E, Martíll A, Bornstein R and Arend M 2015 Simulations of a heat-wave event in New York City using a multilayer urban parameterization J. Appl. Meteorol. Climatol. 54 283–301
Habeb D, Vargo J and Stone B 2015 Rising heat wave trends in large US cities Nat. Hazards 76 1651–65
Harlan S L, Brazel A J, Prashad L, Stefanov W L and Larsen L 2006 Neighborhood microclimates and vulnerability to heat stress Soc. Sci. Med. 63 2847–63
Hengl T, Heuvelink G B M and Rössler D G 2007 About regressionkriging: from equations to case studies Comput. Geosci. 33 1301–15
IPCC 2014 Climate Change 2014: Impacts, Adaptation, and Vulnerability: A Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed Field et al. (Cambridge: Cambridge University Press)

IPCC 2000 Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change ed N Nakicenovic (Cambridge: Cambridge University Press)

Jin S, Yang L, Danielson P, Homer C, Fry J and Xian G 2013 A comprehensive change detection method for updating the National Land Cover Database to circa 2011 Remote Sens. Environ. 132 159–75

Kalkstein L S, Greene S, Mills D M and Samenow J 2011 An evaluation of the progress in reducing heat-related human mortality in major US cities Nat. Hazards 56 113–29

Keller R C 2013 Place matters: mortality, space, and urban form in the 2003 Paris heat wave disaster Fr. Hist. Stud. 25 283–304

Kershaw S E and Millward A A 2012 A spatio-temporal index for changes in observed climate extremes in global urban areas Environ. Res. Lett. 7 024005

Laaidi K, Zeghnoun A, Dousset B, Bretin P, Vandentorren S, Keller R C 2013 Place matters: mortality, space, and urban form in the 2003 Paris heat wave disaster Fr. Hist. Stud. 25 283–304

Li D, Sun T, Liu M, Yang L, Wang L and Gao Z 2015 Contrasting consumption in of heat consumption in the urban heat island: impact on current and future energy consumption in office buildings Energy Build. 47 302–11

Klinenberg E 2002 Heat Wave: A Social Autopsy of Disaster in Chicago (Chicago: University of Chicago Press) p 328

Kolokotroni M, Ren X, Davies M and Mavrogianni A 2012 London’s urban heat island: impact on current and future energy consumption in office buildings Energy Build. 47 302–11

Kucharik C et al 2011 Wisconsin initiative on climate change impacts Climate Working Group Report: Climate change in Wisconsin (Madison, WI: Nelson Institute for Environmental Studies and the Wisconsin Department of Natural Resources) (25 March 2015) (http://wici.wisc.edu/report/ClimChange.pdf)

Laaidi K, Zeghnoun A, Dousset B, Bretin P, Vandentorren S, Giraudet E and Beaudeau P 2011 The impact of heat islands on mortality in Paris during the August 2003 heat wave Environ. Health Perspect. 119 201–6

Landsberg H E 1981 The Urban Climate vol 28 (New York: Academic) p 275

Li D and Bou-Zeid E 2013 Synergistic interactions between urban heat islands and heat waves: the impact in cities is larger than the sum of its parts J. Appl. Meteorol. Climatol. 52 2051–64

Li D, Sun T, Liu M, Yang L, Wang L and Gao Z 2015 Contrasting responses of urban and rural surface energy budgets to heat waves explain synergies between urban heat islands and heat waves Environ. Res. Lett. 10 054009

Loikith P C and Broccoli A J 2012 Characteristics of observed atmospheric circulation patterns associated with temperature extremes over North America J. Clim. 25 7266–81

Luber G and McGeehin M 2008 Climate change and extreme heat events Am. J. Prev. Med. 35 249–55

Malevich S B and Klink K 2011 Relationships between snow and the wintertime Minneapolis urban heat island J. Appl. Meteorol. Climatol. 50 1884–94

Meir T, Orton P M, Pullen J, Holt T, Thompson W T and Arend M F 2013 Forecasting the New York city urban heat island and sea breeze during extreme heat events Weather Forecast. 28 1460–77

Mercer J 2003 Cold—an underrated risk factor for health Environ. Res. 92 8–13

Mishra V, Ganguly A R, Nijssen B and Lettenmaier D P 2015 Changes in observed climate extremes in global urban areas Environ. Res. Lett. 10 024005

Nakamura R and Mahrt L 2005 Air temperature measurement errors in naturally ventilated radiation shields J. Atmos. Ocean. Technol. 22 1046–58

Oke T 1973 City size and the urban heat island Atmos. Environ. 7 769–79

Oke T R 1982 The energetic basis of the urban heat island Q. J. R. Meteorol. Soc. 108 1–24

Oleson K W, Monaghan A, Wilhelm O, Barlage M, Brunssell N, Feddema J, Hu L and Steinhoff D F 2015 Interactions between urbanization, heat stress, and climate change Clim. Chang. 129 525–41

Onset Computing 2010 HOBO Pro v2 user’s manual 10694–N MAN-U23 (http://onsetcomp.com/products/data-loggers/u23-003/#)

Osczevski R and Bluestein M 2003 The new wind chill equivalent temperature chart Bull. Am. Meteorol. Soc. 86 1453–8

Pinheiro J, Bates D, DebRoy S, Sarkar D and Core Team R 2014 Nlme: linear and nonlinear mixed effects models R package version 3.1-117 (http://CRAN.R-project.org/package=nlme)

Robinson P J 2001 On the definition of a heat wave J. Appl. Meteorol. 40 762–75

Runnalls K E and Oke T R 2000 Dynamics and controls of the near-surface heat island of Vancouver, British Columbia Phys. Geogr. 21 283–304

Sailer D J 2011 A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment Int. J. Climatol. 31 189–99

Schatz J and Kucharik C J 2014 Seasonality of the urban heat island effect in Madison, Wisconsin J. Appl. Meteorol. Climatol. 53 2371–86

Schwartz J 2005 Who is sensitive to extremes of temperature? A case-study on Epidemiology 16 67–72

Schwartz N, Lutenbach S and Seppelt R 2011 Exploring indicators for quantifying urban heat islands of European cities with MODIS land surface temperatures Remote Sens. Environ. 115 3175–86

Semenza J C, Rubin C H, Falter K H, Selankio J J, Flanders W D and Howe H L 1996 Heat-related deaths during the July 1995 heat wave in Chicago New Engl. J. Med. 335 84–90

Seneviratne S I, Donat M G, Mueller B and Alexander L V 2014 No pause in the increase of hot temperature extremes Nat. Clim. Change 4 161–3

Seto K C, Guneratp B and Hutrya L R 2012 Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools Proc. Natl. Acad. Sci. USA 109 16083–8

Smolik B, Snyder P, Twine T, Myklebust P and Hertel W 2015 Dense network observations of the Twin Cities canopy-layer urban heat island J. Appl. Meteorol. Climatol. in press (doi:10.1175/JAMC-D-14-0239.1)

Steadman R G 1984 A universal scale of apparent temperature J. Clim. Appl. Meteorol. 23 1674–87

Stewart I D and Oke T R 2012 Local climate zones for urban temperature studies Bull. Am. Meteorol. Soc. 93 1879–900

Stone J 2012 The City and the Coming Climate: Climate Change and the Places We Live (Cambridge: Cambridge University Press) p 206

Streetfield P K and Karar Z A 2008 Population challenges for Bangladesh in the coming decades J. Health Popul. Nutr. 26 261–6

Tan J, Zheng Y, Song G, Kalkstein L S, Kalkstein A J and Tang X 2007 Heat wave impacts on mortality in Shanghai, 1998 and 2003 Int. J. Biometeorol. 51 193–200

Tan J et al 2010 The urban heat island and its impact on heat waves and human health in Shanghai Int. J. Biometeorol. 54 75–84

Unger J 2004 Intra-urban relationship between surface geometry and urban heat island: review and new approach Clim. Res. 27 253–60

United Nations, Department of Economic and Social Affairs, Population Division 2015 World urbanization prospects: the 2014 revision (ST/ESA/Ser.A/366) (http://esa.un.org/unpd/wup/FinalReport/WUP2014-Report.pdf)

US Census Bureau 2012 Quantifying urban areas for the 2010 Census Department of Commerce Federal Register 77(59) pp 18652–69 (https://census.govgeo/reference/ua/urban-rural2010.html)

Vandentorren S, Bretin P, Zeghnoun A, Mandereau-Bruno I, Croisier A, Cochel G, Riberon J, Siberan I, Declercq B and Siberan I 2014 Impacts of extreme cold air outbreaks under greenhouse warming Int. J. Climatol. 34 1133–47

Vavrus S, Walsh J E, Chapman W L and Portis D 2006 The behavior of extreme cold air outbreaks under greenhouse warming Int. J. Climatol. 26 1133–47
Wisconsin State Climatology Office 2015 Madison lakes ice summary, University of Wisconsin-Madison (25 March 2015) (http://aos.wisc.edu/~sco/lakes/msnicesum.html)

Xian G, Homer C, Dewitz J, Fry J, Hossain N and Wickham J 2011 The change of impervious surface area between 2001 and 2006 in the conterminous United States Photogram. Eng. Remote Sens. 77 758–62

Zaitchik B F, Macalady A K, Bonneau L R and Smith R B 2006 Europe’s 2003 heat wave: a satellite view of impacts and land–atmosphere feedbacks Int. J. Climatol. 26 743–69