Urban Warming Challenges Verification of Frost Advisories and Freeze Warnings in Madison, Wisconsin

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ABSTRACT: Urban heat islands (UHIs) may increase the likelihood that frost sensitive plants will escape freezing nighttime temperatures in late spring and early fall. Using data from 151 temperature sensors in the Madison, Wisconsin, region during March 2012–October 2016, we found that during time periods when the National Weather Service (NWS) issued freeze warnings (threshold of 0.0°C) or frost advisories (threshold of 2.22°C) were valid, temperatures in Madison's most densely populated, built-up areas often did not fall below the respective temperature thresholds. Urban locations had a mean minimum temperature of 0.72° and 1.39°C for spring and fall freeze warnings, respectively, compared to −0.52° and −0.53°C for rural locations. On average, 31% of the region's land area experienced minimum temperatures above the respective temperature thresholds during freeze warnings and frost advisories, and the likelihood of temperatures falling below critical temperature thresholds increased as the distance away from core urban centers increased. The urban–rural temperature differences were greatest in fall compared to spring, and when sensor temperatures did drop below thresholds, the maximum time spent at or below thresholds was highest for rural locations during fall freeze warnings (6.2 h) compared to urban locations (4.8 h). These findings potentially have widely varying implications for the general public and industry. UHIs create localized, positive perturbations to nighttime temperatures that are difficult to account for in forecasts; therefore, freeze warnings and frost advisories may have varying degrees of verification in medium-sized cities like Madison, Wisconsin, that are surrounded by cropland and natural vegetation.

SIGNIFICANCE STATEMENT: The purpose of this study was to understand whether the urban heat island effect in Madison, Wisconsin, creates localized temperature patterns where county-scale frost advisories and freeze warnings may not verify. Approximately one-third of Madison's urban core area and most densely populated region experienced temperatures that were consistently above critical low temperature thresholds. This is important because gardening and crop management decisions are responsive to the perceived risk of cold temperatures in spring and fall that can damage or kill plants. These results suggest that urban warming presents forecast challenges to the issuance of frost advisories and freeze warnings, supporting the need for improved numerical weather prediction at higher spatial resolution to account for complex urban meteorology.

KEYWORDS: Forecast verification/skill; Operational forecasting; Heat islands; Local effects; Urban meteorology

1. Introduction

As urban areas expand, an increasing number of people, plants, insects, and mammals, the soil microbiome, and ecosystems in general will experience warmer temperatures due to expansion and intensification of urban heat islands (UHI) in addition to an increasing frequency and intensity of heat waves associated with climate change (Meehl and Tebaldi 2004; Mishra et al. 2015). Heat islands are urbanized regions that experience warmer temperatures than their less densely built-up and populated surroundings due to the built environment absorbing, retaining, and producing more heat than the ecosystems (e.g., forests, cropland, grassland or prairie) that they replaced (Oke 1982). Anthropogenic heat generation associated with motor vehicles and heating and cooling of buildings can further exacerbate the intensity and seasonal behavior of the UHI (Schatz and Kucharik 2014; Zhou et al. 2017). Urban heat islands also exist for a wide range of city size and population density (Oke 1973; Zhou et al. 2017).

The UHI is often associated with increased human health risks due to increased average temperatures experienced by humans and because the impacts of extreme heat events can be exacerbated (Mishra et al. 2015). Heatwaves are the biggest cause of weather-related deaths in the United States (Changnon et al. 1996). While UHIs contribute to heat intensity in urban areas (Basara et al. 2010; Schatz and Kucharik 2015), UHIs can also mitigate extreme cold events, reducing heating demand and providing shelter from cold hazards to people and animals during persistent extreme cold weather events (Schatz and Kucharik 2014, 2015; Yang and Bou-Zeid 2018). UHIs can also impact soil temperatures, ground freeze–thaw cycles, and the accumulation and melting rates of

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snow and ice, and therefore may necessitate the use of less road salt applications compared to more rural locations away from city centers during winter in mid- and northern latitudes to achieve safe driving conditions.

Despite the breadth of studies on UHI effects, to our knowledge few studies have suggested any benefits of UHI associated warming to crop or other plant growth through increased growing degree days (GDDs) and mitigating freezing temperatures during spring and fall that extends the growing season (Schatz and Kucharik 2016). Each year, cold weather hazards (e.g., freeze or frost) pose expected seasonal risks to large scale agriculture, private gardens, and other vegetation. Waffle et al. (2017) suggested UHIs expand agricultural opportunity in northern latitudes, and used the city of Toronto, Canada, as an example. Toronto has experienced an increase in GDDs from 1000 to 1500 since the mid-1800s, but surrounding rural location GDDs have remained unchanged (Waffle et al. 2017). Baker et al. (2002) reported that urban areas of Phoenix, Arizona, can grow oranges and bougainvilleas without risk of frost damage because the UHI effect prevented temperatures from reaching threshold required to harm these plants. However, Baker et al. (2002) also reported that cotton planted at agricultural sites at the urban edge of Phoenix suffered high heat stress, reducing the quality and quantity of the harvest. These contrasting results suggest that the benefits of UHI to plants will be dependent on the typical climate of a region, with colder latitudes likely benefiting the most.

The UHI effect in Madison, Wisconsin, has been studied extensively including Madison's reduced exposure to extreme cold temperatures and increased severity of extreme heat events (Schatz and Kucharik 2015). Generally, Madison's UHI intensities were found to be higher during summer months (and nighttime) and lower during winter months (Schatz and Kucharik 2014). The UHI effect has also lengthened Madison's freeze-free growing season by several weeks compared to surrounding rural areas (Schatz and Kucharik 2016; Zipper et al. 2016) and increased GDDs by 14% in the most densely populated urban areas (Schatz and Kucharik 2016). Urban heat effects on the growing season (either start or end) were found to be greater in fall than in spring, likely due to colder and more uniform subsurface temperatures in the spring as a result of frozen subsurfaces in winter (Schatz and Kucharik 2016).

Freezes and the formation of frost are cold weather hazards that can cause widespread damage to plants, and in recent decades the occurrence of false springs has been increasing, putting agricultural crops and other vegetation at higher risk for damage from cold temperatures (Augspurger 2013; Peterson and Abatzoglou 2014; Westby and Black 2015). The NWS local weather forecast offices (WFO) generally issue frost advisories and freeze warnings when minimum temperatures are forecast to reach 0.56°–2.2°C (33°–36°F) and 0.0°C (32°F) or below, respectively, during the locally defined growing season (National Weather Service 2019). However, the values of 0.0° and 2.2°C are sometimes nominal thresholds because the decision to issue frost advisories or freeze watches and warnings can be based on the expected impacts. Temperature is often combined with other factors such as cloud coverage, wind, length of time below temperature thresholds, and dew or frost deposition when making specific decisions (J. Gagan, National Weather Service, 2023, personal communication). Hard freeze warnings can also be issued when temperatures are below −2.2°C (28°F) (National Weather Service 2019). The NWS freeze warnings and frost advisories alert citizens to protect sensitive outdoor vegetation and serve to notify farmers that crops—sometimes newly emerged in spring—may be susceptible to tissue damage. During late summer or fall, the NWS notifications generally signal the end of the growing season to all.

Official NWS forecasts currently rely on the National Blend of Models (NBM) including the High Resolution Rapid Refresh (HRRR). The higher spatial resolution models and other supplemental observation networks (e.g., the Meteorological Automated Data Ingest System or MADIS) used by the NWS have improved the representation of urban–rural temperature differences. However, forecasting challenges in urban regions can still persist depending on the ability to perform bias correction with other observations such as those from MADIS and the MesoWest network. For example, in the Madison region, only a few supplemental observation sites are available for bias correction, and therefore the influence of the UHI may not be fully represented in gridded temperature forecasts and the issuance of frost advisories and freeze warnings. Until NWP models improve upon their representation of the urban environment and the influence of the land surface on boundary layer interactions, their accuracy will likely be challenged in regions of high population density (McNorton et al. 2021).

To our knowledge, no previous studies have examined how UHIs challenge low temperature forecasts and influence the verification of NWS WFO issued frost advisories and freeze warnings. In this study, we examined the influence of urban warming on minimum temperatures during valid NWS freeze warnings and frost advisories issued for the Dane County, WI region that includes Madison, Wisconsin. The key objectives of this study were to 1) examine the spatial patterns of average nighttime low temperatures when freeze warnings and frost advisories were valid by the NWS Milwaukee/Sullivan WFO; 2) evaluate whether verification of freeze warnings and frost advisories differed in spring versus fall seasons; and 3) quantify the typical range of low temperatures across the heterogeneous rural–urban landscapes during the issuance of freeze warnings and frost advisories.

2. Data and methods

a. Study area description

This study focuses on Dane County, Wisconsin, and the state capital city of Madison, located near the center of the county. Dane County has a population of roughly 561 504, and nearly half of the county's residents (269 840 total) live within the city of Madison (U.S. Census Bureau 2021). The Madison region includes the Yahara chain of lakes and is surrounded by a rural landscape consisting of agriculture, forests, wetlands, and grasslands (Fig. 1). Across Dane County, 15% of land area is developed and 46% of the area is cropland, with corn and soybeans the two most commonly grown crops.

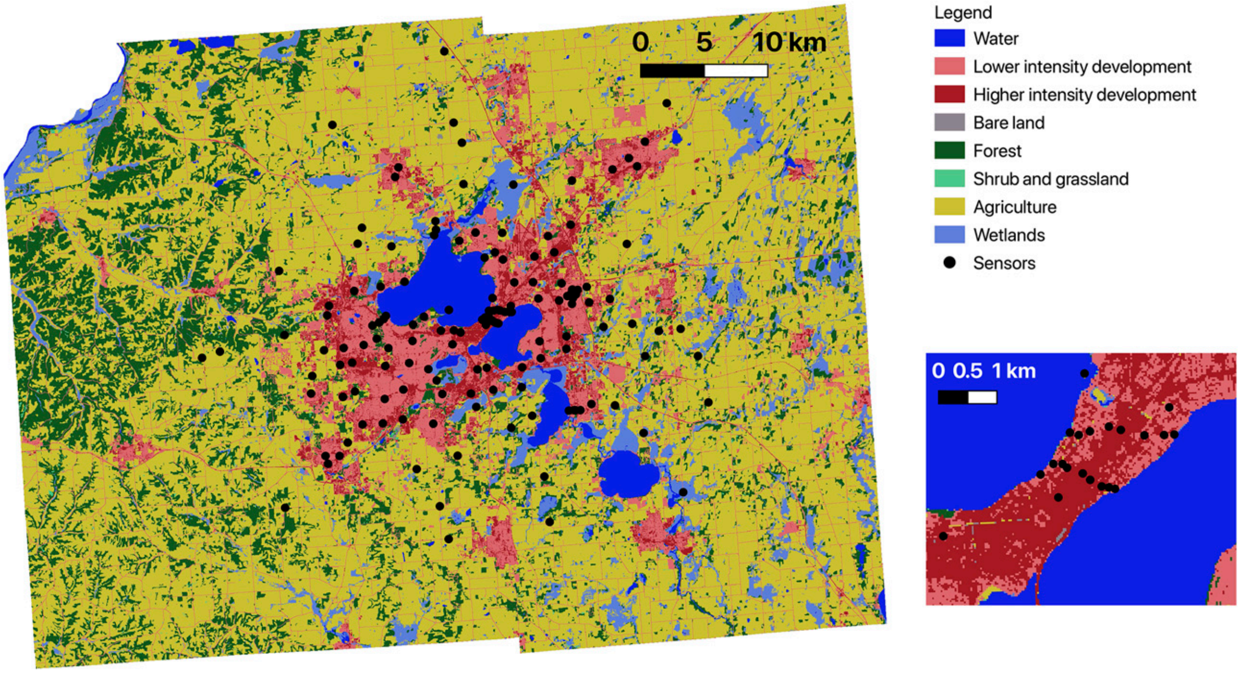

FIG. 1. Map of Dane County, Wisconsin, and the study region including the City of Madison; National Land Cover Database (NLCD) land cover classes from 2016 and temperature sensor locations are also illustrated. The inset map shows the downtown Madison isthmus between Lake Mendota and Lake Monona.

(U.S. Department of Agriculture 2017). Impervious surface coverage and population density is highest on Madison's isthmus, which is situated between Madison's two largest lakes (Mendota to the north and Monona to the south) at the center of the study region (Fig. 1). The official NWS weather observation station for Madison (MSN) is located 9 km northeast of the downtown area at the Dane County–Truax Regional Airport. Madison has a humid-continental climate (Köppen: Dfa), 1991–2020 mean annual precipitation of 943 mm, mean annual average temperature of 8.3°C, and a range in monthly average from −6.9°C in January to 22.2°C in July (NOAA/National Centers for Environmental Information 2022).

b. *Designation of freeze warning and frost advisory events*

Freeze warnings are typically issued by the NWS when minimum shelter temperatures are expected to be 0°C (32°F) or less during the locally defined growing season (National Weather Service 2019). Frost advisories are typically issued when minimum shelter temperatures are forecast to be 0.56°–2.22°C (33°–36°F) during the locally defined growing season, on nights with good radiational cooling conditions (National Weather Service 2019). The growing season is defined as the approximate period of time between the average date of the last killing frost in the spring and the average date of the first killing frost in the fall. In the Dane County region, the growing season for field crops and garden plants typically begins in late April or early May and ends in late September or early October.

The Iowa Environmental Mesonet (IEM), administered by Iowa State University, was used to collect dates and times that the NWS issued freeze warnings and frost advisories for Dane County including the city of Madison between March 2012 and December 2016. The IEM collects data from cooperating members with observing networks, including the NWS. Freeze warnings and frost advisories were issued a total of 27 times by the Milwaukee/Sullivan NWS forecast office for Madison and Dane County between January 2012 and December 2016 (Table A1). In total, 14 freeze warnings (7 in spring, 7 in fall) and 13 frost advisories (9 in fall, 4 in spring) were issued between April 2012 and October 2016. The starting time at which freeze warnings and frost advisories were valid was typically between 2300 and 0100 local time (LT) with an expiration time around 0600–0900 LT. Springtime frost advisories and freeze warnings occurred in the 6 April to 18 May time window, and during fall they occurred between 19 September and 22 October. Throughout this study, references to spring and fall seasons are by meteorological definitions (i.e., March–May for spring and September–November for fall).

c. *Madison region air temperature data*

In March 2012, 135 HOBO U23 Pro v2 internal temperature and relative humidity sensors and solar radiation shields from Onset Computing (Onset Computer Corporation, Bourne, Massachusetts) were placed on utility and streetlight poles across Madison and surrounding rural areas in coordination with local government and energy companies (Schatz and Kucharik 2014)

(Fig. 1). The sensors were strategically placed to best represent a diversity of land cover types and population densities spanning from high density urban development to rural farmland (Schatz and Kucharik 2014). In October 2012 and August 2013, 6 and 10 more sensors were placed across Madison, respectively, for a total of 151 sensors. Sensors have an operational temperature range from −40° to 70°C, ±0.25°C accuracy from −40° to 0°C, ±0.2°C accuracy from 0° to 70°C, a resolution of 0.04°C, and sensor drift of <0.01°C yr^{-1} (Onset Computer Corporation 2021). The sensors were installed at a uniform height of 3.5 m above ground to minimize the risk of damage from unwanted disturbance and on the north side of poles, except in six cases where they were placed on the east or west side to avoid the public road right of way (Schatz and Kucharik 2014). Instantaneous temperature measurements were taken every 15 min and recorded continuously during the study period. Numerous research projects have published work using this long-term UHI sensor network (Berg and Kucharik 2022; Schatz and Kucharik 2014, 2015, 2016; Zipper et al. 2016; Ziter et al. 2019). For additional reference, comparisons of minimum temperature data from the Madison Truax–Dane County Regional Airport (MSN; official NWS observation site for Madison) with UHI observations that are in closest proximity are provided in appendix (Fig. A1). All UHI observational data are made freely available through the National Science Foundation (NSF) North Temperate Lakes Long Term Ecological Research (NTL-LTER) and the Environmental Data Initiative (EDI) portal (Schatz et al. 2021).

d. Analyses of temperature data

Two approaches were used to analyze temperature data and generate useful statistics to address research objectives. In one approach, individual temperature sensor data were pooled into urban ($n = 88$) and rural categories ($n = 63$) and averaged for each 15-min reading for the 24-h period that encompassed freeze warning or frost advisory events. The time period was extended outside the actual time range of the event in case minimum temperatures occurred when freeze warnings and frost advisories were not active. Sensor locations that were generally outside of the Madison urban boundary and were surrounded by agricultural land use, pasture, wetland, or forest with 0%–20% impervious surface coverage were categorized as rural. Urban sensors were generally within the Madison urban region (with varied impervious surface) or other regional cities with a range of building density from low to high, but had impervious surface coverage of greater than 20% (Fig. 1). The JMP Pro 13 statistical package (JMP 2021) was used to test for normality of data distributions, calculate summary statistics and graphs, and create summary figures.

In a second approach, the individual temperature sensor data were spatially interpolated to allow estimation of the fractions of total land area that experienced temperatures above or below freeze warning and frost advisory thresholds. QGIS, a free and open-source geographic information system (QGIS Development Team 2021), was used to create inverse distance weighted (IDW) interpolations (grids) of the 15-min individual temperature sensor data at 400 m × 400 m spatial resolution for all land areas. This type of interpolation approach and use of the resulting gridded data for other UHI studies of Madison, WI have been previously published (Schatz and Kucharik 2014, 2015). These gridded 15-min data were processed using Python to calculate the following: 1) the absolute minimum air temperature at each 400 m × 400 m grid cell location for each individual freeze warning or frost advisory event; 2) the average minimum temperatures that occurred across all spring freeze warnings ($n = 7$), all fall freeze warnings ($n = 7$), all spring ($n = 4$) frost advisories, and all fall ($n = 9$) frost advisories at each 400 m × 400 m grid cell; 3) the percentages of total land area confined to Madison's urban area—defined by the City of Madison—that reached freeze warning and frost advisory temperature criteria during each individual freeze warning and frost advisory event; and 4) the average percentages of total Madison urban land area that reached temperature thresholds across all spring freeze warnings ($n = 7$), all fall freeze warnings ($n = 7$), all spring ($n = 4$) frost advisories, and all fall ($n = 9$) frost advisories. Madison's urban area boundary shapefiles were obtained from the City of Madison's Open Map Data website (City of Madison 2022). The Madison urban area boundary was approved on 3 April 2013 and determines or affects the eligibility of areas for federal transportation and transit funding, the functional classification of roadways, and roadway levels of service and access management standards.

3. Results

a. Urban–rural temperature differences during frost advisories and freeze warnings

Across all events, urban average minimum temperatures were significantly warmer (1.2°–2.0°C) than rural average minimum temperatures for all categories of comparison (Fig. 2, Table 1). The average minimum temperature of urban temperature sensors during frost advisories and freeze warnings during spring and fall did not fall below the temperature thresholds, respectively, for those events (Fig. 2, Table 1), but there was a significant amount of spatial variability that was generally larger in magnitude during the fall (Fig. 2, Table 1). The variance was always greater among urban temperature observations compared to rural observations across all categories, but the differences were most pronounced during issuance of freeze warnings. There was a larger difference between urban and rural temperatures in fall (~1.9°–2.0°C) compared to spring (~1.2°–1.4°C) for both freeze warnings and frost advisories. This applies to the mean and the median temperatures, the average minimum and maximum temperatures of individual sensors, and the range of temperatures recorded (Table 1). The average low temperatures in urban areas were warmer in fall (1.39°C) compared to spring during freeze warnings (0.72°C), but there was no significant difference during frost advisories (Table 1). The rural mean minimum temperatures across all sensors were nearly identical during freeze warnings in spring and fall (Table 1).

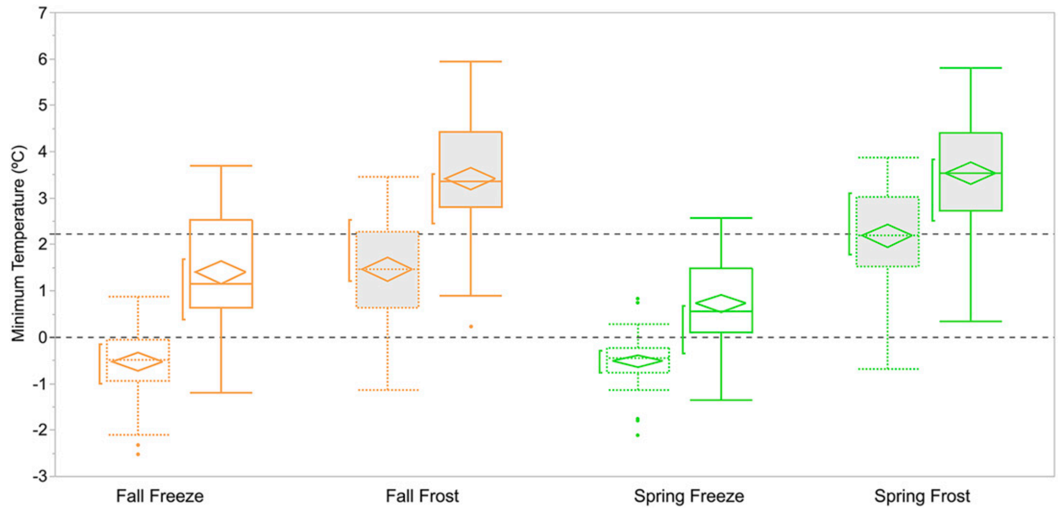

FIG. 2. Statistical analysis of minimum air temperatures for rural vs urban temperature data grouped according to season and cold temperature warnings (freeze) and advisories (frost). The boxplots show the interquartile range, the median (horizontal line), upper and lower whiskers (1.5 × IQR), and any outliers (dots). The top and bottom of the diamond represents the 95% confidence interval for the mean, and the vertical bracket to the left of each boxplot is the shortest half of the data (or the densest region). The horizontal dashed lines represent 0.0° and 2.2°C temperature thresholds for freeze warning and frost advisory issuance, respectively. Green colors denote spring, and gold denotes fall; solid lines are urban and dashed lines are rural sensors; no fill indicates freeze warning events, and gray shading represents frost advisory events.

Across all frost advisory and freeze warning events, the average temperatures for rural locations were below the criteria established by the NWS for issuance of these events. The average mean minimum nighttime temperatures were −0.52° and −0.53°C for freeze warnings in spring and fall, respectively, and 2.18° and 1.45°C for spring and fall frost advisories, respectively (Fig. 2, Table 1). In urban locations, average temperatures were 0.7° and 1.4°C above the freeze warning criteria in spring and fall, respectively, and 1.3° and 1.2°C above the frost advisory criteria in spring and fall, respectively (Fig. 2, Table 1). In urban locations, temperatures were closer to freeze warning temperature criteria in spring compared to fall (Table 1). Fall freeze warning average temperatures were warmer than spring (+0.67°C; $p < 0.0001$) for urban sensors, but there was insignificant difference for rural sensors ($p = 0.836$). However, frost advisory average temperatures were warmer in spring for rural sensors (+0.723°C, $p < 0.0001$), but there was no significant difference for urban sensors ($p = 0.511$).

b. Diurnal temperature behavior during frost advisories and freeze warnings

The rate of late afternoon and evening radiative cooling after peak daily temperatures were reached was generally greater during springtime freeze warnings for both rural and urban locations (Fig. 3a). Rural locations reached similar minimum temperatures across seasons, but urban locations had a higher average minimum temperature during fall freeze events (Fig. 3a, Table 1). During frost advisory events, the rate of temperature decline after reaching maximum daily temperatures is clearly greater for rural observations (Fig. 4a), especially during 1700–2200 CDT. The rate of temperature increase and warming after sunrise is nearly identical for urban and rural locations in both spring and fall (Figs. 3a and 4a).

Average temperatures during fall events began cooling several hours sooner than temperatures during spring events, and temperatures warmed more slowly in the morning hours during fall events than spring. These responses are due to seasonal differences in daylength and sun angle as nights are longer during the fall advisory/warning season compared to the spring advisory/warning season. Because of this, minimum temperatures occur at least one hour later during fall warning/advisory events compared to spring events. During freeze warnings, fall average temperatures reached maximum and minimum values of 9.6°C at 1600 CDT and 0.70°C at 0715 CDT, respectively, and spring average temperatures reached maximum and minimum values of 9.5°C at 1730 CDT and 0.27°C at 0615 CDT, respectively (Fig. 3a). During frost advisories, fall average temperatures reached maximum and minimum values of 11.6°C at 1500 CDT and 2.74°C at 0600 CDT, respectively, and spring average temperatures reached maximum and minimum values of 12.2°C at 1745 CDT and 3.02°C at 0545 CDT, respectively (Fig. 4a).

The average minimum temperatures in diurnal plots (Figs. 3 and 4) are different from the average absolute minimum temperature across all sensors (Table 1) because sensor minimum temperatures do not occur at exactly the same time (across all sensors) during each event; there is variability in the minimum value and time of occurrence across all sensors and events. Statistics shown in Table 1 do not have a time component and are using data that represent the average minimum temperature across all categorical freeze or frost events for each of the 151 temperature sensors analyzed.

TABLE 1. Summary statistics for urban ($n = 88$) and rural ($n = 63$) temperature sensors during frost advisories and freeze warnings from 2012 to 2016. The mean, median, standard deviation, and variance are values across all temperature sensors. The minimum and maximum denote the lowest and highest average temperatures for single temperature sensors, and the range is derived from these values. All temperature related statistics are given in degrees Celsius. The official Madison, WI, NWS observation station (MSN Airport) mean minimum temperature averages are also provided for reference. The t tests and nonparametric (Mann–Whitney, Wilcoxon/Kruskall Wallis) tests for significance between urban and rural were performed only for mean temperature and average hours below thresholds. Results denoted with *** had $p < 0.001$, ** for $p < 0.01$, and * for $p < 0.05$.

Statistic	Spring freeze warnings	Fall freeze warnings	Spring frost advisories	Fall frost advisories
Urban mean temperature	0.72	1.39	3.53	3.41
Rural mean temperature	−0.52	−0.53	2.18	1.45
Urban–rural difference	1.24***	1.92***	1.35**	1.96***
MSN airport	−1.19	−0.63	1.81	0.87
Urban median temperature	0.55	1.14	3.53	3.35
Rural median temperature	−0.47	0.50	2.19	1.45
Difference	1.02	1.64	1.34	1.90
Urban minimum temperature	−1.37	−1.20	0.33	0.22
Rural minimum temperature	2.12	−2.53	−0.69	−1.15
Difference	0.75	1.33	1.02	1.37
Urban maximum temperature	2.57	3.68	5.80	5.94
Rural maximum temperature	0.82	0.86	3.86	3.46
Difference	1.75	2.82	1.94	2.48
Urban range	3.93	4.87	5.47	5.72
Rural range	2.94	3.39	4.55	4.61
Urban standard deviation	0.86	1.16	1.13	1.13
Rural standard deviation	0.51	0.75	0.97	1.02
Urban variance	0.75	1.35	1.27	1.29
Rural variance	0.26	0.57	0.95	1.04
Urban Shapiro–Wilk (Prob $< W$)	0.0353	0.0166	0.4339	0.1437
Rural Shapiro–Wilk (Prob $< W$)	0.0171	0.1963	0.0540	0.5230
Urban average hours below threshold	2.91	4.76	2.17	3.30
Rural average hours below threshold	3.64	6.16	2.51	5.25
Difference (rural–urban) hours below threshold	0.73**	1.40*	0.34*	1.95***

Urban–rural temperature differences were at a maximum during nighttime and reached a peak of approximately 2.0°C in fall and 1.5°C in spring during both freeze warnings and frost advisories (Figs. 3b and 4b). During daytime, the urban locations were approximately 0.2°–0.6°C warmer than rural locations (Figs. 3b and 4b). During fall events the magnitude of the diurnal fluctuation of the urban–rural temperature differences was greatest and the length of time that the urban–rural temperature differences were at a maximum was generally 2–5 h longer than spring events (Figs. 3b and 4b). During freeze warning events, the average temperature range across all sensors was relatively consistent—around 2.5°–4°C—in during both spring and fall for rural locations, but the range in temperature across urban sensors exhibited a weak diurnal pattern and reached a maximum of 5°–6°C around 2000–0100 CDT local time in both spring and fall (Fig. 3c). During frost advisories, the temperature range in springtime across urban sensors was relatively constant during all hours of the day (approximate 4.5°–6°C), while rural sensors exhibited a diurnal pattern in springtime of being lowest during the daytime and reaching a maximum during the nighttime hours (Fig. 4c). A diurnal pattern was present for both urban and rural locations during the fall frost advisories, with the temperature range reaching a maximum of about 6°C for urban sensors and around 5°C for rural sensors, and both reaching a minimum range of 2°–3°C between 1100 and 1800 CDT local time (Fig. 4c).

c. Spatial temperature patterns of minimum temperatures

The Madison UHI generally prevented many urban locations from reaching the respective temperature thresholds for freeze warnings (0°C) and frost advisories (2.22°C). Spatially, the warmest nighttime temperatures were concentrated on Madison's isthmus—which is the downtown urban core that is positioned between the two largest lakes (Figs. 5 and 6). Here, impervious surface coverage and population density is

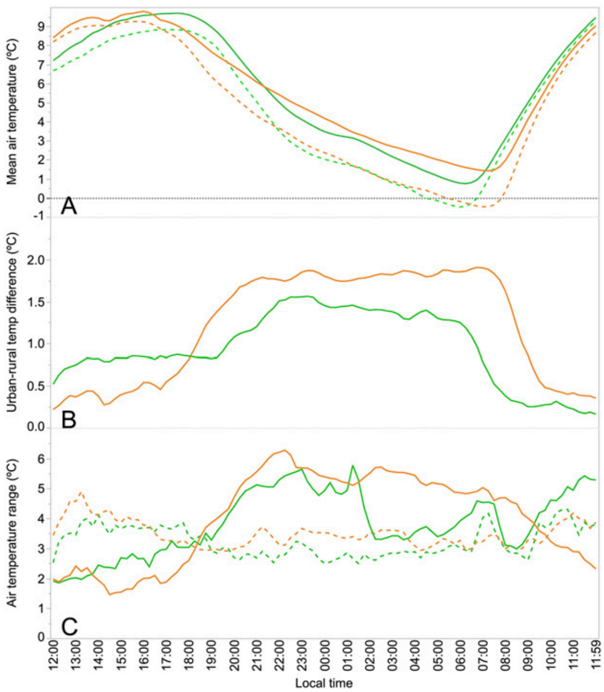

FIG. 3. For spring and fall freeze warning events, diurnal changes in (a) mean rural (n = 63) and urban (n = 88) air temperature, (b) urban–rural air temperature differences, and (c) range in air temperature across all rural and urban sensors. In all panels, green colors denote spring and gold denotes fall. In (a) and (c) solid lines are urban and dashed lines are rural sensors.

the highest. On average, nighttime minimum temperatures did not fall below warning and advisory criteria in many regions of the city and some more sparsely populated outlying regions (Figs. 5 and 6). The average minimum temperature during fall freeze warnings was slightly warmer than during spring (Fig. 2). Average minimum temperatures during spring and fall freeze warnings were up to 2.6° and 3.7°C warmer on the isthmus, respectively, than the 0°C temperature criteria connected to freeze warnings (Fig. 5). On average, the coldest regions during freeze warnings, away from the core of the urban center, reached minimum temperatures of −2.1° and −2.5°C for spring and fall, respectively (Fig. 5). Similarly, average minimum temperatures during spring and fall frost advisories were up to 3.6° and 3.7°C warmer on the isthmus (actual average minimum temperatures of 5.8° and 5.9°C), respectively, than the 2.22°C temperature criteria connected to frost advisory issuance (Fig. 6). On average, the coldest regions during frost advisories, again away from the core of the urban city center, reached average values of −0.7° and −1.1°C for spring and fall, respectively (Fig. 6).

Averaged across all spring and fall freeze warning events, 14.1% and 31.0%, respectively, of the Madison urban area extent experienced temperatures above the temperature threshold of 0°C. Conversely, across all spring and fall frost advisories, 52.1% and 27.8%, respectively, of the land area experienced temperatures above the temperature threshold of 2.22°C. When comparing all spring events—freeze warnings and frost advisories—to all fall events, however, there was significantly less disparity between the seasons. Approximately 33.1% of the land area experienced temperatures above the freeze warning and frost advisory temperature thresholds in the spring, while 29.4% of the land area experienced temperatures above temperature thresholds in the fall. Overall, on average 31.2% of the land area experienced temperatures above the respective temperature thresholds across all 27 freeze warnings and frost advisories combined during the study period.

d. *Average number of hours spent below critical temperature thresholds*

The duration of spring events was shorter than fall events for both frost advisories and freeze warnings (Fig. 7, Table 1). For freeze warning events, those occurring in fall had the longest duration below 0.0°C with 4.76 and 6.16 h for urban and rural locations, respectively. For freeze warning events, the duration was 1.85 and 2.52 h longer during fall versus spring across urban and rural locations, respectively. For frost advisory events, the duration was 1.13 and 2.74 h longer in fall versus spring for urban and rural locations, respectively (Fig. 7, Table 1). The average duration of time spent below freeze and frost temperature thresholds at urban locations was shorter than rural locations by 0.34 to 1.95 h (Table 1). Out of all event categories, average temperatures during spring frost advisories exhibited the shortest duration below the critical temperature threshold (2.22°C), with 2.17 and 2.51 h for urban and rural locations, respectively.

4. Discussion

a. *Seasonal differences and variability in air temperature*

Greater spatial variability in average air temperature across sensors during fall compared to spring suggests that there is likely a continuing impact of the summer season—when the UHI effect is maximized—on soil and ground heat storage, which translates into larger variability in heat fluxes across the region in fall. The long winter season effectively causes spatial differences in thermal properties and heat storage during spring to be at a minimum (Schatz and Kucharik 2015). The variance is also larger among urban temperatures compared to rural temperatures across all categories, but the differences are most pronounced during freeze warning events. This could be attributed to more heterogeneity in land surfaces and land cover (trees, grass, and other vegetation; impervious surfaces) in urban regions; these areas are generally more heterogeneous and have a higher range in minimum temperatures than compared to rural landscapes which are largely homogeneous agricultural or natural land areas dominated by vegetation (and bare soil during some times of the year) and have little impervious surfaces.

The increased temperature amplitude during fall versus spring is evident in the spatial patterns and areal extent of minimum temperatures that are at or below the freeze warnings threshold during fall. In early springtime, the preceding wintertime conditions for approximately 4–5 months with

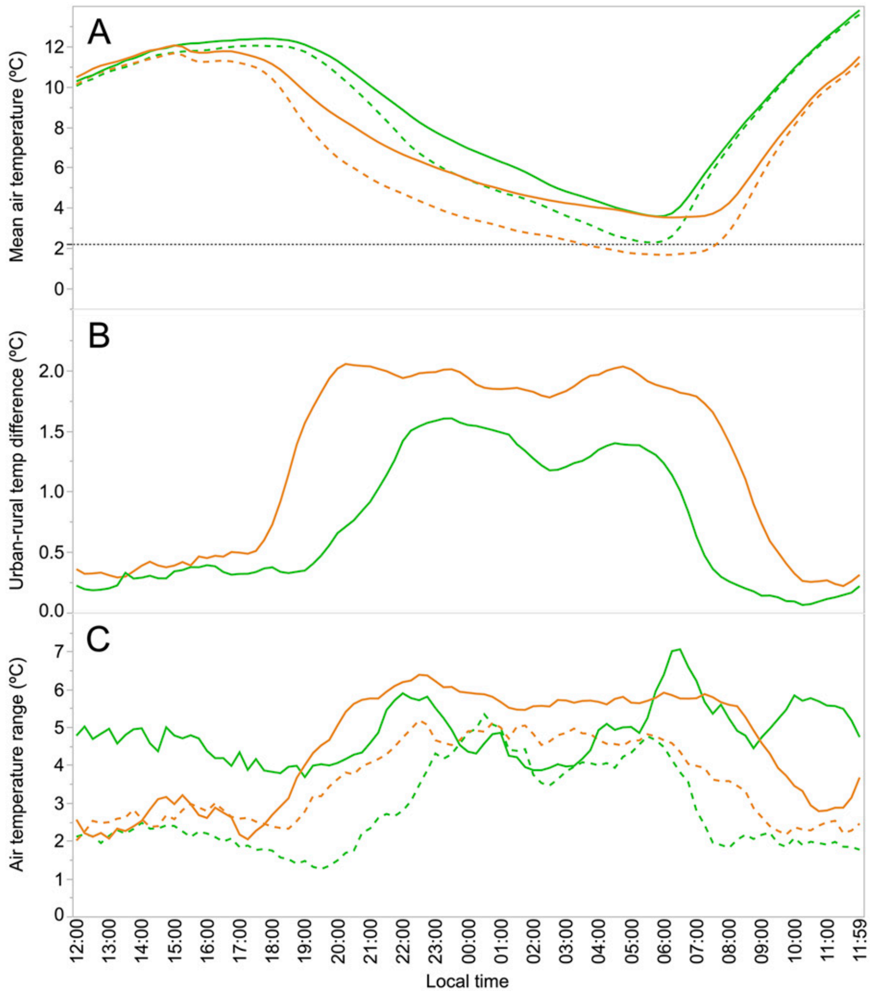

FIG. 4. For spring and fall frost advisory events, diurnal changes in (a) mean rural (n = 63) and urban (n = 88) air temperature, (b) urban–rural air temperature differences, and (c) range in air temperature across all rural and urban sensors. In all panels, green colors denote spring and gold denotes fall. In (a) and (c) solid lines are urban and dashed lines are rural sensors.

frozen soils and a general decline in the intensity of the UHI (Schatz and Kucharik 2014, 2015) contribute to a reduction in the magnitude of spatial variability across temperature sensors. Given the increased hours of darkness during fall compared to spring when advisories and warnings are issued, locations that do occasionally reach the minimum threshold temperatures during freeze warnings experience a longer time period at those cold temperatures compared to springtime, and occur over a larger spatial extent. Therefore, while freeze events that occur in spring have a colder average minimum temperature, they are shorter in duration. These results reinforce the idea that when the growing season is forecast to come to an end, vegetation in rural areas is more likely to succumb to freezing temperatures given the duration of freezing temperatures is longer. During springtime, sensitive plants and newly emerged crops may stand a better chance of survival given the duration of freezing temperatures during a warning is generally shorter.

b. Challenges to forecasting cold weather events in urban regions

In every individual freeze warning or frost advisory event, the average urban temperature was approximately 1°–2°C higher than the average rural temperature, and these differences were generally larger in fall than spring. Advisory or warning thresholds were not often reached at most urban sensor locations, while most rural temperatures did meet the advisory or warning temperature criteria during each event. These results illustrate the current challenges to forecasting cold weather events in urban regions.

The NWS has established temperature criteria for issuing freeze warnings and frost advisories and encourages weather forecast offices (WFOs) to work with local agricultural and horticultural experts to determine the seasonality for freeze warning and frost advisory issuance (Lawhorn and Balling 2020; National Weather Service 2019). We note that issuance of advisories and warnings is often more complex than just

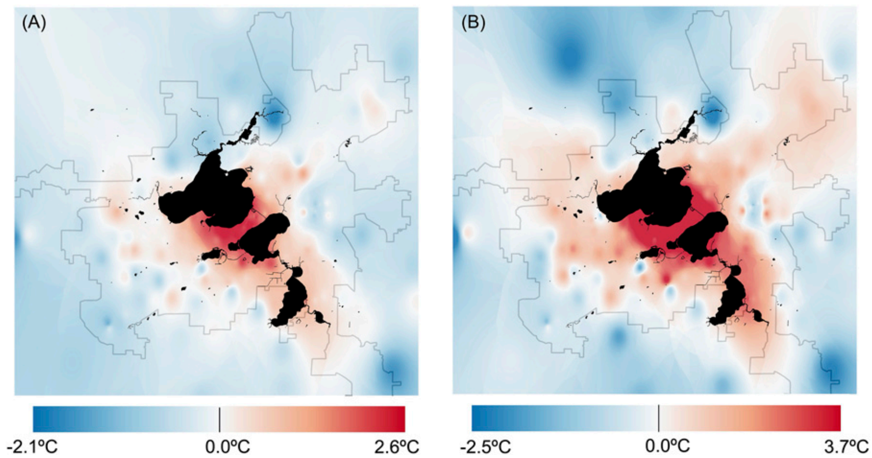

FIG. 5. Average minimum temperatures for freeze warnings in meteorological (a) spring, and (b) fall. Madison's urban area boundary is the gray outline. The black areas denote water bodies (e.g., lakes and rivers).

looking at temperature forecasts, and can also be based on a number of other factors such as cloud cover, wind, and amount of time that temperatures will remain below key thresholds (J. Gagan, National Weather Service, 2023, personal communication). Efforts to adjust temperature thresholds to account for the UHI effect appear to be focused on extreme heat events in larger cities. Recent advances in numerical weather prediction (NWP) and higher spatial resolution models and other supplemental observation networks (e.g., from the Meteorological Automated Data Ingest System) used by the NWS have allowed for improved representation of urban–rural temperature differences. However, some challenges still persist depending on the ability to perform bias correction with other surface observations such as those from the MesoWest network. Weather forecast offices suggested that distinct criteria for issuing warnings for extreme heat events should be developed for urban areas because of the UHI effect (Hawkins et al. 2017). However, the UHI effect is also prevalent during transition seasons (fall and spring) and winter in Madison as demonstrated in this study, in previous studies of the Madison UHI (Schatz and Kucharik 2014, 2015), and in other cities across the United States (Oleson et al. 2018; Yang and Bou-Zeid 2018). To our knowledge, there are currently no formal guidelines from the NWS for altering warnings and advisories for cold events in urban areas to account for warming or "heat islands." The NWS and WFOs may wish to pursue modification of how issuance of cold weather advisories for counties with distinct urban areas are handled and that separate messaging or alerts are necessary. Furthermore, it should also be considered that the behavior of cold weather

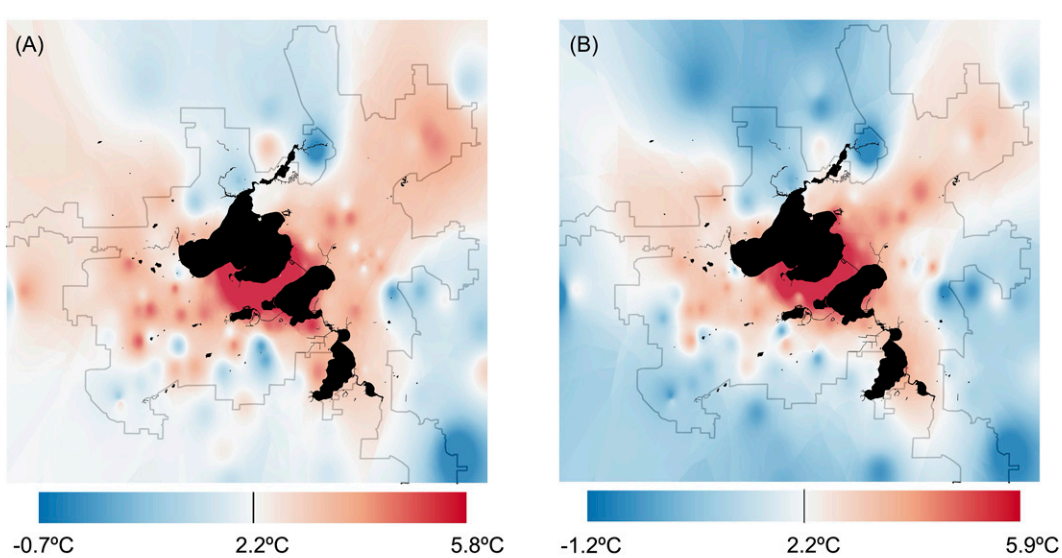

FIG. 6. Average minimum temperatures for frost advisories in (a) spring and (b) fall. Madison's urban area boundary is the gray outline. The black areas denote water bodies (e.g., lakes and rivers).

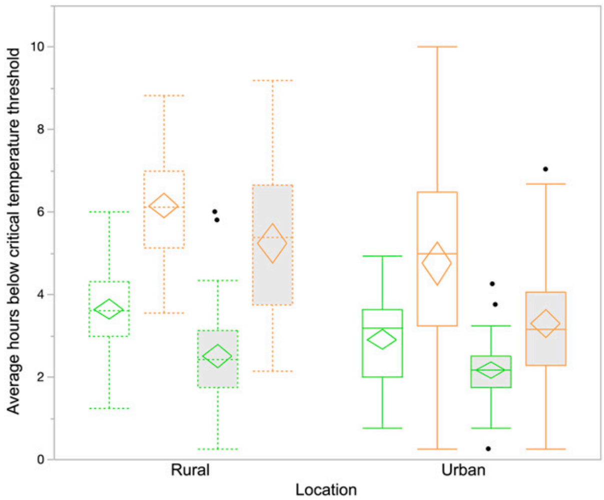

FIG. 7. For frost advisory and freeze events, statistical analysis of rural ($n = 63$) and urban ($n = 88$) sensors showing the average number of hours below critical minimum temperature thresholds (2.22°C for frost advisories and 0.0°C for freeze warnings). The boxplots show the interquartile range, the median (horizontal line), upper and lower whiskers (1.5 × IQR), and any outliers (black dots). The top and bottom of the diamonds represent the 95% confidence interval for the mean. Green colors denote spring, and gold denotes fall; solid lines are urban and dashed lines are rural sensors; no fill indicates freeze warning events, and gray shading represent frost advisory events.

events are different whether they occur in fall versus spring. Based on wording provided in freeze warning products from the Milwaukee/Sullivan NWS WFO on 18 September 2012 and 21 October 2013 (see supplemental material), mention of how urban areas of Milwaukee, Racine, and Kenosha may be buffered from experiencing the coldest temperatures, there is some evidence that urban heating is already considered in modifying messaging to the public. However, we did not find any text product during the period of study that mentioned the influence of urban heating or influence in Madison, which is Wisconsin's second largest city by population.

c. *Potential impacts to people and vegetation*

Freeze warnings and frost advisories are of great importance to Dane County farmers with cropland in rural areas and other residents with gardens in urban areas, as cold temperatures associated with frost formation and freezing temperatures can damage or kill plants and crops. Madison comprises 8.2% of Dane County's land compared to 47.8% of Dane County's population (City of Madison 2016) Madison's population is densest on the isthmus, with areas that contain over 40 000 people per square mile. Outside of city limits, population density decreases to fewer than 1000 people per square mile outside of city limits (City of Madison 2016).

Schatz and Kucharik (2014) found a positive relationship between the log of Madison's population density and maximum UHI intensity, which was first described by Oke (1973). This is a major reason why temperatures are warmest on the isthmus (Madison's downtown) during freeze warnings and frost advisories, and decrease as population density decreases and land becomes less densely built (Figs. 2 and 3). A sizable portion of Dane County's population, but a comparatively smaller land area, experience temperatures warmer than expected during freeze warnings and frost advisories due to the UHI effect. Likewise, a sizable portion of Madison's population likely does not experience temperatures colder than respective thresholds for freeze warnings and frost advisories based on the results in this study.

Historically, urban community gardens in the United States have helped contribute to improve local fresh food access (Armstrong 2000; Saldivar-Tanaka and Krasny 2004). In Madison, community gardens are widespread. A study of 26 of the 50 community gardens in the city found that 701 families representing over 2000 people rented garden plots (Public Health Madison and Dane County 2014). Urban community gardens and gardeners in Madison and across the greater United States may respond to freeze warnings and frost advisories that do not verify, impacting local communities that rely on gardens for fresh food access. Gardeners may pull up tender crops, such as tomatoes and lettuce before they have ripened, reducing the quality and quantity of the harvest.

Residents and farmers living in rural areas, which compromise over two-thirds of Dane County's land, need to respond appropriately to freeze warnings and frost advisories when issued by the NWS. Corn and soybean, which compromise over half of cropland in Dane County (U.S. Department of Agriculture 2017), experience damage when temperatures drop below −2.22°C for several hours, which is often considered a hard freeze. Because rural areas typically reach the temperature thresholds for freeze warnings and frost advisories when they are issued by the NWS, farmers and rural residents need to heed this guidance to plan for management and take any potential action to protect agricultural crops and other sensitive vegetation.

5. Conclusions

Data collected from 151 temperature sensors in the Madison, Wisconsin, region during March 2012 through October 2016 suggested that during time periods of valid NWS issued freeze warnings (threshold of 0.0°C) or frost advisories (threshold of 2.22°C), temperatures in the most densely populated, built-up areas often did not fall below the respective temperature thresholds. Previous research on Madison's UHI has already demonstrated how urban warming contributes to modified plant phenology and supports longer growing seasons and more growing degree days (Schatz and Kucharik 2016; Zipper et al. 2016). Although a majority of rural Dane County reaches the respective temperature thresholds of 0° and 2.22°C when freeze warnings and frost advisories are issued by the NWS, a larger majority of Madison's population, community gardens, and other residential vegetation do not likely experience the coldest temperatures and likely escape the potentially detrimental impacts of these specific cold weather events in spring and fall. This could have negative consequences for individuals

TABLE A1. Listing of frost advisories and freeze warnings used in this analysis that were issued by the Milwaukee/Sullivan National Weather Service forecast office for Dane County, Wisconsin. Freeze warning and frost advisory event information were obtained from the Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/), and minimum daily temperature data for the official NWS Madison reporting station (Madison Truax–Dane County Regional Airport) was obtained from the Midwest Regional Climate Center (http://mrcc.purdue.edu).

Date of event	Category	MSN airport T_{min} (°C)
6 Apr 2012	Freeze warning	−3.33
10 Apr 2012	Freeze warning	−1.67
11 Apr 2012	Freeze warning	−1.67
12 Apr 2012	Freeze warning	1.67
21 Apr 12	Freeze warning	−1.67
19 Sep 2012	Frost advisory	1.11
23 Sep 2012	Freeze warning	1.11
24 Sep 2012	Frost advisory	0.00
6 Oct 2012	Frost advisory	2.78
7 Oct 2012	Freeze warning	2.78
8 Oct 2012	Freeze warning	2.78
12 Oct 2012	Freeze warning	−4.44
13 May 2013	Freeze warning	−0.56
14 Oct 2013	Frost advisory	0.00
20 Oct 2013	Frost advisory	−1.11
22 Oct 2013	Freeze warning	−2.78
17 May 2014	Frost advisory	4.44
5 Oct 2014	Frost advisory	2.78
10 Oct 2014	Frost advisory	0.56
11 Oct 2014	Freeze warning	−1.11
13 May 2015	Frost advisory	0.56
17 Oct 2015	Freeze warning	−2.78
23 Apr 2016	Frost advisory	1.11
15 May 2016	Freeze warning	−1.11
18 May 2016	Frost advisory	1.11
13 Oct 2016	Frost advisory	1.11
14 Oct 2016	Frost advisory	0.56

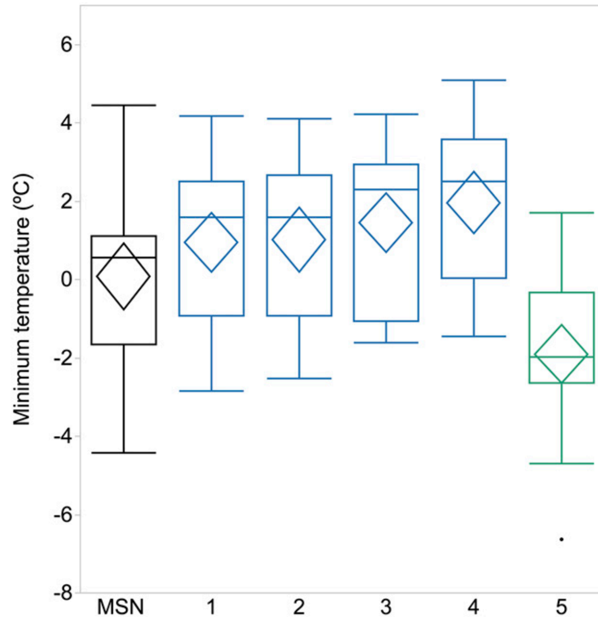

FIG. A1. Comparison of daily minimum temperatures recorded at Madison Truax–Dane County Regional Airport (MSN) across all 27 frost advisories and freeze warnings to five individual temperature sensors as part of the Madison urban heat island (UHI) observational network. The boxplots show the interquartile range, the median (horizontal line), upper and lower whiskers (1.5 × IQR), and any outliers (black dots). The top and bottom of the diamonds represent the 95% confidence interval for the mean. The blue color denotes urban sensor locations (1–4), and green (5) is a rural observation site bounding the Cherokee Marsh State Natural Area.

and communities with gardens or other sensitive plants, who may respond by removing tender plants when the UHI effect will keep temperatures from causing freeze or frost damage, and work to extend the growing season in fall. Furthermore, and maybe more importantly, they may subsequently be caught off guard when killing temperatures occur at a time when a warning or advisory has not been issued because it was determined that the growing season already ended based on previous observations.

In general, farmers and rural residents should always heed freeze warnings and frost advisories and the guidance provided by the NWS. While the NWS tends to focus on populous urban areas when adjusting forecasts for extreme heat events during summer, there is compelling evidence that temperatures during nighttime cold weather events during spring and fall are also affected by the UHI in medium-sized cities like Madison presenting significant forecast challenges. Although this research was specific to the Dane County and Madison, Wisconsin, region, this study contributes new information as the NWS works toward more accurate temperature forecasts and improved messaging of cold weather warnings for urban regions that have elevated temperatures—particularly at nighttime—compared to surrounding rural landscapes.

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Data availability statement. All Dane County/Madison UHI observational data used in this study (as well as data from other years) are freely available through the National Science Foundation (NSF) North Temperate Lakes Long Term Ecological Research (NTL-LTER) and Environmental Data Initiative (EDI) portal at https://doi.org/10.6073/pasta/c1322bd2fb3e6eac0749a83033d24ab6.

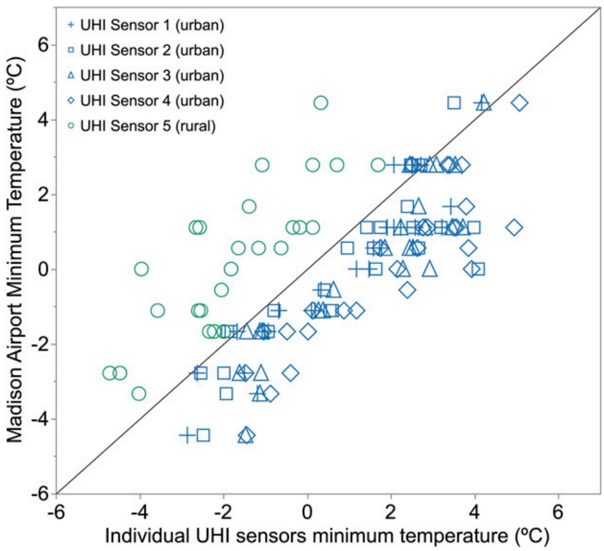

FIG. A2. As in Fig. A1, but illustrated as a scatterplot of individual minimum temperatures across all 27 frost advisory and freeze warning events; a 1:1 line is plotted in solid black for comparison. The blue symbols and locations 1–4 pertain to the four different urban/city locations, and the green circles represent the rural observation location (number 5).

APPENDIX

Comparison of Mean Minimum Air Temperatures at Madison Airport with Madison UHI Sensors

For the 27 dates from 2012 to 2016 that had frost advisories or freeze warnings during our study period (Table A1), a comparison of NWS official observed minimum temperatures for Madison at the Madison Truax–Dane County Regional Airport (MSN) was performed with an array of five UHI temperature sensors that are in closest proximity to the MSN airport. These five sensors are an average distance of 2.5–3.0 km away from the airport meteorological observation equipment. In Fig. A1, individual UHI network sensor locations 1–4 represent urban/city locations to the east, south, and west of the airport; sensor 5 is located 2.5 km directly north of the airport and is bounding the Cherokee Marsh State Natural Area. The MSN airport is located on the northeast side of the city of Madison, bounded by cropland and natural landscapes to the north and west. The MSN airport is located in a flat, low-lying area that was originally being used as a cabbage patch for a sauerkraut factory in the 1920s at the time of land purchase (https://www.msnairport.com/about/facilities_maps/history).

The mean and median temperatures for the MSN airport observations have a magnitude that falls between UHI network data from individual representative urban ($n = 4$) and rural sensor ($n = 1$) locations. The MSN data are approximately 2°C warmer than the rural observation site to the north, which is located adjacent to a wetland/marsh area. The results presented here are expected given the location of the MSN airport is situated between dense, urban development to the south and west and outlying rural areas with low density housing, farmland, and a wetland/marsh directly to the northwest of the airport. Figure A2 uses the same data, but is illustrated as an x–y scatterplot with an accompanying 1:1 line.

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