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Analyses of Nocturnal Temperature Cooling-Rate Response to Historical Local-Scale Urban Land-Use/Land Cover Change

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ABSTRACT

Urbanization affects near-surface climates by increasing city temperatures relative to rural temperatures [i.e., the urban heat island (UHI) effect]. This effect is usually measured as the relative temperature difference between urban areas and a rural location. Use of this measure is potentially problematic, however, mainly because of unclear ''rural'' definitions across different cities. An alternative metric is proposed—surface temperature cooling/warming rates—that directly measures how variations in land-use and land cover (LULC) affect temperatures for a specific urban area. In this study, the impact of local-scale (<1 km^2), historical LULC change was examined on near-surface nocturnal meteorological station temperatures sited within metropolitan Phoenix, Arizona, for 1) urban versus rural areas, 2) areas that underwent rural-to-urban transition over a 20-yr period, and 3) different seasons. Temperature data were analyzed during ideal synoptic conditions of clear and calm weather that do not inhibit surface cooling and that also qualified with respect to measured near-surface wind impacts. Results indicated that 1) urban areas generally observed lower cooling-rate magnitudes than did rural areas, 2) urbanization significantly reduced cooling rates over time, and 3) mean cooling-rate magnitudes were typically larger in summer than in winter. Significant variations in mean nocturnal urban wind speeds were also observed over time, suggesting a possible UHI-induced circulation system that may have influenced local-scale station cooling rates.

1. Introduction

Urbanization alters surface land-use/land cover (LULC) characteristics that, in turn, affect several important factors controlling near-surface and surface climates. An extensively researched example of this is the urban heat island (UHI)—the phenomenon of warmer urban environments relative to their local surroundings (Landsberg 1981). The UHI mainly arises from surface energy balance alterations due to LULC change (Oke 1982), and its intensity is a function of several controls that vary among and within cities. These include urban *structure* (i.e., building dimensions and spacing; street width), urban *cover* (i.e., proportion of urban versus nonurban surfaces), urban *fabric* (i.e., materials used for construction), and urban *metabolism* (i.e., the anthropogenic generation of excess heat, water, and pollutants) (Oke 2004). The strength of the UHI is also modified by other nonurban factors such as topography, wind speed, cloud cover, and cloud type (e.g., Arnfield 2003).

Previous studies usually measured UHI intensity as the difference between surface or near-surface (~2 m AGL) urban and rural temperatures (ΔT_{u-r}; e.g., Sun et al. 2009), or through time series analysis of long-term temperature data (typically minimum or maximum temperatures) from a single meteorological station or a network of stations (e.g., Brazel et al. 2000). UHI intensities, especially maximum ΔT_{u-r}, have been used as indicators for LULC impacts on surface and near-surface climates (e.g., Jenerette et al. 2007; Su et al. 2010). Interpretation of these metrics, however, can be problematic for two reasons. First, ΔT_{u-r} is a relative measurement depending on how both ''urban'' and ''rural'' are defined. A definite lack of clarity exists in most published heat island work in defining rural areas to derive UHI intensities, which in turn affects both method and interpretation of results (Stewart 2010). Second, because measurements of maximum ΔT_{u-r} usually occur at or near the urban core (or downtown), less focus exists on examining thermal impacts of residential areas. This is surprising, because this category dominates urban land

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use within most cities. Thus, these factors potentially confound the accuracy of intercity UHI comparisons, and also limit the relevance of ΔT_{u-r} as an indicator of LULC impacts on near-surface climate. To this end, we instead propose using another urban climate metric—the rate of surface cooling or warming ($\Delta T/\Delta t$). As compared with ΔT_{u-r}, $\Delta T/\Delta t$ is a direct indicator of surface LULC change with respect to micro- and local-scale urban climates. It can also be easily derived from meteorological stations with hourly data. Further, comparisons of $\Delta T/\Delta t$ across different cities could be made for distinct intraurban surface types (i.e., residential, commercial, etc.), with the proviso that one accounts for ideal synoptic and local weather conditions (i.e., cloud-free skies combined with calm or low surface and upper-level winds) that allow for unimpeded surface radiative cooling.

Nocturnal cooling rates are important in explaining UHI dynamics and development, with differential nocturnal urban versus rural cooling being a key factor in identifying rapid UHI growth under ideal weather conditions (i.e., clear and calm weather conditions). In general, magnitudes of urban cooling rates are lower in comparison with rural rates when observed in cities under different climate types, such as in Vancouver, British Columbia, and Montreal, Quebec, Canada (Oke and Maxwell 1975), as well as in Athens, Greece (Kassomenos and Katsoulis 2006), and Singapore (Chow and Roth 2006). Several factors can explain this observation; when vegetated or desert surfaces are converted to concrete or asphalt, there is a resulting increase in surface thermal admittance, which is a measure of surface temperature change from a given change in heat flux (Oke 1987). At night, urban surfaces generally release energy at relatively lower rates, resulting in lower cooling-rate magnitudes when compared with rural surfaces. Precipitation and surface moisture also affect amplitudes of $\Delta T/\Delta t$, with lower rates of heating/cooling observed during and immediately after precipitation events in Seoul, South Korea (Lee and Baik 2010). Intracity variations in urban cover, structure, fabric, and metabolism also influence $\Delta T/\Delta t$. Holmer et al. (2007) documented an inverse relationship between nocturnal cooling-rate magnitudes and site-dependent sky-view factors in Göteborg, Sweden. Open spaces were observed to cool fastest, whereas dense urban canyons cooled slowest; this occurred in the early evening until 3–4 h after sunset. Thus, reductions in cooling-rate magnitudes can be expected as a city expands and develops denser urban structures. Kidder and Essenwanger (1995) documented this effect when examining UHI between city pairs, with lower nocturnal cooling rates observed in larger cities relative to smaller-sized urban areas. Svoma and Brazel (2010) also examined nocturnal cooling rates using long-term temperature data for a single meteorological station that was categorized into preurban and urban land-use periods, with lower cooling rates occurring after urbanization.

These studies illustrate the usefulness of $\Delta T/\Delta t$ as a metric for quantifying local-scale LULC change on near-surface temperatures. There is, however, a lack of research directly examining cooling rates for both *urban versus rural* (i.e., spatial comparison of urban and nonurban land use) and *rural-to-urban* (i.e., temporal transition from nonurban to urban land use) LULC. The latter analysis is especially relevant in urban climatology because it applies a method that approximates the seminal Lowry (1977) framework toward evaluating urban impacts on climate, which has been utilized infrequently in UHI analysis (Oke 2006). In this study, we therefore analyze how variations of nocturnal $\Delta T/\Delta t$ were affected by historical LULC change (i.e., temporal changes in urban cover) for a major subtropical city categorized by both spatial (surface land-use type) and temporal (from rural to urban) changes. We selected and analyzed climate data taken during ideal synoptic weather conditions that do not inhibit surface cooling, and we also qualified our results with respect to measured near-surface wind and advection impacts. We attempt to answer the following research question: During synoptic weather conditions ideal for nocturnal cooling, how are hourly $\Delta T/\Delta t$ at local scales altered by 1) historical LULC change from nonurban to urban, 2) LULC type (urban vs rural), and 3) season (summer vs winter)?

2. Study area and data

Phoenix, Arizona, (33.5°N, 112.1°W) is the center of a large subtropical desert metropolitan area that experiences a hot arid climate (Köppen class BWh), with extremely hot summers and mild winter temperatures. It has experienced uninterrupted rapid urbanization over the past 60 years that has been well documented (e.g., Stefanov et al. 2007). For instance, $\sim$2553 km^2 of adjacent agricultural and desert regions underwent conversion to built-up areas from 1973 to 2003 (Table 1). Residential LULC had the largest increase in spatial extent, especially in housing areas with predominantly xeric landscaping (i.e., residential yards with xerophytic flora that are either native or are adapted to dry climates) as opposed to mesic landscaping (i.e., yards with nonnative or nonadaptive flora requiring greater water consumption). As a consequence, the spatial form of its UHI has also been altered, with higher urban temperatures documented at the expanding urban fringe, especially from 2000 to 2005 (Brazel et al. 2007).

TABLE 1. Estimated LULC change in the Phoenix metropolitan area from 1973 to 2003 on the basis of Landsat and ASTER data (Stefanov et al. 2007).

Period	Agricultural land to urban (km^2)	Desert to urban (km^2)	Total LULC change (km^2)
1973–79	106.25	108.25	214.50
1979–85	259.75	231.50	491.25
1985–91	132.25	289.25	421.25
1991–95	198.25	335.00	533.25
1995–2000	216.75	202.75	419.50
2000–03	149.75	323.00	427.75
Overall	1063.00	1489.75	2552.75

Urbanization impacts on near-surface climate phenomena have been relatively well studied in Phoenix, especially those of surface and near-surface UHI (e.g., Brazel et al. 2000; Baker et al. 2002). A major enabling factor is a large network of meteorological stations sited within urban areas, such as the Phoenix Real-Time Instrumentation for Surface Meteorological Studies (PRISMS) and the Arizona Meteorological Network (AZMET; see online at http://ag.arizona.edu/azmet/index.html). These stations generally possess quality-checked, long-term hourly climate data and sufficient metadata accounting for site and instrument changes. Several stations within these networks are well dispersed throughout metropolitan Phoenix and have recorded continuous climate data since 1990. Further, there has been ample research on long-term surface LULC changes that utilize multiyear, high-resolution remotely sensed satellite images [e.g., the Landsat Multispectral Scanner System (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)] that account for seasonal variations in natural and agricultural vegetation and in soil moisture (e.g., Stefanov et al. 2001; Buyantuyev and Wu 2010). The combination of these two data resources thus facilitates and enables research into the effect of LULC change on near-surface climate in Phoenix.

We examined station locations within several meteorological networks sited within metropolitan Phoenix that had appropriate data length (i.e., commencing from 1990), minimal site and instrument changes, and known LULC characteristics. Eight stations (seven urban and one rural station located in a desert location) were ultimately selected (Fig. 1). Hourly PRISMS climate data consisting of near-surface (<2 m) air temperatures, relative humidity, and vapor pressure, as well as wind speed and direction observed at 10 m, were obtained from the Office of the Arizona State Climatologist. The data for Waddell, however, were downloaded from the AZMET Internet site. Last, data loss at all selected stations during this period was minimal ($<3\%$).

3. Methods

To quantify temporal LULC change, we also obtained 1990, 1995, 2000, and 2005 land cover classification images based on Landsat TM and ETM images for Maricopa County (within which most of metropolitan Phoenix is located) from the Central Arizona-Phoenix Long Term Ecological Research (CAP-LTER) project Internet site (data and metadata are available at http://caplter.asu.edu/data) (Fig. 2). These images were subject to an accurate, expert-based object classification system to determine urban land cover type. This classification system had a mean accuracy of ~85% when compared with field observations of land cover (Stefanov et al. 2001). This method has also been utilized in prior research into LULC impacts on near-surface climate (e.g., Grossman-Clarke et al. 2010). Of note is that the set of 1990 and 2005 images included four additional urban land cover classes relative to the 1995 and 2000 image set. This difference in categorization, however, does not affect distinctions between urban (i.e., commercial, industrial, transportation, residential, concrete, and asphalt) and rural (i.e., undisturbed, farmland, and compacted soil) surfaces used in this study.

We acknowledge that this classification scheme reflects historical variations in urban cover, but it does not account for changes in urban form, structure, and metabolism that may occur in areas close to stations sited in predominantly urban areas throughout the period of record. For instance, building height variations and/or differences in residential energy consumption within similar land cover classes over time could influence cooling rates among study sites. We were unable to quantify these impacts accurately in the absence of relevant data, however, and we also assume that these factors are relatively minor relative to changes in urban cover and are thus unlikely to significantly affect the results from our analysis.

We used ArcMap 9.3 GIS software to examine LULC change around selected urban stations for each of the four land cover classification images from 1990 to 2005. We specifically examined land cover variations within a circular buffer area of 500-m radius for each station over the study period. This distance represents the assumed source area for local-scale, urban canopy layer influences affecting temperature measurements observed at a typical urban meteorological station (Oke 2004). The size of each land cover class within the source area was subsequently ranked for each urban station from 1990 to 2005 (Table 2).

On the basis of changes in temperature source area, we categorized each station into three distinct LULC classes. First, three stations sited in predominantly urban areas throughout the study period were classified as

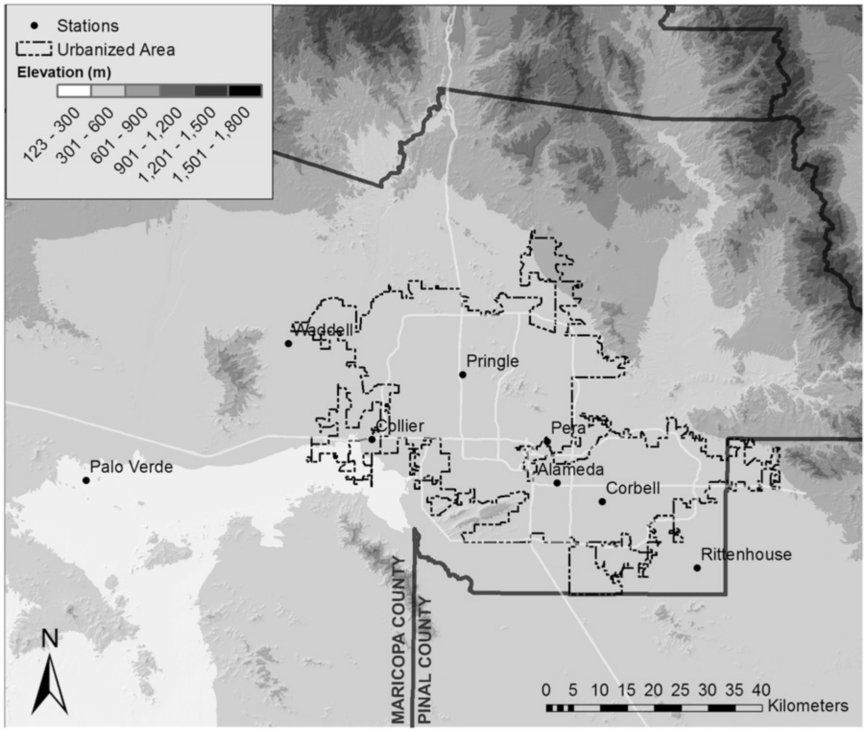

FIG. 1. Selected meteorological station locations within metropolitan Phoenix. The urbanized-area boundary for the year 2000 is displayed.

urban–urban. Both the Alameda and Pera stations are situated in predominantly xeric residential areas, but the Pringle station is sited in an area that has both xeric and mesic residential land cover in approximately equal proportions. Second, four stations that underwent local-scale land cover change were classified as *rural–urban*. These stations are sited away from the urban core, and LULC change occurred over time as the urban fringe expanded. In 1990, land cover adjacent to these stations was documented to be either agricultural or undisturbed desert surfaces. By 2005, there was evidence of suburban expansion around the Corbell and Waddell stations, although the majority of the adjacent land cover was still either vegetation or undisturbed desert surfaces. In contrast, local-scale LULC at Collier station was a predominant mix of urban surfaces that included commercial, industrial, and residential areas, and the land cover surrounding Rittenhouse station was almost evenly distributed between agricultural and residential surfaces. Third, a single station located in a desert location that did not undergo significant urbanization during the study period was classified as *rural–rural* (Palo Verde).

To account for regional weather conditions on the basis of daily synoptic weather types around metropolitan Phoenix, we utilized the Spatial Synoptic Classification scheme (SSC2) (Sheridan 2003; data and metadata are available online at http://sheridan.geog.kent.edu/ssc.html). This scheme characterizes each day of the year as one of seven air mass types: 1) dry polar (DP), 2) dry moderate (DM), 3) dry tropical (DT), 4) moist polar (MP), 5) moist moderate (MM), 6) moist tropical (MT), and 7) transitional (TR). SSC2 data for Phoenix, which were available up to the end of 2009, are based on an Automated Surface Observation System (ASOS) station sited at Sky Harbor International Airport, which is less than 5 km away from the urban core of Phoenix. Given this station's location, previous investigators suggested that a possible UHI bias exists in synoptic weather categorization for Phoenix because local land-use effects were not considered (e.g., Kalkstein et al. 1996; Brazel et al. 2007). Svoma and Brazel (2010) have shown, however, that possible urban biases in the Phoenix SSC2 data remain unchanged since the early 1980s and are thus unlikely to affect results from this study's analysis.

In this paper, we selected SSC2 periods classified as DT conditions, which are associated with hot, dry, and stable cloud-free conditions with upper-air pressure ridges over the southwestern United States. These synoptic weather conditions typically enhance near-surface nocturnal radiative cooling and are considered to be ideal for UHI development. We specifically focused on nocturnal cooling rates during DT conditions in both June (summer)

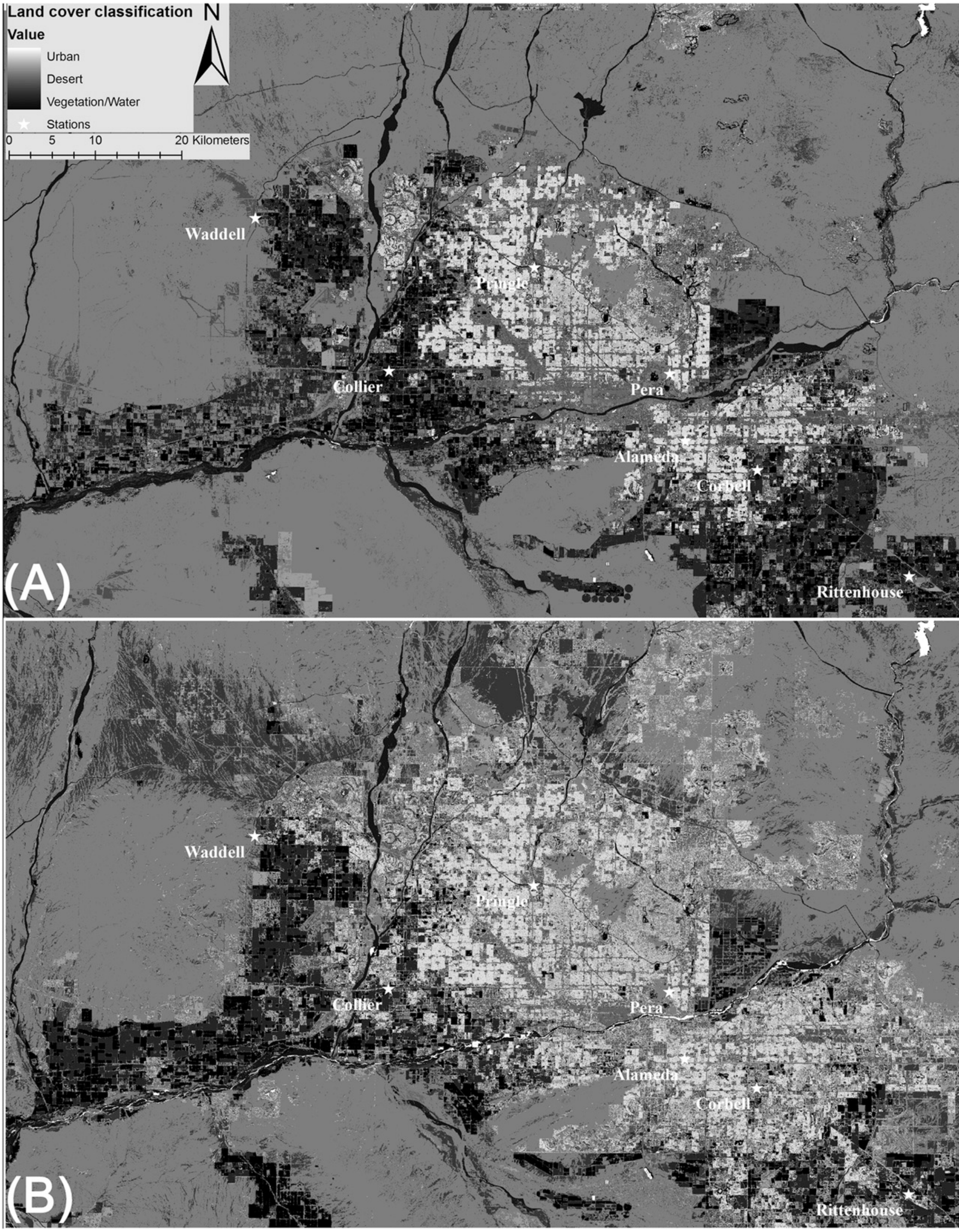

FIG. 2. Locations of urban stations in study and corresponding urban land cover classification in (a) 1990 and (b) 2005.

TABLE 2. Evolution of land cover characteristics around a 500-m-radius circular buffer for urban stations. The top three station classes are shown, together with the proportion of near-surface temperature source area in percent. Boldface text indicates the approximate period during which the majority of the rural–urban station source area underwent the change from rural to urban land cover.

	Proportion of land cover classification within 500-m-radius circular source area for near-surface temperature			
	1990	1995	2000	2005
Rural–urban stations				
Collier	Compacted soil (54%), cultivated vegetation (27%), undisturbed (10%)	Fallow farmland (96%), cultivated farmland (4%)	Fallow farmland (61%), cultivated farmland (27%), urban vegetation (9%)	**Compacted soil (40%), xeric residential (22%), asphalt (21%)**
Corbell	Vegetation (27%), commercial/industrial (26%), compacted soil (19%)	**High-intensity residential (89%), low-intensity residential (11%)**	High-intensity residential (75%), low-intensity residential (12%), commercial/industrial/transportation (13%)	Commercial/industrial (26%), mesic residential (20%), xeric residential (16%)
Rittenhouse	Compacted soil (62%), undisturbed (31%), cultivated vegetation (4%)	Fallow farmland (53%), cultivated farmland (47%)	Fallow farmland (60%), high-intensity residential (40%)	**Compacted soil (46%), xeric residential (38%), mesic residential (16%)**
Waddell	Undisturbed (49%), vegetation (27%), compacted soil (20%)	Unclassified (82%), cultivated vegetation (18%)	Natural land (81%), fallow farmland (19%)	**Undisturbed (33%), compacted soil (23%), mesic residential (13%)**
Urban–urban stations				
Alameda	Xeric residential (73%), commercial/industrial (10%), mesic residential (6%)	High-intensity residential (97%), low-intensity residential (3%)	High-intensity residential (90%), low-intensity residential (10%)	Xeric residential (66%), mesic residential (10%), commercial/industrial (9%)
Pera	Xeric residential (40%), commercial/industrial (28%), mesic residential (10%)	High-intensity residential (88%), low-intensity residential (12%)	High-intensity residential (86%), low-intensity residential (13%), commercial/industrial/transportation (1%)	Xeric residential (39%), mesic residential (17%), asphalt (16%)
Pringle	Commercial/industrial (31%), undisturbed (18%), xeric residential (12%)	High-intensity residential (99%), low-intensity residential (1%)	High-intensity residential (99%), low-intensity residential (1%)	Asphalt (22%), mesic residential (21%), xeric residential (20%)

and January (winter). Nocturnal periods are defined as extending from the hour before sunset to the hour after sunrise (1900–0600 LST for June and 1700–0800 LST for January), and only nocturnal periods characterized by DT conditions spanning at least 2 days were considered. For each station, $\Delta T/\Delta t$ was derived for each hourly interval (e.g., $\Delta T_{00–01} = T_{01} - T_{00}$, where T_{00} is station temperature at midnight LST, T_{01} is temperature at 0100 LST, and therefore the values of $\Delta T/\Delta t$ are predominantly negative real numbers). We also derived mean nocturnal cooling rate ($\mu_{\Delta T}$) for each night and maximum nocturnal cooling rate ($\Delta T_{\max}/\Delta t$) for each station as follows:

$$\text{summer}\ \mu_{\Delta T} = (\Delta T_{19-20} + \cdots + \Delta T_{05-06})/t, \quad (1)$$

$$\text{winter}\ \mu_{\Delta T} = (\Delta T_{17-18} + \cdots + \Delta T_{07-08})/t, \quad (2)$$

$$\text{summer}\ \Delta T_{\max}/\Delta t = \min(\Delta T_{19-20}, \ldots, \Delta T_{05-06}), \quad (3)$$

and

$$\text{winter}\ \Delta T_{\max}/\Delta t = \min(\Delta T_{17-18}, \ldots, \Delta T_{07-08}), \quad (4)$$

where t = duration of nocturnal period, which is 11 h in summer and 15 h in winter. At all stations, both summer and winter $\Delta T_{\max}/\Delta t$ were typically observed in the early nocturnal period (i.e., within 2 h after sunset).

To examine the impacts of LULC change on station cooling rates, we subsequently categorized climate data (i.e., summer and winter $\Delta T/\Delta t$, $\mu_{\Delta T}$, $\Delta T_{\max}/\Delta t$, and hourly wind speed) from selected meteorological stations into time periods that marked early and late urbanization periods in metropolitan Phoenix. We define the early urbanization (EU) period as station data from 1990 to 1995, during which all four rural–urban stations were within predominantly agricultural or desert locations. A notable exception is the Corbell station, which underwent significant urbanization around its source area during 1990–95 (Table 2). To account for this, the EU period for this station was from 1990 to 1992, which is the approximate midpoint of the period during which LULC change occurred. The late urbanization (LU) period for all stations was from 2005 to 2009. We thus accounted for the duration of DT periods according to the SSC2 classification for analysis as described above. In all, 104 summer and 52 winter EU nights and 78 summer and 56 winter LU nights were categorized for analysis at each station, with the exception of Corbell, which had 53 summer and 26 winter nights for its shortened EU period from 1990 to 1992.

Our analysis method is based on the Lowry (1977) framework:

$$M_{itx} = C_{itx} + L_{itx} + E_{itx}, \quad (5)$$

where M is a measured weather element at station x, under synoptic weather type i during time period t. Here, C represents the cumulative climate elements on M when landscape or urban effects are absent, L represents landscape effects on M, and E represents urban effects; M, C, L, and E are derived from distributions with nonzero variances, with $\overline{M}, \overline{C}, \overline{L}$, and $\overline{E}$ being the means of these distributions. Assuming that for all pairs of time periods A and B, $\overline{C}_{iAx} = \overline{C}_{iBx}$, $\overline{L}_{iAx} = \overline{L}_{iBx}$, and $\overline{E}_{i0x} = 0$, then $\overline{M}_{itx} - \overline{M}_{i0x} = \overline{E}_{itx}$, where $t = 0$ represents the start of urbanization. Therefore, under specified assumptions, the true mean urban influence on a given meteorological station under certain synoptic conditions can be estimated as the difference of means between a measured weather variable during specified urban and preurban time periods (e.g., Svoma and Brazel 2010). In this study, $\overline{E}_{itx}$ represents the change from EU to LU. Given that the UHI in metropolitan Phoenix was certainly evident during the EU period, we acknowledge that EU is not truly preurban; because the city has undergone considerable recent growth, however, $\overline{E}_{itx}$ represents the mean change in variable x resulting from this urban expansion period. In addition and assuming that the Palo Verde station is not influenced by urbanization, the transition of EU to LU at Palo Verde allows us to test the validity of the static regional climate assumption above. (Is $\overline{C}_{iAx} = \overline{C}_{iBx}$?) Hence, we use two-sample t tests to determine the significance of the deviation of $\overline{E}_{itx}$ from 0 (where x is any of $\Delta T_{\max}/\Delta t$, $\mu\Delta_T$, $\Delta T/\Delta t$, or mean nocturnal wind speed at 10 m). For each t test, we checked for normality in residuals for each sample through the Ryan–Joiner test and found that, in the vast majority of cases, error normality was confirmed.

4. Results

We compared both mean seasonal $\mu_{\Delta T}$ and $\Delta T_{\max}/\Delta t$ for all eight stations during both EU and LU periods (Table 3). Most stations observed decreases in magnitude of both mean summer and winter $\mu_{\Delta T}$ from EU to LU with varying significance. For rural–urban stations, both Corbell (~0.5°C h^{-1}) and Rittenhouse (~0.2°C h^{-1}) observed relatively large and significant decreases ($p < 0.05$) in summer $\mu_{\Delta T}$ that reflected distinct changes in LULC around both stations. Relatively strong and significant decreases in mean winter $\mu_{\Delta T}$ were also observed at these stations. The variations for summer $\mu_{\Delta T}$ at Collier and Waddell were, however, not significant, and it is notable that the latter had anomalous slight increases for both summer and winter $\mu_{\Delta T}$. There were also decreases in mean summer and winter $\mu_{\Delta T}$ observed at urban–urban stations, with a notable decrease of $\mu_{\Delta T}$ at Alameda (~0.2°C h^{-1}) in both seasons as compared with both the

TABLE 3. Mean nocturnal $\mu_{\Delta T}$ and $\Delta T_{max}/\Delta t$ in EU and LU periods during summer and winter DT conditions. The significance of the change from EU to LU was determined through a two-sample t test ($p < 0.05$ = *; $p < 0.01$ = **).

	Mean $\mu_{\Delta T}$ (°C h^{-1})				Mean $\Delta T_{max}/\Delta t$ (°C h^{-1})			
	June DT		January DT		June DT		January DT	
Station	EU	LU	EU	LU	EU	LU	EU	LU
Rural–urban stations								
Collier	−1.34	−1.24	−1.12	−0.99**	−3.38	−2.76*	−3.51	−2.28**
Corbell	−1.69	−1.19**	−1.11	−0.92**	−3.59	−2.21**	−3.34	−2.77**
Rittenhouse	−1.39	−1.21**	−1.05	−0.96*	−3.85	−3.19**	−3.46	−2.87**
Waddell	−1.51	−1.53	−0.98	−1.07	−4.11	−4.29	−4.83	−4.92
Urban–urban stations								
Alameda	−1.45	−1.19**	−1.08	−0.90**	−2.63	−2.11**	−3.13	−2.84
Pera	−1.34	−1.26*	−0.91	−0.82	−3.19	−2.89*	−3.27	−2.86*
Pringle	−1.26	−1.15**	−0.92	−0.91	−2.35	−2.22	−2.82	−2.88
Rural–rural stations								
Palo Verde	−1.37	−1.29	−1.14	−1.02*	−3.1	−2.99	−2.94	−3.01

Pera and Pringle stations. Last, relatively small and insignificant decreases in mean $\mu_{\Delta T}$ were observed at the rural–rural Palo Verde station (~0.1°C h^{-1}) in summer and winter.

Variations in mean seasonal $\Delta T_{max}/\Delta t$ during the study period for all stations were generally similar in trend to the mean $\mu_{\Delta T}$. Decreases in mean summer $\Delta T_{max}/\Delta t$ from the EU to LU periods were ~0.4°C h^{-1} at urban–urban stations, and the magnitudes of these decreases were significantly larger (~0.7°C h^{-1}) for rural–urban stations, with the exception of Waddell station data. It was also notable that the largest maximum cooling rate for all stations occurred at Waddell during both seasons. There were negligible changes in $\Delta T_{max}/\Delta t$ at the rural–rural Palo Verde station, with a slight but insignificant decrease (increase) in magnitude during summer (winter).

We subsequently analyzed differences in hourly variations in both mean summer (Fig. 3) and winter (Fig. 4) $\Delta T/\Delta t$ between EU and LU periods for all stations. Significant changes in cooling-rate dynamics generally occurred during the first few hours of the nocturnal period for most stations, with the hour of sunset generally displaying the greatest change. These changes in EU versus LU hourly $\Delta T/\Delta t$ were more apparent in summer, with significant decreases observed during the approximate period of 3 h after sunset. Seasonal variations in hourly cooling-rate magnitudes were substantial (e.g., 1.17°C h^{-1} at Collier between 1800 and 1900 LST in January and 1.08°C h^{-1} at Rittenhouse between 1900 and 2000 LST in June; Table 3). In terms of the statistical significance, there appears to be little difference in the seasonal cooling-rate changes between winter and summer; the magnitudes were generally greater during summer than during winter, however. For example, at Corbell, changes in magnitudes of summer cooling rates were more than 2 times those during the winter. The only exception to this is at Collier, where the increases in mean $\mu_{\Delta T}$ and $\Delta T_{max}/\Delta t$ were more substantial (in terms of statistical significance and magnitude) in winter than in summer. In addition, cooling-rate variations were greater during the first 3 h after sunset in January than in June at Collier (Figs. 3, 4).

Last, our calculations of station $\Delta T_{max}/\Delta t$ data also enable comparison of peak urban surface cooling data from other cities. Documented mean $\Delta T_{max}/\Delta t$ magnitudes in urban stations in Phoenix (i.e., between 2.2° and 4.3°C h^{-1} in summer, and 2.3° and 4.9°C h^{-1} in winter) are larger in comparison with peak summer cooling rates recorded under ideal weather conditions in cities sited in different climates, such as in Göteborg [~2°C h^{-1}; Holmer et al. (2007)], Seoul [~1.0°C h^{-1}; Lee and Baik (2010)], Singapore [~0.4°C h^{-1}; Chow and Roth (2006)], and Vancouver [~1.5°C h^{-1}; Oke and Maxwell (1975)]. With the exception of Singapore, however, these reported magnitudes of $\Delta T_{max}/\Delta t$ were measured near the urban core and not in distinct residential areas. Larger observed summer $\Delta T_{max}/\Delta t$ magnitudes relative to other seasons were also reported in these cities.

5. Discussion

The results indicate that LULC change in Phoenix generally resulted in decreased magnitudes of nocturnal cooling rates under ideal synoptic weather conditions at most urban meteorological stations. This finding contrasts with relatively minor and mostly insignificant changes in cooling rates observed at the rural–rural station (Palo Verde), implying that the urban cooling-rate variations are largely due to LULC change rather than to regional climate change. Local-scale urbanization affects the magnitudes of maximum cooling more than the magnitudes of mean nocturnal cooling in both summer and winter, especially for stations that

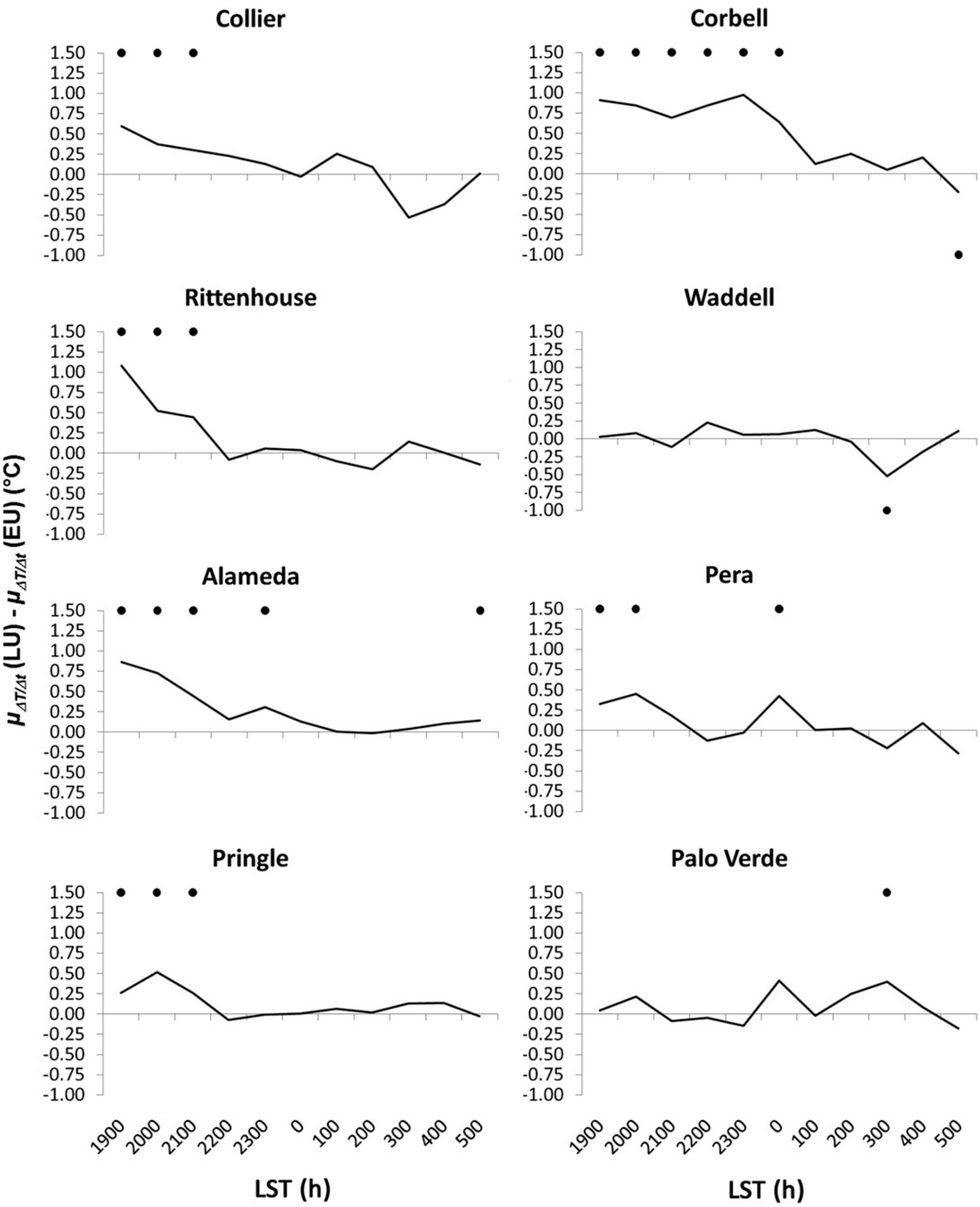

FIG. 3. Mean hourly station cooling-rate change (°C h^{-1}) from EU to LU for June DT conditions. Significant decreases (increases) at $p = 0.05$ in cooling-rate magnitudes as determined through two-sample t tests are indicated by dots above (below) the hourly value.

underwent rural–urban land cover transition. Analysis of hourly cooling-rate changes also shows that the greatest impacts from LULC change occur within the first few hours after sunset. Smaller magnitudes of mean nocturnal cooling were observed in winter than in summer. This result is possibly explained by both the longer nocturnal period and less stored energy at the surface as a result of lower magnitudes of winter insolation. Mean urban $\Delta T_{max}/\Delta t$ magnitudes in this study were generally larger when compared with results documented in other tropical and midlatitude cities, suggesting that climate-type differences (i.e., arid subtropical vs midlatitude vs equatorial climates) are factors that affect surface cooling rates, although differences in LULC characteristics among studies may also account for the difference in maximum cooling-rate magnitudes.

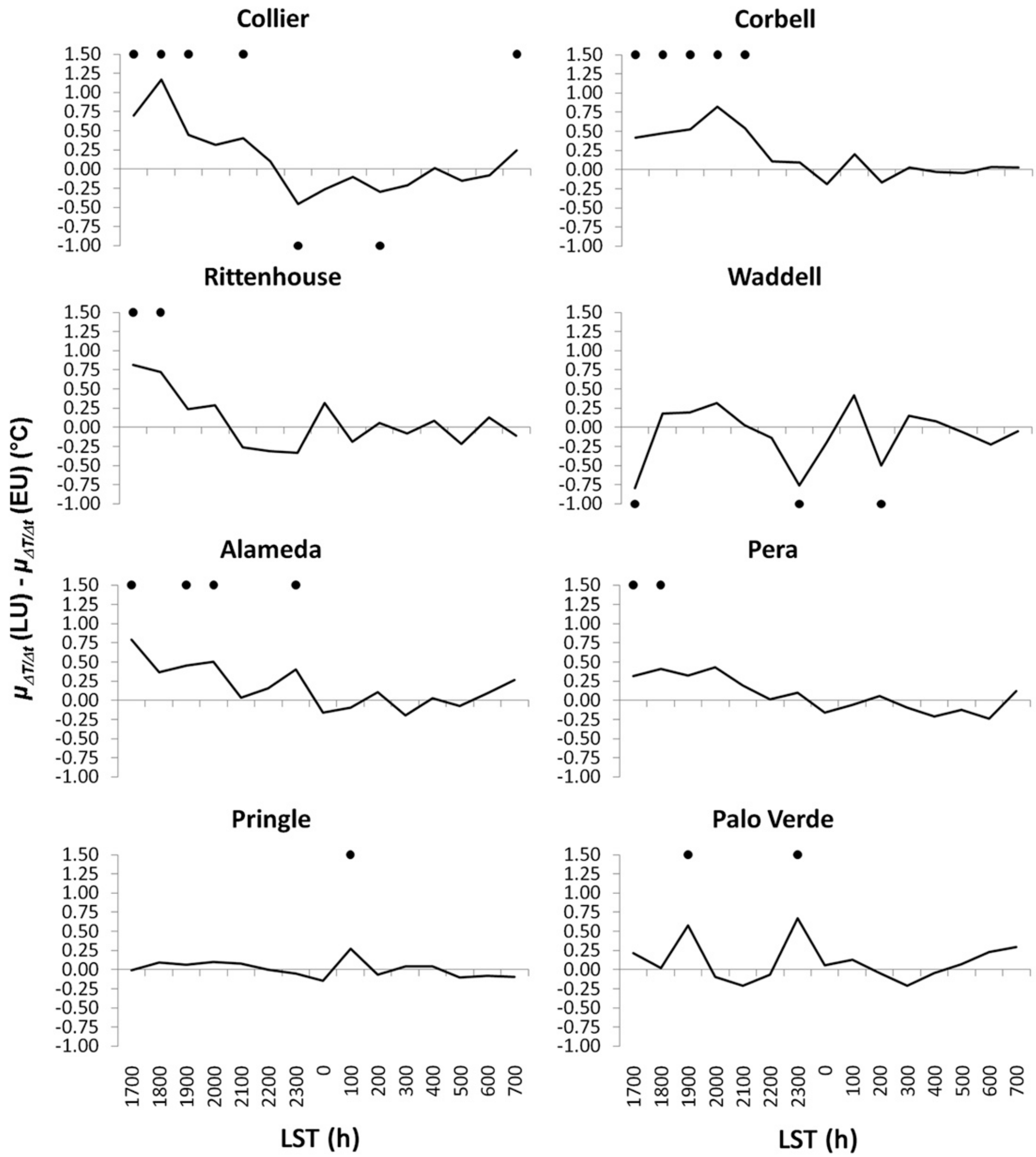

FIG. 4. As in Fig. 3, but for January DT conditions.

These results are mostly in concordance with prior knowledge about UHI and urban versus rural cooling rates. There exist, however, interesting variations in mean $\mu_{\Delta T}$, $\Delta T_{max}/\Delta t$, and hourly $\Delta T/\Delta t$ among stations and seasons that should be discussed. In 2005, two rural–urban stations (Collier and Waddell) were sited in areas that were not as urbanized as those of other stations (Table 2). This likely influenced site cooling rates relative to the more urbanized rural–urban stations at Corbell and Rittenhouse. A large proportion of the source area at Collier in 2005 was still agricultural in LULC, which potentially confounded the urban influence on cooling rates. For instance, observed winter hourly $\Delta T/\Delta t$ also indicates a minor but significant increase in magnitude from EU to LU at 2300 and 0200 LST (Fig. 4). There was still a decrease, albeit not significant at $p < 0.05$, in magnitudes of mean summer $\mu_{\Delta T}$, however (Table 3). Further, both summer and winter hourly $\Delta T/\Delta t$ analyses illustrate that decreases in cooling-rate magnitudes were significant for the first 3 h after sunset (Fig. 3). This is important given that most surface cooling occurs during this timeframe on the basis of evidence from Phoenix and other cities (e.g., Oke 1987).

A notable anomalous result is the unexpected, but statistically insignificant, increases in average cooling-rate metrics at Waddell. Like Collier, much of its source area during LU was not urban (i.e., undisturbed or natural desert in 2005). One potentially important difference is that, unlike other stations, Waddell is sited adjacent to a large topographic feature—the White Tank Mountain Range (Fig. 1)—that has ~600 m AGL prominence above the station, and its base was situated less than 5 km west of the station. Hence, possible local- or mesoscale flows from topoclimate effects could affect surface cooling at this site. For instance, higher wind speeds would generate greater near-surface turbulent mixing and thus minimize temperature gradients that drive surface cooling. Conversely, favorable surface cooling conditions would occur with lower wind speeds. To investigate this, we analyzed changes in mean nocturnal 10-m wind speeds from EU to LU for all stations under SSC2 DT conditions (Table 4) and found that Waddell was the only urban station that had observed reductions in near-surface wind speeds. This would likely enhance surface cooling and could explain the anomalous increases in cooling-rate magnitudes despite recent urbanization adjacent to the station. We acknowledge, however, that further investigation of micro- and local-scale site characteristics at Waddell is required to examine the precise reasons for this anomaly.

Although the rural–rural station (Palo Verde) had minor seasonal variations in nocturnal wind speeds between the EU and LU periods, other urban stations observed significant increases of 0.2–1.5 m s^{-1} during both seasons, except for Rittenhouse (~3.5 m s^{-1} increase). It is important to consider possible reasons for these changes given that increased advection disrupts surface cooling. Higher wind speeds could amplify decreases in mean urban station cooling rates that we attributed to LULC change. The basis of this general wind speed increase throughout the urban area is unlikely to be regional or synoptic in scale because of our filtered data that were selected under SSC2 DT conditions; hence, smaller-scale circulation systems affecting metropolitan Phoenix are more probable causes.

One possible mesoscale circulation system that could affect near-surface cooling rates would be the UHI-induced circulation (UHIC; e.g., Eliasson and Holmer 1990). Under dry, stable nighttime conditions, pressure-gradient differences can result from differential urban–rural cooling over a large city. A near-surface advective flux of cooler air from rural surfaces toward the urban core would likely develop, resulting in higher observed wind speeds. This circulation system has been documented in other cities situated in valley–mountain topography (Haeger-Eugensson and Holmer 1999) and is best observed at the urban fringe where the largest pressure gradients are typically located. Because the urban fringe in metropolitan Phoenix clearly expanded through

TABLE 4. Mean nocturnal wind speed change (m s^{-1}) from EU to LU periods under SSC2 DT conditions. Positive (negative) numbers indicate an increase (decrease) in mean wind speed. All results were significant at $p < 0.05$.

	June DT	January DT
Rural–urban stations		
Collier	0.88	0.17
Corbell	0.94	0.75
Rittenhouse	3.65	3.35
Waddell	−1.23	−1.15
Urban–urban stations		
Alameda	0.99	1.49
Pera	0.28	0.86
Pringle	1.20	1.69
Rural–rural stations		
Palo Verde	0.38	−0.34

Rittenhouse from 1990 to 2005 (Fig. 2), it is possible that the relatively large increase in mean nocturnal wind speeds is linked to a UHIC. Further, a developed, citywide UHIC system could also explain the small but significant increases in nocturnal near-surface wind speeds observed at other urban stations. Increased near-surface turbulent mixing at the three urban–urban stations (i.e., Alameda, Pera, and Pringle) could explain the observed decrease in cooling-rate magnitudes even though these stations did not undergo significant changes in urban land cover from 1990 to 2005. Examination of this UHIC scenario, however, requires more observational analysis of vertical profile data from Doppler lidar or radar profilers (e.g., Brazel et al. 2005), which is beyond the scope of this study.

6. Concluding remarks

To summarize, we have found that both spatial magnitudes and temporal dynamics of nocturnal cooling in metropolitan Phoenix are strongly influenced by rural-to-urban LULC conversion, although topographic and advective impacts are also possible factors for explaining intraurban variations in cooling rates for stations at the urban fringe (e.g., Rittenhouse and Waddell). Significant decreases in cooling-rate magnitudes were also observed at stations sited within urban areas throughout the study period. This suggests that larger-scale influences, such as a possible UHIC system that developed in conjunction with rapid urbanization, could increase advective fluxes that reduce cooling-rate magnitudes. This possibly could also distort and/or increase the size of the assumed 500-m circular source area for urban temperatures proposed by Oke (2004).

This study is among the first to utilize several cooling-rate metrics that directly analyze local-scale, historical LULC change with respect to near-surface climates, as opposed to a relative metric such as ΔT_{u-r}. Together with available long-term land cover and synoptic weather data, this approach enabled us to directly apply a method that closely approximates the ideal Lowry (1977) framework of estimating urban impacts on climate. Future applications and results of this method can complement distinct-urban-zone classification schemes (e.g., Oke 2006; Stewart and Oke 2009) that are being developed for cities in directly assessing intraurban thermal variations. For instance, typical reported magnitudes of $\Delta T_{max}/\Delta t$ across different seasons could be associated with each urban climate zone, largely reflective of its urban cover.

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