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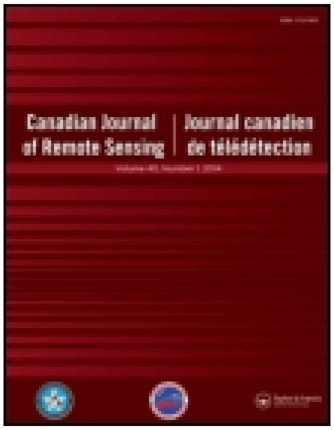

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Ping Zhang[ab], Lahouari Bounoua[a], Marc L. Imhoff[c], Robert E. Wolfe[d] & Kurtis Thome[a]
[a] Biospheric Sciences Laboratory, code 618, NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771 USA
[b] Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland 20740, USA
[c] Joint Global Change Research Institute, PNNL, College Park, Maryland 20740, USA
[d] Terrestrial Information Systems Laboratory, code 619, NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

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Comparison of MODIS Land Surface Temperature and Air Temperature over the Continental USA Meteorological Stations

Ping Zhang[1,2,*], Lahouari Bounoua[1], Marc L. Imhoff[3], Robert E. Wolfe[4], and Kurtis Thome[1]

[1]Biospheric Sciences Laboratory, code 618, NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, USA
[2]Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland 20740, USA
[3]Joint Global Change Research Institute, PNNL, College Park, Maryland 20740, USA
[4]Terrestrial Information Systems Laboratory, code 619, NASA's Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

Abstract. The National Land Cover Database (NLCD) Impervious Surface Area (ISA) and MODIS Land Surface Temperature (LST) are used in a spatial analysis to assess the *surface*-temperature-based urban heat island's (UHI_S) signature on LST amplitude over the continental USA and to make comparisons to local air temperatures. *Air*-temperature-based UHIs (UHI_A), calculated using the Global Historical Climatology Network (GHCN) daily air temperatures, are compared with UHI_S for urban areas in different biomes during different seasons. NLCD ISA is used to define urban and rural temperatures and to stratify the sampling for LST and air temperatures.

We find that the MODIS LST agrees well with observed air temperature during the nighttime, but tends to overestimate it during the daytime, especially during summer and in nonforested areas. The minimum air temperature analyses show that UHIs in forests have an average UHI_A of 1°C during the summer. The UHI_S, calculated from nighttime LST, has similar magnitude of 1–2°C. By contrast, the LSTs show a midday summer UHI_S of 3–4°C for cities in forests, whereas the average summer UHI_A calculated from maximum air temperature is close to 0°C. In addition, the LSTs and air temperatures difference between 2006 and 2011 are in agreement, albeit with different magnitude.

Résumé. L'Aire des Surfaces impérvieuses (ISA) de la banque Nationale de données sur les Couvertures du Sol (NLCD) et les températures de surface de MODIS (LST) des années 2006 et 2011 sont utilisées dans une analyse spatiale pour évaluer la signature des ilots de chaleur Urbains, basés sur la température de surface (UHI_S), sur l'amplitude de la LST aux EUA, et faire des comparaisons avec les températures de l'air locales. Les ilots de chaleur basés sur la température de l'air (UHI_A) calculés à partir des données journalières de température obtenues du Network Historique Climatologique Global (GHCN) sont comparés aux UHI_S pour des arrangements urbains dans des biomes de végétation et des saisons différentes. Les aires impérvieuses (ISA) sont utilisées pour définir les zones urbaines et rurales ainsi que pour stratifier l'échantillonnage des LSTs et des températures de l'air des stations.

On trouve que la LST de MODIS est en bon agrément avec la température de l'air durant la nuit, mais tend à la surestimer durant le jour, spécialement pendant l'été et dans les régions non-boisées. L'analyse des températures minimum montre que les peuplements urbains construits en milieu forestier ont une UHI_A moyenne d'environ 1°C durant l'été. Les LSTs nocturnes ont des amplitudes similaires de 1–2°C. Par contraste, les LSTs de MODIS montrent des UHI_S de 3–4°C dans les centres urbains en milieux forestiers alors que la valeur moyenne d'été des UHI_A obtenue à partir des températures maximales avoisine 0°C. Les différences entre les LSTs et la température de l'air entre 2006 et 2011, sont en agreement quoiqu'avec des intensités différentes.

INTRODUCTION

Urban heating represents a significant attribute of urban land transformation that affects human health, ecosystem function, local weather, and possibly climate through important physical land surface changes. Replacing the vegetated and evaporating soil surfaces with relatively impervious paving and building materials reduces latent heat flux and increases sensible heat in urban areas and thus creates a difference in temperature between urban and surrounding nonurban areas, which is known as the urban heat island (UHI). In this analysis we use a map of impervious surface area (ISA) to delineate urban areas

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[*] Corresponding author e-mail: Ping.Zhang@nasa.gov

and their nearby surrounding rural areas over the continental USA.

Near-surface air temperature, which is measured 1.5 m above the ground level at official weather stations, is one common way to estimate the magnitude of UHI by comparing the observed temperature between urban and rural weather stations (Karl et al. 2006). In general, the air temperature UHI (UHI_A) has a strong diurnal cycle and is more important at night (Roth et al. 1989). In addition, the UHI_A has a strong dependence on the location of the weather stations. In this sense, UHI_A is strongly affected by local climate, as well as the developments surrounding the weather stations. This may have large variations in magnitude even within the same city. For instance, the UHI_A calculated using weather stations in Melbourne, Australia, varies from a summer average of 1.29°C (Morris and Simmonds 2001) to an optimum weather condition value of 10°C (Oke 1973).

Land Surface Temperature (LST), also known as surface skin temperature, is a good indicator of the energy balance at Earth's surface and is one of the key parameters in the physics of land surface processes from local to global scales (Wan et al. 2004; Mildrexler et al. 2011). Because surfaces heat and cool more rapidly than air, surface temperatures can be more variable than overlaying air temperatures, and the greatest UHI_S are observed during midday, whereas UHI_A are largest at night (Roth et al. 1989). The complexity of the surface types in urban environments and variations in urban topography can both affect the LST (e.g., Nichol 1996; Streutker 2002). Remotely sensed thermal imagery has the advantage of providing a time-synchronized dense grid of temperature data at local, regional, or even global scales (e.g., Xian 2008; Imhoff et al. 2010, Zhang et al. 2010). The remotely sensed LSTs (e.g., MODIS LSTs) have been widely used for *surface*-temperature-based UHI (UHI_S) phenomena and for intercomparisons across different urban areas (e.g., Rajasekar and Weng 2009 in Indianapolis, USA; Pu et al. 2006 in Yokohama City, Japan; Zhang et al. 2012 in Northeast USA).

Recent research comparing station air temperature with remotely sensed land surface temperature at regional scales (e.g., Urban et al. 2013) and global scales (Jin and Dickinson 2010; Mildrexler et al. 2011) find that LST and air temperatures are correlated and that the relationship is affected by land cover types and other factors.

The research presented here compares the MODIS daytime and nighttime overpass LST estimates with the maximum and minimum air temperatures obtained from the Global Historical Climatology Network (GHCN) meteorological stations. Although these measurements are not exactly synchronized by time of the day, they are highly correlated and can be used in the analysis of the UHI. We analyze: *i.* the seasonal relationship between MODIS LSTs observed at day and nighttime overpass and maximum/minimum air temperature for each meteorological station; *ii.* the effect of surrounding biomes and ISA at each station on this relationship between MODIS LST and air temperature; *iii.* the seasonal UHI amplitude calculated from these two temperatures for over 300 urban areas in the USA; and *iv.* the seasonal temperature changes from year 2006 to 2011 at each meteorological station.

METHODS AND DATA

Global Historical Climatology Network-Daily

Daily maximum and minimum air temperatures were obtained from the Global Historical Climatology Network (GHCN) at the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center (NCDC).[1]Additional metadata for each station, such as station ID, geographic coordinates, and measured parameters were also extracted. A consistency check was made to eliminate stations with significant missing data from this study. To produce seasonal average minimum/maximum air temperatures at each station, we average valid daily minimum/maximum temperatures from the months of December (from the previous year), January, and February (DJF) for the winter season and from June, July, and August (JJA) for the summer season. In this study, we compare the seasonal average maximum/minimum air temperature of year 2006 (designated year of the ISA product) and 2011 (most recent record for the majority of the stations) to MODIS LST at each station. Recent studies highlight the importance of the thermal source area or footprint for a temperature measurement, which is the surface from which the temperature signals are derived and carried to the sensor (Stewart and Oke 2012). Empirical studies have shown that a source area, on average, is a few hundred meters away in a neutrally stable atmosphere (Runnalls and Oke 2006, Stewart and Oke 2012). In this study, we use the GHCN data along with MODIS LST, both representing the local scale, typically one to several kilometers. At this scale, landscape features such as vegetations and topography, which can affect surface temperatures, are included, and the observed signal should represent an aggregate characteristic of a mix of microclimatic effects arising from source areas in the vicinity of the site (Oke 2004); however, under some meteorological circumstances, rapid advection of cooler or warmer air can alter the representation of the observed air temperature.

MODIS Land Surface Temperature (LST)

To characterize the surface temperature for the area around each of the GHCN stations for the two years of interest, we use MODIS-Aqua and Terra Version 5, daily (MYD11A1 and MOD11A1) LST with high quality control (Wan et al. 2004) at 1 × 1-km resolution. LSTs from MODIS are retrieved from clear-sky (99% confidence) observations at daytime and nighttime using a generalized split-window algorithm (Wan and Dozier 1996). The coefficients used in the split-window algorithm are given by interpolating a set of multidimensional

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[1] http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/

look-up tables (LUT) derived by linear regression of MODIS simulation data from radiative transfer calculations over wide ranges of surface and atmospheric conditions. These look-up tables have been continuously updated (Wan et al. 2004) and comparisons between MODIS LSTs and in situ measurements across a wide set of test sites indicate an accuracy better than 1°C, with a root mean square (RMS; of differences) less than 0.5°C in most cases (Wan 2008; Wang et al. 2008).

In this study, we used the geographic location of each GHCN station to retrieve the closest Terra/Aqua daily LST with highest quality control in a single 1 × 1-km pixel, including the station. Then we compared seasonal average daytime Aqua (local overpass time at 13:30) and Terra (overpass at 10:30) LST to maximum air temperature and the nighttime Aqua (overpass at 1:30) and Terra (overpass at 22:30) to the minimum air temperature at each station.

Classification of Urban and Rural Stations

We used the Landsat-derived National Land Cover Database ISA data for the year 2006 (Xian et al. 2011) to classify each station as urban or rural. This ISA dataset characterizes the continental U.S. urban development intensity as a function of the extent and spatial distribution of a collection of manmade surfaces within a pixel (e.g., Yang et al. 2002, Fry et al. 2011, Xian et al. 2011). The ISA data compare well with independently derived census data estimating urban populations in the USA (Imhoff et al. 2010), represent phenologically different environments (Bounoua et al. 2009), are positively linked to urban warming effects in the U.S. long-term climate record (Hansen et al. 2001), and enable rigorous comparisons of urban density and surface temperature at local scales (Yuan and Bauer 2007; Xiao and Crane 2005).

We use a 25% ISA threshold to define the boundary between urban and rural area (Imhoff et al. 2010; Zhang et al. 2010) with urban areas having more than 25% ISA. We classify GHCN stations as urban stations if they are located within the urban polygons or as rural stations if they are located in a buffer zone 0–25 km adjacent to and outside the 25% ISA contour. For most urban settlements, this 0–25-km buffer zone is a distance far enough from the urban center to represent a nonurbanized or rural area, yet not too far as to infringe into the 25% contour of an adjacent urban area or transition into another biome. In addition, we setup a threshold of 10% ISA to choose the rural stations, in agreement with the previous classification of local climate zones (Stewart and Oke 2012).

Topography and Terrestrial Ecoregion Map

Topographic data are used as a filter in order to exclude from the analysis temperature differences due to elevation and shading due to orography. We use the 30 arc-second (∼925 m) spatial resolution of the Shuttle Radar Topography Mission (SRTM30; Farr and Kobrick 2000) dataset to determine a mean elevation of the urban area and exclude from analysis all pixels whose elevation is outside the +/− 50-meters interval from the mean elevation.

In this study, we use the terrestrial ecoregion map of Olson et al. (2001) to divide the GHCN stations over the continental United States into four major biomes: forest, grassland, desert, and Mediterranean, each representing an assemblage of biophysical, climate, botanical, and animal habitat characteristics of a distinct geographical area. Stations from different biomes might have different local climates or biophysical or environmental characteristics. Stations that fall into overlapping biomes or other urban areas are excluded from the analysis.

Analysis Steps

The comparison of remotely sensed LST observations and air temperature records from the meteorological stations is performed as follows:

1. Extraction of the U.S. meteorological stations (39,659 stations) from the global dataset.
2. Identification of the geographic location of stations that have at least 100 days of observations each year from 2001 to 2011 and extraction of daily maximum and minimum air temperature records. This has reduced the count to 5,070 stations used to calculate seasonal average minimum and maximum temperatures for the years 2006 and 2011.
3. Define 323 urban areas in the United States using the NLCD ISA 25% contour. Urban areas are defined as having 25% or more ISA, whereas their surrounding rural zones are defined within a 0–25-km buffer distance with additional biome and elevation constraints applied.
4. Extraction of ISA and biome type of each station from NLCD 2006 ISA products and global terrestrial ecoregion map.
5. Extraction of LST at 13:30 (10:30) and 1:30 (22:30) for each station location from daily MODIS Aqua (Terra) LST products. Calculate seasonal average LSTs for the years 2006 and 2011.
6. Seasonal comparison of MODIS LST and air temperature.
7. Seasonal comparison of UHI calculated from MODIS LST and from air temperature.
8. Link the results to ISA, biome types, and assess the changes between year 2006 and 2011.

RESULTS AND DISCUSSION

Comparison of LST with Air Temperature

More than 5000 stations are selected from the GHCN to have at least 100 days of air temperature measurement (Figure 1). Using the geographic coordinates of each selected station and the NLCD map, an impervious surface area at 1 × 1-km spatial resolution is calculated around each station for further urban/rural classification. MODIS Aqua and Terra daily 1-km resolution LST values with the best quality assurance (QA) flags are obtained at each station. The maximum (minimum) daily air temperature is compared with daily LST from Aqua at 13:30 (1:30)

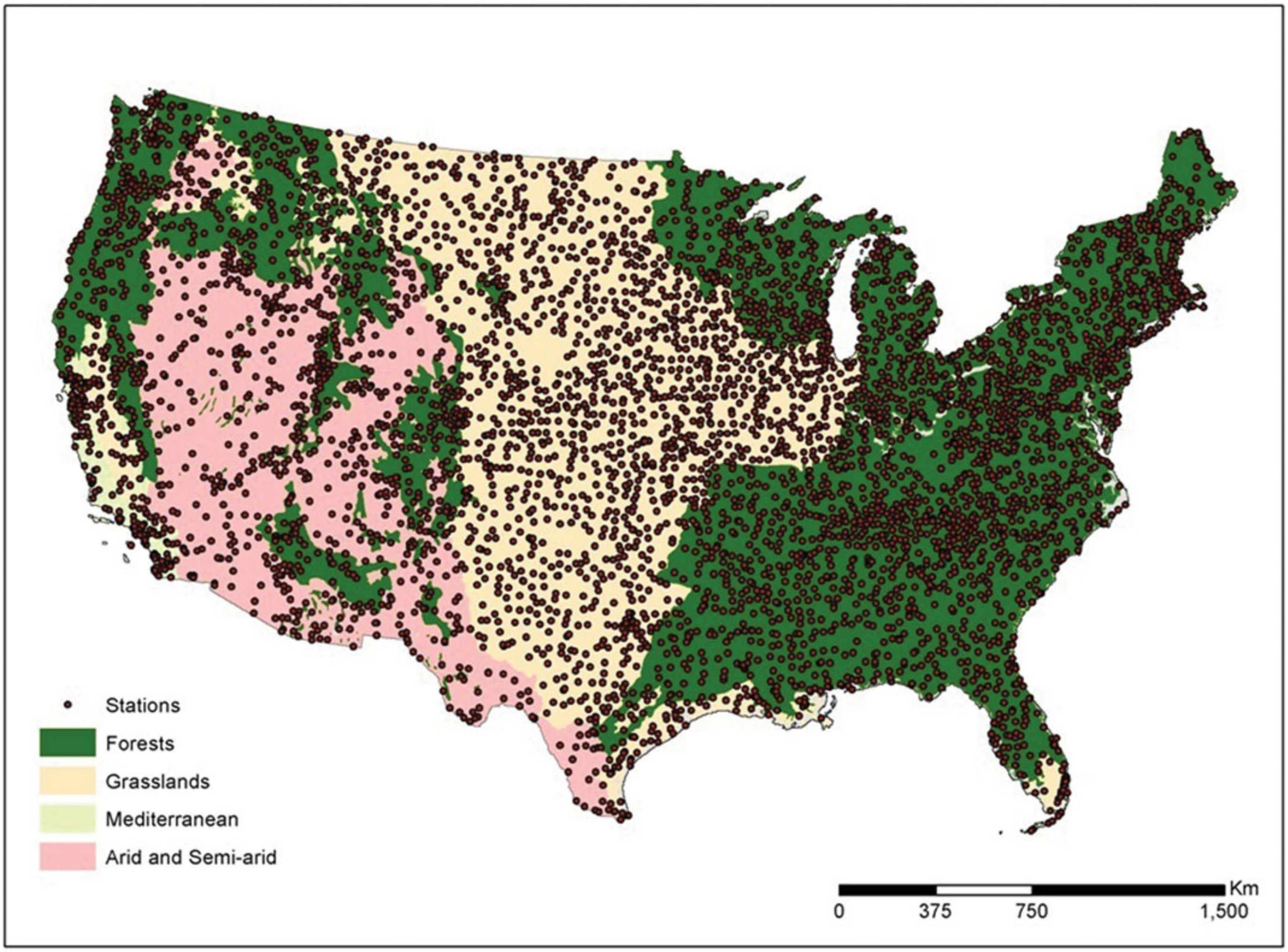

FIG. 1. Distribution of GHCN stations with at least 100 days of air temperature measurement. Four major biomes: forest, grassland, arid and semiarid, and Mediterranean, are shown according to Olson et al. (2001).

and Terra 10:30 (22:30), respectively. Because both the air temperature and the daily LST temperature might have missing measurements during the study period, a minimum of 10 days of measurements in each season are required to eliminate errors due to limited sample size. The LST measurements show a normal distribution in which most stations have about 40 days of QA-filtered measurements during the season, whereas most stations have more than 80 days of air temperature measurements during the season. As a result, stations used for the winter analysis are about 400 fewer than those used for the summer analysis, because of weather conditions, and represent less than 10% of the total number.

During the winter, a strong positive relationship is found between station air temperature and LST (Figure 2). In general, the overall correlation of LST and air temperature is high ($R^2 = 0.88$ for Terra, and $R^2 = 0.93$ for Aqua). Both Aqua and Terra show a close fit of the regression line to the 1:1 line, which agrees with the previous comparison at the Pan-Arctic scale (Urban et al. 2013). During the summer, the relationship between station air temperature and MODIS LST has two different phases. The average summer minimum air temperature is strongly correlated with the nighttime LST ($R^2 = 0.84$ for Terra, and $R^2 = 0.87$ for Aqua) and the regression line is close to a 1:1 line. By contrast, the correlation between the summer maximum air temperature and MODIS daytime LST is less robust ($R^2 = 0.44$ for Aqua or Terra). The relationship becomes loose especially when the temperature is higher than 30°C.

We then grouped the GHCN stations by their proximity to forest, grass, desert, and Mediterranean biomes using the terrestrial ecoregion map (Olson et al. 2001). For each biome, the stations are further subdivided into two groups based on the ISA of each station: stations with ISA $< 10\%$ and stations with ISA $> = 25\%$. Figure 3 shows the R-square and the estimated

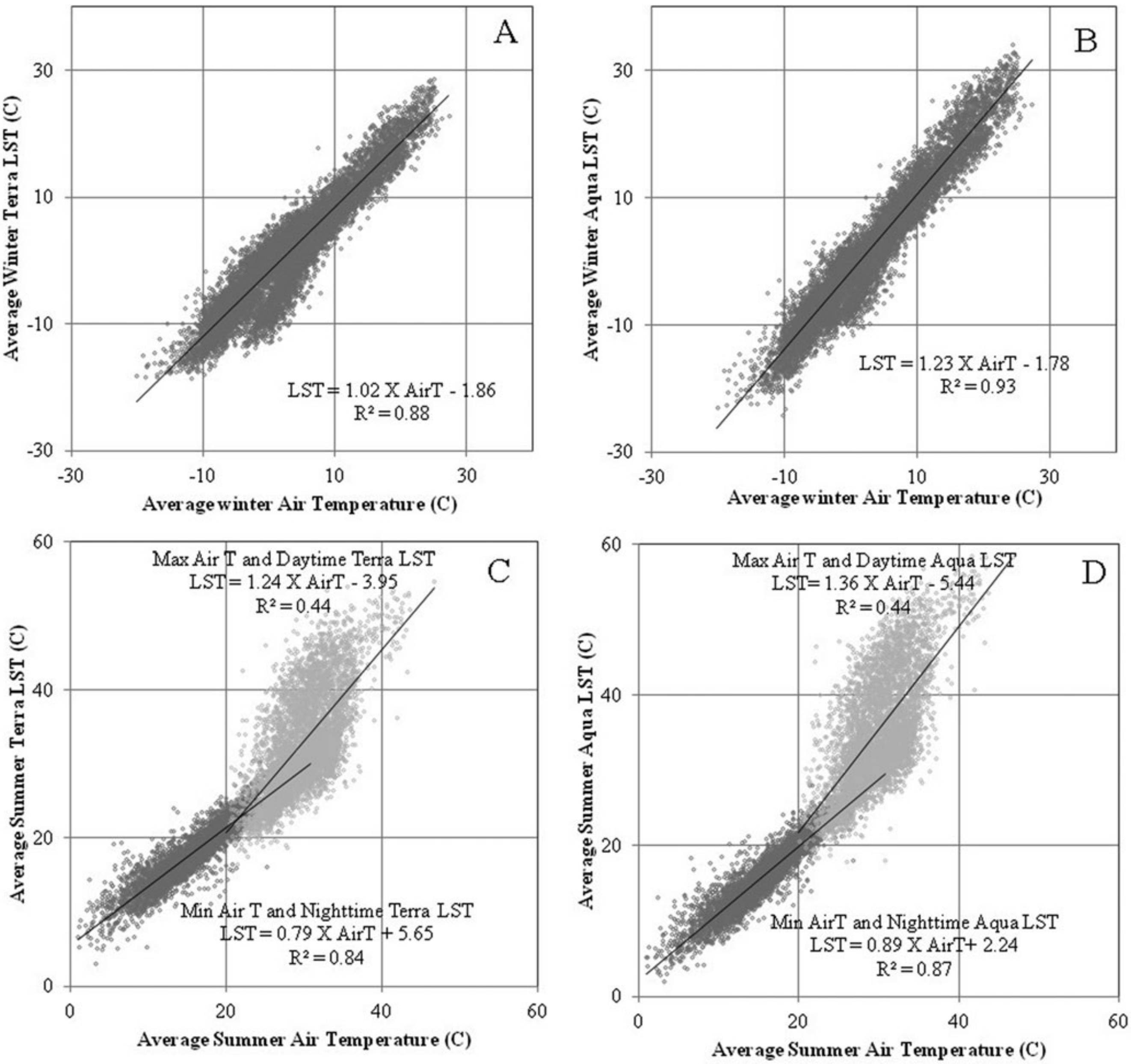

FIG. 2. Comparison of average seasonal LST and air temperature records. Each pair of measurements shows the seasonal average of daily observations. The MODIS TERRA LST at 10:30 and Aqua LST at 13:30 are compared to the maximum air temperature record. The MODIS Terra LST at 22:30 and Aqua LST at 1:30 are compared to the minimum air temperature record.

slope of the positive relationship between LST and air temperature during winter. The error bar shows the 95% confidence interval of the linear slope. The linear relationships between LST and air temperature are similar for stations with ISA $> =$ 25% and ISA $<$ 10% located in the same biome. In addition, daytime measurements tend to have better correlation and larger slope than nighttime measurements. For different biomes, the correlations between LST and air temperature are higher than 0.9 for all stations except those located in the Mediterranean biomes, which had a limited sample size. For 1°C of air temperature increase, the LST tends to increase more than 1°C during winter over forest, grassland, and desert stations. Furthermore, the daytime LST tends to change more than the nighttime LST. This is in agreement with previous regional and global comparisons suggesting that air temperature can significantly underestimate the actual radiative surface temperature, especially at high temperatures and in nonforested areas (Urban et al. 2013; Mildrexler et al. 2011).

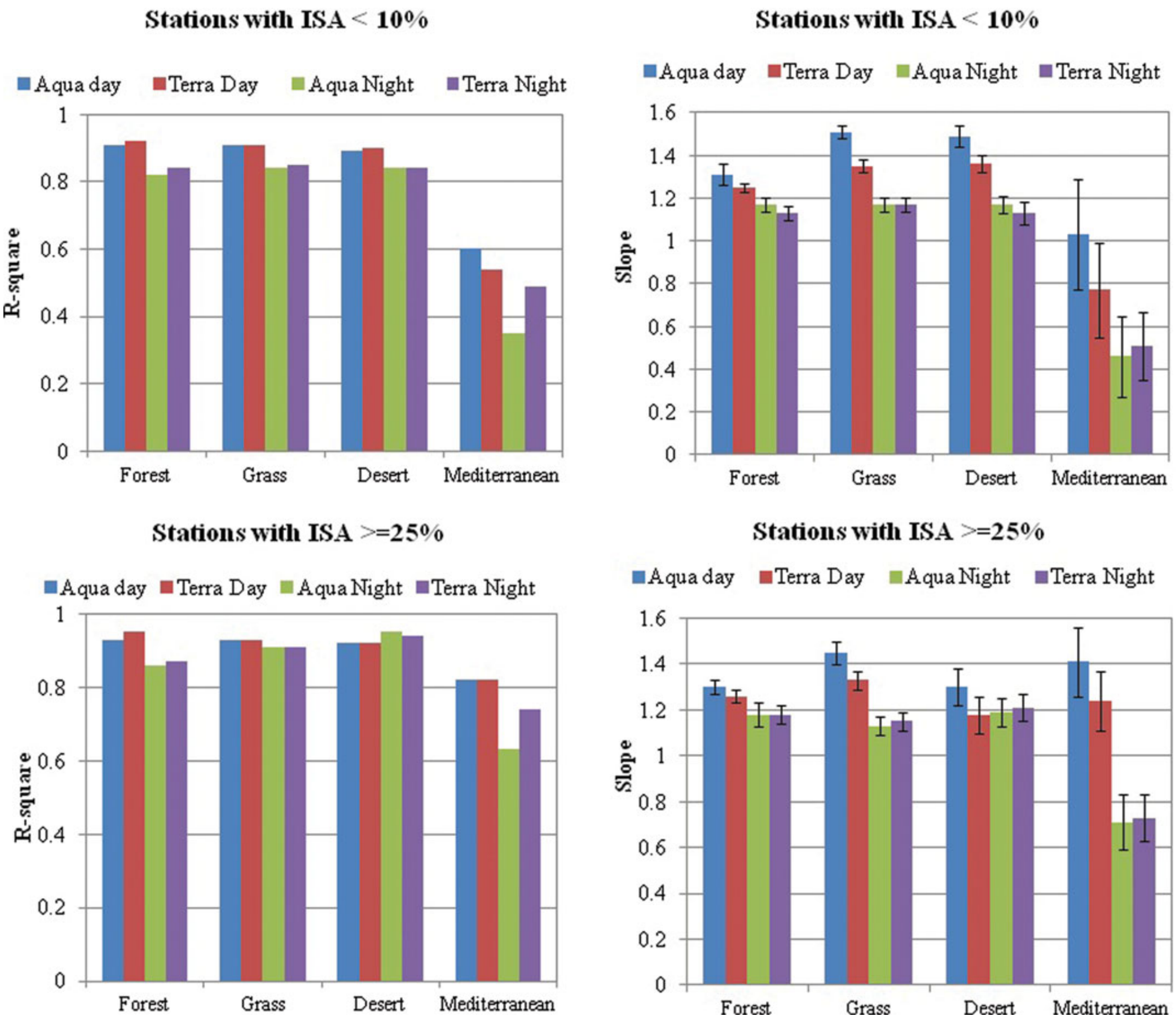

FIG. 3. The coefficient (with 95% confidence interval) and R-square between MODIS LST and GHCN air temperature averaged over winter at different stations classified by biomes and impervious surface area (ISA).

The relationship between LST and air temperature is similar during the summer but with a larger variation, especially during daytime. Our result shows that for both Aqua and Terra nighttime LSTs, the R-square is between 0.8 and 0.9 for all biomes except the Mediterranean, where it is about 0.5–0.8. However, the R-square for daytime LSTs is about 0.4 for all biomes, except for stations with ISA more than 25% surrounded by grass or desert biomes. We also calculated the seasonal diurnal temperature range (DTR) using both air temperature and LST. Figure 4 shows that the DTR from Aqua LST estimates is larger than the DTR from air temperature, whereas the DTR from Terra LST estimates is smaller than that from air temperature. These differences are mainly caused by the Terra and Aqua overpass time: Terra observes at 10:30 and 22:30, whereas Aqua observes at 1:30 and 13:30, which is closer to the actual occurrence of the observed maximum and minimum temperatures. Gallo et al. (1996) used the U.S. Historical Climatology Network weather station observations and found that stations built in rural regions usually have larger observed DTR than those built in urban areas. Our seasonal average DTR obtained from air temperature shows a similar result: for each biome type, the DTR of stations with ISA smaller than 10% is larger than that of stations with ISA equal to or larger than 25%, especially for stations built in forests and grasslands environments in which the difference is

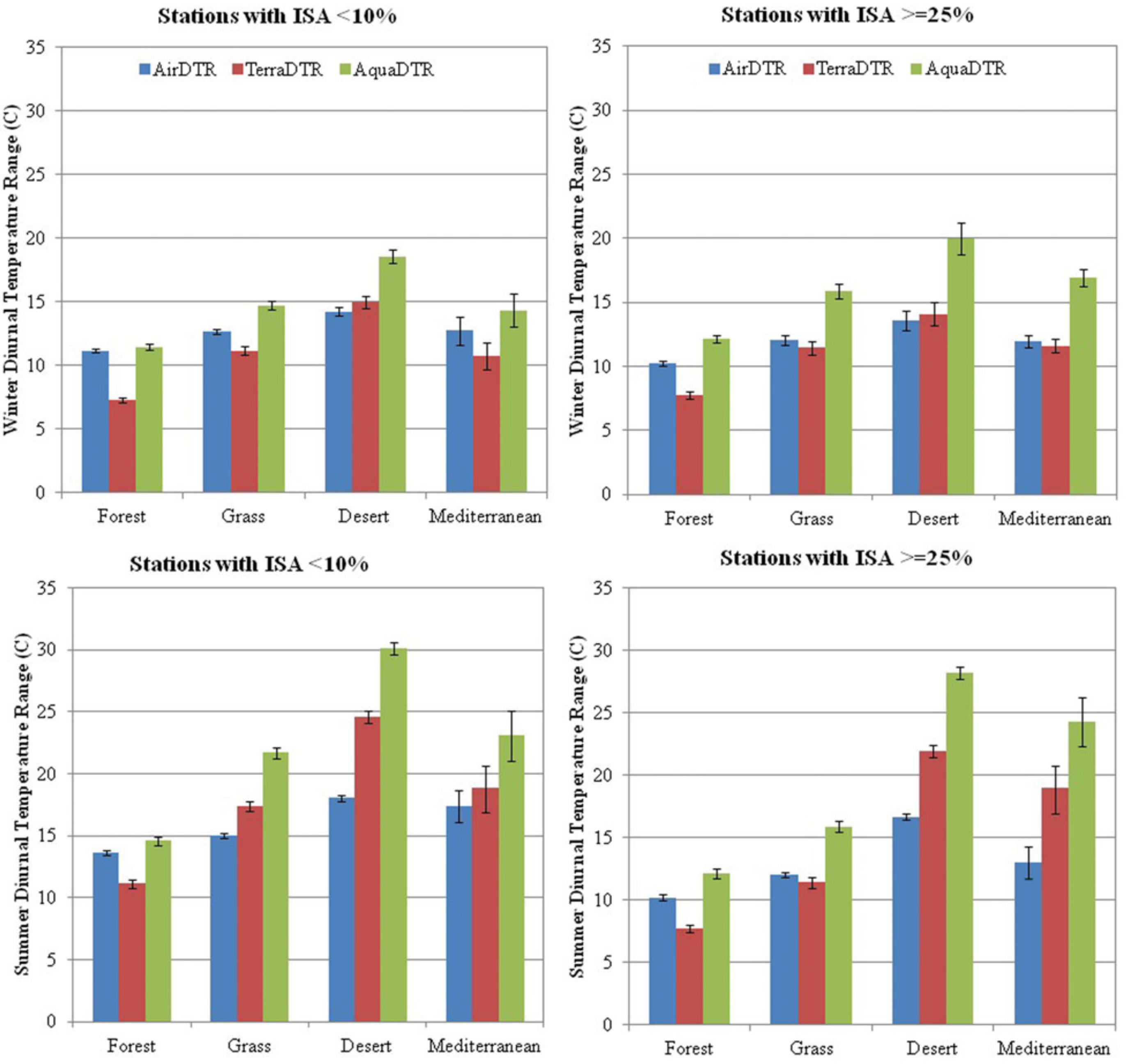

FIG. 4. The average seasonal diurnal temperature range (DTR) for different stations classified by biomes and ISAs. The 95% confidence interval is shown as an error bar. The top two panels show the results of winter average (December–January–February), the bottom two panels show the results of summer average (June–July–August).

significant at a 95% confidence level (Figure 4). Specifically, forest stations with ISA smaller than 10% have an average winter DTR of 11.2°C, which is 1.0°C more than those for stations with an ISA equal to or larger than 25%. Similarly, the grassland stations with ISA smaller than 10% have an average winter DTR of 12.6°C, which is 0.6°C more than that of grassland stations with ISA equal or larger than 25%. This difference is more significant during the summer when the average summer air temperature DTR for forest stations with ISA smaller than 10% is 3.0°C higher than that in stations with ISA equal to or larger than 25%.

Although surface temperatures can both cool and warm faster and are more variable than concurrent air temperatures as a result of the complexity of the surface types in urban environments and variations in urban topography (e.g., Nichol 1996; Streutker 2002), the DTR from the summer LST shows similar results:

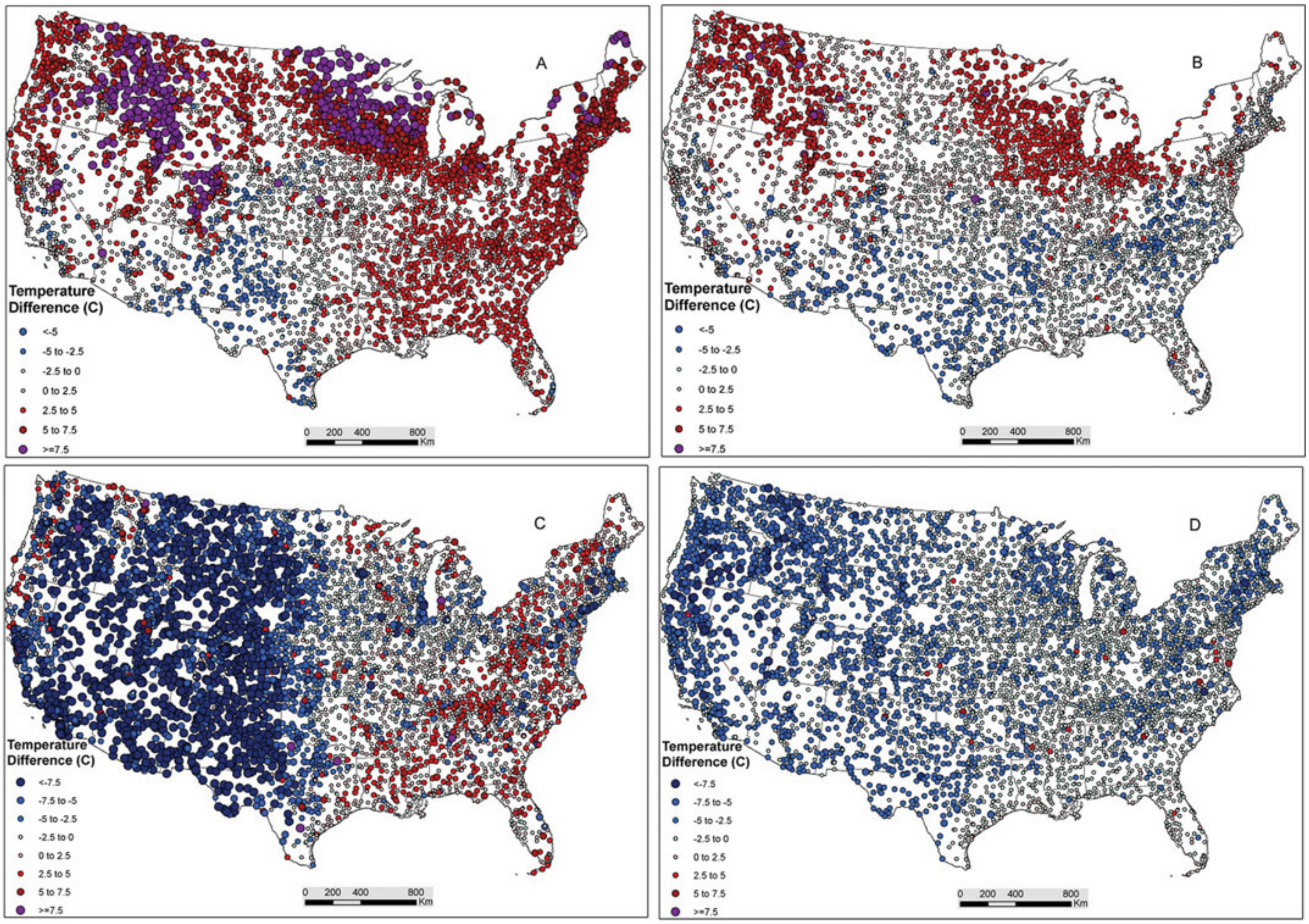

FIG. 5. Temperature difference between seasonal GHCN air temperature and Terra LST at each station: a. the difference between winter average maximum air temperature and Terra morning LST at 10:30; b. the difference between winter average minimum air temperature and Terra night LST at 22:30; c. the difference between summer average maximum air temperature and Terra morning LST at 10:30; and d. the difference between summer average minimum air temperature and Terra night LST at 22:30.

stations with ISA equal to or larger than 25% tend to have smaller DTR than stations with ISA smaller than 10% ISA, especially when using Aqua LSTs.

In addition to seasonality, biomes also affect the relationship between air temperature and LST. Figure 3 shows that for the same change in air temperature, forest stations have smaller change in LST when compared to short vegetation (grassland and desert). This is associated to the nonlinear coupling of the air temperature to the land surface temperature, which involves simultaneously the surface energy, water, and carbon balance in an interplay that is highly dependent on the land surface cover. Although forested covers are deeply rooted and can sustain a substantial and longer amount of transpiration, short vegetation such as grasslands and shrubs in desert areas have shallower rooting depth and are more sensitive to soil moisture and temperature stress. It is likely that more-sensitive, short vegetation underwent a soil moisture stress that reduced the stomatal conductance "shunting," thus, most of the absorbed energy went into sensible heating (Bounoua et al. 2009). This would cause a more frequent reduction of the transpiration rates in those biomes, thereby increasing the surface temperature at the canopy level. This phenomenon is also noticeable in the magnitude of DTR. On average and at the 95% confidence level, the DTR of forest stations is significantly less than that obtained in stations with other biomes. For example, for stations having an ISA equal to or larger than 25%, forest stations have a winter air temperature DTR of 10.2°C compared to 12.0°C in grassland stations, 13.6°C in desert stations, and 11.9°C in Mediterranean stations. Similarly, the Terra/Aqua DTR of forest stations is 7.7/12.1°C, compared to 11.4/15.9°C in grassland stations, 14.1/20.0°C in desert stations, and 11.6/16.9°C in Mediterranean stations (Figure 4). The biome effects on the magnitude of DTR is in line

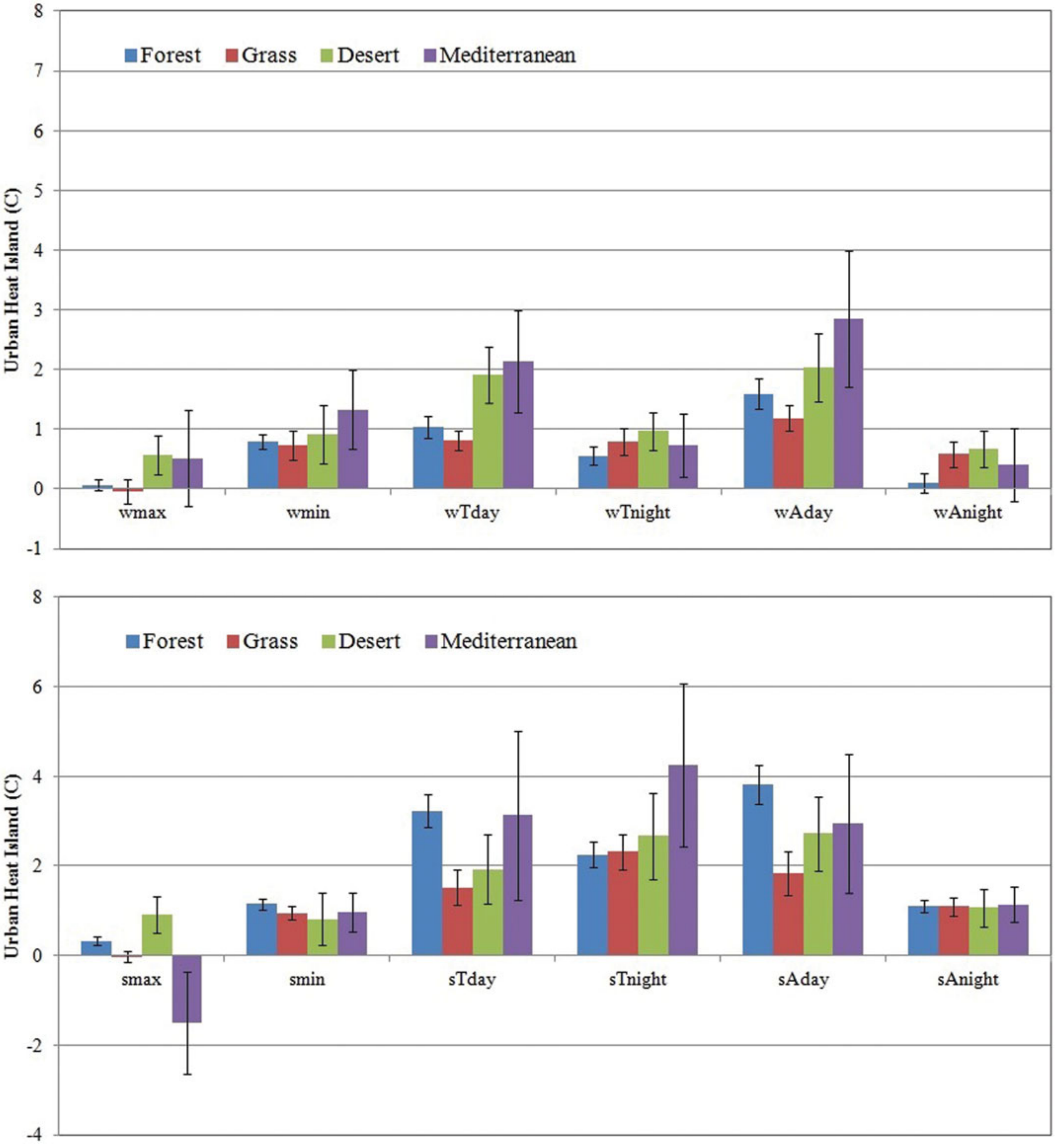

FIG. 6. Air and surface temperature urban heat island (UHI) for different biomes with standard error. The top panel shows the results from winter, and the bottom panel shows the results from summer. UHI are calculated using daily measurements of maximum air temperature, minimum air temperature, Terra day LST, Terra night LST, Aqua day LST, Aqua night LST over December–January–February (wmax, wmin, wTday, wTnight, wAday, wAnight) and over June–July–August (smax, smin, sTday, sTnight, sAday, sAnight), respectively.

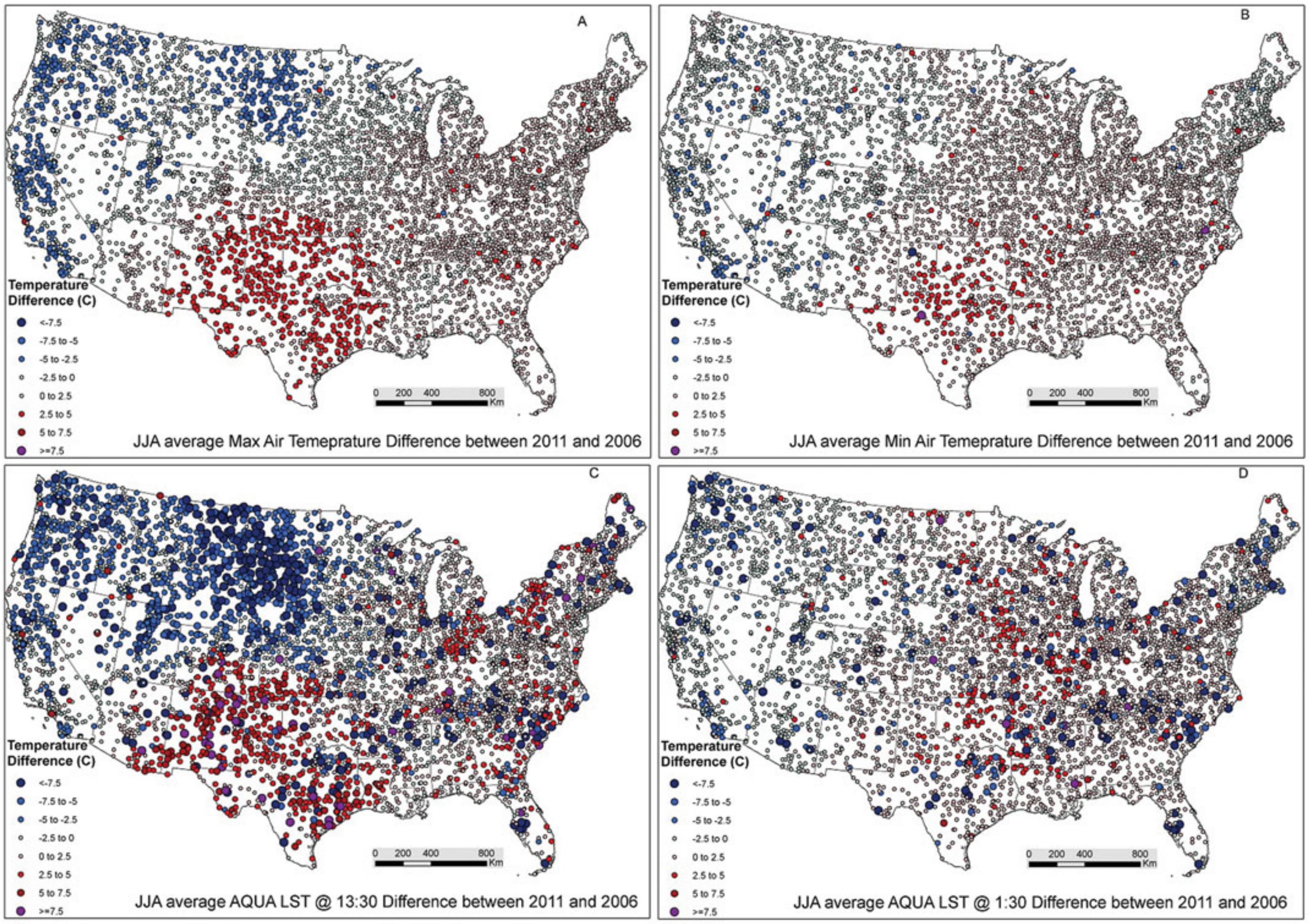

FIG. 7. The average summer (June–July–August) temperature difference between 2011 and 2006: a. the temperature difference using maximum air temperature; b. the difference when using minimum air temperature; the surface temperature difference when using daytime Aqua LST; and the surface temperature difference when using nighttime Aqua LST.

with results from Jin and Dickinson's (2010) results, which show, at a global scale, that desert regions such as the Sahara have larger LST diurnal variations than forest regions such as the Amazon.

We calculated the average temperature difference between seasonal air temperature and MODIS LST at each station and illustrate the spatial distribution of the difference in Figure 5. In general, the temperature difference ranges from less than −7.5°C (blue) to more than 7.5°C (red and purple). The size of the points represents the magnitude of the difference: the larger the point, the bigger the absolute temperature difference is. The winter maximum difference map (Figure 5a) shows that maximum air temperatures are warmer than Terra LST at 10:30 for most of the stations, especially in forest biomes. Two warm centers are located in the Wisconsin–Minnesota and Idaho–Montana regions, where the temperature difference is more than 7.5°C. These two warm centers are also identified by the temperature difference between winter minimum air temperature and Terra LST at 22:30 (Figure 5b); however, the magnitude of the difference is about 2.5–5°C or more, not as significant as the difference in maximum. Most GHCN stations located in southeastern forests shows that air temperatures are 2.5–5°C warmer than Terra daytime LST, and are 0–2.5°C cooler than Terra nighttime LST.

Summer temperature difference has a different spatial pattern. Most of the GHCN stations located in the western USA indicate that the summer maximum air temperatures are 7.5°C cooler than Terra daytime LST estimates (Figure 5c). Specifically, this cooler difference is more significant in stations over western grassland and desert biomes. The average summer temperature difference is around −2.5 to 2.5°C in most eastern forest GHCN stations. However, the average nighttime summer difference (Figure 5d) shows that the minimum air temperature is cooler than or very close to Terra nighttime LST. The difference between air temperature and Aqua LST are similar to the result of Terra (not shown).

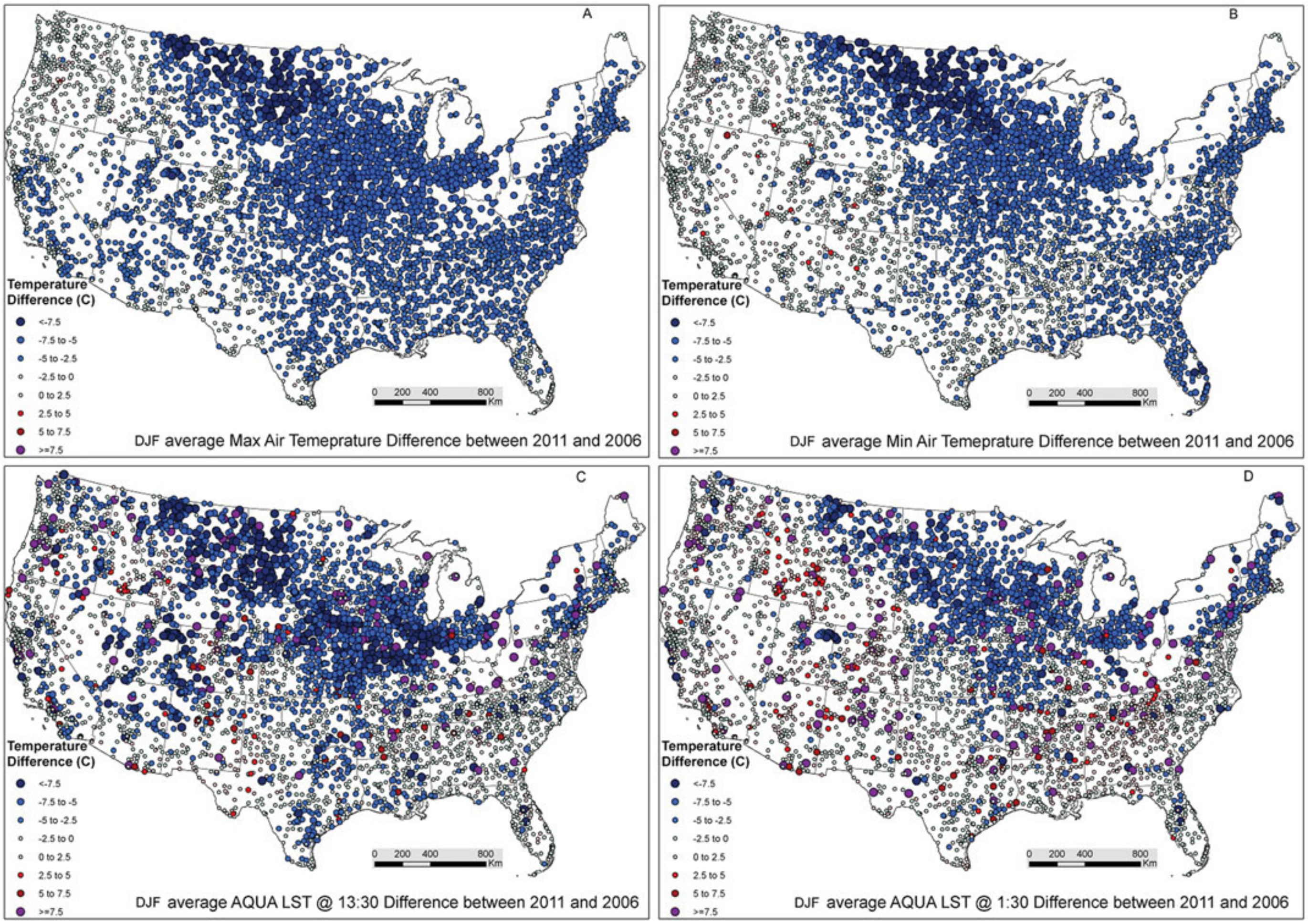

FIG. 8. The average winter (December–January–February) temperature difference between 2011 and 2006: a. the temperature difference using maximum air temperature; b. the difference when using minimum air temperature; c. the surface temperature difference when using daytime Aqua LST, and d. the surface temperature difference when using nighttime Aqua LST.

Urban Heat Island Difference Between Air Temperature and LST

Overlaying the NLCD ISA map and the GHCN station distribution map, we define more than 300 urban settlements over the continental United States, over which we estimate the UHI. Almost 2000 stations are located in these 300 urban settlements and their surrounding rural areas. As discussed in "Methods and Data," we use the average temperature of the stations located within the urban boundary as the urban temperature and the average temperature of stations located within the 0–25-km buffer zone as the rural temperature.

Figure 6 shows the average $\mathrm{UHI_A}$ and $\mathrm{UHI_S}$ and associated standard errors grouped by different biomes and temperature measurements. The winter $\mathrm{UHI_A}$ is more important for the minimum temperature compared to the maximum temperature. However, the winter $\mathrm{UHI_S}$ is more significant around midday. In terms of biome difference, urban settlements built in forests have an average $\mathrm{UHI_A}$ of 1.1°C during summer nighttime. The summer nighttime LST from Aqua (1:30) and Terra (22:30) are quite close and indicate a nighttime $\mathrm{UHI_S}$ of 1–2°C. By contrast, the summer daytime LST from Aqua and Terra LST show a midday $\mathrm{UHI_S}$ magnitude of 3–4°C for cities in forested biomes, whereas the average summer $\mathrm{UHI_A}$ calculated from maximum air temperature is close to 0°C. The $\mathrm{UHI_A}$ and $\mathrm{UHI_S}$ magnitude for grass and desert cities have similar patterns but less intensity. The $\mathrm{UHI_A}$ and $\mathrm{UHI_S}$ of Mediterranean cities have large variance due to a limited sample size and the fact that most of the Mediterranean stations are located in urban areas.

It should be noted that because of the limited sample size of the GHCN stations, as well as the uneven spatial distribution of these stations in an urban settlement, the UHI magnitude calculated based on station samples will be less intense. For instance, our previous studies showed that the average $\mathrm{UHI_S}$ for large cities located in forest biomes is 6–9°C (Imhoff et al. 2010). On a global average, the Aqua summer daytime $\mathrm{UHI_S}$ for forest cities is about 3.8°C (Zhang et al. 2010). In those studies, the MODIS LST is averaged using all the land pixels located in a high-intensity urban zone and surrounding rural zone. However, the GHCN stations in this study tend to be located in low-to-middle intensity urban zones, hence, a less intense $\mathrm{UHI_S}$ would be expected.

The Mean Temperature Difference Between 2011 and 2006

We used a similar method to calculate the seasonal temperature of each station for the year 2011 and analyzed the temperature difference between 2006 and 2011. The choice of this period is dictated by the availability of the ISA for 2006 and 2011 and the availability of both MODIS Terra and Aqua. Figure 7 shows the summer mean temperature difference between 2011 and 2006 for all the stations over the contiguous USA. Each point represents the average summer temperature difference between 2011 and 2006 for each station. The colors and formats of the stations are similar to those of Figure 5. In general, the stations located in northern grasslands, such as North Dakota and South Dakota, are cooler in 2011 than 2006 for maximum air temperature (Figure 7a) and MODIS daytime LST (Figure 7c). By contrast, stations located in southern grassland, such as Texas and New Mexico, are warmer. Furthermore, the magnitude of difference is higher for the LST than the air temperature, indicating higher variations of the land surface temperature. For instance, the absolute temperature difference of maximum air temperature between these two years is about 2.5–5°C, whereas the absolute difference of daytime LST is 5–7.5°C or more. For the minimum air temperature (Figure 7b) and MODIS nighttime LST (Figure 7d), the average summer difference between 2011 and 2006 is relatively small with no significantly warmer or cooler regions.

The average winter temperature difference shows different spatial patterns. Most GHCN stations show a colder winter maximum and minimum air temperature, especially the stations in North Dakota, where the temperatures in 2011 are 5–7.5°C or colder than 2006 (Figure 8a and 8b). The winter daytime LST also shows colder signals in 2011 over the stations in North Dakota (Figure 8c), but night LST difference is less intensive (Figure 8d). Both GHCN and MODIS data show a colder 2011 winter compared to 2006, and these results are in agreement with those of the NCDC, which showed the average temperature of North Dakota in 2011 to be 1.8°C cooler than in 2006. Interannual variations in climate could be responsible for this observed difference; however, the presence of snow or changes in rural areas' soil moisture could also affect the results. In addition, winter daytime LST shows a second cooler center around Illinois–Iowa–Missouri.

SUMMARY

We compared air temperature measurements from the NCDC over more than 5000 GHCN meteorological stations over the continental United States with MODIS Aqua and Terra land surface temperatures. The datasets were grouped by biome and stratified by impervious surface area to delineate urban versus rural stations.

In the continental United States, our results show both MODIS daytime and nighttime LSTs are strongly correlated to air temperature in the winter (December–January–February), but this relationship decreases during the summer season (June–July–August) especially for daytime observations wherein the satellite-based LSTs have much higher diurnal amplitude than the station-observed air temperature. In addition, the rate of LST increase with air temperature increase appears to be influenced by ecological context because forest stations have the least LST change for the same variation in air temperature. Although increasing ISA is seen to increase both air temperature and LST, our results show that no significant differences between LST and air temperature are found between stations with ISA smaller than 10% and stations with ISA equal to or larger than 25%. This would indicate that seasonality and biome location are more important in creating a divergent LST–air temperature relationship than ISA.

In general, air-temperature-based $\mathrm{UHI_A}$ is more significant when using minimum temperature. LST-based $\mathrm{UHI_S}$ is more significant when using summer daytime estimates. By comparing the seasonal temperature difference between 2011 and 2006, strong agreements of spatial distribution are found between air temperature and LST, with significantly warmer and cooler centers found between these two years at different seasons.

It should be noted that the main purpose of this work is not to use in situ station air temperature to validate the MODIS LST estimates but rather to develop a comparison between these two products. Our results indicate strong agreement and correlations between these two products during different seasons, over different biomes, and in the changes between two different years. Slight differences in the amplitudes of the changes could be due to the fact that MODIS LST and air extreme temperature are not completely synchronized in time. However, even if the overpass time of MODIS is retrievable, the extreme air temperatures provided by the GHCN and used in this study do not have timestamp information of daily occurrences. This research compares the MODIS daytime and nighttime overpass LST estimates with maximum/minimum air temperature. Future studies will focus on improving these comparisons with exact time-of-day observations.

The urban heat island studies in this paper are based on average temperature difference under all weather conditions. Future work will focus on studying the effects of these conditions on UHI magnitude and its difference when using air temperature and remotely sensed land surface temperature.

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