Seasonal Variations of the Urban Heat Island at the Surface and the Near-Surface and Reductions due to Urban Vegetation in Mexico City

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ABSTRACT

The contrast of vegetation cover in urban and surrounding areas modulates the magnitude of the urban heat island (UHI). This paper examines the seasonal variations of the UHI using the Moderate Resolution Imaging Spectroradiometer (MODIS), surface meteorological observations, and the Weather Research and Forecasting (WRF) model. A distinction is made between the land surface UHI observed by satellite and the near-surface UHI observed by measuring the air temperature. The land surface UHI is found to be high at night throughout the year but drops during the wet season. The daytime UHI is low or even exhibits an urban cool island throughout the year but increases during the wet season. The near-surface air temperature UHI trend is similar to the land surface temperature UHI at night. By day, however, the air temperature UHI remains constant throughout the year. Regression analysis showed that the daytime land surface UHI correlates with the difference in vegetation fraction between the urban and surrounding areas, and, to a lesser extent, with daytime insolation. At night, the UHI correlates with nighttime atmospheric stability and only weakly with differences in vegetation cover and daytime insolation. WRF simulations with the single-layer Urban Canopy Model were initialized with MODIS data, especially for the urban fraction parameter. The simulations correctly represented the distinct seasonal variations of both types of UHIs. The model was used to test the impact of changes in vegetation fraction in the urban area, indicating that increased vegetation would reduce both the land surface UHI and the air temperature UHI at night, as well as the land surface UHI during the daytime.

1. Introduction

Urbanization has caused cities to experience higher temperatures than the surrounding countryside does, a phenomenon known as the urban heat island (UHI). UHIs can enhance the formation, concentration, and transportation of urban ground-level ozone and other air pollutants (Yoshikado and Tsuchida 1996; Saitoh et al. 1996; Chen et al. 2003). Moreover, summer heatwave events can exacerbate the mortality resulting from heat stroke and air-quality problems (Meehl and Stocker 2007; Borden and Cutter 2008; Krayenhoff and Voogt 2010). This has led to research into mitigating UHIs, for example by increasing green vegetation cover or by installing white roofs (Rosenzweig et al. 2006; Zhang et al. 2009; Oleson et al. 2010).

The Mexico City metropolitan area (MCMA) is located in the Valley of Mexico, a mountain basin at an elevation of 2240 m MSL, and is the second largest metropolitan area in the world. The MCMA has a tropical mountain climate with a relatively small annual temperature range (Jauregui 1997), which is usually classified into three seasons: the cold dry season (November–February), the warm dry season (March–April), and the rainy season (May–October). Industrialization and high population density in the MCMA have caused high ozone concentrations and aerosol pollution, which have led the government to implement a series of plans to address the problem (Molina and Molina 2002). The MCMA experiences weak synoptic forcing with variable winds that are strongly influenced by local topography and land use (Fast and Zhong 1998; de Foy et al. 2005, 2008). The impact of land-use change on climate and air quality over the MCMA has been simulated by Jazcilevich et al. (2000, 2002): historically recorded warming in the Valley of Mexico could be attributed to the growth of the urban area. They used modeling...
results to show that a partial recovery of the lake, which had previously filled the wide basin, could reduce the concentration levels of some air pollutants. With respect to the effect of urbanization, the near-surface air UHIs (1994–95) over the MCMA were analyzed using automatic weather stations at an urban site and a rural site (Jáuregui 1997). A maximum intensity of the nocturnal heat island intensity at 7.8°C was observed in February (dry season) during a calm clear night. The average urban–rural thermal contrasts were positive throughout the year, varying from 5°C at daybreak in the middle of the dry season to 1°–3°C around noon during the wet months.

Satellites are an invaluable tool for UHI studies because of their ability to detect the thermal features of the earth’s surface with broad spatial resolution. They can provide dense time-synchronized and continuous grids of temperature data over an entire city to perform a larger and more regular sampling than is possible with surface observations (Streutker 2003; Hung et al. 2006; Arnfield 2003). Several groups have applied Terra Moderate Resolution Imaging Spectroradiometer (MODIS) operational data to study the land surface UHI seasonal behavior. For example, Terra MODIS data (2001–03) on least-clouded day and night scenes were used to analyze the spatial patterns of UHIs for eight Asian megacities (five temperate cities and three tropical cities) over the course of seasonal cycles (Hung et al. 2006). For temperate cities in Asia, the maximum intensity of surface UHIs is in July–August and the intensity of UHIs is much lower in winter. For the tropical cities, the highest intensity occurred during the dry season and there was no clear signal of the UHI during the rainy season because of the effect of clouds. A 3-yr-long time series of Terra MODIS data was also used to derive the seasonal variation of monthly mean UHI over nine populated central European cities (Pongracz et al. 2010). For central Europe, the most intense UHI occurs in the daytime during the summer, but during the rest of the year the UHI intensity is mostly larger at night than during the day.

Satellite remote sensing has also been used to analyze the spatial relationship between vegetation cover and surface thermal conditions in relation to land surface UHIs at the canopy layer. For instance, Owen et al. (1998) used a boundary layer model to examine the regional-scale spatial climatic impact of urbanization with fractional vegetation cover, and they suggested that the climatic response in surface radiant temperature is linked to the replacement of vegetation by surfaces with considerably lower evaporation rates. An Enhanced Thematic Mapper Plus (ETM+) image of the city of Indianapolis, Indiana, was analyzed by Weng et al. (2004) to estimate the spatial relationship of land surface temperature (LST) and vegetation abundance. They found that the interplay between thermal and vegetation dynamics in the context of different land-cover types leads to variations in the spectral radiance and texture of LSTs, suggesting that contrasting vegetation dynamics between urban and rural areas are responsible for the spatial patterns of UHIs. The surrounding biome was found to have a significant impact on the seasonality and magnitude of the daytime UHI (Imhoff et al. 2010). In contrast to most urban areas, the daytime UHI in arid environments was small and was not greatly affected by the impervious surface area.

Whereas satellites measure the LST (the “skin” temperature), human health and comfort depend more directly on the near-surface air temperature. Although we expect the two to be closely related, there can be significantly greater differences during clear-sky conditions than during cloudy-sky conditions (Gallo et al. 2011). The UHI is usually more distinct when the skies are clear, however (Oke 1988). Using clear-sky data, we therefore seek to establish the relationship between the two types of UHIs. Furthermore, this study will examine the extent to which the land surface UHI can be used as a proxy for the air temperature UHI since measurements of the skin temperature are much more readily available all over the globe than are surface observations.

The Weather Research and Forecasting model (WRF; Skamarock et al. 2005) is used to analyze simulations of the UHI over Mexico City using the “Noah” land surface model (LSM; Chen and Dudhia 2001) in combination with an urban canopy model (UCM). This configuration has been tested for large midlatitude cities such as Tokyo, Japan (Kusaka and Kimura 2004); Taipei, Taiwan (Lin et al. 2008); and Beijing, China (Miao et al. 2009). By integrating the simulation of the mesoscale circulation and the surface energy processes, the system can bridge the gap between mesoscale and microscale modeling (Chen et al. 2011). Furthermore, fitness-for-purpose of the Noah/single-layer UCM (SL-UCM) has been evaluated offline to identify both strengths and weaknesses (Loridan et al. 2010). In this study, we therefore use the model as a bridging tool to analyze the skin temperature measured from remote sensing and the near-surface meteorological observations. Having demonstrated the ability of the model to represent the significant features of the Mexico City UHI, we use the model to test the impact of varying vegetation cover in the urban area.

2. Data description

a. Satellite data

The land products of the MODIS data are used here to study the land surface UHI (UHI_{skin}). MODIS is
aboard both the *Terra* and *Aqua* polar-orbiting satellites, which pass the equator 2 times per day (Wan 1999). Over the MCMA, the local crossing times are approximately 1030 and 2230 central standard time (CST) for *Terra* and 1330 and 0130 CST for *Aqua*. MODIS has a high accuracy (1 K) and high spatial resolution (250 m per pixel in the visible and 1 km per pixel in the infrared channels). The MODIS 1-km LST data are obtained by using the generalized split-window algorithm with screening for cloud effects (Wan 1999; Wan et al. 2002) using bands 31 and 32 in the 10.78–12.27-μm spectral range. MODIS products provide quality-assurance flags (Wan 2006) that can be easily used to limit cloudy conditions for monitoring UHIs. This is especially helpful for cities in tropical climates (Hung et al. 2006). The day/night characteristic of *Terra* MODIS and *Aqua* MODIS is able to provide LST data 4 times daily, further offering the possibility of studying the seasonal behavior of UHI$_{skin}$ in the morning, afternoon, evening, and late-night hours. MODIS land products will be used to analyze the behavior of UHI$_{skin}$ over the MCMA for both day and night. *Terra* was launched 2.5 yr earlier than *Aqua*. UHIs have already mainly been analyzed and documented using *Terra* MODIS data (Pongracz et al. 2010; Hung et al. 2006). Because the *Aqua* passing time is shortly after the middle of the day and the middle of the night, however, there is a clearer signal in the UHI values in the *Aqua* MODIS dataset. We will therefore focus on the latter in this study.

MODIS land products have two separate uses in this study. The first, described here, is to use land-use categories and LST data to analyze UHI$_{skin}$ in seasonal variations over the MCMA. The second, described in section 3b, is to use these as well as surface albedo and vegetation fractions to initialize the land surface in the WRF simulations. The intensity of UHI is defined as the temperature contrast between the urban area and its surrounding rural area. Figure 1 shows the *Terra* MODIS land use and land cover (LULC) (2004) for the MCMA using the International Geosphere–Biosphere Programme (IGBP) classification scheme. The 1-km data (h08v07; h08v06) will be mapped to the 3-km grid size of the WRF simulations (section 3b). On this basis, an urban domain (from 19.33° to 19.50°N and from 99.2° to 99.0°W) and a rural domain (from 19.6° to 19.8°N and from 98.7° to 98.5°W) were chosen for general assessment of UHI$_{skin}$ in seasonal variations. The choice was constrained by the need to have a flat domain, with uniform land use. The rural domain is entirely natural landscape consisting of grassland, croplands, woody savannas, and open shrub. In terms of uniform land cover of the urban and rural domains, we average the surface temperature of all grids.
(1 km × 1 km) in each domain to obtain a representative value to determine the intensity of UHIskin.

The 8-day average LST Terra MODIS and Aqua MODIS data (2006) at 1-km resolution are used to obtain seasonal time series of UHIskin under clear-sky conditions (section 4a). With higher time resolution, 1-day Aqua MODIS data (2006) at 1-km resolution are used to study the seasonal behavior of UHIskin by comparison with the neighboring 2-m air temperature UHI (UHIair) observations (see section 4b). The MODIS cloud masks are used to screen for clear skies (Platnick et al. 2003). This mask can suffer from reduced accuracy at night and over nonvegetated areas. For this study, we limit the data to conditions of totally clear sky. After the screening, we obtain 165 measurements of UHIskin in the afternoon and 127 measurements during the late night of 181 potential days during the dry seasons, and we obtain 39 measurements in the afternoon and 57 measurements in the late night of 184 potential days during the wet season.

b. Surface observations

The near-surface temperature measurements presented in this study were measured at approximately 2 m above the ground, with a 10-min time resolution, by using two automatic meteorological stations installed in Tezontle (hereinafter TEZO) and Montecillo (hereinafter MONT), as shown in Fig. 1. TEZO (19.4°N, 99.1°W) is a surface station of the Mexican National Meteorological Service (http://smn.cna.gob.mx) that is located 6.3 km southeast of the city center (Zócalo). It is inside the urban domain defined above. MONT (19.5°N, 98.9°W) is operated by staff at the Montecillo campus of the Colegio de Postgraduatos, Instituto de Enseñanza e Investigación en Ciencias Agrícolas, which is located 25.1 km northeast of the city center. MONT is on the outskirts of the urban area, and the surroundings consist mostly of fields with scattered buildings. The elevation is nearly the same as TEZO. Note that we were limited in our choice of a rural location because most of the available stations are in the urban area, and many of the remaining ones are at very different elevations. Although the station is not inside the rural domain defined above, the MODIS skin temperatures were found to be similar at both locations. In section 4b, we will analyze UHIair using the measurements from TEZO and MONT and will compare this analysis with UHIskin obtained from the corresponding grid points in the MODIS data.

3. WRF simulations

a. Base-case configuration

We use the Advanced Research version of WRF, version 3.2.1, with three nested grids and one-way nesting, and we follow the WRF configuration in de Foy et al. (2009), which was evaluated for wind transport in the MCMA during the Megacities Initiative: Local and Global Research Observations (MILAGRO) field campaign (Molina et al. 2010).

The grid resolutions are 36, 12, and 3 km, with 40 × 50, 55 × 64, and 61 × 61 cells for domains 1, 2, and 3, respectively. Figure 2 shows the nested domains on a map of Mexico, and Fig. 1 shows the land cover in domain 3. The vertical grid contains the default 23 eta levels from the surface to 50 hPa. Vertical diffusion is calculated in coordinate space for domains 1 and 2 and in physical space for domain 3 (Zängl et al. 2004). The topography in the model is obtained from global databases at 5- and 2-min resolutions for domains 1 and 2 and from 30-s data from the U.S. Geological Survey (USGS) 30 arc-s digital elevation model of the world (GTOPO30) database for domain 3.

The first 42 h of each case are considered to be part of the model spinup, with the remaining 96 h considered to be effective simulation. The initial and boundary conditions for the model are taken from the Global Forecast System (GFS; Kalnay et al. 1990) at a 3-h temporal resolution and 1° spatial resolution. GFS is run 4 times per day starting at 0000, 0600, 1200, and 1800 UTC. Both the analysis and the first forecast step (3 h) of each run are used.

For the choices of WRF physics schemes, the Monin–Obukhov scheme is used for the model surface layer, the Yonsei University (YSU) PBL scheme (Hong et al. 2006) for the model planetary boundary layer, the Kain–Fritsch scheme (Kain 2004) for the cumulus parameterization, the WRF single-moment six-class scheme for microphysics (Hong and Lim 2006), the Rapid Radiative Transfer Model (Mlawer et al. 1997) for the longwave

FIG. 2. WRF domains 1, 2, and 3 shown on a map of Mexico. The extent of the MCMA is shown inside domain 3.
radiation, and the Goddard scheme (Chou et al. 1998) for the shortwave radiation.

WRF simulations are performed for 14–20 March, 14–20 July, 25–31 August, 14–20 October, and 14–20 December 2006. The five episodes are used to represent the seasonal patterns of simulated UHIskin and UHIair. In section 4b, we derive 4-day-average values at the Aqua MODIS passing time and compare these with corresponding 4-day averages of the satellite and observation data. Hourly comparisons with the surface observations will be presented in section 4c for the March and July episodes.

b. WRF land surface model

The Noah LSM (Chen and Dudhia 2001)) was used for both WRF and GFS, albeit at different spatial resolutions. WRF has four options for the treatment of urban surface physics (Chen et al. 2011): a bulk urban parameterization (Taha 1999), the SL-UCM (Kusaka et al. 2001), a multilayer urban canopy model called the Building Effect Parameterization (BEP; Martilli et al. 2002), and the Building Energy Model (BEM). This study will be limited to the first two options (bulk parameterization and SL-UCM) because the BEP and BEM are not compatible with the YSU boundary layer scheme, which is the most effective PBL model for the MCMA (Fast et al. 2007; de Foy et al. 2009). The bulk parameterization accounts for heat storage by using average properties for the urban surface. The SL-UCM is embedded into the first model layer and considers the simple urban geometry (roof, wall, and road surface) for the surface energy budgets and wind shear calculations.

MODIS land products are used to initialize the land surface in WRF (de Foy et al. 2006, 2009). Four types of MODIS data (h08v07 and h08v06) are used for the modeling initialization. The land-use index is updated by the MODIS Terra land cover type 1 (IGBP) yearly L3 1-km product (2004), the surface albedo is obtained from the MODIS (Terra + Aqua) albedo 16-day L3 1-km product (2006), the soil temperature is retrieved from the Terra MODIS and Aqua MODIS LST/E 8-day L3 1-km products (2006), and the vegetation fraction is calculated from the Terra MODIS reflectance 8-day L3 500-m product (2006).

Some simple, yet significant, changes are made to the land surface parameters in the WRF tables as well as in the WRF code itself. In contrast to midlatitude cities, the MCMA has a mild climate year-round and so the default properties for winter and summer in the WRF tables are not applicable. We therefore apply the summer values for the land-use properties in the tables to the whole year. This affects moisture availability, surface emissivity, surface thermal inertia, and surface flux. Furthermore, the MCMA consists mainly of relatively low and flat buildings and so we reduce the surface roughness length for urban areas from 80 to 25 cm. We also modify the rooting depth and canopy stress parameters for urban grid cells to be more similar to surrounding vegetation types. In addition, there are hard-coded modifications inside the model to reduce the latent heat flux in urban cells. This is not applicable for cities in arid environments that are more humid than their surroundings (Grossman-Clarke et al. 2005; Imhoff et al. 2010). We therefore “comment out” (disable the computer code for) those changes, thereby restoring the vegetation fraction of the grid cell and the soil parameters of the underlying soil type. Overall, this restores latent heat fluxes to urban grid cells.

In WRF, the output fluxes from the UCM and from Noah are weighted according to the following equation (Loridan et al. 2010):

\[ Q_{\text{GRID}} = Q_{\text{SLUCM}}f_{\text{urb}} + Q_{\text{NOAH}}(1 - f_{\text{urb}}). \]

where \( Q_{\text{GRID}} \) is the final heat flux for a specific grid cell, \( Q_{\text{SLUCM}} \) is the flux calculated by the urban canopy model, and \( Q_{\text{NOAH}} \) is the flux calculated by the Noah scheme. In addition, \( f_{\text{urb}} \) represents the urban fraction and is equivalent to 1 minus the vegetation fraction \( f_{\text{veg}} \). This was found to be the parameter with the greatest impact in the urban properties table. Whereas the default value of \( f_{\text{urb}} \) for the high-residential-density category is 0.9, we found that the average vegetation fraction of the gridded urban region was approximately 0.2, corresponding to an \( f_{\text{urb}} \) of approximately 0.8. Furthermore, this is the parameter that can be adjusted to test for the UHI impacts of changes in vegetation cover.

4. Results

a. Seasonal variation of UHIskin

The seasonal variations of UHIskin detected by Terra MODIS at 1030 and 2230 CST and Aqua MODIS at 1330 and 0130 CST are shown in Fig. 3 using data averaged over the urban and rural domains. The seasonal trends of UHIskin in the 8-day average over the MCMA during the daytime and nighttime have opposite trends throughout the year: in the nighttime, there are heat islands at both 1030 and 0130 CST, with maximum values of up to 10.5°C during the dry season, whereas the intensities are weaker during the wet season. In the daytime, there was a strong seasonal signal of UHIskin with low, or even negative, values during the dry season and peak values during the wet season. Aqua MODIS detected the early-afternoon UHIskin (Fig. 3b), which had a maximum value (8-day average) of 12.4°C in August, and average values during the dry season are close to 0°C, with 31% of the time
periods experiencing negative values that correspond to cool-island events. These results are shown for 2006 and were found to be representative of 2007–10 (figures not shown).

b. Comparison between \( UHI_{\text{skin}} \) and \( UHI_{\text{air}} \)

Figure 4 shows the seasonal variations of both \( UHI_{\text{skin}} \) and \( UHI_{\text{air}} \) using data at the TEZO and MONT measurement sites for the \textit{Aqua} MODIS overpass time. Comparison with Fig. 3 shows that the satellite results are similar to the ones using the urban and rural domains, suggesting that use of TEZO and MONT does not affect the results of this analysis. During the nighttime, the measured \( UHI_{\text{air}} \) values follow the trend of \( UHI_{\text{skin}} \) but are about 2°–3°C lower throughout the year. During the daytime, however, \( UHI_{\text{air}} \) has values that vary between 0° and 2°C all year long. There is no clear seasonal signal, although there are a few negative values during the coldest part of the dry season and possibly slightly higher values during the latter part of the wet season. Pearson’s correlation coefficients for \( UHI_{\text{air}} \) versus \( UHI_{\text{skin}} \) show the connection at night and the decoupling by day with values of 0.67 and 0.04, respectively.

Figure 5 shows the correlation between LST and air temperature at TEZO and MONT. Pearson’s correlation coefficient is 0.7 in the daytime and 0.8 at night for TEZO and is 0.6 and 0.8, respectively, for MONT. At night there is a fairly strong correspondence between the
two types of temperature measurements, but during the day the surface temperature varies much more than the air temperature. This is to be expected given the intense solar heating that takes place in the MCMA, leading to very high skin temperatures. In comparison, Gallo et al. (2011) found higher correlation coefficients between in situ measurements of LST and air temperature. The best correlation occurs during episodes with cloudy skies, with lower correlation during clear skies. Note further that Gallo et al. (2011) compared in situ measurements for both temperatures, whereas we are comparing satellite data with ground measurements. Given the differences in measurement types and episodes selected, we expect much lower correlation coefficients but nonetheless find that there is a relationship between skin and air temperature. The fact that $U_{\text{HIA}}$ does not correlate with $U_{\text{HIS}}$ during the day is likely to be a true signal that is due to physical reasons rather than being a measurement artifact.

c. Simulations of 2-m air temperature

The WRF simulations of 2-m temperatures are evaluated using a Taylor diagram (Taylor 2001), shown for TEZO in Fig. 6. This figure shows clearly that the base case underestimates the variability of the temperatures and that applying the changes made to the urban land surface parameters (“WRF–no UCM”) improves the simulations. This result suggests that it is important to increase the latent heat flux for the urban grid cells in the MCMA. The “WRF–UCM (80%)” cases, using $f_{\text{urb}}$ equal to 0.8, represent an improvement over the “WRF–UCM” cases (0.9 for $f_{\text{urb}}$). The WRF–UCM (80%) cases still underestimate the diurnal temperature variability during the dry season but have the highest agreement during the wet season.

For the time series analysis, we focus on March and July as representative cases, given that December is similar to March and August and October are similar to the conditions in July. Figure 7 shows the daily time series of 2-m air temperature on 16–18 March and 16–18 July at TEZO and MONT. During the daytime, at the urban site (TEZO), the base case does not experience sufficient nighttime cooling and the simulations can be 4°–5°C too warm. This is remedied using the single-layer UCM, WRF–UCM (80%). There is a cool bias in the peak afternoon temperature (1°–2°C) in the
model for all cases, which is not improved by using the UCM.

At the rural site (MONT), the peak afternoon temperatures in March are better represented than at TEZO, although a small cool bias remains. At night, there is sharp surface cooling in the measurements that is not sufficiently simulated by the simulations. To understand this phenomenon, we examined the simulated planetary boundary layer height, which was found to be 31 m on 16 March and 28 m on 17 March. These results are indicative of very shallow inversion layers associated with nighttime radiative cooling. Note, however, that most of the excess cooling occurs after the Aqua passing time and that the agreement at 0130 CST is in fact in line with the model performance for the rest of the day. Simulating these shallow events remains a challenge for planetary boundary layer model schemes, but they remain very limited in both their temporal and vertical extents and therefore are of limited influence on this study.

During the wet season, the base case has a warm bias at night at TEZO that is removed using WRF–UCM (80%). In the afternoon, the model does not have a cold bias and the simulations correctly capture the peak temperature. There are discrepancies in the afternoon cooling events, which we expect as a result of the very local nature of cloud features in the basin. At MONT, the simulations correctly represent the diurnal variation, albeit with a fairly constant warm bias of around 2.5°C. Note, however, that at night we no longer see extreme cooling events and consequently the simulations are in much better agreement. This is further evidence that the cooling is a localized feature of dry-season nighttime temperature inversions.

On the basis of these results, the WRF–Noah/SL-UCM with the modified urban fraction [WRF–UCM (80%)] is used as the best case. Figure 4 shows the simulated seasonal variations of $UHI_{\text{skin}}$ and $UHI_{\text{air}}$. At night, the model correctly captures the seasonal trend, with higher values during the dry season and lower values during the wet season. The lower intensities of $UHI_{\text{air}}$ relative to $UHI_{\text{skin}}$ are also correctly represented in the model. By day, the model correctly identifies the strong increase in $UHI_{\text{skin}}$ during the wet season. $UHI_{\text{air}}$, in contrast, is simulated to have near-zero values throughout the year. This is within the measured range, albeit on the low end of the measurements.

5. Discussion

a. Regression analysis of $UHI_{\text{skin}}$

Regression analysis is used to explore the correlation between $UHI_{\text{skin}}$ and possible dependent variables. We use a constrained linear least squares method combined with a hierarchical partition method (Mac Nally 2000; Chevan and Sutherland 1991). This method was used to analyze the winter UHI in Minneapolis, Minnesota (Malevich and Klink 2011), and it was found that UHI

![Figure 7](https://journals.ametsoc.org/jamc/article-pdf/51/5/855/3563054/jamc-d-11-0104_1.pdf)
increased with snow cover, especially during the day. On the basis of prior sensitivity tests, we limited the study to three predictors: contrast in vegetation fraction between urban and rural areas, daily insolation, and atmospheric stability. UHI_{skin} was treated as the response to the first two variables during the day and all three variables at night.

Figure 8a shows the seasonal trend in vegetation fraction at TEZO and MONT derived from MODIS using the algorithm of Jiang et al. (2006) (Ghulam et al. 2007). In MONT, the vegetation cover varied from approximately 20% in the dry season to larger than 50% in the wet season, whereas at TEZO, it varied from below 5% during the dry season to values around 10% during the wet season. We base this analysis on the difference in vegetation cover between TEZO and MONT. Figure 9a shows the correlation of this vegetation contrast with UHI_{skin}. A strong positive correlation exists during the day, and a weaker negative correlation occurs during the night.

The second variable in the model is the incident solar radiation Q_{day} calculated for clear-sky conditions at the top of the atmosphere for the average latitude of the two sites. The third variable is a proxy for atmospheric stability obtained from upper-air profile data from the Mexico City radiosonde site (19.43°N, 99.07°W), which is in the western part of the MCMA. We take the gradient of the potential temperature between the surface and 1000 m aloft at 0600 CST (Rogers and Yau 1989). The value of the atmospheric stability is obtained close to sunrise and is representative of nighttime atmospheric stability. Figure 8b shows the seasonal variation of the stability parameter, with increased stability (stronger inversions) during the cold dry season and decreased stability during the wet season, as expected. Figure 9b shows that there is a positive correlation between UHI_{skin} at night and surface stability. We calculate 8-day-averaged values of vegetation fraction, insolation, and atmospheric stability.
Table 1. Regression analysis of the seasonal variations of UHI_{skin} during the daytime and nighttime, where f_{avg} is the vegetation contrast between the urban and rural measurement sites, Q_{day}^{ave} is the daily insolation, and Δθ/Δz is the atmospheric stability parameter. In addition, R^2 is the coefficient of determination.

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<th>UHI_{skin} (day)</th>
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<th>UHI_{skin} (night)</th>
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<td>R^2 (%)</td>
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to correspond to the 8-day-averaged values of UHI_{skin} obtained from MODIS.

Table 1 shows the results of the statistical analysis for the day and night UHIs. During the day, the relationship of UHI_{skin} with vegetation fraction contrast is very significant (significance level α = 0.001) and the relationship with daily insolation is significant (significance level α = 0.05). The vegetation parameter contributes 58% of explained variance to the observed seasonal variations, and the insolation contributes 42%. Overall, the model significantly predicts UHI_{skin} at 95% confidence interval with 52% coefficient of determination.

For the nighttime model, the dominant predictor is the atmospheric stability (significance level α = 0.05), which contributes 52% to the observed variations. The vegetation fraction contributes 37%, and the daily insolation contributes 12%, but neither is significant at the 0.05 level. Nevertheless, the model is significant at the 95% confidence interval overall and has a 41% coefficient of determination. Both the daytime and nighttime models pass the F test and the t test.

The result of the model is that the contrast in vegetation between the rural and urban areas correlates significantly with the daytime UHI_{skin}. In the wet season, this extensive vegetation growth around the city that enhances surface evapotranspiration and reduces rural temperatures. This connection has been extensively documented (e.g., Shukla and Mintz 1982). MONT therefore experiences more surface cooling during wet-season afternoons than does TEZO, leading to increased UHI_{skin}. During the dry season, the contrast in vegetation fraction is reduced, and the urban area can be more humid than its surroundings because of the presence of irrigated trees and parks in the urban area and arid conditions surrounding it. This has been documented for Phoenix, Arizona (Grossman-Clarke et al. 2005), as well as in a study of 38 cities in the continental United States (Imhoff et al. 2010). Takane and Kusaka (2011) found that extreme high surface temperatures in Tokyo resulted from extended dry conditions, leading to a reduction in latent heat and an increase in sensible heat fluxes. When this condition occurs preferentially in the rural areas, it can lead to an urban cool island or urban heat sink, which was found for multiple arid-climate cities (Zhang et al. 2010) and also for Santiago de Chile, Chile (Pena 2008).

At night, the result of this analysis suggests that the UHI is mainly due to atmospheric stability and nocturnal inversions. The urban areas experience higher nighttime boundary layers whereas the rural areas experience more stable conditions with shallower and stronger nighttime temperature inversions. This situation was shown to lead to UHI formation by Oke (1988). The impact of atmospheric stability may well be related to differential cooling rates in urban and rural areas. This has been analyzed for Phoenix (Chow and Svoma 2011), where faster cooling in the rural areas contributes to nighttime UHIs along with significant variations in urban wind speeds.

b. Surface heat fluxes

The regression analysis shows that UHI_{skin} is correlated mainly with vegetation fraction and insolation by day and atmospheric stability by night. In the absence of surface heat flux measurements, WRF simulations can be used to explore possible mechanisms for UHI formation. Figure 10 shows the sensible heat flux, latent heat flux, and ground heat flux at the urban site (TEZO) and the rural site (MONT) for the March and July episodes (see Fig. 7 for the corresponding time series of surface temperature).

In March, during the dry season, UHI_{skin} is higher at night when compared with the annual average and is low to nonexistent during the day. Figure 10 shows that the maximum sensible heat fluxes are in the range of 400–500 W m\(^{-2}\) at TEZO and 350–410 W m\(^{-2}\) at MONT. The latent heat fluxes are much lower, with values below 100 W m\(^{-2}\) at TEZO and below 200 W m\(^{-2}\) at MONT. The ground heat fluxes at TEZO have up to 200 W m\(^{-2}\) coming into the ground during the day and around 100 W m\(^{-2}\) going into the atmosphere at night (a value that can reach up to 200 W m\(^{-2}\)). The values of ground heat fluxes are similar at MONT but with slightly lower magnitudes, especially for the daytime flux into the ground.

In July, during the wet season, UHI_{skin} is lower at night than the annual average and is substantially higher during
The sensible heat fluxes are similar at both sites and are much lower than the dry-season values, with peaks below 300 W m\(^{-2}\). At TEZO, the latent heat flux is similar to that of the dry season, with values below 100 W m\(^{-2}\). This heat balance is achieved by much greater ground heat fluxes into the ground during the day, with peak values up to 300 W m\(^{-2}\). At MONT, the lower sensible heat fluxes are compensated by higher latent heat fluxes that reach values in the range of 300–400 W m\(^{-2}\). The ground heat fluxes during the day are consequently left relatively unchanged. By night, the ground heat fluxes are similar to those during the dry season at TEZO and are slightly lower at MONT, leading to a greater difference between the two (see Fig. 10).

These plots show that a significant amount of thermal energy is stored during the day and released at night at both the urban site and the rural site. The difference in nighttime ground heat flux does not explain the seasonal behavior of UHIskin at night, however: if anything, it would predict a seasonal variation similar to the daytime UHIskin. The regression analysis above found that the main variable correlating with UHIskin was nighttime stability. This analysis therefore suggests that the greater cause of nighttime UHIskin is more likely to be the behavior of the boundary layer than the thermal budget of the land surface.

During the daytime, there is a strong increase in the evaporative fraction from the dry season to the wet season even though the differences in sensible heat remain small between the sites. There is also a stronger contrast in ground heat flux during the day in the wet season than in the dry season. This suggests that more thermal energy is being absorbed during the day in the urban area than in the rural area, which would lead to increased UHIskin. The regression analysis found the greatest correlation of UHIskin to be with the contrast of vegetation fraction between the two sites. Increased vegetation in the rural area would lead to higher latent heat fluxes and lower ground fluxes, in agreement with the thermal budget analysis.

c. Impact of vegetation fraction on UHI

The WRF–Noah/SL-UCM simulations were used to examine the impact of changes in urban vegetation on UHIskin and UHIAir. An increase in vegetation leads to a decrease in urban fraction and modified surface fluxes, as described by Eq. (1). Three values of vegetation fraction in the urban area were tested: a low value of 10%, the actual value of 20%, and a hypothetical value of 40%.

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**Fig. 10.** WRF simulations of surface energy heat fluxes [(left) sensible heat flux, (center) latent heat flux, and (right) ground heat flux] at TEZO and MONT for the (a)–(c) dry-season (March) and (d)–(f) wet-season (July) episodes.
These correspond to using 90%, 80%, and 60% for the urban fraction parameter.

Figure 11 shows the impact of the different vegetation fractions on UHI_{skin} and UHI_{air} for both day and night. The strongest decrease is for the daytime UHI_{skin}, which was reduced by approximately one-half. This is to be expected on the basis of the strong correlation between UHI_{skin} and vegetation fraction found in the regression analysis. UHI_{air} during the daytime remains stable and has low values throughout the year. The simulations did not influence daytime UHI_{air}—a situation that is little changed by the variations in vegetation fraction.

At night, UHI_{skin} was decreased by 2\degree–4\degree{C} and UHI_{air} was decreased by 0\degree–3\degree{C}. Given the plot of surface heat fluxes in Fig. 10, we expect a modest change to the nighttime UHI that is due to a lower heat flux from the ground into the atmosphere. The actual decrease may reflect this as well as changes to the nighttime stability resulting from changes in land cover. An expanded modeling study and observational dataset would help to analyze the complex interplay between these factors. These results are comparable to those of Grossman-Clarke et al. (2010), who find limited changes to daytime UHIs but increases in nighttime UHIs with the expansion of Phoenix.

6. Conclusions

This paper studied the seasonal variations of the land surface UHIs (UHI_{skin}) derived from satellite data and air temperature UHIs (UHI_{air}) obtained from surface observation stations in the Mexico City metropolitan area. Strong daytime UHI_{skin} was found in the wet season and much weaker UHI_{skin} was found during the dry season, with not infrequent occurrences of urban cool islands. At night, UHI_{skin} was high throughout the year but decreased during the wet season. UHI_{air} was lower than UHI_{skin} at night but had the same seasonal trend or higher values during the dry season and lower values in the wet season. The biggest difference between UHI_{air} and UHI_{skin} occurred during the day. Whereas UHI_{skin} had low values during the dry season and high values during the wet season, UHI_{air} had low values throughout the year with very little seasonal variation.

The WRF modeling system was found to correctly represent the contrasting seasonal variations of UHI_{skin} and UHI_{air}. Changes to the default WRF land-use parameters were adopted to improve the simulations. In particular, the urban fraction parameter was found to have a big impact on the simulations and was set using MODIS data of vegetation cover. This study suggests that future work on UHIs should use gridded two-dimensional fields of this parameter that account for its seasonal variations. Given these modifications, WRF was found to be an effective bridging tool to integrate results from very different data sources, in this case satellite remote sensing and surface observations, and to explore the physical mechanisms at work in UHI formation.

Multiple regression analysis and simulated surface heat fluxes suggest that during the day UHI_{skin} is a function of the difference in vegetation fraction between the urban and rural areas. At night, however, UHI_{skin} is mainly linked to the strength of nighttime surface inversion layers that are due to radiative cooling. WRF simulations of hypothetical increases in vegetation cover in the urban area suggest that UHIs at night would be reduced...
for both UHI_{skin} and UHI_{air}. During the day, there is only limited UHI_{air}, which was little changed, but UHI_{skin} would experience strong reductions. The main finding of this paper is that UHI_{air} and UHI_{skin} can have very distinct behaviors that should be taken into consideration when evaluating UHIs and performing scenario analyses.

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