

The relationship between land cover and the urban heat island in northeastern Puerto Rico

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ABSTRACT: Throughout the tropics, population movements, urban growth, and industrialization are causing conditions that result in elevated temperatures within urban areas when compared with that in surrounding rural areas, a phenomenon known as the urban heat island (UHI). One such example is the city of San Juan, Puerto Rico. Our objective in this study was to quantify the UHI created by the San Juan Metropolitan Area over space and time using temperature data collected by mobile- and fixed-station measurements. We also used the fixed-station measurements to examine the relationship between average temperature at a given location and the density of remotely sensed vegetation located upwind. We then regressed temperatures against regional upwind land cover to predict future temperature with projected urbanization. Our data from the fixed stations show that the average nighttime UHI calculated between the urban reference and rural stations ($\Delta T_{\text{CBD-rural}}$) was 2.15°C during the usually wet season and 1.78°C during the usually dry season. The maximum UHI value for San Juan was calculated as 4.7°C between the urban and forest sites and 3.9°C between the urban and an open, rural site. Comparisons of diurnal temperature trends at urban, grassland, and forested sites indicate that canopy cover reduced daytime warming. Temperature was predicted best ($r^2 = 0.94$) by vegetation in upwind easterly directions, especially that within 180 m of the sensor. Results from the mobile measurements show that the UHI has reached the base of the Luquillo Mountains. Predictions of future development and temperatures suggest that if the present pattern of development continues, over 140 km² of land that showed no signs of UHI in 2000 will have an average annual UHI between +0.4 and +1.55°C by 2050. Furthermore, more than 130 km² of land area with a current UHI between +0.4 and +1.4°C in 2000 will have an average UHI greater than +1.55°C by 2050. Copyright © 2010 Royal Meteorological Society

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1. Introduction

As development continues in Puerto Rico, forests and grasslands are being converted to non-vegetated cover, which may be changing the magnitude and geographic range of the excess urban temperature phenomenon known as the urban heat island (UHI). This study aims to quantify the spatial and temporal variations of the UHI in and around the San Juan Metropolitan Area (SJMA). From this we assess the present and potential future range of the UHI and the impacts it may impart on the nearby tropical forest ecosystem, which is highly valued by Puerto Ricans, provides much of the fresh drinking water for San Juan, and serves as the tropical forest site for the US National Science Foundation – Long-Term

Ecological Research Program. Our specific objectives were to: (1) quantify the magnitude and timing of the average diurnal and seasonal UHI created by the SJMA, (2) explore correlations between air temperature and land cover, (3) assess the geographical range of the UHI created by the SJMA, and (4) predict the growth of the geographical range of the UHI in the future.

An important reason for studying the UHI in northeastern Puerto Rico is that much of the freshwater for the SJMA originates in the Luquillo Mountains, located 17 km to the east of the SJMA (Figure 1). This water supply is barely adequate in dry years. There is new concern that overall precipitation trends within Puerto Rico during the 20th century have decreased about 16% (van der Molen, 2002) and that three of the top 10 driest years in the past century were recorded in the 1990s (Larsen, 2000). Furthermore, a growing body of evidence suggests that urbanization may affect regional climates even more than increasing global temperatures (Hulme and Viner, 1995; Scatena, 1998; Brazel *et al.*, 2000). Therefore, we

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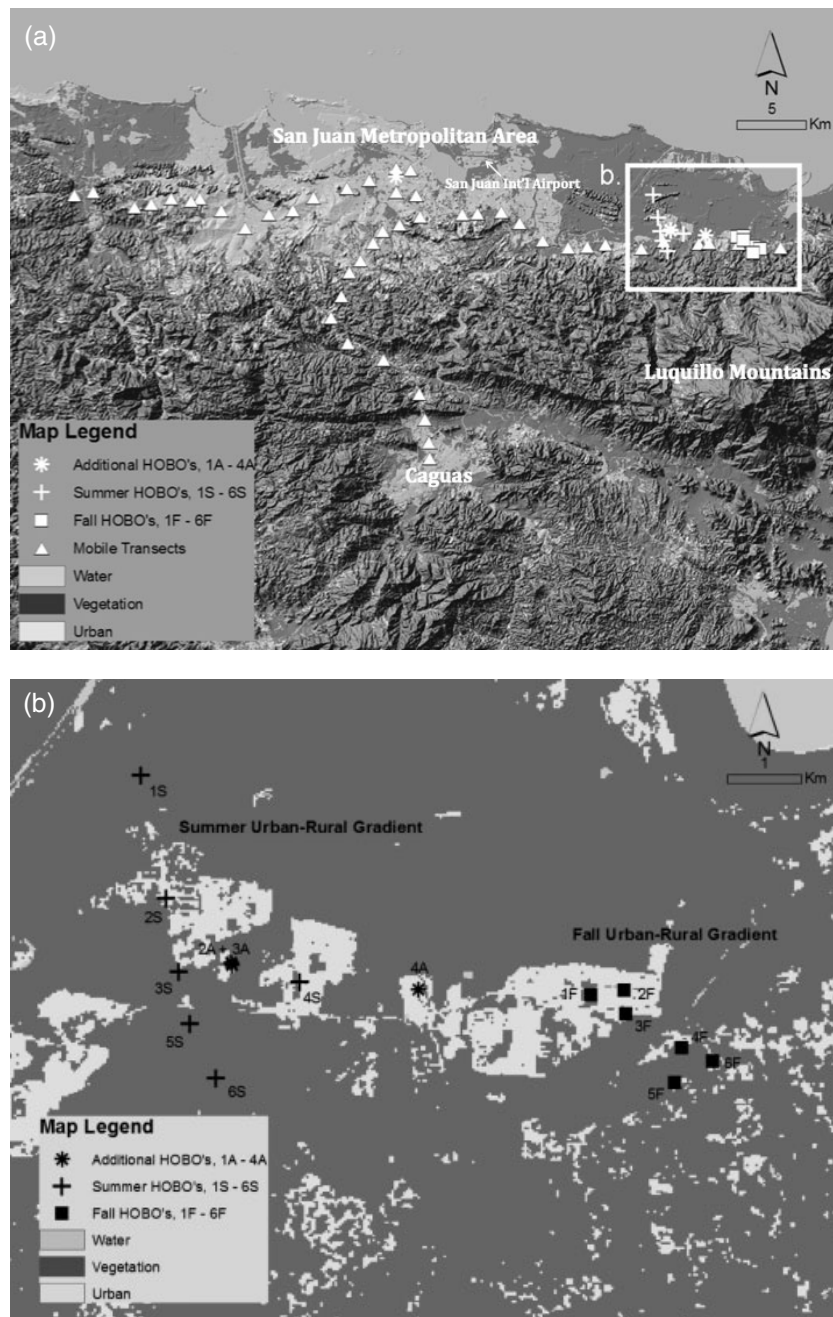


Figure 1. (a) Land-cover map of northeastern Puerto Rico with triangles labelling checkpoints along the mobile transects. The crosses, asterisks, and squares mark the locations of the HOBOS. The box represents the area magnified in Figure 1(b). (b) A map of fixed-station measurements. The crosses, labelled HOBOS 1S–6S, were moved during the fall and became HOBOS 1F–6F. The additional HOBOS 1A–4A (1A shown in Figure 1(a)) remained at the same locations for both the summer and fall data periods.

believe that research efforts should focus not only on global climate change, but also on the regional climatic effects of urbanization, especially the effects of UHIs.

Anthropogenic alterations to the earth's surface cause microclimatic changes that result in the formation of UHIs (Landsberg, 1981). Land-cover types common to urban areas, such as dark-coloured pavement, brick, and asphalt, absorb large amounts of incident radiation during the day and release it during the evening, causing maximum temperature differences between urban and rural environments to occur usually at night (Chandler, 1965; Oke and East, 1971; Landsberg, 1981; Roth, 2007).

Reduced longwave cooling caused by diminished sky view factors and materials with high thermal inertia in urban areas also contributes to the UHI effect.

Urban areas tend to remain warmer throughout the evening, making the diurnal (intra-day) range of air temperatures smaller in urban areas when compared with that in surrounding rural areas in the same locale. Chandler (1965) studied the London UHI over a 10-year period and found that on most days the difference in daily minimum temperature between an urban and a rural location was larger than the difference in daily maximum temperature. Oke and East (1971) compared

the diurnal cooling rates ($^{\circ}\text{C}/\text{h}$) for three meteorological stations placed in rural, suburban, and urban sites and found that both the rural and suburban locations had decreasing temperatures by 1700 h, whereas the urban area temperature did not decrease, but in fact increased until 2200 h.

Anthropogenic heat release can also cause inter-day fluctuations in UHI intensity. Mitchell (1961) showed that differences in daily minimum temperature between the city of New Haven, Connecticut, and a neighbouring airport (a non-urban site) were consistent for all days except Sunday, for which the differences were half as great. Landsberg and Brush (1980) found similar results for Baltimore, Maryland. Both studies concluded that the UHI intensity is more severe on weekdays due to an increase in anthropogenic activity, such as use of automobiles and office air conditioners, which release large amounts of heat into the atmosphere.

Synoptic effects that modify wind speed and atmospheric stability, in addition to the intra- and inter-day trends discussed earlier, impact UHI formation. Oke (1976) found that as wind speed increases, the temperature differential between urban and rural sites ($\Delta T_{\text{U-R}}$) decreases asymptotically. More recently, Comrie (2000) measured the effect of winds on the UHI in Tucson, Arizona, and found that even in the presence of strong katabatic flows from surrounding mountains (12 m s^{-1}), the central city can still maintain urban temperatures 2°C warmer than upwind rural areas. Another recent study by Morris *et al.* (2001) in Melbourne, Australia, found that the UHI was proportional to the inverse of the third root of the wind speed.

Heisler *et al.* (2006) found that low wind speeds ($<1.8 \text{ m s}^{-1}$) on clear evenings in Baltimore, Maryland, created UHIs of 3.4°C , and evenings with moderate wind speeds ($>3.4 \text{ m s}^{-1}$) and cloud cover had UHIs of 1.4°C on average. In general, low wind speeds and clear evenings create stable atmospheric conditions near the surface, which foster the formation of UHIs.

It is commonly thought that the intensity of UHIs depends on the local surrounding land-cover characteristics of both rural and urban sites. Most recent studies used either fixed- or mobile-station measurements, or a combination of both, to study the relationship between land cover and the UHI. For example, Hawkins *et al.* (2004) used fixed stations in Phoenix, Arizona, to study the specific effects of different land-cover types in rural landscapes on ambient temperature. When compared with temperature at an urban reference, they found significant differences ($\sim 3.4^{\circ}\text{C}$) in the UHI ($\Delta T_{\text{U-R}}$) depending on cover type, with the smallest to the largest occurring between the urban reference and hardpan 'dirt', cultivated vegetation, and a mowed grass field, in this order.

Hedquist and Brazel (2006) used a combination of fixed stations and mobile measurements to study the differences in temperature, also in Phoenix, Arizona, between urban, residential neighbourhoods and rural landscapes for times after sundown. Their mobile data

showed an average urban–rural temperature difference ($\Delta T_{\text{U-R}}$) of $\sim 7^{\circ}\text{C}$ and an urban–residential neighbourhood temperature difference ($\Delta T_{\text{U-RES}}$) of $\sim 3^{\circ}\text{C}$. In our research, we extend the methods used in these studies to examine the UHI in the tropical city of San Juan, Puerto Rico.

1.1. A brief review of the literature on UHIs in tropical wet areas

Roth (2007) published a comprehensive review of both tropical and sub-tropical UHI literature. Puerto Rico is classified, according to Roth, as a Tropical Wet Climate, comparable with the cities of Bangkok, Manila, Ho Chi Minh City (Hung *et al.*, 2006), and Mumbai (Kumar *et al.*, 2001), where recent UHI research has been conducted. Hung *et al.* (2006) used remote sensing to measure the magnitude and geographical extent of the surface UHI (SUHI) in and around Bangkok, Manila, and Ho Chi Minh City. A SUHI, detected by remote sensing from above, represents differences in the upper skin temperatures of land surface objects in the urban versus rural environment. Hung *et al.* (2006) concluded that the average nighttime SUHI was 3, 2, and 2°C , respectively. They found that for all of the cities they examined, these three tropical cities and five other sub-tropical cities, the daytime SUHI was greater than the nighttime, and in the case of Manila, the daytime SUHI was more than 3 times greater than the nighttime UHI. It has long been recognized that SUHIs generally will be larger in the daytime than at night (Roth *et al.*, 1989), in contrast to atmospheric heat islands in the urban canopy layer (UCL, air layer below about half the height of buildings), which generally are larger at night (Voogt and Oke, 2003).

The two other UHI studies for tropical wet climates reported by Roth (2007) were those by González *et al.* (2005) and Velazquez-Lozada *et al.* (2006), both of which were located in San Juan, Puerto Rico. González *et al.* (2005) used a combination of *in situ* UCL atmospheric air-temperature data and Airborne Thermal and Land Applications Sensor (ATLAS) data during February 2004 to study the San Juan UHI. Their results show a late morning peak in the SUHI, a less intense night SUHI, and a noon atmospheric heat island of about 2.5°C determined from four weather stations, assumed to be placed at a few meters height in the UCL. González *et al.* (2005) propose that the pattern of their temperature observations indicates that the UHI effects dominate the sea breeze effect, which under normal conditions would refresh the urban area during the day. However, much of the daytime atmospheric UHI temperature differences of 2.5°C or less presented by González *et al.* may be caused by radiation effects on the sensors if they were not uniformly shaded or protected by radiation shields.

Velazquez-Lozada *et al.* (2006) used a combination of four co-op stations and a Regional Atmospheric Modelling System (RAMS) to assess the magnitude of the UHI created by San Juan and its impacts on regional climate. They found that San Juan has been warming at a

rate of $0.06^{\circ}\text{C yr}^{-1}$ over the last 40 years, and predicted that the UHI in the SJMA may be as much as 8°C warmer than surrounding rural areas by 2050.

We continue the work of González *et al.* (2005) and Velazquez-Lozada *et al.* (2006) by assessing quantitatively the UHI created by the city of San Juan, using both fixed-stations and mobile measurements. As noted in the opening paragraph, an objective (number 2) of our study was to evaluate the influence of upwind cover on air temperatures in the UCL measured downwind. In a recent work, Voogt and Oke (2003) acknowledged that studying upwind source areas for points in the UCL is the subject of current research, and that the effects of surface roughness above the UCL are well-documented.

2. Study area

Puerto Rico is the smallest of the Greater Antilles Island chain, and is located between the Caribbean Sea and the Atlantic Ocean, at 18° north latitude and 66° west longitude. San Juan, the capital and largest city, is located on the eastern half of the island along the north coast. Trade winds from the southeast at low elevations (<300 m) and from the northeast at high elevations (>300 m) along with strong afternoon shore breezes dominate mesoscale wind regimes (Odum, 1970; Brown *et al.*, 1983). There are two mountain ranges within Puerto Rico. The Luquillo Mountains, which contain the Luquillo Experimental Forest (LEF), are located 17 km east of the SJMA and have a maximum elevation of ~ 1100 m. The Mid-Island Mountains begin about 60 km southwest of San Juan and extend east–west through the centre of the island, with a maximum elevation of ~ 1300 m.

Average temperatures for Puerto Rico range from 24 to 29°C year round, with a moderate dry season from February to April. Roth (2007) used the Köppen climate classification system to correlate UHIs and urban climates around the world. Based on the average temperature and precipitation regimes in Puerto Rico, most areas are, on average, either ‘Am’ – tropical monsoon or ‘Af’ – wet tropical. The difference between these two classifications depends on the precipitation totals during the dry times of the year, where the criterion for Af classification requires greater than 6 cm of precipitation in the driest month (Akin, 1990). According to this system, both the SJMA and the areas lying east of the SJMA in which we did our study are classified as Af.

3. Methods

We employed two methods to capture the variation of the UHI over space and time: (a) a series of fixed-station temperature sensors (HOBOS) and (b) a series of mobile measurements from a vehicle-mounted temperature sensor (Figure 1(a) and (b), Table I).

3.1. Fixed-station measurements

The overall goal of the fixed-station transects was to establish simultaneous temperature measurements to assess the timing of the peak diurnal and seasonal UHI, and the influence of land cover on temperature. The fixed-station measurements consisted of a network of 10 automated Series-8 HOBO Pro-Temp Data Loggers (Onset Corporation, Pocasset, MA), calibrated to each other and to the automated surface observing system (ASOS) temperature sensor at San Juan Airport, to record temperature measurements near different types of land cover ranging from the centre of San Juan to barely developed regions 20 km to the east of the city centre. We attached the HOBO sensors to telephone poles about 3 m above the ground surface. The sensors were all placed within 50 m of sea level, so that elevation does not influence our results. Air-temperature measurements were logged automatically at 5-min intervals, and then aggregated into hourly averages for data analysis. We did not measure humidity because temperature was the primary focus of this study and because the atmospheric controls on humidity are varied and different than that for temperature.

The HOBO temperature loggers had internal sensors that, according to the manufacturer’s specifications, have a 90% response time in still air of up to 35 min and an accuracy of $\pm 0.2^{\circ}\text{C}$ over the range of temperatures measured in Puerto Rico. The error would be larger if radiation errors were present, but we placed the loggers in naturally ventilated radiation shields provided by Onset specifically to reduce radiation-caused error. Temperature measurements collected during calibration exercises performed in a laboratory resulted in an average standard deviation among all sensors of 0.11°C .

The intensity of UHIs is related to sky view (Landsberg, 1981). Where sky view is restricted by buildings, outgoing thermal radiation is restricted at night, turbulent exchange is reduced, and thermal radiation is emitted from vertical building surfaces. To estimate sky view at the sites, we mounted a fish-eye lens on a digital camera to take photographs from which we calculated sky view factors for the site in the central business district (CBD), HOBO 6S (mowed grassland), and the Forest site (Figure 2). To estimate sky view, we used the Gap Light Analyzer program (www.ecostudies.org/gla/). Using these photographs as a reference, we made visual estimations of the sky view factor for all other sites (Table I).

Due to the large geographical extent of San Juan, we established a series of sensors within a small suburban centre to the east of San Juan and compared temperature data collected there with that from the sensor located in the CBD of San Juan (Figure 1(a) and (b)). The sensors were placed downwind (to the west) of various land-cover types, including urban, grassland, and forest cover (Table I). These types correspond generally to those found in the 2000 land-cover classification carried out by Helmer and Ruefenacht (2005). We placed the HOBOS to the west of the various land-cover types selected, with

Table I. Site description for all HOBOS including predominant upwind and local land cover, as well as sky view factor. 'S' designates HOBOS locations during the 'summer' data collection period, and 'F' designates HOBOS locations during the 'fall' data collection period. 'A' designates the 'additional' HOBOS used during both the summer and fall data collection periods. The top section of the table lists the HOBOS that were used to calibrate the upwind vegetation model, and the bottom section lists the HOBOS used to validate the upwind vegetation model. The site titles, listed under 'Land-Use', were assigned according to the dominant land cover to the east within a radius of 50 m, whereas the detailed site descriptions describe the local land cover in all directions from the station. 'General Classification' refers to the partitioning of the stations into one of three categories: urban, suburban, or rural. The column titled '% Veg.' refers to the percent vegetation found within the best-fit upwind fetch wedge (east by southeast up to 180 m upwind) as determined from our model.

HOBOS ID	Land use	Detailed site description including local land cover	General classification	% Veg.
<u>Stations used to calibrate the model</u>				
1S	Abandoned agricultural fields	Thickly vegetated fields with multiple types of long grass species. Few trees present. Sky view factor >75%. No buildings. One single-lane asphalt road.	Rural	100
2S	Suburban centre	Intersection of two double-lane old asphalt roads. Buildings on three of four corners, with the exception of one larger church steeple, the building height/street width (H/W) ratio was about 1 : 1. Sky view factor >50%.	Suburban	40
3S	Industrial	<500 m downwind of a major pharmaceutical plant. A single one-storey building lying within 100 m upwind from the sensor. Mainly grass and bushy vegetation surrounding nearby building. Sky view factor >75%. H/W ratio around 1 : 1.	Suburban	78
4S	Residential	Hobo was near a two-lane road bisecting two neighbourhoods, one directly east and one directly west. H/W ratio of about 1 : 1, and a sky view factor >50%.	Suburban	33
5S	Major road crossing	Hobo was near an intersection of two four-lane roads. Car traffic extremely high during rush hours. Two-storey mall located 300 m southeast across a major road intersection, and an industrial complex located 400 m northeast. Sky view factor >50%.	Suburban	73
6S	Mowed grassland	Mowed grassland located approximately 200 m south of a major shopping centre, and about 50 m south of the parking lot for the shopping centre. Vegetated hills about 100 m to the east and south, about 30 m in height, and covered approximately 30% by trees. Sky view factor of 82.5% (Figure 2).	Rural	100
1A	San Juan central business district (CBD)	Located at the intersection of one large road and one side street. Small trees line the south side of the side street, and also the west side of the large road, but do not limit sky view much. Two large buildings to the southeast and southwest have an H/W ratio of about 8 : 1, whereas the building to the northeast has an H/W ratio of 3 : 1. Sky view factor of about 68.8% (Figure 2).	Urban	0.0
2A	Old-growth forest	HOBOS placed on tree trunk 10–20 m below a full canopy and about 30 m from the edge of the forest. Broadleaf, climax tree species dominate. Sky view factor is 6.5% (Figure 2).	Rural	100
3A	Grassland mix	This site is located on a road 15 m south of the old growth forest. There is a field of short grass species to the east, and an industrial complex directly to the west. Sky view factor >50%, with an H/W ratio of 1 : 1.	Rural	100
4A	Residential limits	HOBOS placed at the northern end of a residential neighbourhood. The area due east and northeast is wild grassland with sparse tree coverage for +5 km upwind. Housing structures about 100 m south. Placed near one short tree (about 4 m high). Sky view factor >75%.	Rural	100
<u>Stations used to validate the model</u>				
1F	Residential recreation park	HOBOS placed in neighbourhood recreational park. There is a baseball field and basketball court to the south and one-storey houses to the north. The sky view factor is >75%.	Suburban	33
2F	Residential church	HOBOS placed near the west side of a two-lane road adjacent to a house. Little vegetation at this site, including only a few trees and shrubs. H/W ratio is 2 : 1 Sky view factor >75%.	Suburban	18

Table I. (Continued).

HOBO ID	Land use	Detailed site description including local land cover	General classification	% Veg.
3F	Suburban mix	HOBO is located at the eastern side of a small commercial area. One-storey houses are located to the north, two-storey commercial buildings are located to the east, a small one-storey shopping centre is located to the west, and a cemetery is located to the south. Overall, the site has <20% vegetation cover. H/W ratio is 1 : 1. Sky view factor is >75%.	Suburban	15
4F	Rural road	HOBO is located adjacent to a one-lane paved road, with large trees located to the north, trees and one-storey houses located to the south, and a truck stop located to the west. Sky view factor is greater than 50%.	Rural	100
5F	Major road	HOBO is located 1 m north of a four-lane highway. A few trees line the north side of the highway. The sky view factor is greater than 75%.	Suburban	43
6F	Rural dirt road	HOBO is placed near a short, dirt cross road connecting a two-lane road to a gas station. Mainly grass and bushes surround the HOBO. A four-lane highway is located 100 m to the north, a one-lane road is located 30 m to the west, and a gas station is located 50 m to the east. Sky view factor is >75%.	Rural	55

the assumption that the trade winds would dominate and that the sea breeze effect, with its directional component coming mainly from the north, would not be a factor. This wind pattern was supported by observations of González *et al.* (2005), by our observations during the study period, and by data collected *post hoc* from the San Juan Airport ASOS records showing the prevailing wind coming from easterly directions over 80% of the time during our sampling period (Figure 3). The airport is located closer to the shoreline than any of our stations. Therefore, we believe that if the airport is not recording sea breezes, then our sensors will also not be impacted by this phenomenon.

The forest is a lowland old-growth forest located between a residential community and an industrial park. It is a remnant of the original natural environment of pre-development Puerto Rico, and as such is considered our natural control. We recorded measurements here and at nine considerably developed sites, for a total of 10 sites (HOBOS 1S–6S, 1A–4A) from 26 June to 5 July 2006. From September 10 to October 7 of the same year, we moved HOBOS 1S–6S to 6 new locations (HOBOS 1F–6F) to add greater spatial coverage to the 10-HOBO data set (HOBOS 1F–6F, 1A–4A). For each site, the UHI was calculated as the difference in temperature from the CBD to all other HOBOS ($\Delta T_{\text{CBD-HB}}$).

We partitioned all sites except the CBD into two groups, suburban and rural, and calculated two statistics, $\Delta T_{\text{CBD-Suburban}}$ and $\Delta T_{\text{CBD-Rural}}$. These represent the UHI calculated between the CBD and the average of all suburban stations, and the CBD and the average of all rural stations, respectively. These statistics are commonly used in the literature to report UHI values and are important when comparing our results with those of others. The selection of rural versus suburban was based upon the general land-cover descriptions listed in

Table I, including some common metrics used to classify local land cover in the literature, such as height/width ratio and sky view factor (Stewart and Oke, 2009).

Comparisons between data collected at the summer and fall locations are because the average temperatures in Puerto Rico for the months of July, August, and September were 27.8, 28.0, and 27.8°C, respectively (NCDC, 2008). We also used 5 HOBOS (2A, 3F–6F) to record data during the months of March and April of 2007 to gauge dry season effects on the UHI. As these five stations were in the same location during the dry and wet seasons, we assume that any inter-seasonal temperature differences are due to seasonal effects only and not spatial effects.

3.2. Mobile measurements

The goal of the mobile data collection was to capture the current geographical range of the UHI. For the mobile measurements, we attached an external thermistor temperature probe to a PVC pipe about 1 m above the roof of a Jeep Cherokee. A cable from the thermistor probe ran down the PVC pipe into the passenger side window, where it was connected to a data logger that recorded measurements automatically every minute. As there was good ventilation of the sensor as the vehicle was moving, the response time was not a critical factor.

We collected data by driving along three different routes radiating out from the CBD of the SJMA to surrounding rural areas at an average speed of less than 56 km h⁻¹ (35 miles per hour), which was chosen based on similar studies conducted by Oke (1976). To drive to the rural areas and return to the starting point within a reasonable time, we chose mid-size roads, with two lanes in each direction. We averaged temperature measurements from the departure leg and return leg of the transect to avoid any drift in temperature due

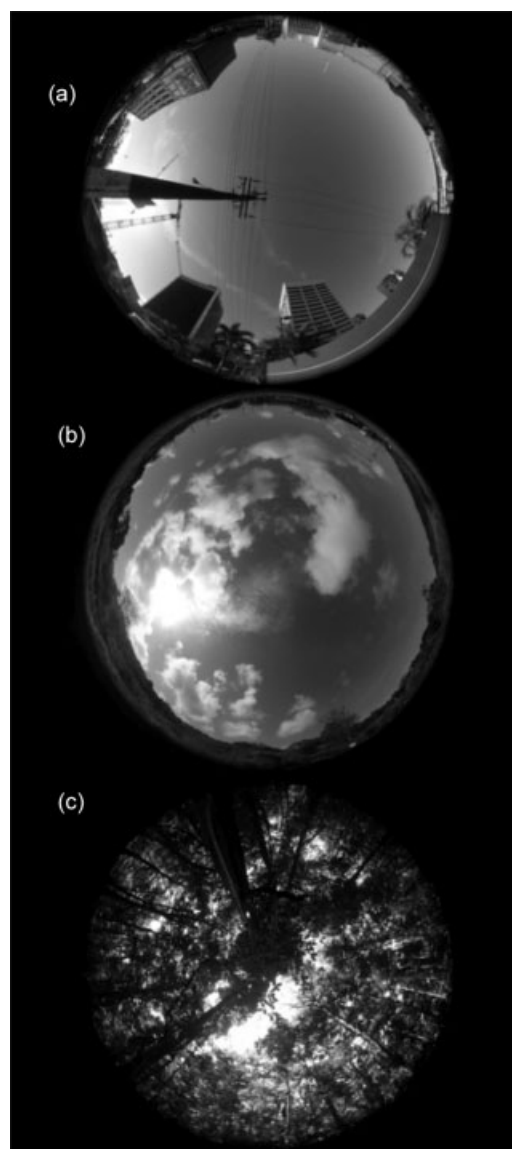


Figure 2. Fish-eye photos of (a) the central business district (CBD) site, (b) HOB0 6S (mowed grassland), and (c) the forest site. Sky view factors for each respective site are (a) 68.8%, (b) 82.5%, and (c) 6.5%.

to the change in time between start and end points, which was generally less than 1 h each way (total elapsed time of <2 h). To evaluate UHI formation under similar conditions favourable for heat island formation, the mobile measurements were performed only during days and nights with moderate to low wind speeds (average $\sim 3.17 \text{ m s}^{-1}$) and usually with low cloud cover (Table II).

We traversed each of the three routes thrice daily: from 0400 to 0600 h (pre-sunrise), 1200 to 1400 h (mid-day), and 1800 to 2000 h (post-sunset). We replicated the post-sunset mobile measurement twice, but due to time constraints, the morning and daytime transects were performed only once, for a total of 12 mobile transects (Table II). As there were two replicates for the post-sunset trip, we averaged the data to calculate the UHI. A linear regression analysis was conducted to evaluate whether cooling varied with increasing distance from

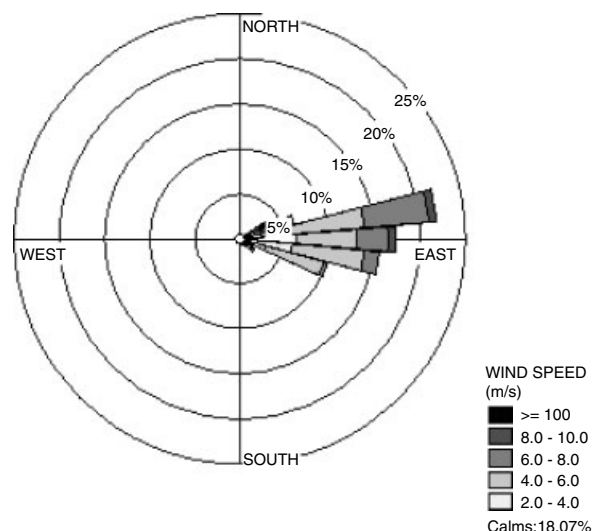


Figure 3. Sample of wind speed and direction distribution at 10 m above ground at the San Juan Marin Airport from 26 June to 5 July 2006, sampling period. Dotted circles indicate the percentage of time that winds remained at a particular direction, with 10-degree resolution of the wind direction report.

the city centre. Due to the presence of a large urban area at the end of the southern route (see Figure 1), the distance from the city centre was calculated as the shortest distance to either the SJMA, at the northern end of the route, or the distance to the termination point at the southern end of the route. In other words, for the southern route, the furthest distance from the city centre was located in the middle of the route, i.e. furthest from either the southern or the northern end.

4. Upwind fetch model

The 10-m height wind direction at the San Juan International Airport was on average from the east during our period of study (Figure 3), and because of the importance of upwind land cover on the magnitude of UHIs found in other studies (Comrie, 2000; González *et al.*, 2005; Heisler *et al.*, 2006, 2007), we explored correlations between the percent vegetation upwind from each sensor and the average temperature during the period of data collection measured at each sensor. For this, we developed a computer model in FORTRAN-90 language that calculated the percent of vegetation within a wedge-shaped upwind area, termed 'upwind fetch wedge'. The percent vegetation is derived from a year 2000 raster land-cover map of Puerto Rico (Helmer and Ruefenacht, 2005), and is calculated according to the following equation:

$$\text{Percent vegetation upwind} = \frac{\text{Number of vegetated pixels within upwind fetch wedge}}{\text{Total number of pixels within upwind fetch wedge}} \times 100$$

Table II. General climate description for the dates and times of the mobile transects.

Time	Route	Date	Sky cover ^a	Cloud ceiling ^b (m)	Wind speed (m/s)	Wind direction ^c
0400–0600	East	16-Jun-06	FEW	1006	1.34	130
	West	12-Jun-06	SCT	1524	1.34	VR
	South	14-Jun-06	CLR	NC	1.79	150
1200–1400	East	12-Jul-06	SCT	914	8.05	60
	West	10-Jul-06	SCT	732	4.47	80
	South	9-Jul-06	SCT	1372	4.47	100
2000–2200	East	15-Jun-06	FEW	914	2.68	80
	West	11-Jun-06	FEW	1829	3.13	80
	South	13-Jun-06	FEW	1676	1.79	VR
2000–2200	East	12-Jul-06	BKN	1829	3.13	120
	West	20-Jul-06	FEW	1372	3.13	90
	South	8-Jul-06	SCT	1829	2.68	VR

^a Percent of sky covered by clouds is: CLR = 0–10%, FEW = 10–25%, SCT = 25–50%, BRK = 50–90.

^b NC = no ceiling.

^c VR = variable.

We hypothesized that only eastern winds would have an effect on UHI formation for two reasons: (1) the winds originated in the east greater than 80% of the time during our study period and (2) initial modelling results indicated that vegetation from 360° around the sensor was a poor predictor of UHI. Therefore, we limited the model to upwind fetch wedges in easterly directions. The model analysed the percent vegetation over a total of 180 azimuth degrees, from due north to due south, and from zero to a maximum of 2520 m upwind from each sensor. For this analysis, we divided the 180 azimuth degrees into 18 windows of 10° each, termed ‘azimuth windows’, and divided the ‘upwind distances’ into 84 intervals of 30 m each (Figure 4). From each HOBO sensor location, the model calculated the percent vegetation within all upwind fetch wedges. This amounts to 1512 calculations at each sensor (18 azimuth windows × 84 upwind distances).

We assumed that vegetation in the upwind direction would create lower temperatures, whereas impervious surfaces would create higher temperatures at the downwind HOBO sensor. To measure this, we regressed the average temperatures over the sample period for each of the HOBOs as the dependent variable against percent vegetation as the independent variable and calculated the coefficient of determination, r^2 . The regression model was

$$T = \alpha + \beta x,$$

where ‘ T ’ is the average temperature (collected by HOBOs 1S–6S and 1A–4A in June and July 2006), ‘ x ’ is the percent vegetation for each HOBO within a distance and azimuth window, ‘ α ’ is the y intercept, and ‘ β ’ is the slope parameter characterizing the relationship between average temperature and percent vegetation. Sample size was 10 values of averaged temperatures calculated for the period of data collection and percent vegetation measured for each of 1512 land-cover wedges. As the model uses average temperature values and assumes a predominant wind direction, it may apply only to areas

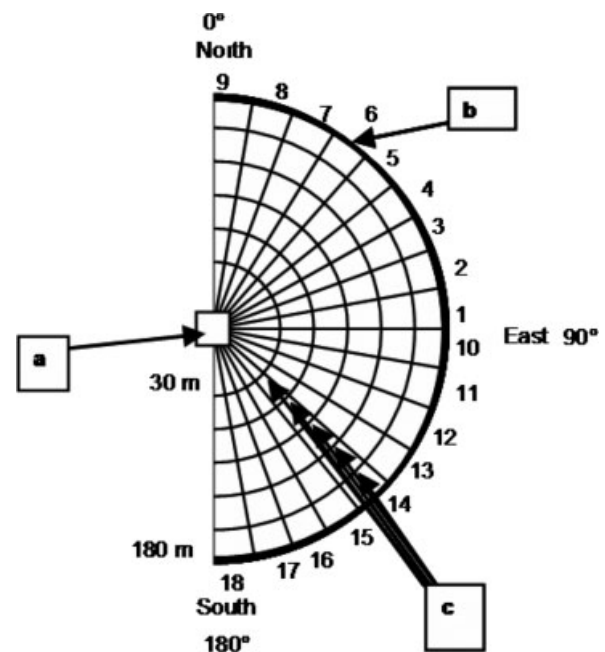


Figure 4. Conceptual diagram of the upwind fetch wedge model. (a) Centre pixel, i.e. location of HOBO for regression analysis, (b) Azimuth window: 180 degrees azimuth divided into 18 azimuth windows of 10 degrees each, numbered here as 1–18. (c) Upwind distance: 30 m increments away from centre pixel to a maximum of 2520 m upwind, totalling 84 different distances upwind (only first six distances shown).

with temperature and wind patterns that exhibit similar characteristics. For example, the model may not predict temperature well during periods with strong atmospheric instability or very low wind speeds.

The output of this analysis was 1512 r^2 values from which the highest was selected and assumed to represent the area of upwind fetch, to have the most influence on the sensible temperature downwind. This was termed the ‘best-fit’ upwind fetch wedge. All 1512 r^2 values were grouped into five classes for ease of

graphical visualization and plotted in a gradient space dimensioned by azimuthal degree on the y -axis and upwind distance on the x -axis (see Figure 12, explained in Section 5.3).

We used data from the six fall stations (1F–6F) that were not used to develop the regression models, to validate the model. For each of these six stations, we calculated the percent vegetation for the ‘best-fit’ upwind fetch wedge and inserted those values into the estimated regression equations to predict temperature. These predicted temperature values were compared with the actual observed average temperature value collected at each of the fall stations.

4.1. Predicting the future UHI

We used the GEOMOD module (based on those presented by Hall *et al.*, 1995; Pontius *et al.*, 2001) within the IDRISI Kilimanjaro mapping software to analyse the pattern and quantity of past urbanization. GEOMOD creates a suitability map based on empirical trends in land-cover change over time. The suitability map represents the ability of any pixel on the land-cover map to transition from its current land cover to an urban land cover (Pontius *et al.*, 2001). The relative level of suitability for each pixel on the map was based on five variables: slope, aspect, distance to roads, distance to urban areas, and distance to coast, which explain the location of urban areas in 2000. Based on this map of ranked suitability, we predicted urban growth at decadal intervals starting with the 2000 land-cover map and ending in year 2050. Distance to urban areas is updated each decade and input to the next decade’s projections of urban growth. We derived a ‘business as usual’ rate of urbanization for this model by subtracting urban areas in a 1991 land-cover map from urban areas in the 2000 land-cover map, adjusting the results to a time-step of 10 years.

Using each future land-cover map, we applied the derived temperature/land-cover regression results to predict average summer temperature at each pixel as a function of the percent vegetation in the ‘best-fit’ upwind fetch wedge. To show the geographical growth of the UHI explicitly over time, we subtracted the average forest temperature (from our measurements at HOBO 2A) from predicted average temperature at all pixels on the temperature maps to represent the average temperature departure from the lowland forest ecosystem. This statistic is reported as an UHI index.

5. Results and Discussion

5.1. Fixed measurements

Fixed HOBO temperature measurements indicate the existence of a pronounced nocturnal UHI (Table III). The average early night UHI (1900–2359) calculated between the CBD and rural stations ($\Delta T_{\text{CBD-rural}}$) was 1.86°C during the summer wet season and 2.44°C during the fall wet season, for an average UHI of 2.15°C during both wet season sampling periods. The average early night UHI calculated between the CBD and suburban stations ($\Delta T_{\text{CBD-suburban}}$) was 0.78°C during the summer wet season and 2.06°C during the fall wet season, for an average $\Delta T_{\text{CBD-suburban}}$ of 1.42°C during both wet season sampling periods (Figure 5). During the dry season, $\Delta T_{\text{CBD-rural}}$ was 1.48°C and $\Delta T_{\text{CBD-suburban}}$ was 1.41°C during the early night. $\Delta T_{\text{CBD-rural}}$ was greater than $\Delta T_{\text{CBD-suburban}}$ for all seasons and time periods but less pronounced during the day in the dry season. The nocturnal UHI is greater than the day UHI in both rural and suburban locations, a trend that is consistent with UHI theory and the findings of others (Chandler 1965; Oke and East, 1971; Landsberg, 1981). Individual values of $\Delta T_{\text{CBD-HB}}$ were highly variable, ranging from 0.31°C at the HOBO 4S (residential) to 3.02°C at the HOBO

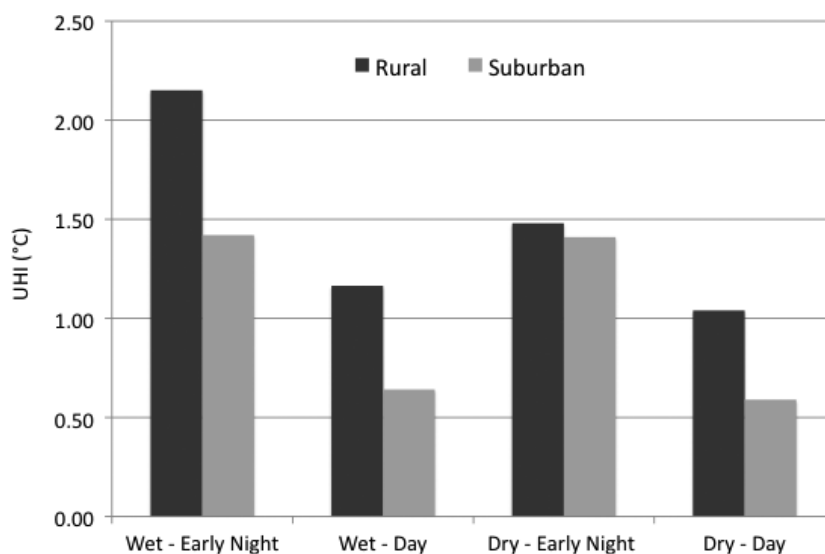


Figure 5. Early night and daytime UHI values calculated between . . . and suburban stations ($\Delta T_{\text{CBD-suburban}}$), during both wet and dry seasons.

Table III. Average temperature difference calculated during the three data collection periods as CBD – individual HOBOS for all HOBOS along the urban to rural gradient. The stations have been stratified further within each season based on whether they were designated suburban or rural, and by time of day.

HOBO	Local land use	% Vegetation	UHI (°C), $\Delta T_{\text{CBD-HB}}$		
			Early night UHI (1900–2359)	Late night UHI (0000–559)	Day UHI (0600–1859)
Wet season, summer (26/6/2006–5/7/2006)					
			Suburban stations, $\Delta T_{\text{CBD-Suburban}}$		
2S	Urban Centre	40	0.71	0.83	0.55
3S	Industrial	78	1.32	1.61	0.90
4S	Residential	33	0.31	0.64	0.25
5S	Major road crossing	73	0.78	0.93	0.55
Average $\pm$ Standard Error		N/A	0.78 $\pm$ 0.21	1.00 $\pm$ 0.21	0.56 $\pm$ 0.13
			Rural stations, $\Delta T_{\text{CBD-Rural}}$		
1S	Abandoned agricultural fields	100	1.25	1.47	0.97
6S	Mowed grassland	100	2.44	2.43	0.91
2A	Old-growth forest	100	2.14	1.86	2.23
3A	Grassland mix	100	1.47	1.44	1.10
4A	Residential limits	100	2.01	1.76	1.81
Average $\pm$ Standard Error		N/A	1.86 $\pm$ 0.22	1.79 $\pm$ 0.18	1.40 $\pm$ 0.26
Wet season, fall (10/9/2006–7/10/2006)					
			Suburban stations, $\Delta T_{\text{CBD-Suburban}}$		
1F	Residential recreation park	33	2.05	2.28	0.80
2F	Residential church	18	1.47	1.74	0.55
3F	Suburban mix	15	1.69	1.90	0.51
5F	Major road	43	3.01	2.80	1.02
Average $\pm$ Standard Error		N/A	2.06 $\pm$ 0.34	2.18 $\pm$ 0.24	0.72 $\pm$ 0.12
			Rural Stations, $\Delta T_{\text{CBD-Rural}}$		
4F	Rural road	100	2.09	2.42	0.65
6F	Rural dirt road	55	2.79	3.02	1.20
Average $\pm$ Standard Error		N/A	2.44 $\pm$ 0.35	2.72 $\pm$ 0.30	0.925 $\pm$ 0.28
Dry season (1/3/2007–30/4/2007)					
			Suburban stations, $\Delta T_{\text{CBD-Suburban}}$		
3F	Suburban mix	15	0.86	1.32	0.40
5F	Major road	43	1.95	2.27	0.77
Average $\pm$ Standard Error		N/A	1.41 $\pm$ 0.55	1.80 $\pm$ 0.48	0.59 $\pm$ 0.19
			Rural stations, $\Delta T_{\text{CBD-Rural}}$		
2A	Old-growth forest	100	1.78	2.02	1.77
4F	Rural road	100	1.21	1.95	0.34
6F	Rural dirt road	55	1.48	2.22	1.00
Average $\pm$ Standard Error		N/A	1.49 $\pm$ 0.16	2.06 $\pm$ 0.08	1.04 $\pm$ 0.41

6F (rural dirt road). In general, the larger $\Delta T_{\text{CBD-HB}}$ values at night were found between the CBD and stations in open, vegetated areas, rather than the forested or thickly vegetated areas, which echo previous findings by Hawkins *et al.* (2004). Large sky view factors at the stations in the open, vegetated areas allow also for enhanced longwave cooling and thus decrease the temperatures quickly after sunset.

$\Delta T_{\text{CBD-Rural}}$ was almost 1 °C higher during the wet season than the dry season, and roughly 0.6 °C higher in the fall than the summer within the wet season itself (Table III). $\Delta T_{\text{CBD-Suburban}}$ remained relatively constant between seasons (Figure 5). We expected the dry season to show a higher UHI such as has been found in other cities (Roth, 2007). This is a phenomenon due to generally higher thermal inertia and higher humidity levels in wet periods, both of which should decrease

rates of cooling more in rural areas than in urban areas. The higher wet season than dry season UHI may have occurred because the specific climatic conditions of our sampling periods were not representative of the usual dry and wet seasons in the San Juan area. A comparison of several climate variables at the San Juan Airport shows that the wet season measurements were in fact drier than those of the dry season (Table IV). The wet season measuring period was drier than the comparable 40-year average and the dry season measuring period was much wetter than the 40-year average. In addition, the average wind speed was greater during the dry season than that during the wet season, and the percentage of clear skies during the measurements in the normally wet season was greater than that during the dry season. Both these climate factors were contrary to the 40-year history and promote

Table IV. Data averages for the usually wet season (26 June to 5 July and 10 September to 7 October 2006) and the usually dry season (March and April 2007) during our period of data collection and 40-year average data covering the same dates for comparison.

Season	Length (days)	Rain (cm/day)	% Clear hours	Average wind speed (m/s)	Average RH (%)	DP (°C)	Day length (h)
Wet – Summer	10	0.27	11.54	3.51	75.7	23.2	13.22
Wet – Fall	28	0.097	11.15	2.55	75.89	23.2	12.1
Dry	60	0.525	10	4.24	72.3	20.4	11.8 to 12.8
Wet (40-year ave)	91	0.396	14	5.36	77.8	22.8	N/A
Dry (40-yearave)	60	0.192	27	5.59	73.3	20.8	N/A

N/A = Not available, DP = Dew point, RH = Relative humidity, ave = Average.

UHI formation in the wet season and reduce it in the dry season.

Within the wet season itself, the average climatic conditions of the fall wet season favoured UHI formation more than the conditions present during the summer wet season (Table IV). For example, both average rainfall and average wind speed were lower in the fall wet season compared with that in the summer wet season. Our results from both the within wet season comparison and the wet–dry season comparison echo findings in the literature that rainfall and wind speed are important factors influencing UHI formation (Hawkins *et al.*, 2004).

We compared diurnal temperature data by hour at the CBD, HOB0 2A (old-growth forest), HOB0 1S (abandoned agricultural fields), and HOB0 6S (mowed grassland) to view the effects of different upwind land-cover types on air temperature over the day (Figure 6). As expected, the CBD was warmer than all other sites throughout the day and night, emphasizing the impacts of the thermal storage capacity of the large urban area. The grassland site had high daytime air temperatures and low nighttime temperatures; and at the forest site, the temperatures were consistently cooler throughout both the day and night. These trends resulted in large diurnal

temperature ranges at grassland sites, and small diurnal temperature ranges at both the forest and CBD sites (Figure 7). The diurnal temperature trends described in this study are mainly the result of the balance between insolation and thermal storage capacity. The urban site receives large amounts of insolation on average and is able to retain that energy in the urban materials present, such as cement, asphalt, etc. However, the grassland sites that receive equal amounts of insolation cool rapidly at night due to very low thermal storage capacity. Furthermore, a lower sky view factor at the urban site (68.8%) compared with that at the mowed-grassland site (82.5%) will slow longwave cooling at night, increasing the UHI. The forest achieves low temperatures during the day and night by retaining moisture and limiting overall insolation (sky view factor = 6.8%).

According to these results, the presence of grass-covered ‘green space’ will not impede daytime warming. This can be a problem for businesses and residences operating air-conditioning units during daytime hours where properties are normally not surrounded by canopy cover. Our results concur with those of Akbari *et al.* (2001) who showed that shading and evaporative cooling, both provided by trees, are essential to negate the effects

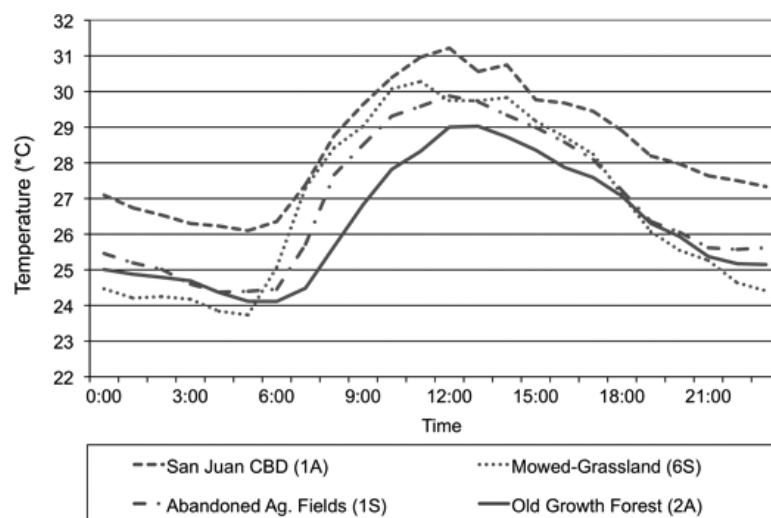


Figure 6. Diurnal temperature trends calculated as hourly averages from the summer data collection period for the San Juan CBD (1A), Old-growth forest (2A), Abandoned agricultural fields (1S), and Mowed grassland (6S).

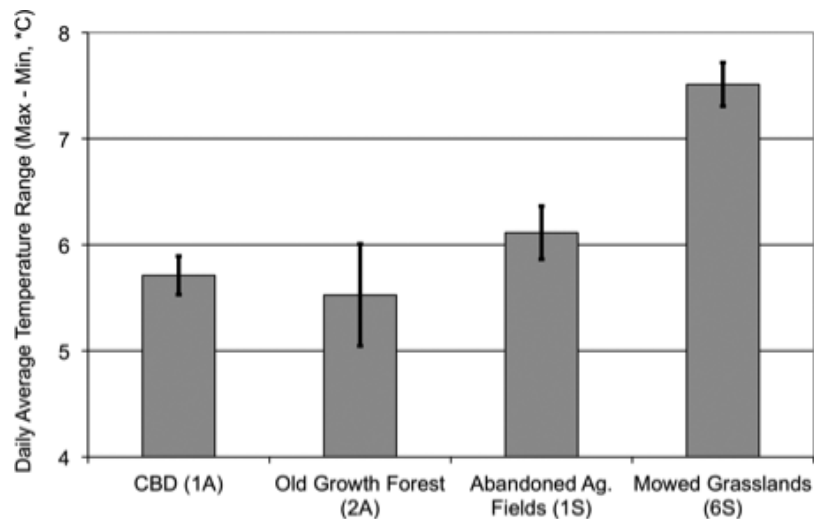


Figure 7. Diurnal temperature range, calculated as the average daily maximum–daily minimum, for data collected during the summer months at the San Juan CBD (1A), the Old-growth forest (2A), the Abandoned agricultural fields (1S), and the Mowed-grassland (6S) locations with standard error bars.

of urban warming. This suggests that ‘greening’ efforts to combat UHIs in the tropics need to focus on increasing tree-cover instead of simply creating park-like ‘green spaces’.

5.1.1. Maximum UHI

We estimated the maximum UHI for the SJMA from the pattern of temperature differences between both the urban and the forest site and between the urban and the mowed-grassland (6S) site on 3 days with relatively clear skies and low wind speeds at night. The urban site began cooling about noon and continued cooling until sunrise (Figure 8(a)). Cooling from sunset to sunrise was the slowest at the urban site, next slowest at the forest site, and then the mowed-grassland site. At the urban site, cooling from sunset to sunrise occurred at a generally constant rate of $0.32^{\circ}\text{C h}^{-1}$. The forest site also cooled throughout the night but at a somewhat greater rate of $0.41^{\circ}\text{C h}^{-1}$ on average, whereas the mowed grassland cooled the most rapidly throughout the night at an average rate of $0.55^{\circ}\text{C h}^{-1}$. These cooling rates are smaller than typical rates described by Oke (1982) for temperate climates. Oke also indicated that cooling rates, especially for rural areas, would be the greatest at about sunset, typically $2\text{--}3^{\circ}\text{C h}^{-1}$, and then decline through the night. The smaller cooling rates we observed may have been partly caused by higher humidity that led to smaller net outgoing longwave radiation in this tropical climate.

Daytime heating began at sunrise at the urban reference (CBD) and mowed-grassland sites, with the mowed grassland warming most rapidly. Heating rates in the old-growth forest, mowed grassland, and the urban reference (CBD) were approximately equal, but the forest did not begin increasing in temperature until about an hour after sunrise, whereas the mowed grassland began increasing in temperature about a half hour after sunrise. This delay caused the maximum temperature difference to occur a

short time after sunrise. The Max UHI calculated as urban reference – old-growth forest was 4.7°C , and the Max UHI calculated as urban reference – mowed grassland was 3.9°C (Figure 8(b)).

The Max UHI calculated between the urban reference and mowed-grassland site is analogous to other Max UHI calculations that use urban areas and rural stations in agricultural or otherwise open areas. There were a few short time periods with urban – rural temperatures greater than 4.7°C , but these were caused apparently by the timing of showers, with cooling rains occurring first in rural areas and a short time later at the urban site; thus these temperature differences were aberrations and were not representative of common UHI intensity.

The pattern of wind speed during the 3 days (Figure 8(a) and (b)) is representative of most days during our data collection period, with low wind speeds at night and higher speeds during the day, as daytime turbulence brought the momentum at higher elevations to ground level. The diurnal influence is also seen in the cloud pattern with clear skies at night giving way to scattered clouds during mid-day. This wind and cloud pattern would tend to increase UHI intensity during the night and reduce it during the day.

We plotted the two Max UHI values for San Juan with that shown in Figure 3 of Roth (2007), which shows Max UHI as a function of population for numerous temperate and tropical cities around the world (Figure 9). We assumed a population for San Juan of 2 million, which is roughly the population of the greater SJMA. The San Juan Max UHI falls within the range of values for other wet tropical cities, but generally less than Max UHI values for temperate ones.

5.2. Mobile measurements

A preliminary analysis of the data from the mobile transects ($\Delta T_{\text{CBD-TF}}$) shows considerable variation in temperature (Figure 10(a)–(c)), and a general pattern

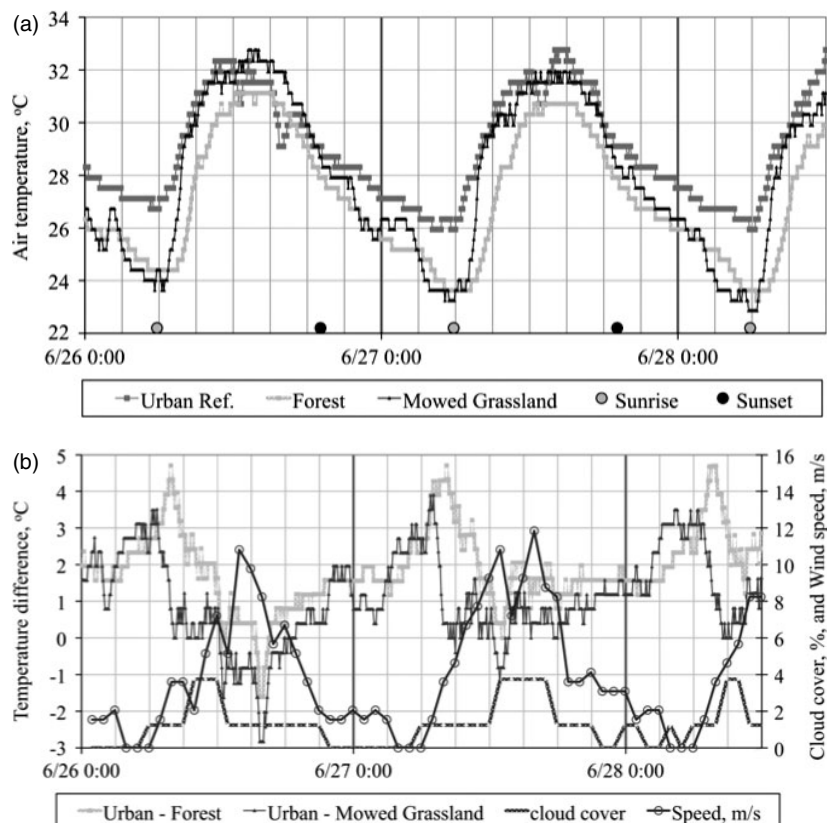


Figure 8. (a) Temporal patterns of air temperature at the Urban reference (San Juan central business district-1A), the Old-growth forest (2A), and Mowed grassland (6s). Times of sunrise and sunset are also marked. (b) Temperature differences, urban reference – old-growth forest and urban reference – mowed grassland, wind speed, and cloud cover. Cloud cover is represented as clear 0%, few clouds 1.25%, and scattered clouds 3.75%. Data for cloud cover and wind speed taken from San Juan Airport.

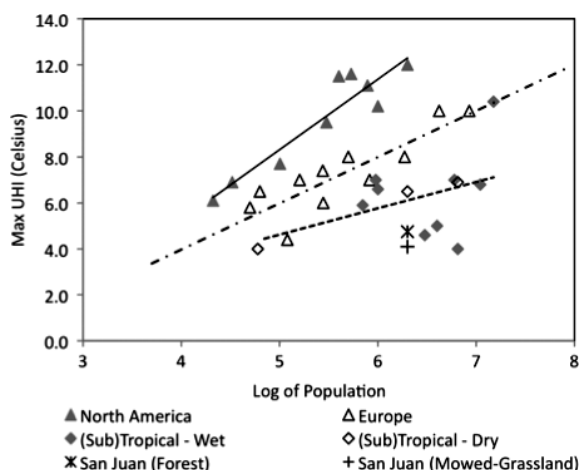


Figure 9. Maximum nocturnal heat island intensity *versus* population. The solid trendline is a regression through North American cities, and the discontinuous dotted line is a regression through European cities, adapted from Oke (1973). The continuous dotted line is a regression through tropical wet cities, excluding San Juan, adapted from Roth (2007). The large asterisk marks our estimated maximum heat island for San Juan calculated between the CBD and the old-growth forest (2A) site, and the large plus sign is the same calculation between the CBD and the mowed-grassland (6S) site.

of cooling with distance from the urban centre. Thus $\Delta T_{\text{CBD}-\text{Tr}}$ decreases as distance from the urban centre increases. This trend was the strongest between 0400

and 0600 h ($\sim 2.5^\circ\text{C}$) and the weakest between 1200 and 1400 h ($< 1^\circ\text{C}$), which agrees with the fixed-station results showing a nighttime peak in UHI intensity, with less difference at mid-day.

The relationship between cooling and distance from the city centre was not constant because distance from the city is not a perfect surrogate for the amount of urbanized land cover. We found negligible cooling along the east route (Figure 1) between 2000 and 2200 h (Figure 10(c)). Further through the night, between 0400 and 0600 h, the transect stations farther from the CBD along the east route finally cooled relative to the CBD. The east route goes through the town of Rio Grande, a highly developed area. Along the east route and throughout the Rio Grande area especially, there are very large areas of new dense suburban housing and commercial developments, which are most likely slowing the evening cooling trend. A more thorough analysis with results that could be extrapolated to other cities might examine $\Delta T_{\text{CBD}-\text{Tr}}$ as a function of differences in upwind cover between the CBD and each of the transect stations, and with other independent variables such as antecedent precipitation and atmospheric stability. With this preliminary analysis, we are simply able to explain quantitatively the difference in results between the transect routes and to present a picture of the temperature pattern for part of the SJMA.

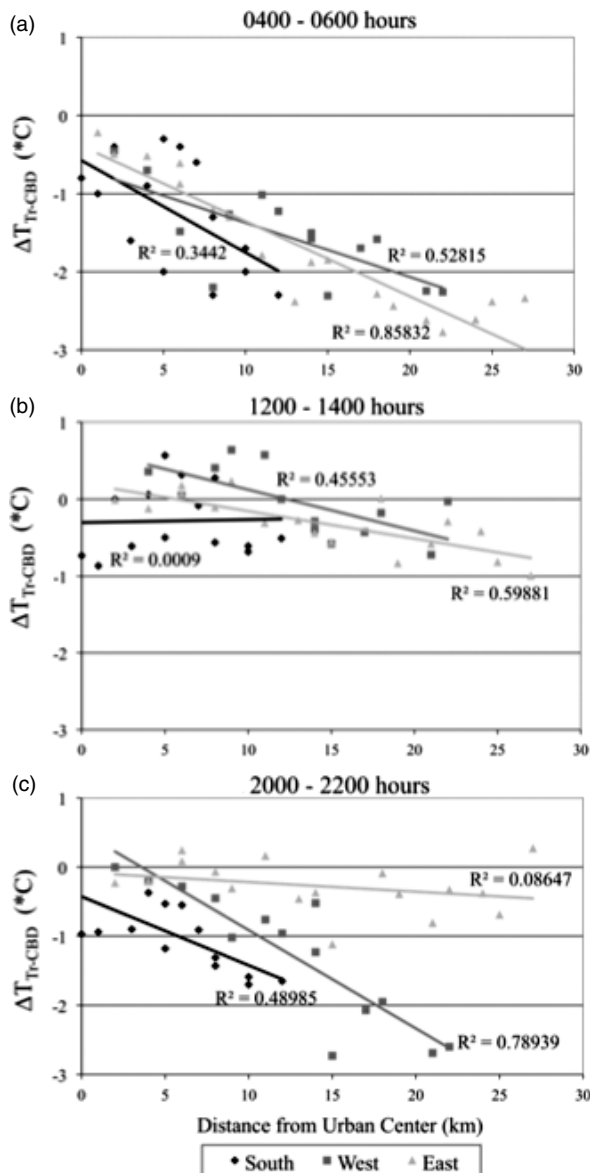


Figure 10. (a–c) $\Delta T_{\text{CBD}-T_r$ trends along three routes emanating from the San Juan central business district to surrounding rural areas. Data from all three routes is stratified by time of day: (a) 0400–0600, (b) 1200–1400, and (c) 2000–2200.

The east route ends at the base of the Luquillo Mountains (Figure 1(a)); thus an evening UHI extends to the foothills of the Luquillo Mountains. The east route cools at a faster rate than the CBD but more slowly than other rural areas, such as the South and West routes, throughout the night. Furthermore, it is possible that the cooling trends along the east route are impacted by katabatic winds from the Luquillo Mountains. Comrie (2000) found that katabatic flows from surrounding mountains influence UHI measurements many kilometers upwind. If the east route continues to be developed, the UHI may begin to have impacts on climate patterns in the mountains, such as orographic cloud formation and precipitation. At this time, however, we are unable to assert whether the UHI is impacting precipitation within the Luquillo Mountains.

5.3. Modelling future temperature

The best-fit regression ($r^2 = 0.94$) between upwind vegetation and average temperature at the fixed sensors was obtained using azimuth window 11 (angle = 101–110°, essentially east by southeast, at a distance of 180 m upwind; Figure 11). We validated this model in three ways. First, we predicted temperature at the six fall data sites, calculated using the ‘best-fit’ regression, and found that the predicted temperatures differed from actual average temperature collected at those six stations by an average of only 0.36 °C, with a standard error of 0.2. Second, a clear and consistent pattern of high r^2 values can be seen to the east and southeast. If the r^2 calculated for the best-fit regression was spurious, one would expect to find other high r^2 values scattered randomly throughout the gradient plot. Third, we plotted the best-fit regression and labelled each point. Figure 12 shows that the land-cover categories align intuitively along the vegetation gradient from 0% to 100%, with the urban reference (1A) at 0% vegetation and the old-growth forest (2A) at 100% vegetation.

Our findings appear to agree with those of Oke (1976) regarding upwind fetch models in his response to the work by Summers (1964). In a simple UHI model by Summers (1964, 1977), the maximum ΔT_{U-R} was found to be proportional to the square root of L , the ‘distance from the edge of the city to the centre along the wind direction (m)’. Oke (1976) found that in UCL measurements of temperature, ΔT_{U-R} was not proportional to L , and therefore the upwind fetch model of Summers did not function well. But Oke (1976) also suggested that the close positive correlation of maximum UHI with city population that had been found in many studies occurred because population is a surrogate for physical structure of the city, and that it is not the length of the upwind urban fetch, but the character of the upwind urban structure that determines maximum UHI. Oke found that a large UHI could develop with relatively short upwind urban fetch. Therefore, we believe that upwind cover is important in determining maximum ΔT_{U-R} in the canopy layer, but not simply the distance of the urban point to a rural area. Rather, the important factor is the difference between the urban and more rural points in the structure of the upwind canopy layer at horizontal microscale distances. In the case of our measurements, the most influential upwind distance was about 180 m. Voogt and Oke (2003) and Oke (2006) visualized ellipsoidal upwind source areas within the UCL (see Figure 2 in both articles.) We visualize our results as being simplifications of that source area concept by approximating the distance and direction to the centre of such ellipsoidal source areas. Improvements in our method might be achieved by adding antecedent precipitation and an index of atmospheric stability as independent predictor variables.

Assuming no change in vegetation type in the unchanged pixels, our maps projecting future UHI in northeastern Puerto Rico (see Section 3.1) show intensification of the UHI within the SJMA and geographic

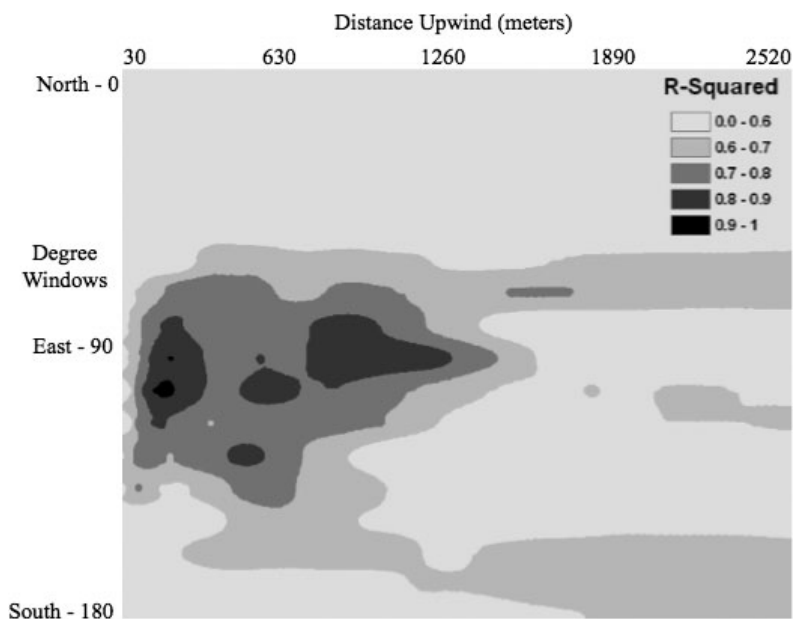


Figure 11. Isocorrelation plot showing the coefficient of determination (r^2) for all 1512 regression analyses for $\Delta T_{\text{CBD-HB}}$ as a function of upwind vegetation. Degree windows 10–12 ($91\text{--}120^\circ$), from 150 to 270 m upwind, represent the 0.91–1.0 isocorrelation, and hence the best upwind fetch wedges for predicting temperature based on land cover.

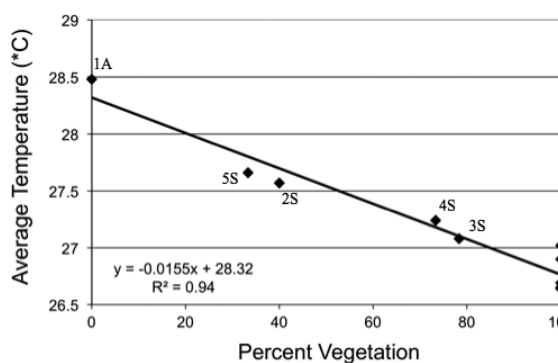


Figure 12. Best-fit regression of average temperature at the fixed stations in the summer of 2006 as a function of the percent vegetation found within degree window 11 ($101\text{--}110$) and 180 m upwind. The alphanumeric refer to the HOBOs listed in Table I: 1A = Urban reference, 5S = Major road crossing, 2S = Urban centre, 4S = Residential, 3S = Industrial, 3A = Grassland mix, 1S = Abandoned agricultural fields, 2A = Old-growth forest, 6S = Mowed grassland.

expansion of the UHI, especially towards the Luquillo Mountains (Figure 13(a)–(f)). The greatest changes predicted between years 2000 and 2050 are marked by large decreases in land area with a UHI index equal to or less than $+0.2^\circ\text{C}$, and large increases in land areas with a UHI index of $+1.55^\circ\text{C}$. Over 140 km^2 with an UHI index of $+0.2^\circ\text{C}$ is converted to land cover with a higher UHI index, whereas an additional 130 km^2 is converted to a land cover with a UHI index of $+1.55^\circ\text{C}$.

The largest changes in the projected UHI index between 2000 and 2050 occur in the $+0.2^\circ\text{C}$ category. This means that urbanization is expanding geographically into presently vegetated areas rather than becoming more intense within previously established urban or suburban areas. Much of this projected urbanization is concentrated

in lands to the southeast of the CBD, towards the Luquillo Mountains, which is consistent with our observations. Our results relating land cover and the UHI, in addition to those of Scatena (1998) who found that land-cover change throughout the island is influencing cloud formation and rainfall patterns within the Luquillo Mountains, highlight the need for research that explicitly studies the effect of land-cover change on precipitation within the Luquillo Mountains.

6. Conclusion

The major findings of this study were: (1) San Juan, Puerto Rico, exhibits a nocturnal UCL atmospheric heat island of 2.15°C measured between our urban and rural stations during the usually wet season and 1.78°C during the usually dry season ($\Delta T_{\text{CBD-Rural}}$). The fixed-station data show greater UHI values in the wet season than the dry season, which may be due in large part to data that were collected during a relatively dry and clear climatic period within the usually wet season, and data collected during a relatively wet and cloudy period within the usually dry season. In the long term, however, regional drying due to global climate change may reduce dry season precipitation, and, in line with findings common in other studies, increase the difference between dry and wet season UHIs. (2) The Max UHI calculated between the urban site and the forest was 4.7°C , and the Max UHI calculated between the urban site and the mowed grassland (i.e. an open, rural site) was 3.9°C . (3) The UHI stretches to at least the base of the Luquillo Mountains during the early evening. (4) ‘Green spaces’ were ineffective in combating warming during the day, whereas tree cover

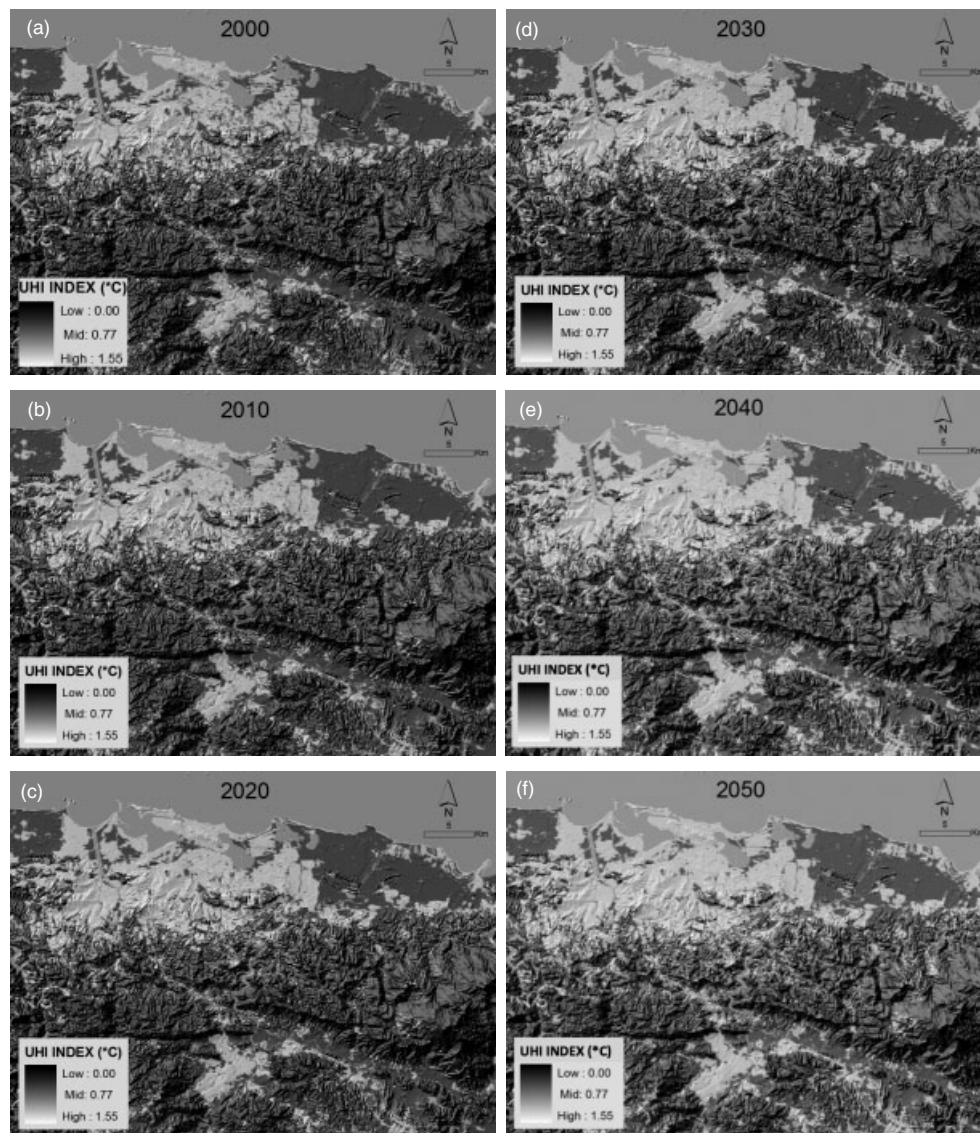


Figure 13. Maps showing the current (a) and projected (b–f) UHI in northeastern Puerto Rico.

and the shade it provides were successful agents in diminishing daytime warming. (5) Land cover up to 180 m upwind predicted downwind average summer temperature the best ($r^2 = 0.94$). (6) Predictions of future development and temperatures suggest that if the present pattern of development continues in Puerto Rico, over 140 km² of land that showed no signs of UHI in 2000 will have an average UHI between +0.4 and +1.55°C by 2050. More than 130 km² of land area with a UHI between +0.4 and +1.4°C in 2000 will have an average UHI greater than +1.55°C by 2050.

Both fixed-station and mobile temperature measurements showed the presence of a nocturnal peak in UHI intensity. Usually there is a nocturnal peak in the UHI, which was the case for our measurements as well, except when measuring the UHI between the CBD and the forest site on mostly clear and low-wind days when the peak occurred just after sunrise.

The forested site was the coolest on average and able to negate effects of daytime warming within the canopy

layer. This effect occurs because of the absorption of incident solar radiation in the upper tree canopy, where much of the radiation is converted to latent heat via evaporative cooling, thus preventing the penetration of solar radiation to warm the soil surface and resulting in its conversion to sensible heat to the air near the ground. Grassland sites showed not only significant daytime warming, but also pronounced nighttime cooling, resulting in large diurnal temperature ranges. Canopy cover should therefore be encouraged to maintain cooler temperatures throughout the day, thus reducing expenditures on air conditioning.

The report by the 2007 Intergovernmental Panel on Climate Change predicted that global temperatures will increase by 0.3°C per decade (average of scenarios B1, A1T, B2, A1B, A2, and A1FI; IPCC, 2007). At this rate, the global temperature will increase by 1.2°C by 2050. However, the UHI in northeastern Puerto Rico is already increasing daily temperatures by more than 2°C in many locations, and the Max UHI estimates are almost 5°C.

Furthermore, the UHI is expected to expand geographically by 2050, raising daily temperatures between 0.2 and 1.5 °C over much of northeastern Puerto Rico. According to the findings in this study, development projects encroaching on the forests of the Luquillo Mountains may impact regional climate more in the next half century than the changes brought by global climate change. Future research efforts should focus on the specific effects of deforestation, suburbanization, and urbanization on the urban boundary-layer heat island and its effect on lifting condensation levels so as to provide more detailed information pertaining to the future of the freshwater supply for the SJMA.

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