

THE RELATION BETWEEN LAND-COVER AND THE URBAN HEAT ISLAND IN NORTHEASTERN PUERTO RICO

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1. INTRODUCTION

As development continues in Puerto Rico, forests and grasslands are being converted to impervious cover, changing the magnitude and geographic range of the Urban Heat Island (UHI). As part of the U.S. National Science Foundation Long Term Ecological Research Program, this study aims to quantify the various meteorological effects that urbanization may be imparting on the nearby tropical forest ecosystem. The specific objectives of this study are: (1) to quantify the timing of the peak urban heat island created by the San Juan Metropolitan Area (SJMA), (2) to explore correlations between air temperature and land-cover, (3) to assess the geographic range of the urban heat island created by the SJMA, and (4) to predict the growth of the geographic range of the UHI into the future.

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The SJMA receives much of its freshwater from the Luquillo Mountains, a large forested area located 17 kilometers to the east (Figure 1). There is new concern about a 16% decrease in overall precipitation trends within Puerto Rico during the 20th century (van der Molen 2002), and that three of the top ten driest years in the past century were recorded in the 1990's (Larsen 2000). Furthermore, a growing body of evidence suggests that urbanization may affect regional climates more than the changes predicted by the influence of global climate change (Hulme and Viner 1995; Scatena 1998a; Brazel et al. 2000). Therefore research efforts should focus not only on global climate change, but also on the regional climatic effects of urbanization, especially the effects of UHI's.

2. DATA COLLECTION

We employed two methods to capture the variation of the UHI over space and time: (a) a fixed-station transect of temperature sensors (HOBO's), and (b) a mobile temperature measurement transect. (Figure1).

For the fixed-station transect we installed a network

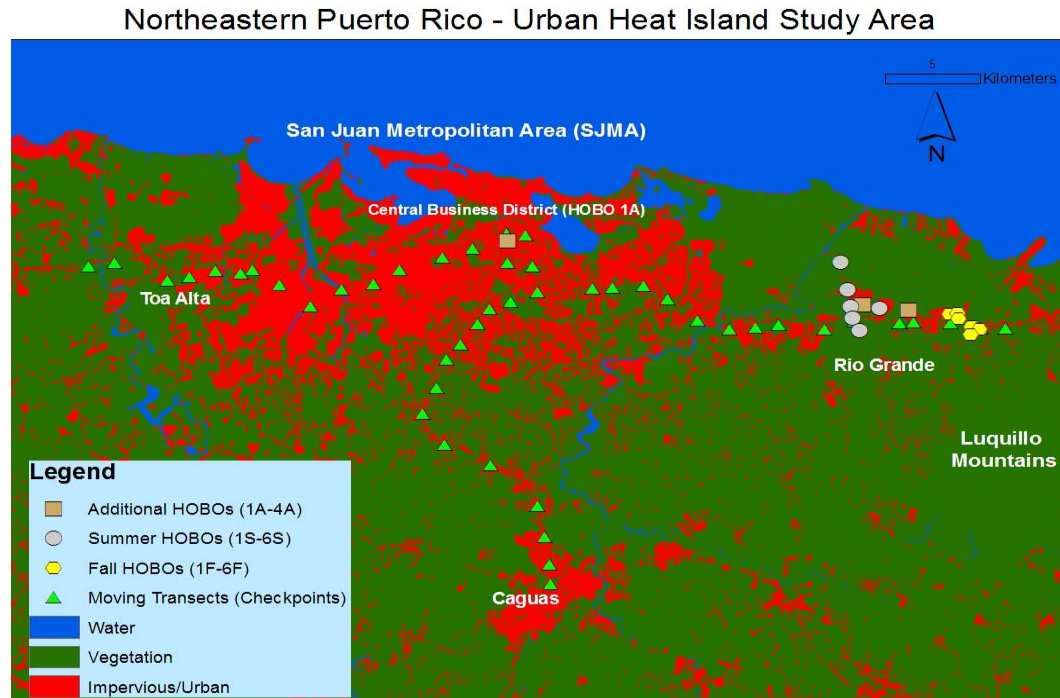


Figure 1. Land-cover map of Northeastern Puerto Rico with green triangles labeling checkpoints along the mobile transects. The grey circles, yellow hexagons, and the brown squares mark the locations of the HOB0s.

of ten automated Series-8 HOBO Pro-Temp Data Loggers (Onset Corporation; Figure 1), to record temperature measurements along several urban-rural gradients throughout the SJMA. The goal of the fixed-station transect was to establish near-simultaneous temperature measurements along the gradients to assess the timing of the peak UHI and the influence of land-cover on temperature.

For the mobile measurements we attached a thermistor-temperature sensor to a PVC pipe about one meter above the roof of a Jeep Cherokee and drove along different routes radiating out from the central business district (CBD) of the SJMA to three different surrounding rural areas. The goal of the mobile data collection was to capture the current geographic range of the UHI.

3. AIRSHED MODEL

Due to the importance of wind mitigation on the magnitude of UHIs (Summers 1964; Oke 1976; Comrie 2000; Morris 2001; Gonzalez et al. 2005), we decided to look upwind from each sensor and analyze the percent vegetation at different angles and distances upwind. To do this we developed a computer model in Fortran-90 language that calculated the percent of vegetation within a cone-shaped upwind area, termed an "airshed". The percent vegetation is derived from a year 2000 land-cover map of Puerto Rico (Helmer and Ruefenacht 2005), and is calculated according to the formula:

$$\text{Percent vegetation upwind} = \frac{\text{Number of vegetated pixels within upwind airshed}}{\text{Total number of pixels within upwind airshed}} * 100$$

The model analyzed a total of 180 azimuth degrees, from due north to due south, and a maximum of 2520 meters upwind. We divided the azimuth degrees into 18 windows of 10 degrees each, termed "degree window", and divided the "upwind distance" into 84 intervals of 30 meters each (Figure 2). Due to the predominance of easterly trade-winds in Puerto Rico, we limited the model to airsheds in easterly directions.

The model begins with the 'center pixel', which represents the hobo on the ground for which the average vegetation upwind is being calculated (Figure 2). The program starts on degree window 1, the wedge just above 90° east, and calculates the percent vegetation within the upwind wedge using all possible distances upwind from 30 to 2520 meters, at 30 meter intervals. Once this calculation is complete for all distances in degree window 1, the program switches to degree window 2 and repeats the calculation for all distances in degree window 2. Once degree window 9 is reached, which is the most northern facing wedge (1° - 10°), the program will switch to degree window 10 and repeat the process for degree windows 10 - 18, ending with the most southern facing wedge (171° - 180°).

We calculated r^2 values between percent vegetation for each of the 1512 airsheds (18 degree windows * 84 upwind distances) and average temperature data collected by HOBOS 1S-6S and 1A - 4A during the summer of 2006. All 1512 r^2 values were grouped into 9 classes and plotted in a gradient space dimensioned by azimuthal degree on the y-axis and upwind distance on the x-axis. The airshed with the highest r^2 , i.e. the best-fit airshed, was used to calculate the best-fit regression

between average temperature and percent upwind vegetation, according to the formula:

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

Where, T = average temperature
 α = y -intercept
 β = parameter estimate for percent vegetation
x = percent vegetation

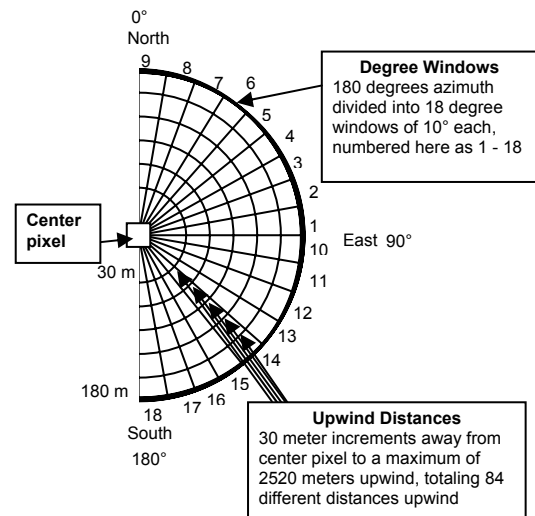


Figure 2. Conceptual diagram of the airshed model.

3.1 Predicting Future UHI

We used the GEOMOD module within the IDRISI Kilimanjaro mapping software to predict urbanization to the year 2050 in Northeastern Puerto Rico. We predicted urban growth at decadal intervals starting with the 2000 land-cover map and ending with the year 2050. For each future decadal land-cover map, we calculated percent vegetation upwind for the best-fit airshed for every pixel, and then converted these percent upwind vegetation maps to maps of predicted average temperature by using the best-fit regression to solve for predicted temperature at each pixel on each map.

In order to show explicitly the geographic growth of the UHI over time, we subtracted the average forest temperature from all pixels on the temperature maps to represent the average temperature departure at each pixel from the natural vegetated ecosystem in Puerto Rico. This statistic is reported as an UHI index.

4. RESULTS AND DISCUSSION

4.1 Fixed Transects

Our results show the existence of a pronounced nocturnal UHI (Table 1). The UHI, calculated as the difference in temperature from the central business district of San Juan to all other HOBOS along

the fixed-station transect ($\Delta T_{\text{CBD-HB}}$), was 1.70°C during the early night (1900 – 2359) and 1.81°C during the late night (0000 – 559). Daytime (0600 – 1859) UHI measurements were only 0.93°C. Thus the night UHI is twice as great as the day UHI. Individual values of $\Delta T_{\text{CBD-HB}}$ were highly variable ranging from 0.31°C at the HOBO 4S to 3.02°C at HOBO 6F. The larger $\Delta T_{\text{CBD-HB}}$ values were calculated between the CBD and stations in open, vegetated areas, however not forested areas.

Table 1. Average temperature difference calculated as urban reference – (individual HOBOs) for all HOBOs along the urban-rural gradient.

HOBO	Local Land Cover	UHI (°C), $\Delta T_{\text{CBD-HB}}$		
		Early Night UHI (1900 - 2359)	Late Night UHI (0000 - 559)	Day UHI (0600 - 1859)
1S	Abandoned agricultural fields	1.25	1.47	0.97
2S	Urban Center	0.72 (min)	0.83 (min)	0.55 (min)
3S	Industrial	1.32	1.61	0.90
4S	Urban center	0.31	0.64	0.25
5S	Major road crossing	0.78	0.93	0.55
6S	Mowed-grassland	2.44	2.43	0.91
2A	Old-growth forest	2.14	1.86	2.23 (max)
3A	Grassland/tree/impervious mix	1.47	1.44	1.10
4A	Abandoned agricultural fields	2.01	1.76	1.81
1F	Residential	2.05	2.28	0.80
2F	Residential	1.47	1.74	0.55
3F	Mowed-grassland/trees	1.69	1.90	0.51
4F	Major road crossing	2.09	2.42	0.65
5F	Grassland/tree/impervious mix	3.01 (max)	2.80 (max)	1.02
6F	Abandoned agricultural fields/trees	2.79	3.02	1.20
Average ± Standard Error		1.70 ± 0.19	1.81 ± 0.17	0.93 ± 0.13

We compared the CBD, forest, HOBO 1S, and HOBO 6S diel temperature data to view the effects of different land-cover types on air temperature (Figure 3). The CBD was warmer than all other sites throughout the day and night. At the grassland site we found high daytime air temperatures and low nighttime temperatures, while at the forest site temperatures were consistently cooler and at the CBD consistently warmer throughout both the day and night. These trends resulted in large diel temperature ranges at grassland sites, and small diel temperature ranges at both the forest and CBD sites (Figure 4).

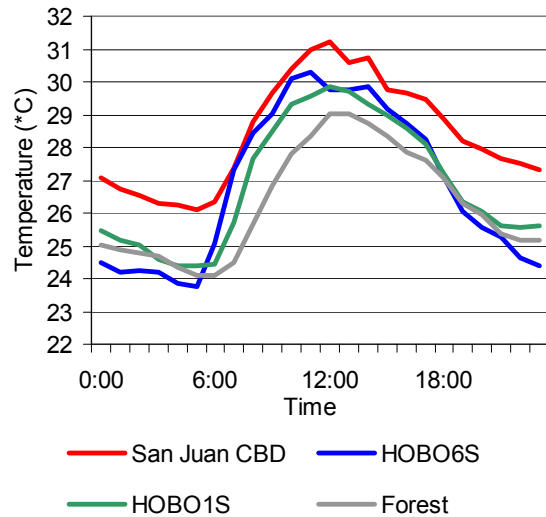


Figure 3. Average diel temperature trends for the central business district (CBD) of San Juan, forest location, HOBO 6S, and HOBO 1S. HOBO 1S is located downwind of a large abandoned agricultural field and HOBO 6S is located in a small mowed grassland site upwind of a large shopping center and downwind of the foothills of the Luquillo Mountains.

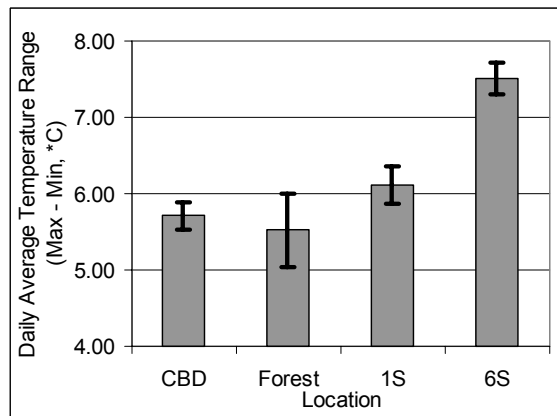


Figure 4. Average diel temperature range, calculated as daily max – daily min, for the central business district (CBD) of San Juan, the forest location, HOBO 1S, and HOBO 6S locations.

Rapid warming at the site outside the forest (3A), and at the grassland sites (HOBO 6S and 1S), as opposed to slower warming in the forest site, indicates that tree canopy cover is necessary to mitigate daytime warming. However, the grassland sites cool quickly during the night which indicates that canopy cover is not needed to mitigate the nighttime UHI. Grassland areas allow large amounts of shortwave and longwave radiation to reach the ground and warm the surface

during the day, but unlike concrete, grass cannot store large quantities of thermal energy, resulting in quick and pronounced cooling during the evening. This is also demonstrated by the large diel temperature ranges at the grassland sites.

Both the forest and the CBD have small diel temperature ranges. The CBD achieves a small diel temperature range by limiting nighttime cooling. The thermal storage capacity of the CBD allows for prolonged warming throughout the night resulting in a small diel temperature range in the urban areas. On the other hand, the forest site has a small diel temperature range because extensive canopy cover limits the amount of incident radiation reaching the forest floor, and high soil moisture allows for continual evaporative cooling, both of which result in minimal warming in the daytime.

According to these results, the presence of grass-covered 'green space' will not impede UHI formation during the daytime. This is problematic for businesses and homeowners that operate air conditioning units during daytime hours, and whose properties are normally not surrounded by canopy cover. Evaporative cooling and shading provided by canopy cover are essential to negate the effects of urban warming. This suggests that "greening" efforts to combat UHIs need to focus on increasing canopy-cover and deepening soils instead of simply creating park-like 'green spaces'.

4.2 Mobile Transects

Analysis of temperature (ΔT_{CBD-Tr}) data from the mobile data collection shows considerable variation (Figures 5a – 5c), but a clear pattern of cooling with distance from urban center is discernable, supporting the idea that the urban heat island effect decreases as the distance from urban center increases. This trend is strongest between 0400 and 0600 hours (Figure 5a) and weakest between 1200 and 1400 hours (Figure 5b), which is in agreement with the fixed-station results showing a nighttime peak in UHI intensity.

We found negligible cooling along the East Route (Rio Grande in Figure 1) between the hours of 2000 and 2200 (Figure 5c), demonstrating that the UHI effect is strong along this route during the early evening. Throughout the Rio Grande area there are massive development projects, which are most likely responsible for the evening warming trend. The Rio Grande route ends at the base of the Luquillo Mountains (Figure 1); thus an evening UHI may extend to the foothills of the Luquillo Mountains. If the developments continue, the UHI may interfere with orographic cloud formation, and hence precipitation, within the Luquillo Mountains.

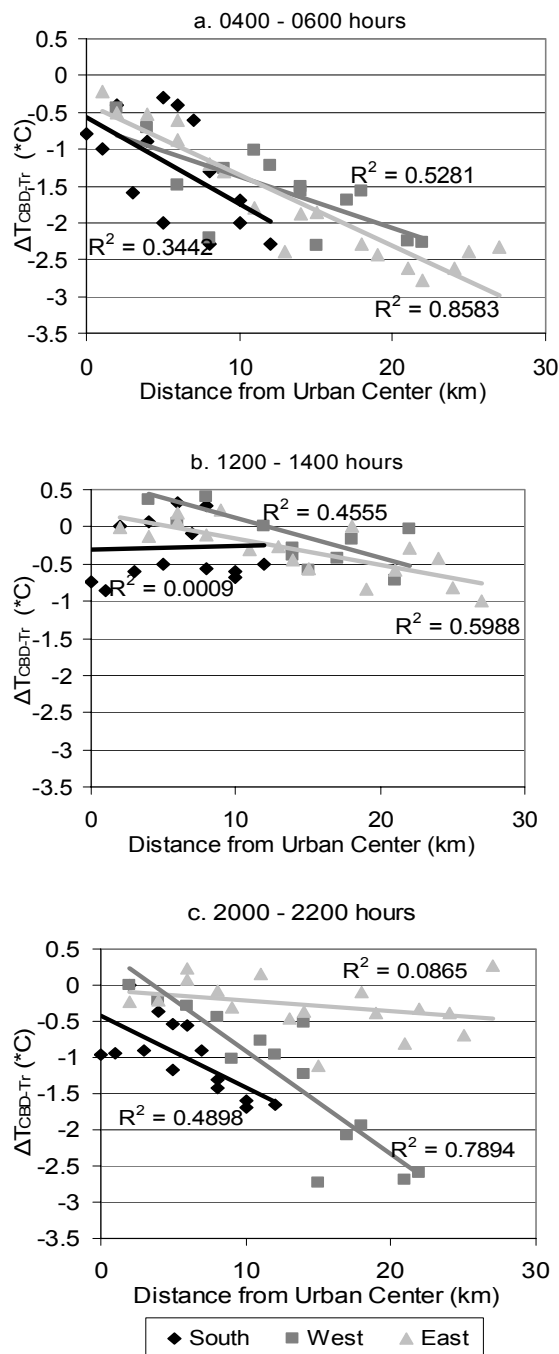


Figure 5a–c. ΔT_{CBD-Tr} trends along 3 routes emanating from the San Juan central business district to surrounding rural areas. Data from all three routes driven between the hours of (a.) 0400 – 0600. (b.) 1200 – 1400. (c.) 2000 – 2200.

4.3 Modeling Future Temperature

Percent vegetation values calculated using east to southeast degree windows and up to around 1300 meters upwind seem to best explain variation in

temperature collected by the HOBOs (Figure 6). The best-fit regression ($r^2 = 0.94$) obtained was calculated using degree window 11 (angle = $101^\circ - 110^\circ$, due north being 0°) and an upwind distance of 180 meters.

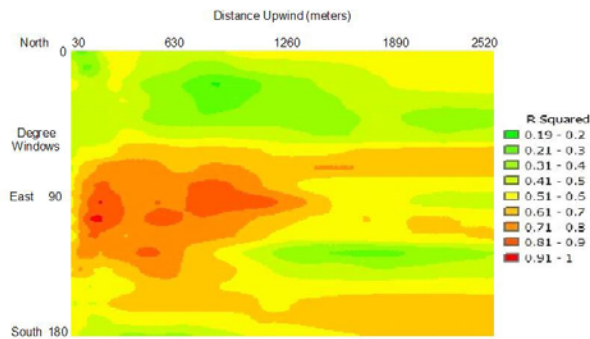
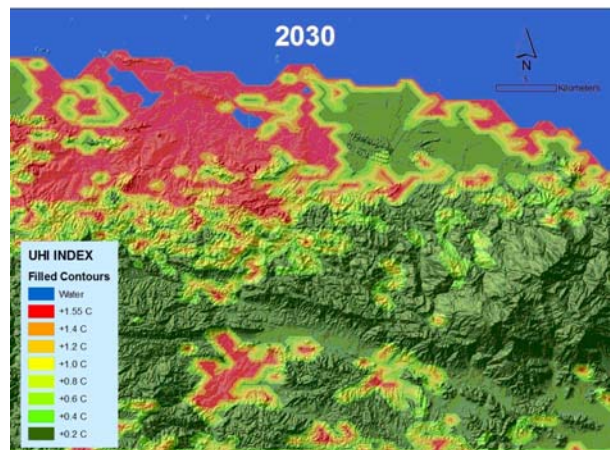
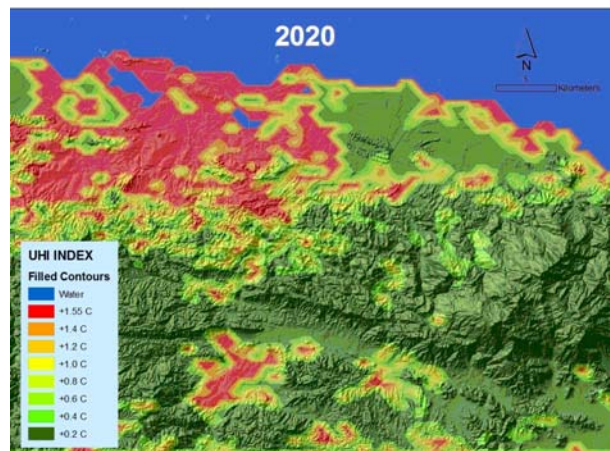
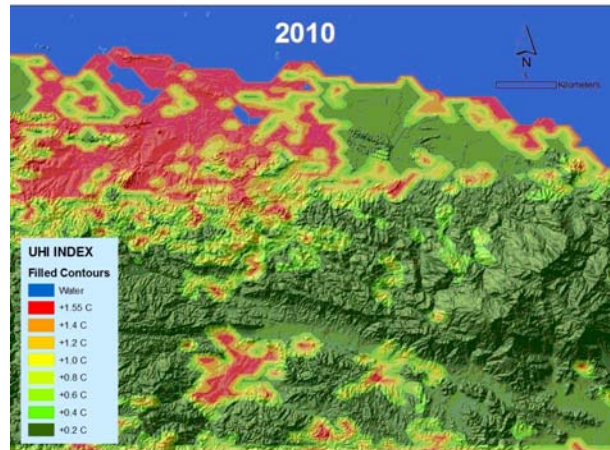
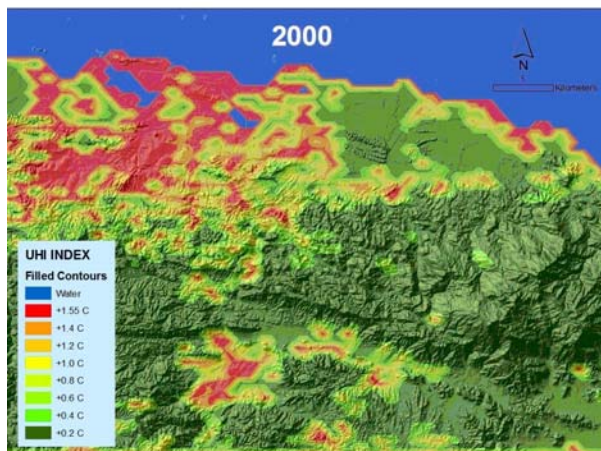


Figure 6. . Isocorrelation plot of average temperature versus percent airshed vegetation along gradient of upwind distance (x) and upwind azimuthal angle (y). Degree windows 10 – 12 ($91^\circ - 120^\circ$), from 150 to 270 meters upwind, represent the 0.91 – 1.0 isocorrelation, and hence the best airsheds for predicting temperature based on land-cover.

Predictive maps (see Section 3.1) of the UHI in northeastern Puerto Rico using the temperature versus upwind vegetation regressions show intensification of the UHI within the SJMA, and geographic expansion of the UHI, especially towards the Luquillo Mountains (Figure 7a – 7f). The greatest changes between years 2000 and 2050 were marked by large decreases of land area with a UHI index equal to or less than $+0.2^\circ\text{C}$, and large increases of land areas with a UHI index of $+1.55^\circ\text{C}$. Over 140 km^2 with a UHI index of $+0.2^\circ\text{C}$ was converted to land-cover with a higher UHI index, while an additional 130 km^2 was converted to a land-cover with a UHI index of $+1.55^\circ\text{C}$.



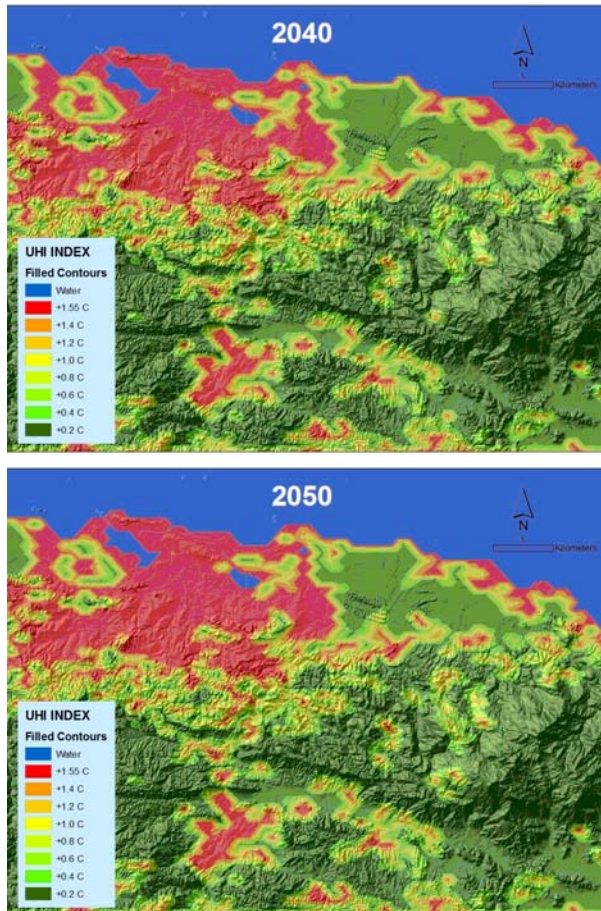


Figure 7a-f. Maps showing the current (a) and projected (b – f) geographic expansion of the UHI in northeastern Puerto Rico.

The largest changes in the projected UHI index between 2000 and 2050 occur in the +0.2 °C category, indicating that urbanization is expanding geographically to vegetated areas rather than becoming more intense within previously established urban or suburban areas. Much of this urbanization is concentrated in lands to the southeast, towards the Luquillo Mountains, which is consistent with our observations. Our results relating land-cover and the UHI, in addition to the findings of Scatena (1998b), 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 orographic cloud formation within the Luquillo Mountains. Specifically, future research efforts should focus on the effects of deforestation, suburbanization, and urbanization on the urban boundary-layer heat island and its effect on lifting condensation level so as to provide more detailed information pertaining to the future of the freshwater supply for the SJMA.

5. CONCLUSION

Fixed-station and mobile measurement data show the presence of a nocturnal peak in UHI intensity. The forested site was the only site able to negate urban warming within the canopy layer throughout the day. This effect occurs because of the removal of latent heat via evaporative cooling within the canopy and soil and because the active surface for the forest is lifted to the upper part of the canopy. Grassland sites showed significant daytime warming, but also pronounced nighttime cooling, resulting in large diel temperature ranges. Therefore, human efforts to combat UHI formation need to focus on maintaining canopy cover in order to counteract the UHI effect.

Development projects encroaching on the Luquillo Mountains may impact regional climate by decreasing orographic cloud formation and ultimately water supply to the SJMA. Most of the larger Caribbean Islands have rapid urbanization rates as well, and rely on orographic cloud formation to supply freshwater, so as urbanization continues it will become ever more important to study the effects of UHIs on regional climate in this region.

6. ACKNOWLEDGEMENTS

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