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Historical differences in temperature between urban and non-urban areas in Puerto Rico

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ABSTRACT: Previous studies of the influences of land use/land cover changes (LULCC) on the climate of continental areas have provided a basis for our current understanding of LULCC impacts. However, continental climates may not provide complete explanations or answer specific scientific questions for other regions, such as small tropical-maritime dominated islands. Here we present a detailed analysis of temperature change over the past century for the tropical island of Puerto Rico, using an approach that accounts for internal climate variability and spatial resolution issues and assesses the degree to which some of this change might be related to urban development. Long-term weather data, digital maps, geographic information systems (GIS) and statistical analysis were used to detect and assess differences between urban and non-urban temperature records. Strong evidence of a relationship linking temperature magnitudes to local urban development was detected, and the analysis suggests that urbanization has increased minimum, maximum and average temperatures by 0.5 °C in the warmest regions to 2 °C in the coolest regions. The results also show that the magnitude of temperature impacts depends on the contextual ecology or environment where the development has occurred. Temperature differences between urban and non-urban areas are higher in colder and wetter microclimates than in dryer warmer ones, and were less pronounced for minimum temperature than for maximum temperature. However, because the levels of impacts are based on data that had some prior adjustment intended to control for urban signals, they represent minimum estimates of the impacts of land use on temperature in Puerto Rico.

KEY WORDS land use change; land cover change; urban impacts; Puerto Rico; maritime climate; tropics; climate change; GIS

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1. Introduction

Land use/land cover change (LULCC) reflects socio-economic patterns of human activity and is one way in which people can impact ecological systems and threaten vulnerable human populations and communities. LULCC also plays a role in climate feedbacks, particularly influencing regional and local temperatures and precipitation (Jauregui and Romales, 1996; Arya, 2001; Kalnay and Cai, 2003; Velazquez-Lozada *et al.*, 2006; Ezber *et al.*, 2007; Pielke *et al.*, 2007; Han and Baik, 2008; Fall *et al.*, 2011; Imhoff *et al.*, 2010; Murphy *et al* 2011; Oleson, 2012; Comarazamy *et al.*, 2013; Torres-Valcárcel *et al.*, 2014). However, the level of understanding of surface and atmosphere exchanges in the Tropics, where local surface interactions are expected to dominate boundary-layer processes, is very limited compared to the mid latitudes. Climate feedbacks could be different at different latitudes and Pielke *et al.* (2011) reviewed several studies where similar LULCC in different geographic locations led to different forcing values and in some cases altered the sign of the forcing. To advance our understanding of LULCC impacts on climate it is important to study a range of settings and scales, including smaller scale areas such as islands, especially if these sites have long term datasets and a good distribution of observational stations (Fall *et al.*, 2006). Climate change studies on small islands are also particularly important because of the vulnerability of small islands to severe natural phenomena and unique sociological challenges (IPCC Working Group II, 2007). In addition, small islands have a higher degree of endemism (number of local and unique species) that could be threatened by synoptic and global changes.

Assessing the magnitude of past impacts of LULCC, as the basis for assessing and responding to future impacts, is critical for resource management and conservation, vulnerability assessment and emergency planning. However, few such analyses have been attempted to date for small tropical islands (Torres-Valcárcel *et al.*, 2014). In the work reported here, we undertake an assessment of historical temperature changes related to LULCC in Puerto Rico, an island that offers good opportunities for studying climate change and land use because of its size and land use change history. Moreover, Puerto Rico has a high density of climate stations that have a century-long record of temperature and precipitation, and high spatial

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resolution digital land cover maps for recent periods (Torres-Valcárcel, 2013).

The work presented here was designed to assess changes in temperature patterns over time in Puerto Rico's major ecological life zones, and to assess whether temperature records include variations related to LULCC. This work is structured as follows: in the first section, we discuss how global and regional synoptic phenomena influence Puerto Rico's climate. We show that despite Puerto Rico's small size, tropical location and maritime influences, where climate might be expected to show very limited spatial variations, there is enough intra-regional variability to require an approach that subdivides the study area into ecological life zones. In third section, we analyze a century of data with different methods to test hypotheses that, after controlling for potential variability related to ecological life zones, there are significant differences in temperature trends between urban and rural areas, with higher absolute values and warming trends in urban areas.

1.1. Global and regional synoptic influences

Global land-surface and sea-surface average temperature anomalies over the last century show three distinctive phases (Figures 1 and 2): decreasing negative anomalies (warming) for about 30 years after 1910; then alternating positive and negative anomalies around a long-term average from the 1940s to the 1970s, and; a period of notably increasing positive anomalies (warming) since the 1970s. Puerto Rico's average temperature anomalies for the century follow similar trends (Figures 1 and 2), suggesting that global drivers play a major role in the large-scale trends in Puerto Rico's temperature record. Yet the variability of the Puerto Rican data record around these broad trends is quite large, suggesting that local influences might also be important.

Regional synoptic phenomena also influence Puerto Rico's climate. The island is in the path of tropical cyclones and the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) are major synoptic scale atmospheric phenomena that potentially influence

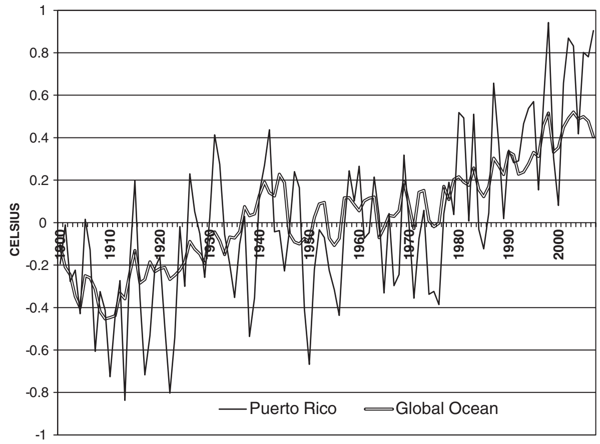

Figure 1. Puerto Rico and Global Ocean 1900–2007 average temperature anomalies. Global data from NOAA, Puerto Rico FILNET 2 adjusted temperature data from surface stations.

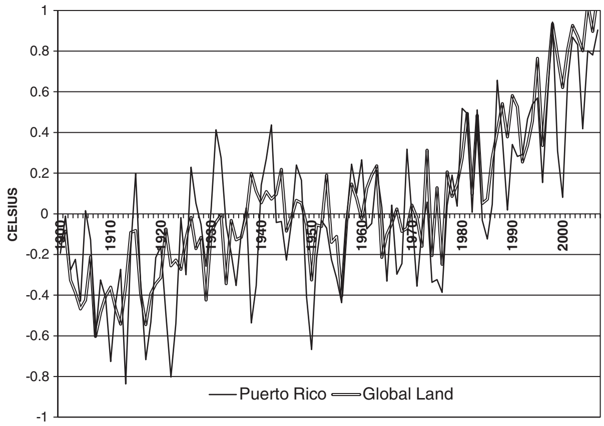

Figure 2. Puerto Rico and Global Land 1900–2007 average temperature anomalies. Global data from NOAA, Puerto Rico FILNET 2 adjusted temperature data from surface stations.

climate in the Caribbean and Puerto Rico (Comarazamy *et al.*, 2013). Jury *et al.* (2007) found that ENSO has no observable effects on Puerto Rico's yearly precipitation. However, Malmgren *et al.* (1998) concluded that ENSO has a positive effect on temperatures in the southeastern Caribbean including the eastern half of Puerto Rico. Malmgren *et al.* (1998) also observed that after 1970 there were increasing local average temperatures regardless of ENSO strength. Malmgren *et al.* (1998) found no primary impact of the NAO on Puerto Rico's temperature. Thus, global climate changes and regional phenomena influence temperature patterns over Puerto Rico.

1.2. Puerto Rico's local climate and meteorological conditions

Puerto Rico is about 180 km wide from east to west, and 60 km from north to south. The center of the island is dominated by the Cordillera Central mountain range and there are plains to the north and south (Malmgren and Winter, 1999). Puerto Rico has a maritime tropical climate typical of Caribbean islands (Daly *et al.*, 2003). The climate is generally humid with warmer temperatures along the coastline, decreasing temperatures with increasing elevation, and small seasonal temperature variations (Daly *et al.*, 2003). Trade winds blowing east – northeast from the Atlantic have a large influence on the island's climate but local land surface characteristics and topography drive the climate on synoptically calm days (Velazquez-Lozada *et al.*, 2006; Comarazamy *et al.*, 2013). The mountains at the center of the island generate orographic precipitation (Malmgren *et al.*, 1998; Comarazamy *et al.*, 2013), shielding the southern part of the island from the Atlantic moisture of the trade winds and causing higher precipitation and lower temperatures in the north and a dryer and warmer climate in the south. Temperatures are higher at the coastlines (Comarazamy *et al.*, 2013) and lower in the central mountains according to topography-corrected PRISM datasets (Daly *et al.*, 2003). The Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate mapping system is explained in more detail in Section 2. Average

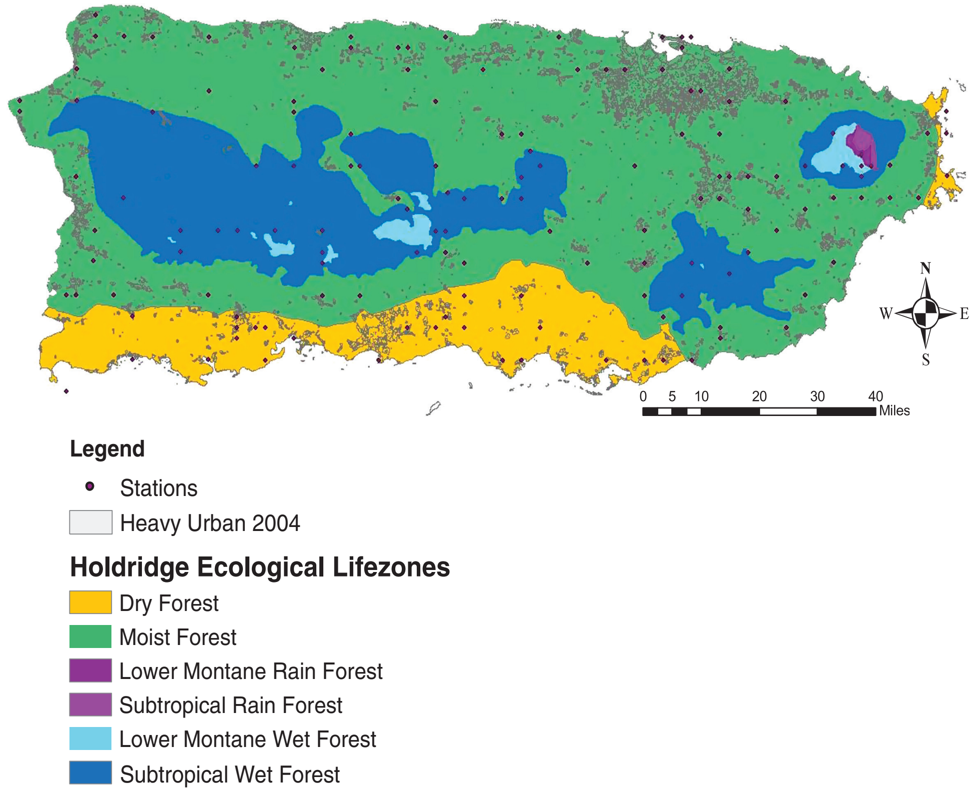

Figure 3. Puerto Rico Holdridge Ecological Lifezones (HELZ), urban areas and weather stations. HELZ data were from US Forest Service, urban areas data from Puerto Rico GAP 2004 and weather stations data from NOAA Historical Climate Network.

temperature anomalies for Puerto Rico computed from temperature adjusted data (FILNET 2, see Section 2) from all stations track consistently with global changes in land and ocean temperatures with an overall increase of ~1.52 °C in average temperature over the past century (Figures 1 and 2).

Puerto Rico has two primary seasons, a 5-month dry season (winter) from December to April and a 7-month wet (summer) season from May to November (Malmgren and Winter, 1999). Temperatures begin to rise in February, are highest from June to September, and then decline from October to January. Precipitation trends generally resemble the temperature trend, with low precipitation in the winter and increasing precipitation in March through May when the wet season starts. The driest period of the wet season is during June and July, and then precipitation rises from September to October to a peak in November before the winter dry season starts in late December.

During the dry season, cold fronts occasionally produce orographic rain (Malmgren and Winter, 1999) and the thermal equator is farthest south with the inter-tropical convergence zone (ITCZ) located south of the Caribbean Sea between 0° and 5°S (Malmgren and Winter, 1999). During the wet season, the ITCZ is located between 6° and 10°N (Etter *et al.*, 1987 in Malmgren and Winter, 1999). Atlantic trade winds carry ITCZ moisture inland causing orographic rain (Malmgren and Winter, 1999) and the island is subject to tropical systems and storms (Lopez-Marrero and Villanueva-Colón, 2006).

2. Data and methods

The goal of this study was to assess changes in temperature patterns over time in Puerto Rico's major ecological life zones, and to assess whether temperature records include variations related to LULCC (Torres-Valcárcel, 2013). Temperature datasets used include: (1) National Climatic Data Center (NCDC) FILNET-adjusted maximum and minimum temperatures from all 57 Historical Climatology Network (HCN) temperature stations in Puerto Rico; the FILNET-adjusted data are a complete set of records that include estimates for missing values based on data from highly correlated neighbouring stations controlling for inconsistencies in measurement instruments, station placement and ground sources of variation (Menne *et al.*, 2009) and (2) the PRISM temperature (Daly *et al.*, 2003).

The land use and land cover datasets used in this study originate from the Institute of Tropical Forestry of the United States Forest Service in Puerto Rico: (1) the Puerto Rico forest type and land cover 1992 (30-m resolution and 33 LULC classes) from Helmer *et al.* (2002) and (2) the Puerto Rico Gap Analysis Project 2004 15 × 15 m grid and 72 land use/land cover classes digitized map (Gould *et al.*, 2007). In addition, we used a Holdridge ecological life zones (HELZ) dataset created using a vegetation mapping system based on ecological and ecophysiological tolerance of plant communities to temperature, humidity, precipitation and elevation (Figure 3; Lugo *et al.*, 1999). Six HELZs are found in Puerto Rico

Table 1. Holdridge ecological life zone (HELZ) relative coverage and number of temperature stations for Puerto Rico.

Puerto Rico HELZ	Coverage (% of Puerto Rico's land area)	Number of HCN temperature stations
Subtropical dry forest (DF)	14	7
Subtropical moist forest (MF)	62	35
Subtropical wet forest (WF)	23	10
Subtropical lower montane wet forest*	<1	0
Subtropical lower montane rain forest*	<1	1
Subtropical rain forest*	<1	1

*Recoded as WF zones excluded from regional analysis breakdown. HELZ data from International Institute of Tropical Forestry, weather stations from NOAA Historical Climate Network .

Table 2. Characteristics of major land use/land cover classes used in this study (see text for detailed descriptions of classes).

LULC	Code	Area*	# Stations
Dry forest	DF	14%	7
Moist forest	MF	62%	35
Moist forest non-urban**	MFNU	N/a	27
Urban LC 1992 A***	U1992A	N/a	7
Urban LC 1992 B***	U1992B	N/a	9
Urban LC 2004 A***	U2004A	N/a	3
Urban LC 2004 B***	U2004B	N/a	5
Wet forest	WF	23%	11
Unregenerated wet forest East	UnWF	N/a	9
Regenerated wet forest West	RWF	N/a	2
Puerto Rico	PR	100%	57†

*Area as a percentage of Puerto Rico's total area. **Consists of all moist forest stations excluding all stations coded as urban for 1992. ***All urban temperature stations were located in the moist forest HELZ. †One station was excluded from all preliminary analysis because of data errors.

(Table 1), however, three HELZs cover less than 1% of the island and are mostly limited to the Rain Forest reservation, and so were merged with the more similar HELZ in the geographical analysis (Torres-Valcárcel *et al.*, 2014). The wet forest HELZ was further subdivided into Eastern (unregenerated, see description below) and Western (regenerated) for comparative analysis. Code names, extension area and # of stations for each and land cover sub-regions annual and seasonal temperature statistics for the corresponding HELZ in Puerto Rico are provided in Tables 2 and 3.

Five geographic areas of interest were identified for particular focus in this study because of their climatic properties or because of the large scale of historical LULCC (Torres-Valcárcel, 2013):

- *San Juan urban area*: the most dense and extensive urban landscape in the island and representative of urban conditions and impacts where Urban Heat Island (UHI) effects have been detected in previous studies (Comarazamy *et al.*, 2010; Velazquez-Lozada *et al.*, 2006).
- *Rain forest reserve*: a forest climate that has Puerto Rico's highest rainfall totals and coldest temperatures, and which is currently under pressure from urban development and expansion.
- *Regenerated forest*: a wet mountainous region with evidence of clear LULCC consisting of a transition from agriculture to forest, which is opposite to the impacts typical of development related to human activity.
- *Unregenerated forest*: a wet mountainous region without significant LULCC that serves as a baseline for comparison with the regenerated forest.
- *Dry forest*: the warmest and driest HELZ or region on the island.

The FILNET HCN 2 data used in this study include an adjustment using an algorithm designed to control for urban signals in the temperature record. However, at the time of this study this was the first time that such data were available for long-term analysis, and so we examine here whether it is possible to detect and quantify impacts of urbanization on local temperatures in the adjusted dataset. Average temperatures were computed directly from the FILNET monthly data by averaging monthly maximum and minimum temperatures for the 1900 to 2007 period. Monthly temperature averages were then computed for each region for the period 1900–2007. For the decadal temperature analysis, the years were grouped by chronological decades starting with 1900–1909; however, the final decade in the analysis consists of only 8 years (2000–2007). Seasonal temperatures were computed by averaging monthly temperatures corresponding to the dry season from December to April and the wet season from May to November (Malmgren and Winter, 1999).

The FILNET data were selected for sites across the different HELZ and urban LULC and analyzed statistically to test for decadal, monthly and seasonal differences. Temperature stations from HELZ and urban LULC in Puerto Rico were grouped together in this study to examine temperature changes by region with particular focus on urban *versus* non-urban LULC in each HELZ. Regional temperatures were computed by averaging values of all stations inside each HELZ, the subdivided HELZs and the urban areas from the 1992 and 2004 LULC maps. Temporal variation was analyzed on monthly, seasonal and decadal scales for each geographical region.

Only stations located inside the main three HELZ (which account for ~99% of the island) were considered for statistical analysis but all (56) stations were used to generate interpolated maps. The 'urban' areas were selected from the 1992 and 2004 LULC maps based on their physical characteristics (land cover) as defined by each dataset. The 1992 map urban area was defined as 'urban and barren' while the 2004 map had two types of urban classes, 'high density urban' representing the most built and developed lands and 'low density urban' that represented urban population based on its density (Gould

Table 3. Seasonal and annual temperature statistics for HELZ, moist forest urban land use areas and non-urban, and areas of regenerated and unregenerated forest 1900–2007.

Region	Temperature (°C)								
	Annual			Dry season			Wet season		
	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
DF	21.58	26.12	30.66	20.03	24.86	29.69	22.70	27.04	31.38
MF	20.41	25.41	30.41	18.83	24.05	29.27	21.56	26.41	31.25
WF	17.33	22.26	27.19	15.85	20.98	26.11	18.41	23.20	27.98
RWF	17.17	22.16	27.16	15.67	20.85	26.02	18.27	23.13	27.99
UWF	18.03	22.68	27.33	16.64	21.56	26.48	19.05	23.51	27.97
MFNU	19.51	24.63	29.76	17.97	23.32	28.67	20.63	25.59	30.56
U1992A*	20.73	24.57	28.41	19.20	23.21	27.23	21.83	25.55	29.27
U1992B*	20.95	24.93	28.90	19.44	23.59	27.73	22.04	25.90	29.76
U2004A*	20.84	24.92	29.00	19.20	23.50	27.81	22.03	25.95	29.87
U2004B*	21.24	25.26	29.28	19.70	23.90	28.11	22.36	26.25	30.14

*Stations located in the moist forest HELZ.

et al., 2007). The 'high density urban' classification from the 2004 land cover map was therefore selected for study and only the stations located within this area were selected for analysis (Torres-Valcárcel *et al.*, 2014). All stations considered 'urban' by our geographic information system (GIS) selection method are located within the moist forest (MF) HELZ. The two urban area extents derived from the 1992 and the 2004 maps were coded U1992 and U2004, respectively. The MF was subdivided in to moist forest overall (MFO) consisting of all stations including those selected as 'urban' for analysis purposes between the three HELZ, and the moist forest non-urban (MFNU) that excluded all urban stations from the 1992 LULC map.

Two datasets were identified for the analysis of urban regions, reflecting different selection strategies to control for possible definition and selection method bias of ARC MAP 10. Method A involved selecting stations contained inside the 1992 and 2004 areas that were classified as urban land cover. Method B included all of the stations in Method A plus additional stations known to be in the San Juan urban area and surrounded by built-up areas but which were excluded from the urban classification in Method A because they do not fall inside the urban area as derived using a default automated method based on a traditional 'urban land use' definition. We were cautious about using such a double definition of the urban landscape, but felt that it was potentially significant and worth investigating as 'urban' is both a 'land cover' and a 'land use' and these are not necessarily identical. The urban land cover refers to the physical environment of a landscape (such as roads, parking lots, roofs, medians) while the urban land use refers to a set of activities (uses) that take place in association with an urban area, and may include features such as parks within a city. Consider, for example, a weather station located in the middle of Central Park in New York City. In Method A this weather station would be considered non-urban because it is in a large forested and grassy area. In Method B it would be considered urban because it is used as an integral part of the city. Our sub-goal here was to determine if results were independent from the selection method by testing if there was any significant difference in using these two ways to group station sites. Urban areas from A selection were labelled 1992 A (U1992A) and 2004 A (U2004A), urban areas from the B selection were labelled 1992 B (U1992B) and 2004 B (U2004B). The WF was subdivided into unregenerated wet forest in the east (UnWF) and regenerated wet forest in the west (RWF), to analyze the temperature patterns between the two subdivisions separately (Tables 2 and 3).

Analysis of variance (ANOVA) was performed with maximum, average and minimum temperatures to examine differences between HELZ as well as between urban *versus* non-urban LULC in addition to monthly, seasonal and decadal variations. One-way ANOVA analyses the differences of a dependent quantitative variable against one independent categorical variable such as temperature against HELZs, regions, months, seasons or decades while two-way ANOVA analyses the differences of a dependent quantitative variable against two independent categorical variables (Sincich, 1990; Daniel, 1998). When normal distribution requirements were not met but it was nearly Gaussian, a Student's *t*-test was used as this test is less sensitive to deviations from normality (Gosset, 1908; Hogg and Tanis, 1997; Daniel, 1998; Wigley, 2006; Montgomery and Runger, 2010; Laerd Statistics, 2013). The significance level for all statistics was set at the conventional 95% ($\alpha = 0.05$). Additional variability analysis involved computing a coefficient of variation, ($C_{V,}$ standard deviation divided by mean) for each station at monthly, seasonal and decadal time scales, as a measure of variability relative to the magnitude of the data.

The GIS tools were used to select stations from across the island and the areas of interest for a various analyses. In addition, GIS was used to generate maps based on interpolated station data and to extract generated map values for areas of interest for further statistical analysis.

3. Temperature analysis results and discussion

3.1. Puerto Rico's intra-regional climate variation

HELZs are based on temperature, humidity, precipitation and elevation (Lugo *et al.*, 1999) and although there are six HELZ in Puerto Rico, three HELZ cover 98.5% of

Table 4. Ratios and differences in 1900–2007 average annual temperature by HELZ.

HELZ	Ratio of average annual temperature (HELZ Temp/PR Temp; °C)			Difference in average annual temperature (HELZ Temp – PR Temp; °C)			Remarks
	Min.	Ave.	Max.	Min.	Ave.	Max.	
DF	1.10	1.07	1.05	1.93	1.74	1.45	At least 1.5° warmer than PR
MF	1.04	1.04	1.04	0.76	1.03	1.21	Around 1° warmer than PR
WF	0.88	0.91	0.93	−2.32	−2.12	−2.02	Over 2° colder than PR
PR	1	1	1	0	0	0	Over 1° of temperature differences between HELZ's

Table 5. Significance of station temperature differences between HELZ (ANOVA).

HELZ	Decadal			Seasonal wet			Seasonal dry			Monthly		
	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
DF	**0.000**	**0.000**	0.315	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.145	0.365	0.836
MF	**0.000**	**0.000**	0.315	**0.000**	**0.000**	0.768	**0.000**	**0.000**	**0.032**	0.145	0.365	0.836
WF	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.768	**0.000**	**0.000**	**0.032**	**0.000**	**0.000**	**0.000**

Bold values are significant ($\alpha = 0.05$).

the island (Figure 3). Figure 3 also shows the locations of the HCN stations used in this study; the HCN is a subset of the cooperative station network and includes stations that were selected on the basis of having the most complete, long-term temperature records (Menne *et al.*, 2009). Given that HELZ are defined in part based on temperature, it is not surprising that temperature ratios and differences between HELZ are distinct (Table 4), but it is interesting to note that the magnitude of differences between HELZs is on the same order as differences between urban and rural areas in UHI studies in the continental United States; yearly average changes between urban and rural areas are 2.9 °C in US continental UHIs (Imhoff *et al.*, 2010) while in tropical locations similar to Puerto Rico changes of around 2.0 °C are considered sufficient to qualify as an UHI effect (Velazquez-Lozada *et al.*, 2006, Murphy *et al.*, 2011). Ecological context and seasonality is also important in the determination of UHI intensity because different biomes respond differently to impervious surfaces (Imhoff *et al.*, 2010). Considering that differences in magnitudes of ≥2.0 °C are important, it becomes evident that any accurate LULCC analysis must consider ecological context and control for microclimate variability, and in this study we achieve this by using HELZ as an underlying classification scheme. Table 4 summarizes temperature characteristics for HELZ in Puerto Rico, presented as ratios and differences from Puerto Rico overall averages. Analysis of variance (one-way ANOVA) for temperatures across HELZ showed statistical differences between HELZs for most decadal, seasonal and monthly time periods (Table 5).

GIS was used to create subsets of stations with respect to the HELZs, 1992 and 2004 LULC maps. Table 2 details the area and number of stations, Table 3 shows maximum, average and minimum temperatures seasonally and annually for all of these stations from all regions under study for the period of analysis (1900–2007).

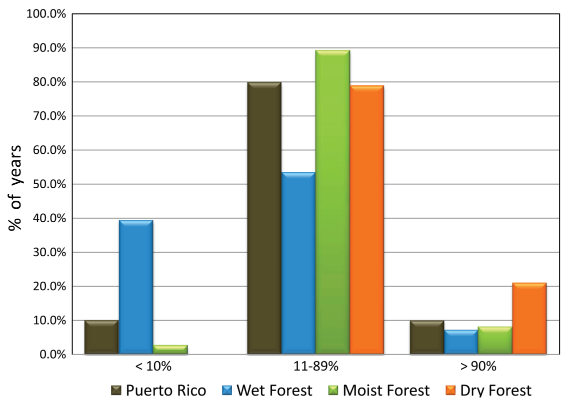

Figure 4. Distribution of years registering normal (80% frequency), above normal (>10% frequency) and below normal (<10% frequency) minimum temperature at each HELZ.

Considering 80% of the years as usual temperatures and 20% as extreme (<10% and >10%) for Puerto Rico as a whole (using the entire database), the frequency of years with usual *versus* extreme temperatures during the century for maximum, average, minimum temperatures followed a consistent 80% usual temperatures to 20% extreme temperature distribution for the island (Torres-Valcárcel, 2013) (Figures 4–6). Breaking up the temperatures by HELZ, we found that moist forest frequencies were similar across maximum, average and minimum temperatures. However, the wet forest had a higher frequency of years with minimum extremes while the dry forest had a higher frequency of years with maximum extremes.

Puerto Rico has undergone notable LULCC, over the past century mainly characterized by rapid urban growth and development in combination with a large decline in agricultural activities (Grau *et al.*, 2003; Helmer, 2004). This has resulted in the regeneration of forest in some

Table 6. Temperatures variation explained by HELZ (R^2).

HELZ	Monthly variation			Dry season			Wet season			Decadal variation		
ANOVA	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
% explained (R^2)	61.7	66.0	70.8	97.4	97.8	96.7	96.4	95.5	94.0	97.72	96.59	94.72

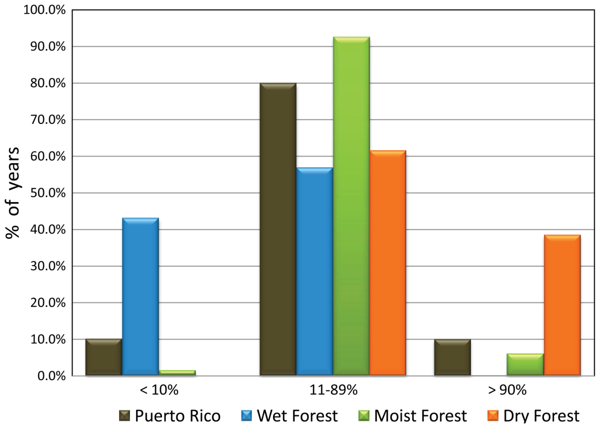

Figure 5. Distribution of years registering normal (80% frequency), above normal (>10% frequency) and below normal (<10% frequency) average temperatures at each HELZ.

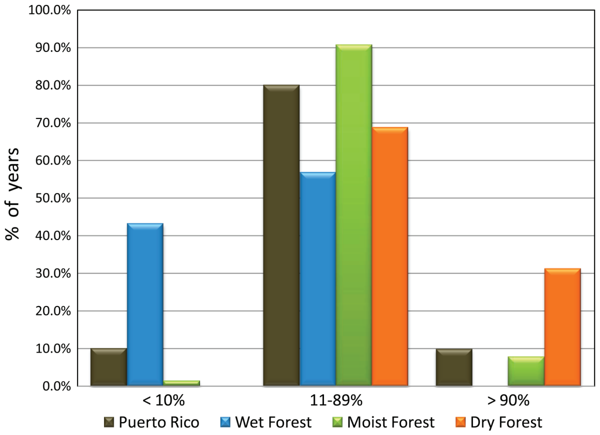

Figure 6. Distribution of years registering normal (80% frequency), above normal (>10% frequency) and below normal (<10% frequency) maximum temperature at each HELZ.

areas that were formerly used for agriculture (Grau *et al.*, 2003) and the intense development of a coastal tropical city (San Juan) (Helmer, 2004). Given local variability and statistically distinct life zones a main question addressed here is whether there are differences in temperature changes related to LULCC (in particular urbanization) that are distinct from differences between HELZ or, in other words, are impacts of urbanization on temperature observable when evaluated against temperature changes in non-urban areas in the same HELZ.

3.2. HELZ regional statistical analysis

We hypothesized that HELZs would have significantly different temperature statistics, meaning that differences in temperatures across Puerto Rico can be explained by HELZ as well as LULC. We found significant differences in wet season, dry season and decadal average temperatures as function of HELZ at a 95% significance level or above. Monthly variation impacted maximum temperatures more while seasonal variation impacted average and minimum temperatures more (Table 6). Monthly data shows higher variability as compared to the seasonal and decadal datasets and therefore the data need to be assessed at different temporal scales to identify regional differences. One-way ANOVA shows that HELZs are significantly different from each other for most temperature measures and time periods (Table 5) and this validates our use of HELZ as an important organizing structure within which to examine LULC impacts. The wet forest was different from the other HELZs in all temperature parameters and all time periods. However this was not the case for all HELZ and all time periods. For example, the moist forest and dry forest showed no statistically significant variation in monthly temperature by HELZ ($\alpha = 0.05$) meaning that they are not different from each other, or that all months are the same when comparing both. All maximum temperatures for the dry and moist forests are statistically similar. Minimum and average temperatures for the three main HELZs (wet forest, moist forest and dry forest) are significantly different at the 95% ($\alpha = 0.05$). Average and minimum temperatures of the three sampled HELZs are significantly different; the dry forest and moist forest maximum temperatures were statistically similar (not significant differences). This suggests that it is important when comparing urban with rural stations to determine if they are in the same HELZ. If not, then temperature differences will reflect a combination of LULC differences and HELZ differences.

We also found that HELZs have significantly different temperature variability, as indicated by the coefficient of variation, C_V, across monthly, seasonal and decadal data. The three HELZ regions all had highest average monthly temperature variability during March (dry season) and lowest during September (wet season), and had highest decadal variability during the 1950s and lowest decadal variability during the 1940s. The wet forest had the highest average monthly temperature and decadal average variability while the dry forest had the lowest monthly and decadal average variability indicating that temperatures are more consistent in the warmest regions while the colder regions have a wider range of temperatures.

3.3. Land use/land cover

Once the existence of HELZ variability was established we addressed the question of whether there were temperature

Table 7. Urban stations *versus* non-urban one-way ANOVA.

Urban versus non-urban one-way ANOVA, for urban classification by selection method												
Urban code	Monthly			Seasonal dry			Seasonal wet			Decadal		
	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
U1992A*	0.245	1.000	**0.022**	**0.000**	0.928	**0.000**	**0.000**	0.998	**0.000**	**0.000**	0.985	**0.000**
U1992B*	0.114	0.977	0.281	**0.000**	0.281	**0.000**	**0.000**	0.180	**0.000**	**0.000**	0.208	**0.000**
U2004A*	0.185	0.980	0.408	**0.000**	0.666	**0.000**	**0.000**	0.092	**0.003**	**0.000**	0.242	**0.000**
U2004B*	**0.037**	0.726	0.799	**0.000**	**0.001**	**0.005**	**0.000**	**0.000**	0.152	**0.000**	**0.000**	**0.045**
Regenerated forest *versus* unregenerated forest one-way ANOVA												
UWF *vs* RWF	0.591	0.842	0.995	**0.000**	**0.000**	**0.040**	**0.000**	0.061	1.000	**0.000**	**0.003**	0.832

Bold values are significant ($\sigma = 0.05$). * All stations located in the Moist Forest HELZ.

differences between the urban and non-urban landscapes within each HELZ using ANOVA and Student's *t*-test where appropriate.

3.3.1. ANOVA of station temperature data

We tested for significant differences (Wigley, 2006) between urban and non-urban sites in the context of differences between HELZ regions and different approaches to selecting stations that were defined as 'urban'. We also compared regenerated and unregenerated wet forest areas. The patterns of statistical differences in the results have the following key features (Table 7):

1. Dry season, wet season and decadal *minimum and maximum* temperatures are significantly different between urban and rural areas, and this holds for almost all alternative ways of selecting urban stations.
2. Dry season, wet season and decadal *average* temperatures are not significantly different between urban and non-urban areas, except for the case where urban areas are selected based on the 2004B land cover selection method.
3. Monthly minimum, maximum and average urban *versus* non-urban temperatures are mostly not statistically different.
4. Regenerated and unregenerated wet forest areas are statistically different in dry season minimum, maximum and average temperature suggesting that land features and/or processes force particular effects during dry periods and local winter. Regenerated and unregenerated wet forest are also significantly different in wet season minimum temperatures while similar regarding average and maximum temperatures suggesting forest regeneration has impacted minimum temperatures during wet periods and local summer. Regenerated and unregenerated wet forest are also statistically different in decadal minimum and average temperatures.

Differences in minimum and maximum temperatures between urban and non-urban areas are the most consistently statistically significant while average temperatures were not. This suggests that focusing on average temperatures may not capture the most important impacts and relationships. For example, in a case where one area has a higher minimum and a lower maximum than another area, there are large differences in minimum and maximum, but because the increase in the minimum offsets the decrease in the maximum, the average may have very little change. For example, urban average annual temperatures (U1992A) have a minimum value 1.22 °C higher than comparable non-urban sites (MFNU) and a maximum value that is 1.35 °C lower. These compensating changes help to explain why the difference in the average temperature for the U1992A to MFNU is only 0.06 °C.

Monthly temperatures showed the least difference between urban and non-urban sites. This is expected because of the high variability in the monthly dataset. Meanwhile seasonal differences are significant primarily because each season groups the highest and lowest temperatures in the yearly cycle.

The large differences between urban 2004B and the other urban selections shows that the method used to select which stations are 'urban' and the specific stations included in each selection can have a major influence on the results, especially when the number of stations is small. Despite the considerable number and density of temperature stations in Puerto Rico for its size, a maximum of nine stations (16%) and just four (7%) in the main city were defined as urban, thus the inclusion or exclusion of particular stations with extreme values can have a large impact in averaged temperature computations and so careful decision making and objective criteria for inclusion or exclusion become important.

3.3.2. Station temperature trends descriptive analysis

Temperature trend descriptive analysis for the places considered most important because of their notable LULCC, or that represent climate opposites, provides insight into temperature patterns related to LULCC over time. The trends analysis was useful to indicate sites with the most rapid change in temperature, and thus the largest potential impact of LULCC. Average and median temperatures, based on all stations in Puerto Rico, have annual

Table 8. Puerto Rico's station average and median period trends for all temperatures.

Trend	Century 1900–2007			PRISM 1963–1995			Warming 1970–2007		
	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.
Average (°C year^{-1})	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03
Median (°C year^{-1})	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03

Table 9. Main locations top 10% temperature stations summary.

Location	HELZ	Century temperatures			Century trends		
		Min.	Ave.	Max.	Min.	Ave.	Max.
San Juan urban*	MF	2/5	1/5	0/5	1/5	0/5	1/5
Regenerated forest	WF	0/5	0/5	0/5	1/5	0/5	1/5
Unregenerated forest	WF	0/5	0/5	0/5	0/5	0/5	0/5
Rain forest	WF	0/5	0/5	0/5	0/5	0/5	0/5
Dry forest	DF	3/5	4/5	2/5	1/5	1/5	0/5

Fraction numbers from the total top 10% (five stations). *Includes urban stations outside San Juan area classified as urban in 1992 and/or 2004.

trends for minimum, average and maximum temperatures of 0.01 °C year^{-1} between 1900 and 2007, but with the higher rates of increase in more recent time periods (Table 8). The period 1970–2007 has the highest yearly temperature increases among the selected periods. The 1900–2007 increases in temperatures were largest at urban and regenerated forest stations (Table 9), the locations with the biggest LULCC. The dry forest has the largest number of stations with positive trends in maximum, average, and minimum temperature values, followed by urban then regenerated forest stations. Stations from the dry forest HELZ had some of the largest temperature increases, however, this is not a location of major urban development or forest regeneration. Abandoned, formerly irrigated cropland dominates this location but whether this land use is a contributor to the temperature increase is unknown and an important question for future study.

Stations with the top temperature trends are found in urban, regenerated forest and dry forest (Table 9), and the highest trends were from maximum and minimum temperatures in the locations with most notable LULCC. However, more urban stations had very low yearly temperature trends than high yearly temperature trends suggesting increased variability or an increased amplitude in temperature range at urban stations.

Most stations registered positive or increasing trends for minimum, average and maximum temperatures for the century (Figures 7–9). However, maximum temperatures (Figure 7) have the highest number of stations registering negative or decreasing yearly trends.

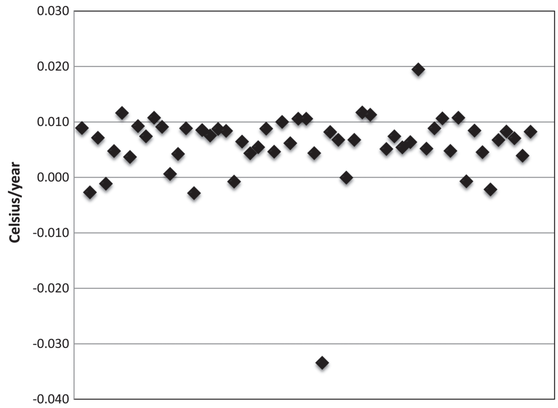

Figure 7. Puerto Rico's 1900–2007 maximum temperature station trends scatter diagram.

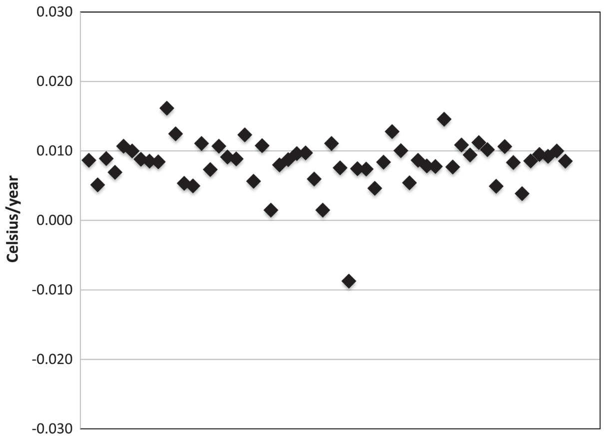

Figure 8. Puerto Rico's 1900–2007 average temperature station trends scatter diagram.

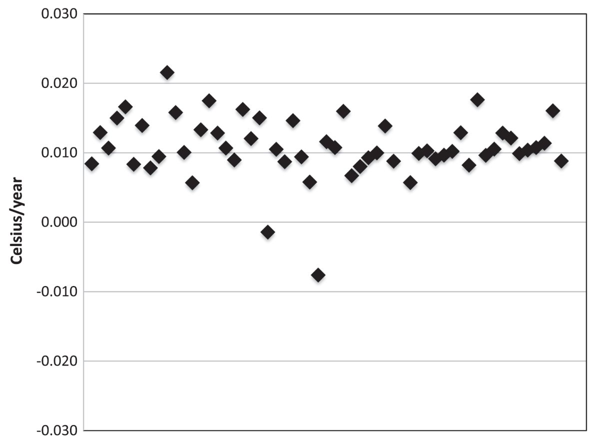

Figure 9. Puerto Rico's 1900–2007 minimum temperature station trends scatter diagram.

For the 1970–2007 warming period most stations yielded yearly trends an order of magnitude higher than those for the entire century. Overall, 18%, 27% and 57% of stations had minimum, average and maximum temperatures, respectively, that increased at rates >0.01 °C year^{-1} (0.1 °C decade^{-1}), but for the 1970–2007 period these

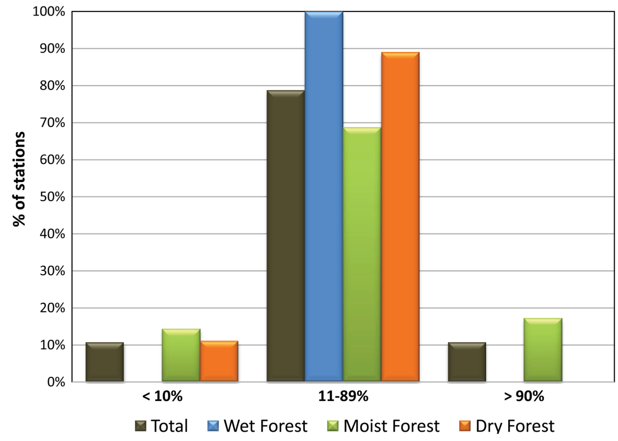

Figure 10. Puerto Rico's 1900–2007 maximum temperature station trend frequency distribution.

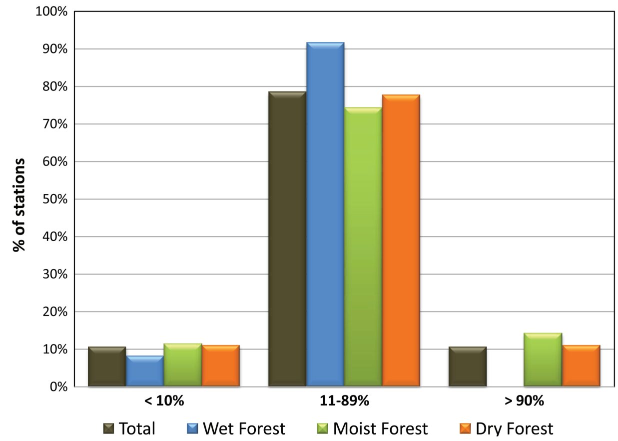

Figure 11. Puerto Rico's 1900–2007 average temperature station trend frequency distribution.

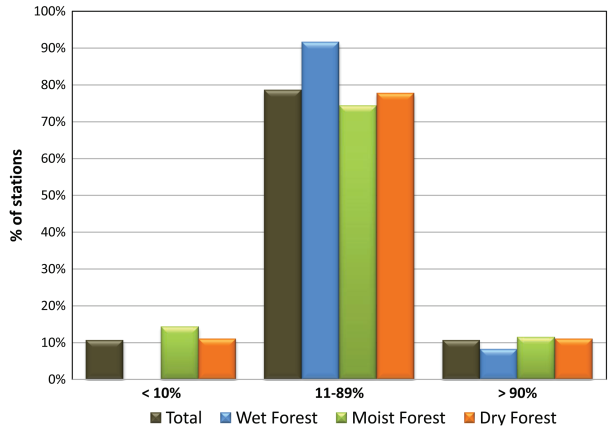

Figure 12. Puerto Rico's 1900–2007 minimum temperature station trend frequency distribution.

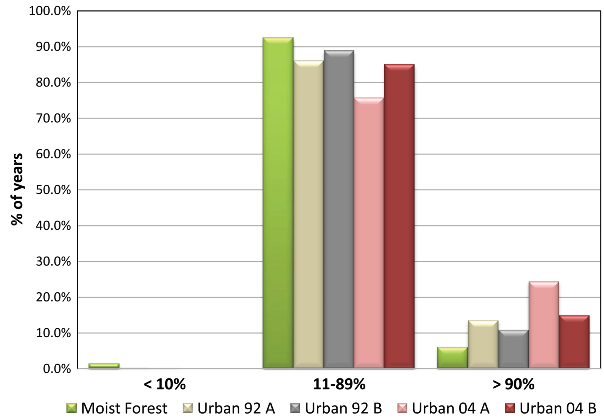

Figure 13. Puerto Rico's urban 1900–2007 average temperature years frequency distribution.

increased to 95%, 100% and 95% of stations, respectively. Thus during the 1970–2007 period minimum, maximum and average temperatures all had higher rates of increase, and the change was most marked for station average and minimum temperatures.

3.3.3. *Temporal and spatial frequency analysis*

Frequency analysis allows the identification of patterns and helps in the detection of internal variability. Here we focus on patterns associated with 80% usual *versus* the 10% higher and 10% lower extreme years distribution (Figures 4–6). This allows a relative comparison of patterns in each HELZ in terms of the frequency of usual *versus* extreme temperatures or trends. Temperature magnitudes and trends were analyzed for stations of each HELZ using number of years for the temporal analysis and number of stations for the spatial analysis, exceeding the base usual values.

The highest maximum, average and minimum temperatures occur in the dry forest, and the urban areas have the next highest minimum and average temperatures. The lowest maximum, average and minimum temperatures are found in the regenerated wet forest and rain forest reserve stations, and all the lowest temperatures on the island consistently occur in stations from the wet forest HELZ. The dry forest HELZ dominated higher extreme temperatures (>90%) followed by the moist forest HELZ while the wet forest HELZ dominated lower extreme temperatures (<10%; Figures 4–6). The wet forest stations had the fewest extreme values while the moist forest dominated with the most stations registering the largest percentage of average and maximum temperature trends (Figures 10–12). Urban stations consistently had a larger percentage of years registering higher extreme temperatures than the moist forest HELZ where urban stations are located (Figure 13). This observation suggests that moist forest warming maybe related to the higher extreme values that urban stations are contributing. For the OMR period the dry forest registered the largest percentage of years with higher extreme temperatures (Figure 14).

3.3.4. *Spatial analysis of temperatures*

GIS tools were used for map generation and to further assess urban impacts in areas where there were no

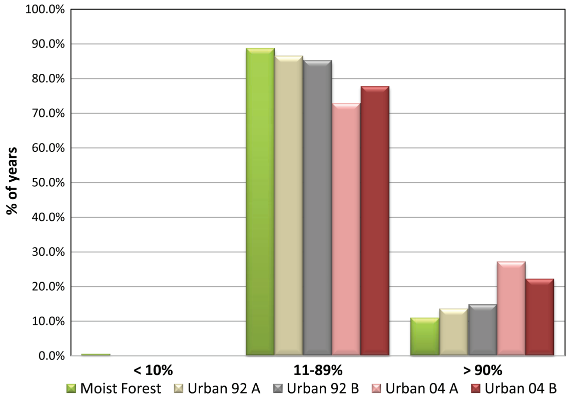

Figure 14. Puerto Rico's urban 1963–1995 average temperature year frequency distribution.

local station data. Geoprocessing tools (SPLINE) from ARC MAP 10 and 10.1 were used to interpolate station temperature data and assess temperature patterns and changes related to urban and non-urban areas in each HELZ. FILNET adjusted data (1900–2007) and PRISM raw data (1963–1995) were independently processed for analysis as a baseline from an independent method in the search for distinctive temperature patterns that may or may not occur in both datasets.

FILNET maximum and minimum temperatures for the century have a wider range than PRISM maximum and minimum temperatures ranges between 1963 and 1995 by over 2 °C. However, while the difference between maximum temperatures in both time periods is less than 1 °C, the difference between both minimum temperatures is over 2 °C. This suggests that although maximum temperatures are very similar for both periods, temperatures during 1963–1995 were warmer because of higher minimum temperatures. PRISM maps were generated for a period of globally and locally increasing positive temperature anomalies (warming pattern) while FILNET century data includes colder temperatures. However, FILNET and PRISM generated maps show high consistency in several locations, particularly the warm coastlines and cooler sites at the mountainous center of the island. Maps generated from both datasets were further processed with GIS tools to extract temperature values from the areas of interest and to assess urban *versus* non-urban temperatures at each HELZ. Average century data for all temperatures from GIS generated maps for the three HELZ under study were all statistically different (Table 10). In other words, the results of interpolated maps maintained the expected temperature ranges and magnitudes for each particular HELZ.

Despite the very small and scattered pattern of urban development in the wet forest, this HELZ produced the highest urban to non-urban differences in temperatures, independent of the dataset (FILNET or PRISM; Table 11). There is a clear pattern in the magnitude of urban to non-urban temperatures depending on the HELZ in which they are located; the colder the HELZ the larger the magnitude of temperature differences between urban *versus* non-urban regions, conversely, the warmer the HELZ the smaller the magnitude of temperature differences between urban *versus* non-urban. This is well established for maximum and average temperatures, however, minimum temperatures in the moist forest unexpectedly have larger temperature differences than even the wet forest, suggesting an increase in temperature ranges from urban areas in this particular HELZ (Figures 15–18). Comparing the analysis based on spatial data with the earlier analysis based on station data, urban temperatures are warmer than non-urban temperatures for minimum, average and maximum temperatures for the spatial data in all HELZ (Table 11), but in the station data for MF (Table 3) there was a more complex pattern with urban maximum temperatures cooler than non-urban, and urban minimums warmer than non-urban, resulting in average temperatures that were similar for urban and non-urban areas.

Two-tailed Student's *t*-tests on data extracted from FILNET and PRISM GIS generated maps confirms that all urban temperatures (maximum, average and minimum) in all HELZs (dry forest, moist forest and wet forest) across the island are significantly different from all non-urban temperatures at each corresponding HELZ (Table 12). This indicates that urban development has increased all temperature magnitudes across the whole island. This finding is remarkably important because it

Table 10. Results of the statistical analysis for century average temperature values for each HELZ from GIS generated maps and each evaluated database.

HELZ	PRISM maps 1963–1995 *t*-test (two tailed)			FILNET SPLINE maps 1900–2007 *t*-test (two tailed)		
	Max. *T*	Ave. *T*	Min. *T*	Max. *T*	Ave. *T*	Min. *T*
Wet forest	0.00	0.00	0.00	0.00	0.00	0.00
Moist forest	0.00	0.00	0.00	0.00	0.00	0.00
Dry forest	0.00	0.00	0.00	0.00	0.00	0.00

Results at 95% confidence interval ($\sigma = 0.05$).

Table 11. Difference in urban *versus* non-urban average century or period temperatures magnitudes from GIS generated maps for each HELZ and dataset.

Temperature	FILNET temperature (°C)			PRISM temperature (°C)		
	U	NU	U – NU	U	NU	U – NU
Wet forest						
Maximum	30.16	28.13	2.02	30.21	27.97	2.24
Average	24.22	23.05	1.17	24.02	22.75	1.27
Minimum	18.28	17.98	0.31	17.88	17.58	0.31
Moist forest						
Maximum	29.62	29.15	0.47	30.15	29.68	0.48
Average	25.00	24.27	0.73	25.22	24.54	0.68
Minimum	20.37	19.70	0.68	20.33	19.49	0.84
Dry forest						
Maximum	30.13	29.80	0.34	31.08	30.78	0.30
Average	25.56	25.32	0.24	25.80	25.53	0.27
Minimum	20.99	20.85	0.15	20.55	20.32	0.23

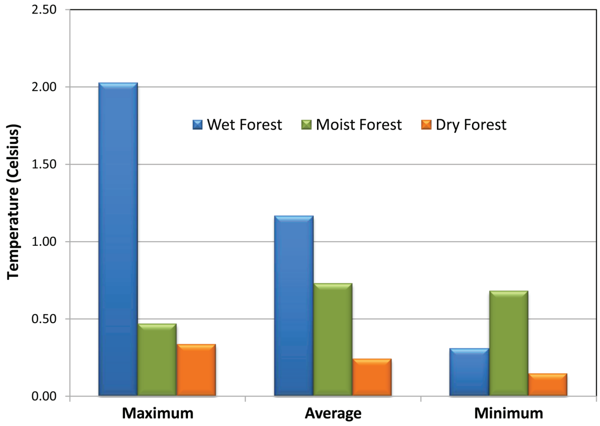

Figure 15. FILNET GIS interpolated data urban minus non-urban temperature differences by type of temperature.

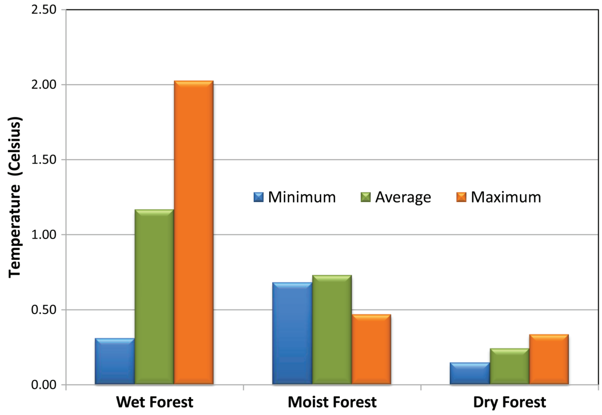

Figure 17. FILNET GIS interpolated data urban minus non-urban temperatures differences by HELZ.

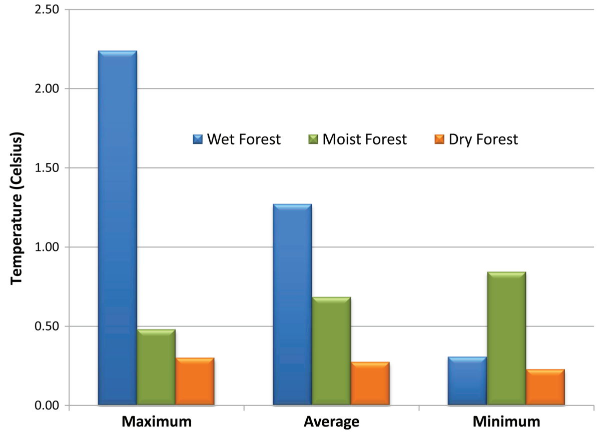

Figure 16. PRISM data urban minus non-urban temperature differences by type of temperature.

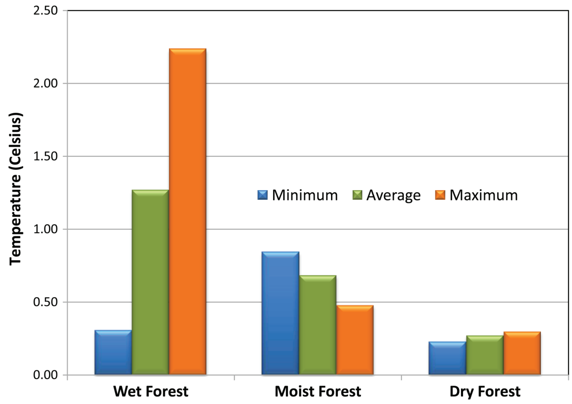

Figure 18. PRISM data urban minus non-urban temperatures differences by HELZ.

corroborated results from two separate datasets (FILNET and PRISM) each generated by different methods and covering differing time periods.

4. Findings and conclusions

The role of land use and land use impacts related to urban development in controlling temperatures in Puerto Rico was examined in several ways. Our work showed that controlling for HELZ was important to avoid drawing erroneous conclusions regarding temperature differences between urban and non-urban areas from stations that might be in different regional settings represented by HELZs.

The most important findings were that, even though FILNET HCN 2 data were adjusted in part to control for urban signals, urban *versus* non-urban temperature differences were detected with an ANOVA analysis of surface stations data from the moist forest and *t*- tests of GIS interpolated data. The magnitude of the differences between urban and non-urban areas are from around 0.5 °C to around 2 °C depending on the HELZ but since they were found in adjusted data that was intended to suppress

Table 12. Results of the statistical analysis for century average temperature values of each urban *versus* non-urban evaluated databases.

	FILNET station U/NU century two-way ANOVA*			PRISM maps U/NU 1963–1995 *t*-test (two tailed)**			FILNET SPLINE maps U/NU century *t*-test (two tailed)**		
HELZ	Max. *T*	Ave. *T*	Min. *T*	Max. *T*	Ave. *T*	Min. *T*	Max. *T*	Ave. *T*	Min. *T*
Wet forest	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0.00	0.00
Moist forest	0.00*	>0.05	0.00*	0.00	0.00	0.00	0.00	0.00	0.00
Dry forest	N/A	N/A	N/A	0.00	0.00	0.00	0.00	0.00	0.00

*Two-way ANOVA done on FILNET station data from urban land cover from 2004B and 1992B maps. **Student's *t*-test done with 95% confidence interval ($\sigma = 0.05$) on 2004 urban land cover map.

the urban signal we expect the differences to be higher in raw data and so these represent minimum estimates of the magnitude of urban effects. Stations in the main urban area of San Juan (moist forest) had the most significant impacts on maximum and minimum temperatures while average temperature differences were not statistically different, however, analysis of GIS generated data did yield statistically significant differences in average temperatures between urban and non-urban across the island. Urban land use/land cover impacted maximum and minimum temperatures in moist forest stations, showing the most impacts in minimum temperatures. This is illustrated in the urban *versus* non-urban maximum temperature values in Table 3: for the 2004 Land Cover Map data, non-urban area values are higher than the urban area, but part of this is because higher maximum temperature values occur in the southwest of the island where several non-urban stations are located thus increasing the average values of maximum non-urban temperatures. However, urban average minimum temperatures in the main city of San Juan were higher than non-urban minimum temperatures. Also, although we expected the highest temperature impacts to be related to urban development, areas of forest regeneration in the wet forest had a larger change in maximum temperatures than urbanization in the moist forest. Analysis of GIS interpolated data from climate stations showed that all temperatures (maximum, average and minimum) are impacted by urban development across the entire island, regardless of HELZ. Also colder-wetter regions such as the wet forest are more impacted by urban development than warmer dryer regions like the dry forest, regardless of the extension of urban development.

Over the last century temperatures in Puerto Rico increased, with rates averaged for all stations in Puerto Rico of 0.67 °C century^{-1} on minimum temperature, 1.11 °C century^{-1} on average temperature, and 1.51 °C century^{-1} on maximum temperature. Temperature changes over the last century show distinct patterns related to Puerto Rico's HELZ, but temperatures produced warming trends in all sampled HELZs (dry forest, moist forest and wet forest). Analysis of changes in temperature stations between urban *versus* non-urban areas from Puerto Rico's major urban setting in San Juan found significant differences in minimum and maximum temperatures between urban and non-urban, but found no significant differences in average temperatures. Differentiating between land use and land cover was found to be important in this study as we assessed the impact of differentiating between remote sensing based classification and a classification that also included local knowledge of land use. Some results were sensitive to the selection method, suggesting that definitions of urban areas need to be considered carefully to avoid having conclusions dependent on selection method. This becomes particularly important when the number of stations is small.

HELZs are related to natural landscapes and can be a useful tool in studies of LULCC impacts on climate. HELZ's must be considered when comparing urban to rural temperature stations because some HELZs have significantly different temperatures and not accounting for this may lead to result misinterpretation and spurious conclusions. The highest temperatures in Puerto Rico are in the dry forest HELZ and the lowest temperatures are in the wet forest, but surprisingly the warming trends in these HELZ are comparable to those in urban regions.

Limitations of this work included data accuracy for map and station locations and climate data. Although the recent 2004 land cover map was useful to provide insight in to land use conditions, a more detailed assessment of impacts related to past land use change could be undertaken in future research by developing detailed historical maps to allow for a carefully structured pre-/post-land use change comparison of temperature data, including sites with land use change and equivalent control sites. In addition, as with any study that relies on a small number of data sites, the statistical results were sensitive to the inclusion or exclusion of individual stations for the HELZ's and urban regions. Although Puerto Rico has a great density of temperature stations, unfortunately only a handful (a maximum of 17% for the 1992 map) are located in urban developed areas, making the inclusion or exclusion of stations as 'urban' an important issue.

As no urban stations from the dry forest and the wet forest were available, the urban station analysis was limited to the moist forest. Station location and GIS selection method play a big role in determining where the LULC categories are located and impact the results of the statistical analysis and the conclusions. Stations that lie close to HELZ borderlines could be considered on one HELZ or another depending on its coordinates and map accuracy. Therefore, station placement historic documentation could become essential for future systematic data adjustment.

4.1. Future suggestions

The potential importance of the distinction between land use and land cover has been highlighted here and may be important for future studies in Puerto Rico and elsewhere. To advance the analysis further in Puerto Rico, urban stations representing the wet forest and dry forest HELZ are needed for station data analysis and more accurate interpolation. Detailed reconstructions of past LULCC in Puerto Rico would also allow for more detailed assessment of changes over time. Varying spatial resolution and LULC classes between maps limits our ability to explain patterns and results, so it would be helpful to standardize LULC classes for Puerto Rico across maps in future work. More detailed studies of non-urban LULC temperatures may further increase understanding of temperature patterns and impacts that may be important for land managers, and more detailed subdivisions of urban land use into residential, industrial and commercial may help in refining our understanding of the details of urban impacts. In addition, comparison of raw data *versus* FILNET data is critical to assess how the use of the algorithm may change the conclusions of this work, and in future using remote sensing to estimate ground temperatures may provide a much needed improvement in spatial coverage of climate data.

Acknowledgements

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