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Climate change, heat, and mortality in the tropical urban area of San Juan, Puerto Rico

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Abstract Extreme heat episodes are becoming more common worldwide, including in tropical areas of Australia, India, and Puerto Rico. Higher frequency, duration, and intensity of extreme heat episodes are triggering public health issues in most mid-latitude and continental cities. With urbanization, land use and land cover have affected local climate directly and indirectly encouraging the Urban Heat Island effect with potential impacts on heat-related morbidity and mortality among urban populations. However, this association is not completely understood in tropical islands such as Puerto Rico. The present study examines the effects of heat in two municipalities (San Juan and Bayamón) within the San Juan metropolitan area on overall and cause-specific mortality among the population between 2009 and 2013. The number of daily deaths attributed to selected causes (cardiovascular disease, hypertension, diabetes, stroke, chronic lower respiratory disease, pneumonia, and kidney disease) coded and classified according to the Tenth Revision of the International Classification of Diseases was analyzed. The relations between elevated air surface temperatures on cause-specific mortality were modeled. Separate Poisson regression models were fitted to explain the total number of deaths as a function of daily maximum and minimum temperatures, while adjusting for seasonal patterns. Results show a significant increase in the effect of high temperatures on mortality, during the summers of 2012 and 2013. Stroke (relative risk = 16.80, 95% CI 6.81–41.4) and cardiovascular diseases (relative risk = 16.63, 95% CI 10.47–26.42) were the primary causes of death most associated with elevated summer temperatures. Better understanding of how these heat events affect the health of the population will provide a useful tool for decision makers to address and mitigate the effects of the increasing temperatures on public health. The enhanced temperature forecast may be a crucial component in decision making during the National Weather Service Heat Watches, Advisories, and Warning process.

Keywords Climate change · Extreme weather events · Heat episodes · Mortality · Puerto Rico

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Introduction

Extreme heat episodes are becoming more common worldwide, including in tropical areas of Australia, India, and Puerto Rico (Wang et al. 2012, Hayhoe 2013; Ratnam et al. 2016). Along with heat intensity and duration, time within the year, repetition, time between adjacent events, and acclimatization of individuals are important determinants of the health outcomes of extreme heat episodes. Extreme heat episodes, as defined by intensity, duration, and frequency, affect human health through heat stress and exacerbate underlying conditions that can lead to an increase in mortality (Ebi and Meehl 2007; Portier et al. 2013). Heat effects on public health and mortality have been analyzed in mid-latitudes, in temperate regions, and in continental areas. Nevertheless, research studies that assess the effects of heat on mortality and public health in tropical island nations are limited or scarce. Over the period 1979–1999, 8015 deaths in the USA were recorded as being heat related, 3829 of which were attributed to weather conditions (Donoghue et al. 2003). If unrecognized and untreated, heat exhaustion can progress to heat stroke, a severe illness with a rapid onset that can result in delirium, convulsions, coma, and death (Lugo-Amador et al. 2004). High nighttime humidity can place additional stress on people already suffering from high daytime temperatures and cause additional deaths. As temperatures continue to rise throughout the next century, climate models indicate that there will be an increased risk of more intense, more frequent, and longer-lasting heat episodes. As an example, the number of days above 90 °F (32 °C) and the frequency are projected to increase across the USA and the Caribbean (Diffenbaugh and Ashfaq 2010; Stephenson et al. 2014; Jones et al. 2015).

Projections of the health effects of future extreme heat episodes need to incorporate a variety of factors, such as the following: the degree to which the population is acclimatized to higher temperatures, the characteristics of the vulnerable population, and the extent to which effective adaptation strategies and measures have been implemented (Ebi and Meehl 2007; Stone et al. 2014). There is evidence that there are upper limits to human adaptation to temperature (Tomlinson et al. 2011). These factors need to be estimated for the geographic region and timescale of interest, recognizing that estimates of these factors become more uncertain for longer time frames and considering all the climatic factors of the area (temperature, relative humidity, wind, time of day, air pollution, etc.).

To understand the factors that lead to this warm to hot weather pattern, it is necessary to understand the local climate and urban climate (Méndez-Lázaro et al. 2015; Mohan and Kandya 2015). Urban areas are particularly vulnerable to these extreme events given their location, concentration of people, and increasingly complex and interdependent infrastructure (Rinner and Hussain 2011; Morabito et al. 2015). The paved surfaces in urban environments absorb, produce, and retain more heat than surrounding areas and can raise surrounding temperatures. Over the last century, this effect has raised average urban air temperatures by 2 to 5 °C higher than surrounding areas during the day and 8 °C more at night (Karl et al. 2009).

The San Juan Metropolitan Area (SJMA) in Puerto Rico (Fig. 1) has been facing longer and more frequent heat episodes in the last decade (Hayhoe 2013). The areas prevailing wind flow, sea breeze development, and urban sprawl determine the location of hotspots, daily temperature range, and the maximum temperature observed. In the summer of 2012, for instance, the city of San Juan experienced 82% of the summer time with very warm conditions with a maximum temperature ranging from 30 to 35 °C and a minimum temperature >25 °C. This period was the longest heat wave that San Juan has experienced in recorded history (Méndez-Lázaro et al. 2015). At the same time, residents of the SJMA are facing enormous environmental and public health issues. The region has the highest asthma prevalence in children and among the highest

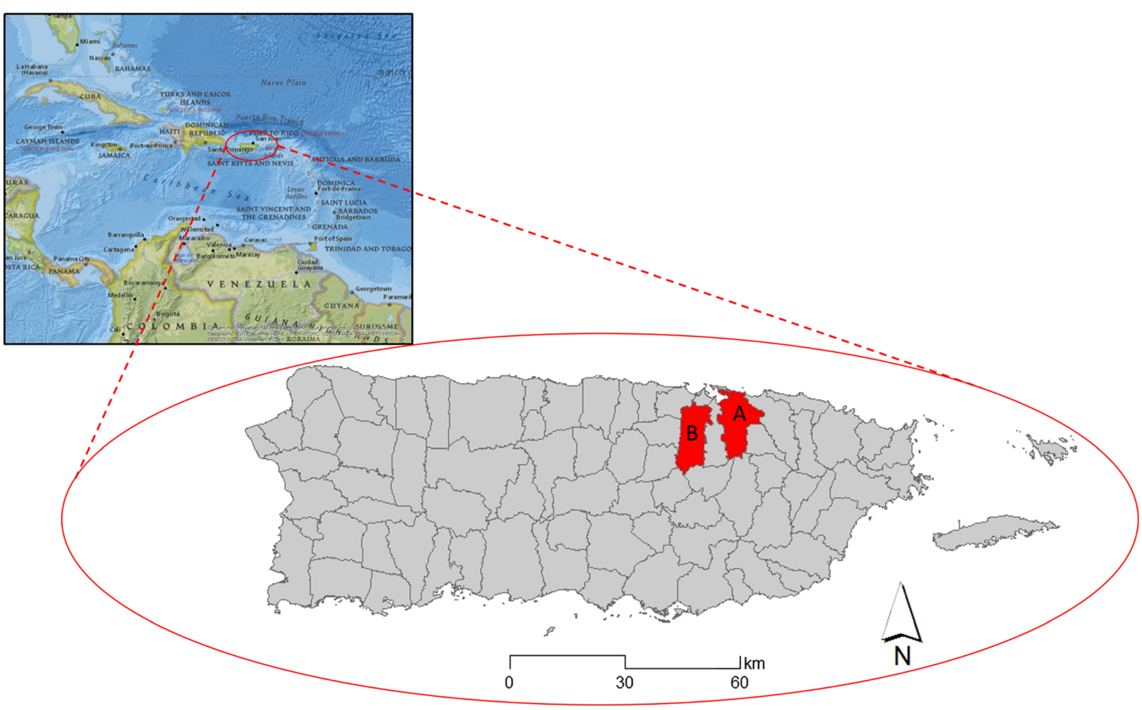

Fig. 1 Location of Puerto Rico in the Caribbean Region. The municipalities of San Juan (*A*) and Bayamón (*B*) are colored in *red* (Color figure online)

Table 1 Descriptive statistics for air surface temperature, overall deaths, and cause-specific deaths in San Juan and Bayamón (2009–2013)

Variables	*n*	Mean	SD	P50	P25	P75	Min	Max
Tmax	1826	86.69	3.27	87	84	89	74	96
Tmin	1826	75.56	2.86	76	73	78	68	82
Tmean	1826	81.12	2.85	81	79	83.5	71	88
Deaths	10,070	5.51	2.54	5	4	7	0	16
CVD	4546	2.49	1.57	2	1	3	0	8
DM	460	0.25	0.50	0	0	0	0	4
Stroke	1130	0.62	0.77	0	0	1	0	4
Respiratory	789	0.43	0.67	0	0	1	0	4
Renal	827	0.45	0.68	0	0	1	0	4
Pneumonia	865	0.47	0.69	0	0	1	0	4
Hypertension	1453	0.80	0.92	1	0	1	0	5

CVD cardiovascular disease, *DM* diabetes mellitus

rates of obesity within the USA. Some of these public health issues in the SJMA are exacerbated by climate change (e.g., rapidly increasing air surface temperature), a rapidly aging population, aging critical infrastructure, a high migration of young professionals, and a shrinking economy (Pérez et al. 2008; Abel and Dietz 2014; Muñoz-Erickson et al. 2014; Elías-Boneta et al. 2015; PRCCC 2013; Hayhoe 2013; Méndez-Lázaro et al. 2014a).

In light of these climatic, environmental, and public health issues, we seek to examine heat-related mortality in two of the most populated municipalities of the SJMA—San Juan and Bayamón. Our main objective is to evaluate the effects of excessive and prolonged heat episodes between 2009 and 2013 on overall and cause-specific mortality in these two municipalities. A better understanding of the effects of heat events on human health provides a useful tool for decision makers in SJMA, and in Puerto Rico in general, to plan accordingly and mitigate the effects of the increasing temperatures on the health of the population. The present analysis of daily mortality in San Juan and Bayamón between 2009 and 2013 provided us with an opportunity to understand, for the first time, the magnitude of extreme heat episodes in the region as it gives updated insights about summer temperatures and mortality in a tropical metropolitan area. The findings will help enhance extreme heat event adaptation strategies in Puerto Rico (e.g., early warning systems, heat advisories, heat warnings).

Study area

Puerto Rico is a tropical island located in the northern-central Caribbean Sea and is 8900 km^2 in area and with 78 municipalities (Fig. 1). The SJMA has a subtropical humid climate, and weather patterns change slowly in the summer months compared to the winter months. The average precipitation over a 30-year period (1981–2010) is ~1800 mm/year. Rainfall has a bimodal pattern with two rainy seasons. A relatively dry season occurs in winter months, June and July. The wet season takes place in May and autumn (Colón-Torres 2009; Méndez-Lázaro et al. 2014a, b). Easterly trade winds prevail most of the year over the island, with local winds influenced by the diurnal heating cycle. Average air surface temperatures range from 22 to 28 °C (Colón-Torres 2009), but maximum air surface temperature and heat index can reach 36 to 38 °C under summer extreme conditions.

This study includes data on residents of San Juan and Bayamón, the two most populated municipalities of the SJMA (Fig. 1). The municipality of San Juan is an urban coastal city and the capital of Puerto Rico, located in the northeast sector of the island. San Juan has 395,326 inhabitants and a population density of 1800/km^2, while Bayamón is the second most populated municipality in Puerto Rico. It has 208,116 inhabitants and a population density over 1500/km^2. Together, they have a population of 603,442 people (U.S. Census Bureau 2010).

Methods

Data collection

During the period of 2009 to 2013, data on non-accidental mortality (records of death occurring in San Juan and Bayamón) and air surface temperature records were

Table 2 Total deaths per year and crude rate per 10,000 population by municipality for the time period of 2009–2013

	2009		2010		2011		2012		2013		Total	
	Total	Crude rates	Total	Crude rates	Total	Crude rates	Total	Crude rates	Total	Crude rates	Total	Crude rates
San Juan	1360	34.4	1330	33.6	1376	34.8	1364	34.5	1371	34.7	6.801	172.0
Bayamón	657	31.6	650	31.2	637	30.6	665	32.0	660	31.7	3.269	157.1
Total											10.070	166.9

analyzed. Based on previous studies in mid-latitudes (Naughton et al. 1999; Schifano et al. 2012; Petkova et al. 2014), daily deaths from all cardiovascular diseases (International Classification of Diseases (ICD)-10 I00–I09, I11, I13, I20–I51), diabetes mellitus (ICD-10 E10–E14), stroke (ICD-10 I60–I69), chronic lower respiratory diseases (ICD-10 J40–J47), nephritis, nephrotic syndrome, and nephrosis (N00–N07, N17–N19, N25–N27), pneumonia and influenza (ICD-10 J09–J21), and hypertension (ICD-10 I10–I15) were obtained from the Vital Statistics Office of the Commonwealth of Puerto Rico. The ICD is the standard diagnostic tool for epidemiology, health management, and clinical purposes (WHO 2016). These causes of death have been associated with high air surface temperature and extreme heat events in cities such as Chicago, Venice, Rome, New York, and Taipei (Kalkstein and Greene 1997; Semenza et al. 1999; Ostro et al. 2009; Basu and Malig 2011; Lin et al. 2012). Sociodemographic characteristics, including age and sex, were not available at the time of the study. No distinction was made by sex or age, and only deaths of those residing and dying in San Juan and Bayamón were analyzed.

The best available dataset for air surface temperature (AST) records was downloaded from the NOAA-National Center for Environmental Information web page (formerly the National Climatic Data Center http://www.ncdc.noaa.gov/) for San Juan, Puerto Rico-Luis Muñoz Marín International Airport (18° 26 N, 66° 01 W). AST sensors are mounted about 2 m above the ground level and no closer than four times the height of any obstruction, at least 30 m away from any paved or concrete surface (Méndez-Lázaro et al. 2015). The data include daily maximum temperature, minimum temperature, and mean temperature for San Juan during the period 2009–2013 with only 0.05% of missing values (October 20, 2012). Stations with more than 10% missing values were discarded as well as those that were missing more than 3 years for each series and more than 3 months for each year (Méndez-Lázaro et al. 2014b).

Data analysis

We developed indices for AST based on previous studies (Méndez-Lázaro et al. 2015) and the methodology suggested by the International Expert Team on Climate Change Detection and Indices (e.g., 90th, 95th, and 99th percentiles) for monitoring changes in extreme environmental conditions (Aguilar et al. 2005; Zhang et al. 2011). Monthly and annual maximum, minimum, averages, and anomalies of these variables were also examined. Categories for maximum/minimum AST were built based on the frequency and percent of occurrence. Daily average temperatures were computed as the mean of their two respective values. Descriptive statistics (mean, standard deviation, percentiles (25th, 50th, and 75th), minimum, and maximum) were computed to describe AST and mortality data. Separate Poisson regression models were fitted to assess the effect of daily maximum and minimum temperatures in the overall and cause-specific number of deaths, while controlling for season and year to account for

Table 3 Monthly and seasonal average air surface temperature (AST) and crude rate per 10,000 population for the municipalities of San Juan and Bayamón (2009–2013)

Season/month	Tmax	Tmin	Tmean	Deaths	CVD	DM	Stroke	Respiratory	Renal	Pneumonia	Hypertension
Winter	93.0	78.0	84.5	14.0	8.0	4.0	4.0	3.0	4.0	3.0	5.0
December	84.2	73.9	79.1	5.8	6.5	0.8	1.6	1.2	1.2	1.3	1.9
January	83.3	72.3	77.8	5.6	6.8	0.6	1.3	1.0	1.1	1.1	2.0
February	84.2	72.4	78.3	5.2	5.2	0.6	1.6	1.1	1.1	0.9	1.9
Spring	94.0	80.0	86.5	14.0	7.0	3.0	4.0	4.0	4.0	4.0	4.0
March	84.6	72.9	78.8	5.4	6.0	0.5	1.7	1.1	1.2	1.2	1.7
April	86.1	74.3	80.2	5.6	6.3	0.8	1.6	1.2	1.3	1.1	2.0
May	86.2	75.8	81.0	5.7	6.0	0.6	1.6	1.4	1.2	1.2	2.4
Summer	95.0	82.0	87.5	16.0	8.0	3.0	4.0	3.0	4.0	3.0	5.0
June	88.9	77.4	83.2	5.4	5.9	0.6	1.5	1.4	1.2	0.9	1.9
July	88.6	78.0	83.3	5.3	6.2	0.7	1.4	0.9	1.0	1.2	1.9
August	89.2	78.3	83.7	5.7	6.4	0.7	1.6	1.0	1.1	1.1	2.5
Autumn	96.0	81.0	88.0	16.0	8.0	2.0	4.0	3.0	4.0	3.0	4.0
September	89.5	78.2	83.8	5.3	6.1	0.5	1.6	0.9	1.3	0.8	1.9
October	89.1	77.4	83.3	5.8	6.4	0.6	1.9	1.2	1.1	1.4	1.8
November	86.1	75.5	80.8	5.5	5.9	0.6	1.7	1.2	1.0	1.2	1.8

CVD cardiovascular disease, *DM* diabetes mellitus seasonality. We then examined whether the associations between the overall and cause-specific number of deaths and daily maximum and minimum temperatures differed by season and year by including interaction terms of daily temperatures with season and year. Due to significant ($p < 0.05$) interaction terms, we present the relative risks (RRs) and 95% CI for mortality stratified by season and year. All statistical tests were two sided and were performed using Stata version 14 (StataCorp LP, College Station, TX).

Results

Summary AST statistics and mortality data for San Juan and Bayamón during the study time period (2009–2013) are presented in Tables 1, 2, and 3. Mean AST for San Juan was 27.2 °C, ranging from 24.2 to 30.6 °C. Maximum AST occurred in July and August, while minimum temperature occurred in January and February (Fig. 2). Heat episodes (defined by AST >90th percentile) were common during the

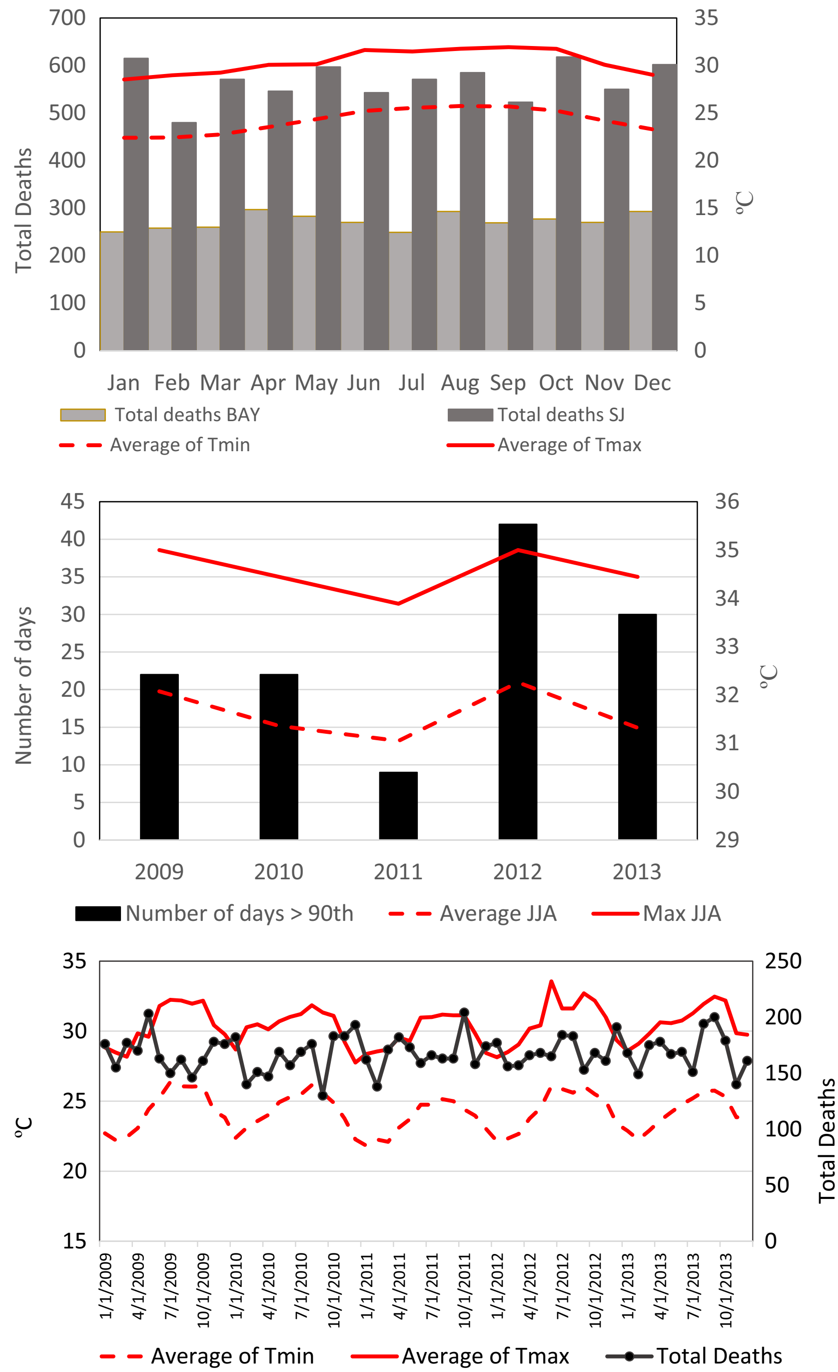

Fig. 2 *Upper panel*: Average monthly air surface temperature and total mortality for the study time period 2009–2013. *Middle panel*: Number of days when daily maximum temperature >90th percentile each year and summer air surface temperature. *JJA* June-July-August. *Lower panel*: Monthly trend of AST and mortality

summer. Our results confirmed that the summer of 2012 ended as the hottest season for the study time period (Fig. 2), the hottest month on record (June), as well as the longest hot spell (42 days), followed by the summer of 2013 (30 days).

A total of 10,070 deaths occurred in San Juan and Bayamón during the study period (Table 2). Most deaths resulted from cardiovascular diseases (45.1%), hypertension (14.4%), and stroke (11.2%), while the rest of the deaths were attributable to respiratory diseases (7.8%), diabetes mellitus (4.5%), pneumonia (8.6%), and renal disease (8.2%). The seasonality of mortality was similar for each year since 2009 (autumn 2507; spring 2554; summer 2511; and winter 2498) (Fig. 2 and Table 3).

The number of deaths reported in San Juan and Bayamón and the summer AST quantiles during the study time period (2009–2013) are shown in Fig. 3. A total of 977 deaths occurred during the summers of 2009 and 2010 (321 in Bayamón and 656 in San Juan), while a total of 1046 deaths were registered during the summers of 2012 and 2013 (342 in Bayamón and 704 in San Juan). Over two thirds (66%) of the summer total mortality during 2012 and 2013 occurred when AST was above the third quantile. As summer temperature increased, the total mortality increased as well, as did the overall relative risk (RR). Knowing that the summers of 2012 and 2013 were the hottest seasons in our record, the summer data for the years 2009/2010 and for the years 2012/2013 were combined in the analysis.

Strong evidence suggests that the heat effect causes an excess risk of non-accidental mortality. This statement was much more pronounced for the summers of 2012 and 2013 (combined) with maximum temperature (RR = 12.94, 95% CI 9.76–17.16) and with mean temperature (RR = 24.35, 95% CI 17.00–34.88). Stroke (RR = 16.80, 95% CI 6.81–41.4) and cardiovascular diseases (RR = 16.63, 95% CI 10.47–26.42) were the primary causes of death most associated with elevated summer temperatures for 2012 and 2013 (Table 4).

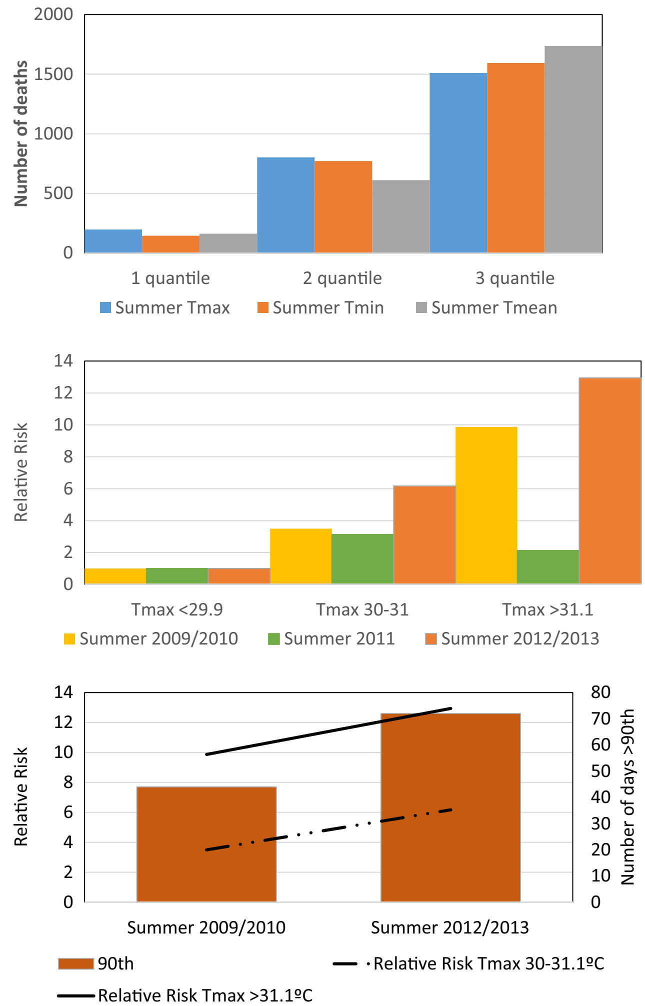

Fig. 3 *Upper panel*: Number of deaths by summer temperature quantiles. *Middle panel*: Total deaths, relative risk, and threshold for AST (Tmax: ≤29.9, 30–31, and ≥31.1 °C; Tmin: ≤23.3, 23.4–25, and ≥25.1 °C; Tmean: ≤26.6, 26.7–28.3, and ≥28.4 °C). *Lower panel*: Relative risk and number of summer days when AST was >90th

Discussion

Heat-related mortality has been analyzed in mid-latitudes, in temperate climates, and in continental cities. Increased temperatures and increases in extreme heat events are associated in these regions with heat exhaustion, heat stroke, and death, especially in vulnerable populations (e.g., elderly, children <5 years old and populations below the poverty level). Strong evidence suggests that, under climate change scenarios, the Caribbean Region is getting warmer and extreme heat episodes are becoming more frequent; however, knowledge about the effects of this kind of extreme events in the region is scarce. More than 100 years of record for San Juan suggest that the occurrence of prolonged heat episodes is becoming more frequent (PRCCC 2013; Méndez-Lázaro et al. 2014a, b). A strong surface high-pressure system northeast of our study area occurred during the summer of 2012 (Méndez-Lázaro et al. 2015). This high-pressure system induced southeasterly winds responsible for the record high summer temperatures.

The main finding of our study was the increase in the significant effect of high temperatures on mortality, especially for stroke and cardiovascular diseases during the

Table 4 Relative risk results of the relation between daily temperature and specific deaths, according to season and year for the municipalities of San Juan and Bayamón (2009–2013)

		Autumn (2009/2010)	Summer (2009/2010)	Autumn (2011)	Summer (2011)	Autumn (2012/2013)	Summer (2012/2013)
Total	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	*1.67*	*3.50*	*2.88*	*3.13*	*3.10*	*6.17*
	3rd	*2.00*	*9.87*	1.26	*2.13*	*7.40*	*12.94*
CVD	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	*1.84*	*3.30*	*2.91*	*3.59*	*2.97*	*8.00*
	3rd	*2.16*	*9.57*	1.24	*2.38*	*7.89*	*16.63*
DM	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	*2.50*	*3.75*	2.25	2.00	*5.30*	*5.67*
	3rd	1.88	*6.50*	1.25	1.80	*9.00*	*11.00*
Stroke	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	*2.13*	*2.67*	*3.42*	*2.78*	*2.71*	*5.60*
	3rd	*2.05*	*6.22*	1.00	*2.22*	*5.00*	*16.80*
Respiratory	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	0.92	*3.17*	*5.25*	2.20	*2.67*	*6.5*
	3rd	1.52	*11.17*	2.25	2.40	*8.17*	*11.00*
Renal	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	1.53	*5.25*	*4.20*	*3.00*	*3.5*	*3.57*
	3rd	*1.79*	*16.25*	1.6	1.43	*9.33*	*7.00*
Pneumonia	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	1.41	2.50	1.85	*3.29*	*3.29*	*4.4*
	3rd	*2.00*	*10.67*	1.38	1.57	*5.86*	*10.8*
Hypertension	1st	1.00	1.00	1.00	1.00	1.00	1.00
	2nd	1.43	*5.00*	*2.44*	*2.91*	*3.31*	*5.67*
	3rd	*2.09*	*11.78*	1.11	*2.09*	*7.77*	*10.33*

Italics: p values <0.05

CVD all cardiovascular diseases (ICD-10 I00–I09, I11, I13, I20–I51), *DM* diabetes mellitus (ICD-10 E10–E14)

summers of 2012 and 2013. These 2 years are considered the hottest summers on record in Puerto Rico. Our results are consistent with previous studies carried out in mid-latitudes (Semenza et al. 1999; Ostro et al. 2009; Petkova et al. 2014). The literature and findings suggest that high temperatures increase heat stress in the body changing underlying physiological responses related to inflammation and cell injury. These responses result in heart failure by increasing injury to heart tissue and inflammation (Wilker et al. 2012).

This study also provides essential information related to climate change as well as results that should encourage Puerto Rico's public health administrators to develop a proactive heat response plan or a heat prevention plan, as has been done in different countries (e.g., Italy in 2004) (Kosatsky 2005). In this context, the University of Puerto Rico and the National Weather Service–San Juan Office have been collaborating over the past 3 years, developing standard definitions of extreme heat episodes for San Juan, heat-related mortality, and heat early warning systems (e.g., methodologies for heat advisories and heat warnings).

One limitation of this research is that we were unable to control the combined effects of exposure to heat and air pollution (e.g., Saharan dust, pollen, molds, and ozone). In addition, sociodemographic characteristics were not available at the time of this study. Therefore, further analysis is needed to identify vulnerable populations and understanding risk factors associated with exposure to extreme heat events. In this context, it is also in our best interest to expand this kind of research to other cities in Puerto Rico and in the Caribbean nations to better understand heat-related effects on human health in the region.

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