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Research, part of a Special Feature on Understanding the Vulnerability and Sustainability of Urban Social-Ecological Systems in the Tropics: Perspectives from the City of San Juan

Trends in total rainfall, heavy rain events, and number of dry days in San Juan, Puerto Rico, 1955-2009

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ABSTRACT. Climate variability is a threat to water resources on a global scale and in tropical regions in particular. Rainfall events and patterns are associated worldwide with natural disasters like mudslides and landslides, meteorological phenomena like hurricanes, risks/hazards including severe storms and flooding, and health effects like vector-borne and waterborne diseases. Therefore, in the context of global change, research on rainfall patterns and their variations presents a challenge to the scientific community. The main objective of this research was to analyze recent trends in precipitation in the San Juan metropolitan area in Puerto Rico and their relationship with regional and global climate variations. The statistical trend analysis of precipitation was performed with the nonparametric Mann-Kendall test. All stations showed positive trends of increasing annual rainfall between 1955 and 2009. The winter months of January and February had an increase in monthly rainfall, although winter is normally a dry season on the island. Regarding dry days, we found an annual decreasing trend, also specifically in winter. In terms of numbers of severe rainfall events described as more than 78 mm in 24 hours, 63 episodes have occurred in the San Juan area in the last decade, specifically in the 2000-2009 time frame, with an average of 6 severe events per year. The majority of the episodes occurred in summer, more frequently in August and September. These results can be seen as a clear example of the complexity of spatial and temporal of rainfall distribution over a tropical city.

Key Words: *climate variability; Puerto Rico; rainfall patterns; San Juan; trend analysis*

INTRODUCTION

Climate change has been a topic of interest to many researchers with multiple areas of expertise. One of the most important necessities of research into climate change is to analyze and detect historical changes in the climatic system (Cannarozzo et al. 2006). Water availability is an important limiting factor for biological activities, and small variations in the amount, frequency, and intensity of water availability may have important consequences for the dynamics of human/natural systems (Ceballos-Barbancho et al. 2008). Changes in precipitation directly affect water resource management, agriculture, hydrology, natural ecosystems, and human health. For this reason it is important to investigate the changes in the spatial and temporal rainfall pattern to improve water management strategies (Cannarozzo et al. 2006).

Studies of yearly and seasonal precipitation on global and local scales reveal trends over many regions of the world (Brunetti et al. 2000, Jury 2009). Krishnakumar et al. (2009) observed a significant decrease in the southwest monsoon rainfall in India and an increase in the postmonsoon season. Ceballos-Barbancho et al. (2008) confirmed in Spain the general provisions of the Intergovernmental Panel on Climate Change, with a predominance of dry years over wet ones and a negative rainfall trend in the central sector of the country. In Botswana, Batisani and Yarnal (2009) identified a trend toward decreased rainfall throughout the nation, which is associated with decreases in the number of rainy days.

More related to the study area of this research, Neelin et al. (2006) observed that several data sets showed a significant summer drying trend in the Caribbean–Central-America region, a main region of intermodal agreement. More specifically in the Caribbean, Laing (2004) studied the environments associated with three episodes of heavy precipitation and flash floods. These cases of heavy precipitation occurred during what is normally the dry season in the Caribbean.

Variations in total precipitation can be caused by a change in the frequency of precipitation events or in the intensity of precipitation per event, or a combination of both. Daily precipitation records must be analyzed to improve the understanding of how precipitation has acted as an indicator of climate variability over the last decades (Brunetti et al. 2000). This type of study has been done by Brunetti et al. (2000), Cannarozzo et al. (2006), and Xu et al. (2010). Changes in the dynamics and patterns of geophysical parameters may significantly affect different components of the hydrological cycle including runoff, floods, and droughts.

General circulation models provide a means of estimating climate change in the future by providing a time series of climatic variables. We believe our research was innovative because we studied the impact of climate change, or variability, on rainfall patterns during appropriately long periods of time using existing knowledge of the dynamics of these effects. We analyzed recent rainfall trends in the metropolitan area of San Juan, Puerto Rico, and their relationship with local climate variation from 1955 to 2009. In the context of climate change, heavy rainfall patterns and dry days were also analyzed.

STUDY AREA

The study area consisted of the metropolitan area of San Juan and the basin of the Río Piedras. This basin of 67.3 km² is the main hydrologic unit in the municipality of San Juan, with a small

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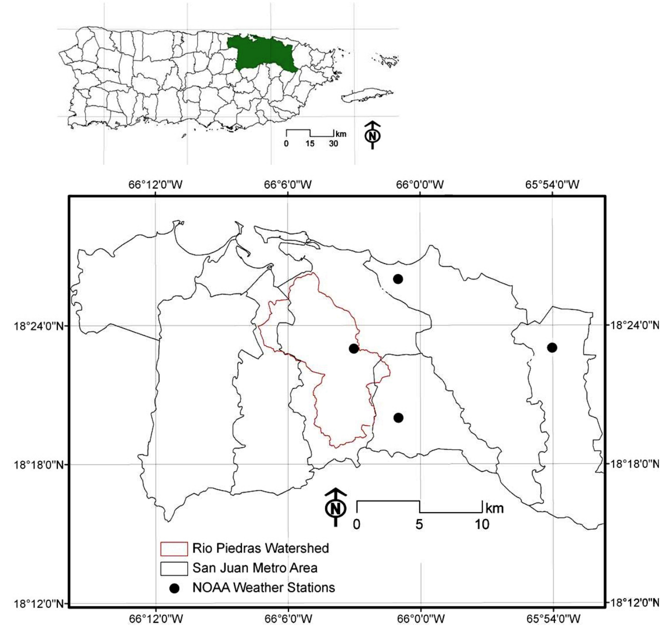
portion also including the municipalities of Guaynabo and Trujillo Alto. These three municipalities constitute the most urbanized basins in the island (Fig. 1).

Fig. 1. San Juan metropolitan area and National Oceanic and Atmospheric Administration (NOAA) weather stations.

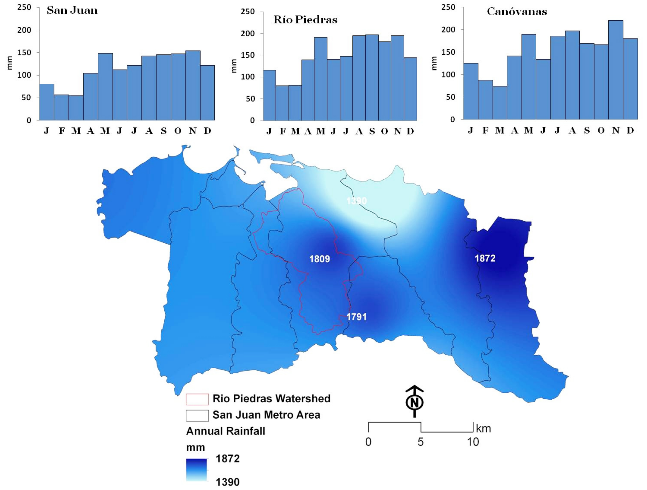


The metropolitan area of San Juan has a subtropical humid climate, very similar to that of other cities in Puerto Rico and in the Caribbean region, with an annual average rainfall of 1800 mm. It has two seasons, a relatively dry season in the winter months with slight increases in rainfall in May and rainfall decreasing again in June and July; and a wet season in summer and autumn (Fig. 2).

DATABASE AND METHODS

Four meteorological stations were used in this research. The weather stations belong to the U.S. National Oceanic and Atmospheric Administration's Southeast Regional Climate Center. To maintain data quality, we selected weather stations that had more than 31 years of available daily data and for which the series was the most recent (Table 1). Stations were discarded if they had large information gaps and large quantities of missing values (more than 10%); for example, those that were missing more than three years for each series and more than three months for each year were discarded (González Hidalgo et al. 2002). Rainfall trends and patterns can be compared with the results of previous studies in Puerto Rico (Méndez Lázaro and Martínez 2012, Méndez-Lázaro et al. 2012).

Fig. 2. Average annual rainfall distribution in San Juan metropolitan area.



Rainfall indices (Table 2) were developed to categorize the available data into dry days (recorded rainfall < 1 mm/24 h; RR0) and wet days (recorded daily rainfall ≥ 1 mm/24 h; RR1). We used a robust statistical method for trend analysis: the Mann-Kendall (MK) trend test (Yue et al. 2001, Kuo et al. 2011). This is a nonparametric test to detect trends in data (McCuen 2003). This test

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

and

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} +1 \text{ if } (x_j - x_k) > 0 \\ 0 \text{ if } (x_j - x_k) = 0 \\ -1 \text{ if } (x_j - x_k) < 0 \end{cases} \tag{2}$$

has been used by different researchers for trend studies with hydro-climatic data (Yue et al. 2001, Hamed 2007, Luo et al. 2008, McBean and Mootie 2008). The MK test involves computing the S statistic, which is the difference between the numbers of pairwise differences that are positive minus the numbers that are negative. The MK test does not assume any particular distributional form and accommodates values below the detection limit by assigning them a common value (Allende and Mendoza 2007, Baggaley et al. 2009).

The variable *n* indicates the number of observed data points in the series. Let the time series consist of *n* data points, and X_k and X_j are two subsets of data where k=1, 2, 3, . . . , n −1 and j=k+1, i+2, i+3, . . . , n. Each data point X_k is used as a reference point and is compared with all the X_j data points (Allende and Mendoza 2007, McBean and Mootie 2008).The alternative hypothesis is that of either an upward trend or a downward trend.

A positive trend is detected when the most recent data tend to be superior to the earlier data. A negative trend is detected when the latest data tend to be inferior to the previous data. When S displays a highly positive value, it shows a positive trend. When S displays a highly negative value, it shows a negative trend.

For a series of data $n > 10$, the Z statistic is used.

$$Z_0 = \frac{S - sign(s)}{\sqrt{V(S)}} \tag{3}$$

1 if $S > 0$, 0 if $S = 0$, -1 if $S < 0$

Table 1. Weather stations within the San Juan metropolitan area.

Stations	Period	Code	Elevation (ft)	Lat/Long.	Missing Values %
Río Piedras Exp. Station	1955-2009	668306	92	18°25N 66°04W	5.7%
San Juan LMM	1955-2009	668812	9	18°26N 66°01W	0.2%
Gurabo Substation	1955-2009	664276	160	18°15N 66°00W	0.9%
Canóvanas	1955-2009		30	18°23N 65°54W	1.7%
Toa Baja 1 SSW / Constancia / Levittown	**1955-1994**	**669421**	**20**	**18°26N 66°16W**	**4.6%**
Trujillo Alto	**1970-2009**	**669521**	**115**	**18°20N 66°01W**	**12.0%**
Caguas 2 WNW / 1 WSN	**1970-1995**	**661309**	**260**	**18°14N 66°03W**	**8.5%**
La Muda Caguas	**1971-1994**	**665123**	**290**	**18°19N 66°06W**	**9.1%**
Cataño	**1955-1977**	**661845**	**20**	**18°25N 66°07W**	**6.2%**
San Juan City	**1955-1977**	**668808**	**20**	**18°28N 66°06W**	**5.6%**

Bold: Stations that did not meet selection criteria.

Table 2. Rainfall index description. Source: ECA&D Project Team 2012.

Acronyms	Description	Units
RR	Precipitation sum is defined as the daily precipitation for 1 day over the period of 24 hours.	(mm)
RR1	Wet days are counted as the number of days where (RR ≥ 1 mm.	(Freq.)
RR0	Dry days are counted as the number of days where (RR < 1 mm).	(Freq.)
CDD	Number of dry days (RR0) over consecutive period of (> 3 (x) < 8 days) the time series.	(Freq.)

In this statistical test, the null hypothesis (H_0) relies on the fact that there is no trend.

The variable g represents the number of tied groups and t_j is the number of points in the j_{th} group when S equals the total number of positive differences minus the total number of negative differences and V(S) is

$$V(S)-\frac{1}{18}\left[n(n-1)(2n+5)-\sum_{j-1}^{g}t_j(t_j-1)(2t_j+5)\right] \qquad (4)$$

Note that sign (S) = 1 if S > 0, sign (S) = 0 if S = 0, and sign (S) = −1 if S < 0. If $z_0 > z_1 - \alpha$, then the null hypothesis of no trend is rejected.

MK statistical significance was also analyzed with the P value. If $P < \alpha$, then we rejected the null hypothesis of no trend. This value does not quantify the probability that a certain hypothesis is accurate in light of the data. It rather quantifies the probability of obtaining certain data, assuming that a certain hypothesis is accurate, as has been noted.

MK statistical analysis is very robust and highly recommended by different researchers, as well as various environmental administrations, for studies of trends with hydro-climatic data (Yue et al. 2001, Luo et al. 2008). The MK test can indicate whether there is any negative or positive trend in rainfall (Allende and Mendoza 2007). Were also analyzed extreme weather events, i.e., rainfall of more than 78 mm in 24 hours, and dry days.

RESULTS AND DISCUSSION

We observed changes in annual and monthly rainfall in the San Juan metropolitan area over the last decades of the 20th century. All stations showed great oscillation and variability compared with normal values, making it possible to identify wet and dry periods (Fig. 3). Positive trends between 1955 and 2009 can be established (Table 3). Similarly, changes in the natural behavior of the hydrological cycle have been identified. In December monthly total rainfall decreased at all analyzed stations, whereas in the winter months of January and February, total precipitation increased (Table 3). These findings are relevant when considering seasonal changes and trends (Table 4). The summer months of June, July, and August showed regressive trends at all weather stations, even though only the trend at Canóvanas reached statistical significance. In contrast, the fall months of September, October, and November had positive trends at all four weather stations (Fig. 4).

These monthly trends can be also confirmed in part by the analysis of dry days (RR0). Between 1955 and 2009 the San Juan metropolitan area used to have an average of 136 dry days per year. Table 5 shows that dry days are decreasing at three out of four stations annually; these patterns can be confirmed by combining data from all the weather stations (Fig. 5). Moreover, with dry spell analysis (consecutive dry days, CDDs), two out of four weather stations had regressive trends (San Juan LLM, Río Piedras Experiment Station), while Canóvanas showed positive values (Table 6). Dry days and the dry season normally occurred in winter; nevertheless, Río Piedras Experiment Station showed a negative trend for both RR0 and CDDs.

Table 3. Annual and monthly rainfall trend analysis. Mann-Kendall (S).

NOAA/ STATIONS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual
Canóvanas	**395**	**123**	-30	132	-232	**-153**	-49	**-121**	167	187	197	-2	**145**
Gurabo	**160**	**169**	246	19	-83	**-125**	131	**-127**	77	243	116	**-70**	**207**
Río Piedras	**196**	**-67**	220	136	3	**-45**	-245	-17	203	**-37**	204	**-314**	**111**
San Juan	**113**	**86**	-251	189	-195	**-67**	69	**-146**	29	**-32**	274	**-81**	3

Bold indicates that the computed Z value was above the significance level (|Z| > 1.645); therefore, one should reject the null hypothesis (there is no trend in the series) and accept the alternative hypothesis.

Fig. 3. Rainfall variability 1955-2009 compared with 1981-2010 climatology (normal values).

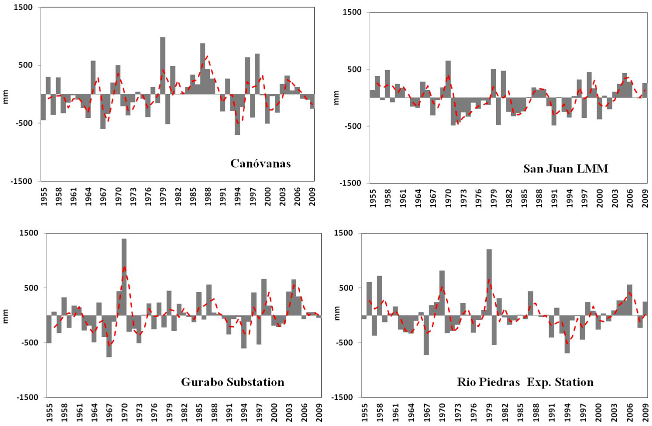
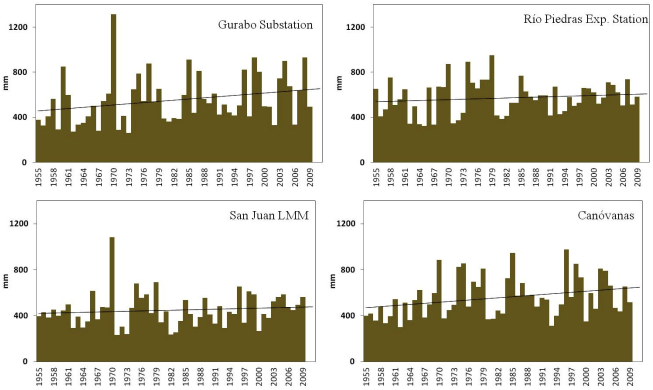


Fig. 4. Fall histogram with trend lines.



A total of 63 severe rainfall events, described as more than 78 mm in 24 hours, occurred over the San Juan metropolitan area between 2000 and 2009, with an average of 6 severe events per year; 4 of these events were recorded at more than one station. Río Piedras Experiment Station (26 severe events) and Gurabo Substation (16 severe events) are the stations where more episodes were registered. The majority of the episodes occurred in summer

Fig. 5. Dry days trends in San Juan metropolitan area. DJF (December-January-February), JJA (June-July-August)

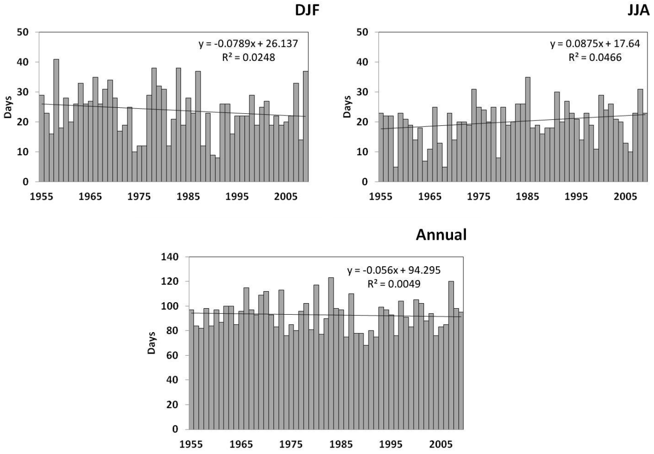


Table 4. Seasonal trends. Mann-Kendall (S).

	Winter (DJF)	Summer (JJA)	Fall (SON)	Spring (MAM)
San Juan LLA	22	-87	180	-59
Río Piedras Exp. Station	-99	-169	175	106
Gurabo Substation	-75	103	**320**	89
Canóvanas	-83	**-895**	**300**	-77

Bold indicates that the computed Z value was above the significance level (|Z| > 1.645); therefore, one should reject the null hypothesis (there is no trend in the series) and accept the alternative hypothesis.
DJF = December-January-February
JJA = June-July-August
SON = September-October-November
MAM = March-April-May

(*n* = 24), the beginning of the hurricane season in the North Atlantic, but were more frequent in August and September. These episodes occasionally occurred in winter (*n* = 4), all of them in the Río Piedras Experiment Station. In general terms, severe events were more frequent in summer in Río Piedras, although more intense in spring, with 139 mm in 24 hours.

Table 5. Mann-Kendall trend analysis for dry days. JJA = June-July-August; DJF = December-January-February.

Station	Annual (p-value)	JJA (p-value)	DJF (p-value)
Río Piedras	**-4.68 (0.001)**	**-2.61 (0.0045)**	**-4.67 (0.001)**
San Juan	**-10.79(0.001)**	-0.85 (0.1977)	-1.47 (0.0708)
Gurabo	**-4.91 (0.001)**	-0.75 (0.2266)	**-3.05 (0.0011)**
Canóvanas	1.11 (0.1335)	**2.87 (0.0021)**	-0.40 (0.3446)
Metropolitan Area	-0.60 (0.2743)	1.31 (0.0951)	-1.26 (0.1038)

Bold indicates that the computed Z value was above the significance level (|Z| > 1.645); therefore, one should reject the null hypothesis (there is no trend in the series) and accept the alternative hypothesis.

Table 6. Mann Kendall trend analysis for consecutive periods of dry days (> 3 days < 8 days).

Station	Annual (p-value)	JJA (p-value)	DJF (p-value)
Río Piedras	**-3.78 (0.0001)**	**-2.50 (0.0062)**	**-2.99 (0.0014)**
San Juan	**-1.67 (0.0475)**	0.12 (0.4522)	**-1.79 (0.0367)**
Gurabo	-0.12 (0.4522)	0.46 (0.3228)	-1.34 (0.0901)
Canóvanas	**1.95 (0.0256)**	**2.75 (0.003)**	1.07 (0.1423)
Metropolitan Area	-0.54 (0.2946)	-0.75 (0.2266)	-0.86 (0.1949)

Bold indicates that the computed Z value was above the significance level (|Z| > 1.645); therefore, one should reject the null hypothesis (there is no trend in the series) and accept the alternative hypothesis.

In the years 2003 and 2004, there were eight and nine registered severe rainfall events, respectively; in 2007 and 2008, there were three and four episodes, respectively. The most intense rainfall event, 207 mm in 24 hours, occurred in spring (24 April 2006) and was only registered in the Río Piedras station. This can be seen as an example of the remarkable complexity of rainfall spatial distribution over a tropical city such as San Juan. Clear patterns and trends of severe rainfall events in the San Juan metropolitan area cannot be established from 1955 to 2009 (Table 7).

These episodes might have a direct effect on environmental public health. As discussed by Quintero et al. (2010), high-intensity rain diminished the concentration of fungal spores in the atmosphere in San Juan, Puerto Rico. Fungal aerosols have been correlated in different studies with respiratory problems (Bolaños-Rosero et al. 2013). Quintero et al. also noted that the concentrations of fungal spore aerosols increased during and after the rain events. Because the prevalence of asthma in Puerto Rico is approximately 16.5% and in some areas is almost 46% in elementary-school children (Loyo-Berríos et al. 2006), our research could be very useful for public health preparedness once the rainfall trends and patterns are well characterized.

Table 7. Mann-Kendall trend analysis for heavy rainfall.

Station	Annual (p-value)	JJA (p-value)	DJF (p-value)
Río Piedras	0.61 (0.2709)	0.60 (0.2743)	0.56 (0.2877)
San Juan	1.17 (0.121)	-0.16 (0.4364)	-0.28 (0.3897)
Gurabo	1.02 (0.1539)	-0.05 (0.4801)	-0.59 (0.2776)
Canóvanas	-0.62 (0.2676)	0.61 (0.2709)	-0.40(0.3446)
Metropolitan Area	1.05 (0.1469)	0.90 (0.1841)	0.19 (0.4247)

These changes in rainfall patterns and events are similar to those reported by Peterson et al. (2002) for the Caribbean as a whole. The maximum number of CDDs is decreasing and the number of heavy rainfall events is increasing in the Caribbean (Peterson et al. 2002). Similar patterns for rainfall have also been registered in Cuba (Centella et al. 1999). In both Puerto Rico and Cuba, annual precipitation is increasing in the winter months and decreasing in the summer (Méndez Lázaro and Martínez 2012). It may be that these results to some extent reflect the complexity of precipitation patterns in tropical areas including Puerto Rico. All these detected changes might be influenced by the El Niño southern oscillation and the North Atlantic oscillation (Giannini et al. 2001, Jury 2008). A warm El Niño southern oscillation and a positive North Atlantic oscillation should have a negative impact on summer rainfall in the Caribbean. Figure 3 shows annual variability, anomalies, and oscillations in each of the four weather stations.

There is global concern that climate change will make certain environments suitable for vector-borne diseases, worsening their already significant global burden and potentially reintroducing some diseases into areas where they had been previously eradicated (Portier et al. 2010, Mendez-Lazaro 2012). The temporal and spatial changes in temperature, precipitation, and humidity that are expected to occur under different climate change scenarios will affect the biology and ecology of vectors and intermediate hosts, and consequently the risk of disease transmission (Githeko et al. 2000). In general, insects are exceedingly sensitive to temperature and rainfall regimens and patterns, and all the tropical and temperate species frequently show high variation in seasonal abundance (Brunkard et al. 2008).

According to Li et al. (1985), a quantitative association between rainfall and the number of dengue cases was found during the first wet period in Malaysia, showing a lag time between the onset of heavy rain and dengue outbreak of about two to three months; a 120% increase in the number of dengue cases was observed when the monthly rainfall was 300 mm or more. Dengue in Puerto Rico is seasonal, with three periods: postepidemic from December to May, with low temperature, little precipitation, and few mosquitoes; pre-epidemic from June to August, with high temperature and abundant precipitation and mosquitoes; and epidemic from September to November, with environmental conditions similar to those in the pre-epidemic period (Barrera 2010). Pre-epidemic and epidemic conditions in Puerto Rico occur in the summer and fall, the same seasons that heavy rainfall events are more frequent. Even though Jury (2008) mentioned that seasonal fluctuations of dengue were driven by rainfall increases from May to November, he concluded that dengue cases were positively related to temperature and weakly associated with local rainfall. New approaches can focus on analyzing how regional and bigger-scale atmospheric phenomena will control and influence the Caribbean region in the next decade (Malmgren et al. 1998, Giannini et al. 2001, Jury et al. 2007).

CONCLUSION

In this paper, we present the most recent and updated research analyzing rainfall trends in Puerto Rico in a climate change context, using registered data from 1955 through 2009. Based on the results, rainfall trends and variability in San Juan, Puerto Rico, appear to be very complex. We observed that the total annual rainfall increased slightly and observed regressive trends more frequently in summer than in winter. These results were confirmed by dry day trend analysis. According to this analysis, dry days decreased in the San Juan metropolitan area between 1955 and 2009 and were more common in the winter months. Heavy rains were more common in summer and fall in accordance with the hurricane season, whereas the most intense rainfall episodes tended to occur in spring.

Taking under consideration the complexity of urban areas and the Caribbean climate conditions, further research should involve characterizing additional rainfall indices, such as defining extreme weather events or expanding the study area. In addition, analyzing trends in previous years in Puerto Rico could enable better understanding of past rainfall conditions. The hydro-climatic information presented here supports further climate change risk assessment and vulnerability adaptation planning in Puerto Rico. Understanding the interrelations between climate and environmental threats, and the effects that climate variability has on both of them, will help define possible effects on life, ecosystems, and public health. Adaptation strategies and measures, i.e., policies, as well as public health interventions then can be applied.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/6464

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