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Key Points:

- Significant trends in sea level extremes are in line with mean sea level rise
- Storm surges are caused by hurricanes and cold fronts
- Extremes result from storm surges, the seasonal cycle, and eddies

Supporting Information:

- Readme
- Fig S1 Quantile plot

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Sea level extremes in the Caribbean Sea

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Abstract Sea level extremes in the Caribbean Sea are analyzed on the basis of hourly records from 13 tide gauges. The largest sea level extreme observed is 83 cm at Port Spain. The largest nontidal residual in the records is 76 cm, forced by a category 5 hurricane. Storm surges in the Caribbean are primarily caused by tropical storms and stationary cold fronts intruding the basin. However, the seasonal signal and meso-scale eddies also contribute to the creation of extremes. The five stations that have more than 20 years of data show significant trends in the extremes suggesting that flooding events are expected to become more frequent in the future. The observed trends in extremes are caused by mean sea level rise. There is no evidence of secular changes in the storm activity. Sea level return periods have also been estimated. In the south Colombian Basin, where large hurricane-induced surges are rare, stable estimates can be obtained with 30 years of data or more. For the north of the basin, where large hurricane-induced surges are more frequent, at least 40 years of data are required. This suggests that the present data set is not sufficiently long for robust estimates of return periods. ENSO variability correlates with the nontidal extremes, indicating a reduction of the storm activity during positive ENSO events. The period with the highest extremes is around October, when the various sea level contributors' maxima coincide.

1. Introduction

Sea level extremes can cause significant economic losses, threaten human welfare, and enhance erosion. It has been anticipated that globally coastal flooding will increase in the future primarily as consequence of mean sea level rise while changes in storminess may affect also some regions [*Church et al.*, 2013]. While big storms are normally blamed for the devastation of coastal floods, in reality, sea level extremes are produced by a combination of different sea level components operating at various frequencies. Thus, when a large storm surge coincides with spring tides extreme sea level occurs. When the seasonal sea level cycle is at its maximum the high extremes are produced even if the storm surge component is submaximum.

Tropical cyclones can be particularly devastating. In areas where they prevail, they are the primary cause of extremes [*Feng and Tsimplis*, 2014; *Grinsted et al.*, 2012]. Theoretical and dynamical modeling studies suggest that their intensity is expected to increase between 2 and 11% by 2100 under greenhouse warming [*Knutson et al.*, 2010]. In relation to changes in the frequency, the models suggest an overall reduction, which is accompanied by an increase in the frequency of the most intense tropical cyclones [*Grinsted et al.*, 2013; *Knutson et al.*, 2010]. This complicated prediction differs significantly among the various models.

Observational studies also give a complicated picture. While a number of studies [*Emanuel*, 2005; *Kuleshov et al.*, 2008; *Webster et al.*, 2005] suggest significant increases in extreme tropical cyclone activity since the 1970s, in terms of occurrence, intensity and lifetime, the significance of such trends has been disputed due to the heterogeneity of the available tropical cyclone data which may introduce artificial trends [*Landsea*, 2007], and the large interdecadal variability in tropical cyclone activity [*Chan*, 2006].

Pugh [1987] suggests that in tropical areas classical extreme value theory is unable to calculate return levels accurately due to the influence of few large events dominated by intense tropical cyclones. For areas where most of the largest events are due to tropical cyclones, *Feng and Tsimplis* [2014] show how such estimates can be made and the large variance these estimates include. An alternative approach is to develop an observationally based stochastic tropical cyclone model used to generate a large synthetic event set [*Church et al.*, 2006; *Haigh et al.*, 2013; *McInnes et al.*, 2003].

The Caribbean Sea basin is located in the tropical region, and extends meridionally from ~7°N in the South Colombian Basin to ~23°N in the Cayman Sea (Figure 1a). Hurricane risk varies significantly [*Pielke et al.*,

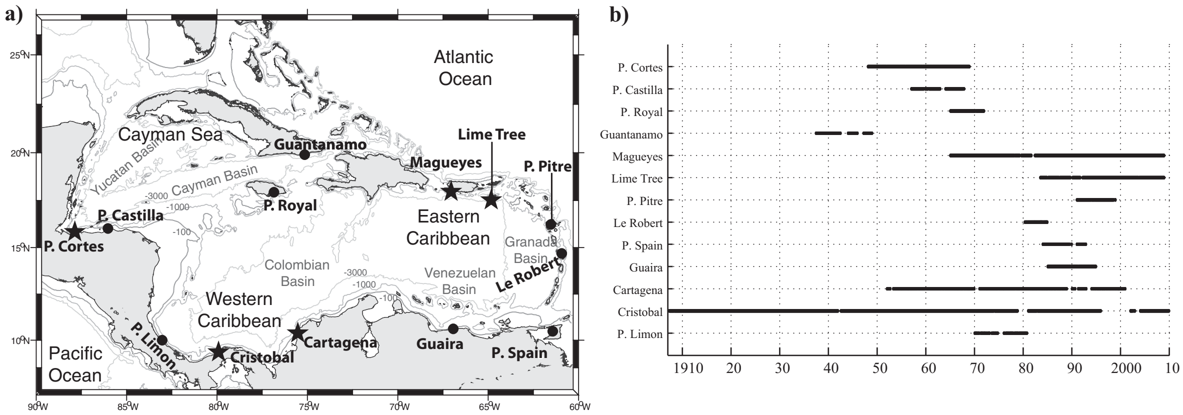

Figure 1. (a) Location of the tide gauges and bathymetry. Positions of tide gauges are marked by black circles and stars when the length of record > 20 years. Contours for 100, 1000, and 3000 m bathymetry. (b) The quality controlled hourly tide gauge data available in the Caribbean Sea.

2003], because tropical storm activity has large spatial and temporal variability [*Klotzbach*, 2010]. Due to the diminution of the Coriolis force close to the equator, any tropical cyclones passing toward the south of the basin are weak. South of 10°N there is less than 1% chance of a hurricane strike per year [*Pielke et al.*, 2003]. Thus, hurricane-induced storm surges are more relevant to the northern part of the Caribbean basin.

In addition to tropical cyclone, cold-front passages in the winter season also produce intense weather events [*Mooers and Maul*, 1998]. The effect of the fronts is to increase and shift surface winds to the north-northwest. Stationary cold fronts can produce storm surges large enough to cause sea flooding and affect the coastal morphology in the south-western Caribbean [*Andrade et al.*, 2013; *Lerma et al.*, 2008].

The Caribbean Sea is an eddy-rich region [*Chelton et al.*, 2007] where eddies can generate sea level anomalies in the order of few decimeters [*Alvera-Azcarate et al.*, 2009; *Andrade and Barton*, 2000], while the tidal contribution is small [*Torres and Tsimplis*, 2011]. Mesoscale eddies have been reported to be a main contributor to sea level extremes events at places where sea level variations are small [*Firing and Merrifield*, 2004]. In the Caribbean Sea, these eddies vary in diameter (~200 km), frequency of occurrence (~3 months), and propagation speed [*Jouanno et al.*, 2008; *Richardson*, 2005]. Their generation and growth have been proposed to be mainly due to the instability of the main Caribbean currents [*Jouanno et al.*, 2009].

Only a few studies on extreme sea levels have been published for the Caribbean Sea. Return periods for Cartagena and two other sites in the Colombian coast were calculated by *Torres et al.* [2008]. Their study analyzed observed sea level and nontidal residual but ignored the changes in mean sea level. *Lerma et al.* [2008] analyzed 50 years of extreme sea levels and the associated flooding risks at Cartagena. *Andrade et al.* [2013] assessed the flooding hazard at Cartagena. They did not find the risk of flooding related to the local meteorological conditions and suggested it was related to swell. Thus, a comprehensive study of sea level extremes in the Caribbean Sea has not yet been published.

In this paper, sea level extremes in the Caribbean Sea are assessed from hourly records obtained from 13 tide gauge stations covering the entire basin (Figure 1a). First, we describe the data used and the methodology followed (section 2). Results are presented in section 3. The spatial distribution of sea level extremes in the Caribbean Sea is described based in the observed values and projected return levels using classical extreme value theory. The temporal variation of the sea level and nontidal extremes is explored—an issue on which there is not any published information for this region. We also assess the contributors to sea level extremes in the Caribbean Sea. In section 4, we summarize the results and present our conclusions.

2. Data and Methodology

Hourly observed sea level data from 13 tide gauges downloaded from the University of Hawaii Sea Level Center were used. Available time series were collected from different parts of the Caribbean Sea; most of them are short and cover different periods of time with lack of common periods (Figure 1b). Four stations

Table 1. Span Years, Data Availability, and 98% Quantiles of the Observed Sea Level, the Tidal and Nontidal Residual in the Tide Gauge Records Used in This Study[a]

			Observed Sea Level				Nontidal Residual			
Station	Span Years	Percent of Data	98%	Mean	Std	Tide 98%	98%	Mean	Std	98% Tide/Res
Guantanamo	12	72.1%	73.5	39.8	3.0	51.9	36.3	19.6	2.4	1.4
Magueyes	44	97.0%	55.7	29.6	9.6	34.1	41.5	23.3	12.7	0.8
P. Royal	7	98.7%	57.9	35.9	4.7	35.6	40.4	19.7	3.4	0.9
Lime Tree	26	93.7%	54.6	32.8	11.2	37.7	33.3	26.1	13.7	1.1
P. Pitre	8	95.6%	63.8	33.4	5.0	47.5	36.5	22.6	6.4	1.3
P. Castilla	11	80.9%	57.9	35.9	4.1	33.4	40.0	27.2	4.5	0.8
P. Cortes	21	98.7%	59.3	29.9	3.8	29.9	40.5	23.5	3.6	0.7
Le Robert	5	84.4%	82.4	40.1	1.7	68.2	32.0	16.9	2.6	2.1
P. Spain	9	74.7%	126.3	68.9	5.6	111.5	57.6	31.2	6.9	1.9
Guaira	10	96.9%	67.1	41.8	5.6	46.1	48.8	26.9	3.6	0.9
Cartagena	49	84.0%	67.6	38.2	3.4	44.1	46.9	19.9	3.4	0.9
P. Limon	11	66.2%	61.1	38.4	3.8	49.2	44.5	19.8	1.7	1.1
Cristobal	103	89.8%	63.4	38.1	4.2	49.8	40.7	18.6	3.8	1.2

[a]The average of the annual maxima (Mean) and its standard deviation (Std) are presented in cm for the observed sea level and nontidal residual. These values and percentiles were computed from the time series after the annual mean was removed. The 98% percentile ratio between the tide and nontidal residual is included (98% Tide/Res).

have less than 10 years of data (Table 2). If such a study had taken place in a data-rich area such records would have been excluded from analysis. However, we will use the data from these stations to check in particular the spatial distribution of extremes and explore the causation of the extremes at each station. Five of the stations have records longer than 20 years, which permit the study of the temporal variability of the sea level extremes. The time series were described in detail by *Torres and Tsimplis* [2011]. However, the Cristobal record has been further extended to 2009 (Figure 1b). Table 1 shows the time span covered and the percentage of valid data after the quality control process. Quality control tests were performed both on the observed hourly data and on the nontidal residuals in order to remove any spurious values. At Cristobal, the values of 1997 and at Cartagena, the values for 1970 and 1993 were removed from the record due to datum errors. Inspection of the hourly data was also used to identify the effect of tropical storms (http://weather.unisys.com/hurricane/atlantic/) in the coastal sea level associated to larger extremes at each station, and to compare the sea level extremes at neighbor stations forced by the same storm.

The observed sea level ($X(t)$) result from the combination of the mean sea level variability ($Z_0(t)$), the tide ($T(t)$), and the meteorological surge ($S(t)$) produced by changes in atmospheric pressure and forces due to wind stress [*Pugh*, 1987]:

Table 2. GEV Parameters for Annual Maxima Method (r = 1), Maximum Observed Extremes, and Predicted Return Levels[a]

	GEV Parameters			Observed Sea Level					
Station	Shape	Scale	Location	Yr	Maximum Extreme	Return Level	Diff	50 year Return Level	100 year Return Level
Cristobal	−0.01	3.2	36.2	94	54.1	51.2	2.9	49.1	51.4
Cartagena	0.26	3.3	37.0	46	45.6	44.9	0.7	45.0	45.7
Magueyes	−0.33	3.9	25.4	44	71.2	54.4	16.8	56.2	67.1
Lime Tree[b]	−0.49	4.4	27.0	26	65.6	62.1	3.5	79.0	103.8
P. Cortes[b]	0.44	4.0	28.8	21	36.4	35.5	0.9	36.2	36.6
Guantanamo[b]	0.07	2.4	38.5	10	45.9	43.6	2.3	46.9	48.2
P. Castilla[b]	0.19	3.6	34.4	10	42.4	40.9	1.4	44.2	45.4
Guaira[b]	0.15	4.8	39.6	10	53.4	48.9	4.5	54.0	55.8
P. Limon[b]	0.56	4.0	37.6	10	43.9	42.7	1.1	44.0	44.2
P. Pitre[b]	0.59	5.3	32.4	8	40.2	38.6	1.5	40.5	40.8
P. Spain[b]	−0.28	3.4	65.9	8	79.4	75.1	4.2	90.0	97.8
P. Royal[b]	−0.28	2.6	33.5	7	45.4	40.0	5.4	52.1	58.2
Le Robert[b]	0.47	1.6	39.7	5	42.3	41.4	0.8	42.5	42.7

[a]For the observed sea level time series: length of the time series in years (Yr); maximum extreme value; predicted return level for the years in the time series (Return Level); and the difference between the maximum observed extreme and the return level (Diff). Last three values in cm. The 50 and 100 year return levels in cm are included.
[b]Stations at which return levels are unstable due to the shortness of the time series.

$$X(t)=Z_0(t)+T(t)+S(t) \tag{1}$$

Mean sea level varies at different frequencies:

$$Z_0(t)=\overline{Z_0}+at+W_{inter}+C_1+C_2+W_{intra}+e(t) \tag{2}$$

this equation includes the long-term mean sea level $\overline{Z_0}$; a linear secular trend a; interannual variability W_{inter} for changes in periods longer than a year not resolved by the trend; C_1 and C_2 for the annual and semiannual cycles; the intra-annual variability W_{intra} for changes in periods longer than 15 days but shorter than a year, not including the annual or semiannual periods; and $e(t)$ accounting for measurement errors and others terms not included in the equation. If the annual mean sea level computed from calendar years is removed from the observed sea level time series, the interannual variability and mean sea level trends contributions are removed. Furthermore, if the tidal signal is also removed, a nontidal residual is generated. This nontidal residual includes the storm surge contribution as well as the mean sea level variability contribution in the intra-annual frequencies including the seasonal cycle. Therefore, the spatial distribution of sea level extremes is assessed from: the observed sea level values; the observed sea level values after the annual mean sea level removal; and from the nontidal residual.

The tidal component was estimated on the basis of the t_tide software package [*Pawlowicz et al*., 2002], performed over each calendar year with the phase lag relative to Greenwich Mean Time-GMT. The tidal signal is then estimated on the basis of most important tidal constituents at each station; M_f, Q_1, O_1, P_1, K_1, M_2, and S_2 were included in all the stations. The hourly nontidal residual is then calculated by subtracting the tidal component from the observed sea level. Years with less than 50% of valid data were omitted from the analysis. The annual (S_a) and the semiannual (S_{sa}) constituents were omitted for the tidal prediction because they are primarily meteorological in nature. Thus, the seasonal sea level variability is included in the nontidal component.

The effect of the seasonal cycle on the nontidal annual maxima extremes distribution is assessed by removing the mean annual and semiannual cycles found by *Torres and Tsimplis* [2012] from the hourly nontidal residual. This was performed at all stations except Le Robert, where the effect of the seasonal cycle was not assessed due to the shortness of the observational record.

There are several methods for estimating the probability of occurrence of extremes. The R-Largest direct Method (RLM) [*Smith*, 1986], an extension of the classical Annual Maxima Method (AMM) for extreme value theory [*Gumbel*, 1958] is used here. It uses the "r-largest values (extremes) per year-(r)" from the observed sea level data to estimate the parameters of the Generalized Extreme Value (GEV) distribution where the family of extreme value distributions $G(x)$ is:

$$G(x)=exp\left\{-\left[1-k\frac{(x-\mu)}{\sigma}\right]^{\frac{1}{k}}\right\}$$
$$1-k\frac{(x-\mu)}{\sigma}>0 \quad \text{for} \quad \mu,\sigma>0 \tag{3}$$

where μ, σ and k are the location, scale, and shape GEV parameters, respectively. When $k=0$ it is called the Gumbel distribution (Type 1), when $k<0$ it is called Type 2 (Fréchet), and when $k>0$ it is called Type 3 (Weibull) extreme value distribution. The maximum likelihood statistical technique was used to obtain these parameters with the associated 95% confidence intervals found by the "delta method" [*Coles*, 2001]. The return level x_p with probability p can be obtained from [*Tawn*, 1988]:

$$x_p=\mu+\frac{\sigma}{k}\left\{1-[-log(1-p)]^k\right\} \tag{4}$$

the 95% confidence intervals for the return levels were obtained from equation (4) using the GEV parameters confidence limits. This theory requires the observations within the year to be independent. To ensure that the r-largest values are produced by different storms (independent values), a storm length of 72 h was used. This storm length was selected after the sea level time series inspection during the quality control process.

To assess the sea level return periods, the sea level observations were preprocessed by subtracting the mean sea level trend. *Haigh et al*. [2010] found that this is the most appropriate method to handle the trends to estimate return levels at sites with less than 50 years of data in the English Channel. This approach seems to be reasonable for the Caribbean Sea, as *Torres and Tsimplis* [2013] showed that at least 40 years of data are needed in order to obtain stable coastal mean sea level trends in the region; thus, sea level return periods computed form shorter periods will be affected by trends' temporal variability. In the Caribbean, only Cristobal has records longer than 50 years (Table 1). As return periods are used to determine coastal structures design levels, mean sea level trends can be included at the design stage.

Percentiles were computed by ranking the hourly data in ascending order and looking for the value that corresponds to the particular level. The 98% percentile was estimated from the observed sea level, tide, and nontidal residual using the entire time series to compare the variation range of these components at the 13 stations. Annual percentiles from the observed sea level and nontidal residual were estimated in the five stations with over 20 years of data to assess the temporal variability and trends in the extremes. Trends were estimated by linear regression and 95% error corresponds to the statistical uncertainty of a trend. The extremes interannual variability was correlated with the North Atlantic Oscillation (NAO) index [*Jones et al*., 1997], downloaded from http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm and the El Niño Southern Oscillation (ENSO) indices (ERSST.V3B) with the base period 1981–2010 (http://www.cpc.ncep.noaa.gov/data/indices/). They include: Niño 3 (5°N–5°S; 90°W–150°W); Niño 4 (5°N–5°S; 160°E–150°W°); and Niño 3.4 (5°N–5°S; 120°W–170°W). Niño 3 indicates a mature phase (cool or warm) of ENSO in the eastern Pacific [*Enfield and Mayer*, 1997]; and Niño 4 has a relatively weak response to El Niño [*Hanley et al*., 2003]. The significance of the correlations was computed by the bootstrap method at a 99.9% confidence level from 5000 iterations.

To assess the contribution of mesoscale eddies to sea level extremes, weekly Maps of Absolute Dynamic Topography (DT-MDAT) covering the 1993–2010 were used. These "Reference" series were produced by SSALTO/DUACS and distributed by AVISO with support from CNES. The data set combines fully processed data from various altimetric missions (Topex/Poseidon, ERS-1/2, Jason-1, Envisat, and OSTM/Jason-2) on a 1/3° global Mercator grid. The product is corrected for ocean tide, pole tide, S_1–S_2 atmospheric tides, solid earth tide, loading tide, and inverse barometer effect, amongst others. The mean, trend, and seasonal cycle were removed from the altimetry data fitting a regression model.

3. Results and Discussion

3.1. Spatial Distribution of Sea Level Extremes

The maximum observed sea level values range between 38 and 83 cm (Figure 2a). There is little spatial coherency. This is partly due to the different periods for which observations exist (Figure 1b). The existence of significant mean sea level trends, with large spatial and temporal variability in the Caribbean [*Torres and Tsimplis*, 2013], is expected to influence the spatial comparison of the observed extremes especially because the record span varies between 5 years in Le Robert and 103 years in Cristobal (Table 1).

After the annual mean is removed, extremes are due to the combination of the tide, the storm surge, and mean sea level variability at intra-annual frequencies. The maximum extreme values found (Figure 2b) range between 36 and 79 cm. The largest value is found in P. Spain. A significant part of the large extreme at this station is due to the tidal component (Table 1) which is larger at the boundaries between the Caribbean and Atlantic [*Torres and Tsimplis*, 2011]. Note the importance of mean sea level change for the maxima estimated at stations with large trends such as Cartagena, where the maximum observed sea level in a 49 year period (66 cm in Figure 2a) is 20 cm smaller after the mean sea level contribution at interannual frequencies is removed (Figure 2b).

The range of the maxima values after the removal of the annual mean and the tidal signal (nontidal residual) is between 20 and 76 cm (Figure 2c). However, with the exception of the tide gauges located at the east part of the Caribbean basin, the observed maxima in the nontidal residuals range between 23 and

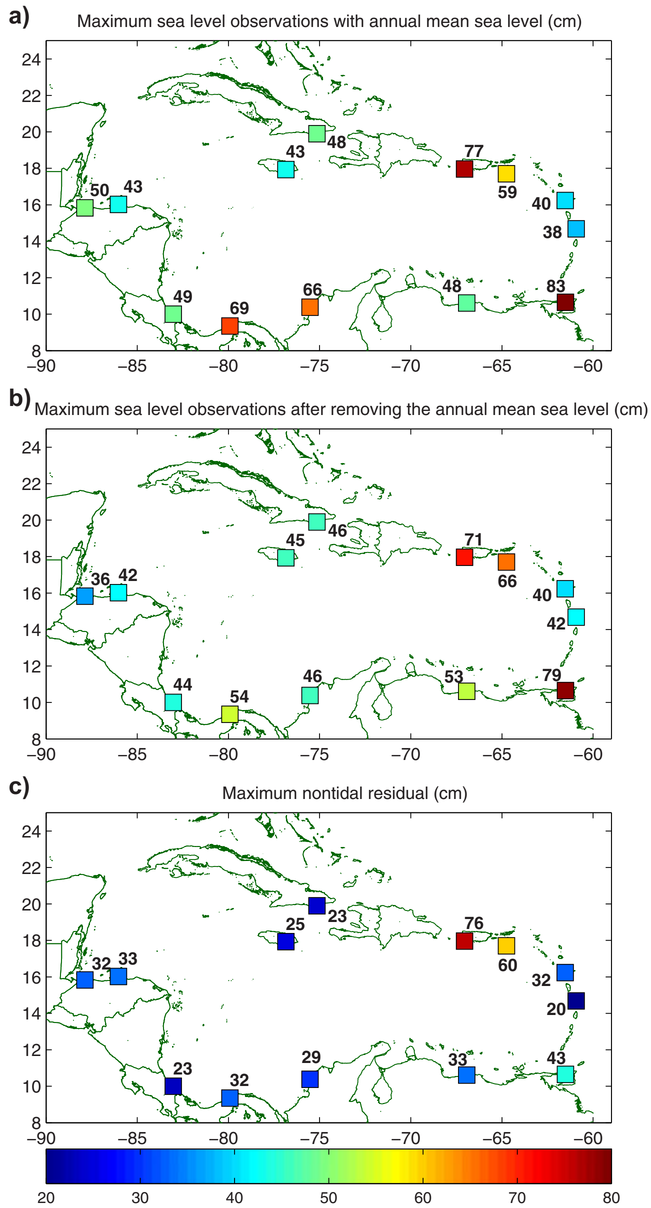

Figure 2. (a) Maximum sea level observations referenced to the mean sea level of the first year of the time series. (b) Maximum sea level observations after removing the annual mean sea level. (c) Maximum sea level observations after removing the annual mean sea level and tidal signal (nontidal residual). Values in centimeter.

33 cm. Thus, despite the different periods covered by the available observations in different parts of the basin there is spatial coherency.

The largest nontidal residual in Magueyes is 76 cm; it is 1 cm smaller than the observed value and 5 cm larger than the largest observed sea level extreme after the removal of the mean sea level trend. This extreme was forced in 1979 by the category 5 hurricane David, which passed south of Magueyes. The maximum of the storm surge coincided with low tide and thus its impact was not as pronounced as it would have been if the passage coincided with spring tide. The second largest nontidal station maximum is at Lime Tree (60 cm) and it was forced in 1989 by hurricane Hugo (category 4). The third largest nontidal station maximum is at P. Spain (43 cm); however, it is not associated to a tropical cyclone. P. Pitre is the only other station where the nontidal maximum (32 cm) is forced by a hurricane (category 1 Marilyn in 1995). The maxima nontidal residuals in the other stations are about half the maximum values in Magueyes and Lime Tree.

The reason why large hurricane-induced nontidal extremes are found only in Magueyes and Lime Tree is because the other stations placed in the tropical cyclones favored tracks [*Reading*, 1990] have short records. Shorter time series are less likely to record large hurricane-induced surges due to the large annual variability in the number of tropical cyclones which affect the area. In the Caribbean, there are some years without any named storm activity and others with up to 15 named storms getting through the basin [*Klotzbach*, 2010]. In addition, the biggest effects of the surge are confined within a few tens of kilometers of the point at which the hurricane makes the landfall [*Church et al*., 2006; *Pugh*, 1987]. The exact path followed, the intensity of the hurricane at the time of crossing, its propagation speed, and the topographic parameters at each particular location all play a role [*Zhong et al*., 2010]. Therefore, the storm surge generated by a hurricane crossing the Caribbean basin will be recorded only at some tide gauges.

For example, in September 1989, hurricane Hugo forced a nontidal extreme of 60 cm at Lime Tree when it passed close to this station as a category 4 hurricane. Twenty-one hours later the same hurricane was classed category 3 and passed 143 km away from Magueyes causing a sea level signal of 35 cm. The distance between Lime Tree and Magueyes is 246 km. For Cristobal and Guaira, the other two stations for which data are available for the same period, no evidence of a storm surge is found. Thus, even powerful hurricanes do not produce basin-wide storm surges in the Caribbean Sea.

Guantanamo, P. Royal, P. Pitre, and Le Robert are within the favored tropical cyclone path in the basin [*Reading*, 1990]. Guantanamo (Cuba) and P. Royal (Jamaica), in particular, are known to have a larger probability to be affected by tropical cyclones than Magueyes (Puerto Rico) [*Klotzbach*, 2010]. However, they have smaller maximum nontidal residuals than those from Magueyes and Lime Tree (Figure 2c) because no strong hurricane passed close to these stations over the short period of measurements (Table 1). Therefore, the distribution of maxima (Figure 2) is sensitive to the length and completeness of the data (Figure 1b).

Neighboring stations of Cristobal and Cartagena are situated in the southern boundary of the basin. They have long records of 94 and 46 years, respectively (Table 2); however, the nontidal maxima are about half the size of the maximum at Magueyes. Storm surges are smaller at these stations because they are located outside the favored tropical cyclone paths [*Pielke et al.*, 2003; *Reading*, 1990]. Similar results can be expected in all the southern boundary of the Colombian Basin.

However, even for these stations there can be some doubts on how representative are the available records with respect to extremes. For example, hurricane Joan passed on the 18th of October 1988 close to Cartagena. The record shows a maximum nontidal residual of 24.3 cm at 10:00 GMT when the hurricane was category 1. The hurricane was upgraded to category 2 on the 19th (00:00 GMT) when it was at a distance of 196 km of Cartagena, and to category 3 twelve hours later at a distance of 315 km from Cartagena. The winds were stronger than 100 knots for over 12 h. The Cartagena sea level record has a gap between 18 October at 12:00 GMT and 21 October at 20:00 GMT. It is likely that the largest surge was not recorded. It is unknown whether the gap in the record was due to malfunctioning of the instrument caused by the hurricane, due to false assessment under quality control or was unrelated to the hurricane.

The P. Cortes record has 21 years of data. The maximum nontidal residual (32.2 cm in 1962) is not linked to a tropical cyclone. In 1961, a nontidal residual of 31.7 cm, forced by the category 5 hurricane Hattie that passed less than 2° north of the station parallel to the coastline was recorded. Thus, at this station over the period of observations, surges generated by hurricanes were of the same order of magnitude to surges produced by other meteorological forcing. This is likely due to the east to west coastline direction, which reduces the hurricane-induced surges as most of them passed north of the station and parallel to the coast during the observational period (http://www.nhc.noaa.gov/climo/). However, tropical cyclones can make landfall perpendicular to the coasts of Central America in this area, which extends from the east to west direction (∼16°N). This was the case in 1998, when hurricane Mitch made landfall in Honduras producing over 10,000 deaths predominately from rain-induced flooding [*Pielke et al.*, 2003]. No sea level record is available.

3.2. Sea Level Return Periods

Sea level return periods can be estimated even from short records composed by a few number of years. However, the estimation of sea level return periods requires stationary time series, a requirement not met in reality due the natural variability of the sea level extremes forcing. It follows that long records, capturing most part of this variability are required for robust estimates of return levels. In this section, return levels for all stations are estimated and then their accuracy is discussed by examining in detail the role the length of the record plays in such estimates.

The 50 and 100 year return levels for observations were computed for the Annual Maxima Method ($r = 1$; Table 2). The 50 year return levels range between 36 cm in P. Cortes and 79 cm in Lime Tree. The 100 year return levels range 37–104 cm at the same stations. *Torres et al.* [2008] using a different methodology found for Cartagena's 50 and 100 year return level 49.1 and 49.8 cm, respectively, values higher but within the 95% error than the values shown in Table 2.

The sensitivity of the return levels to the number of extremes per year used is assessed. This is done by using the largest $r = 10$, $r = 5$, $r = 2$, and $r = 1$ annual values, respectively. With the Annual Maxima Method ($r = 1$), the average of the absolute difference in the 13 stations (hereinafter mean difference) between the maximum observed sea level value and the predicted return level for the same recorded period (column

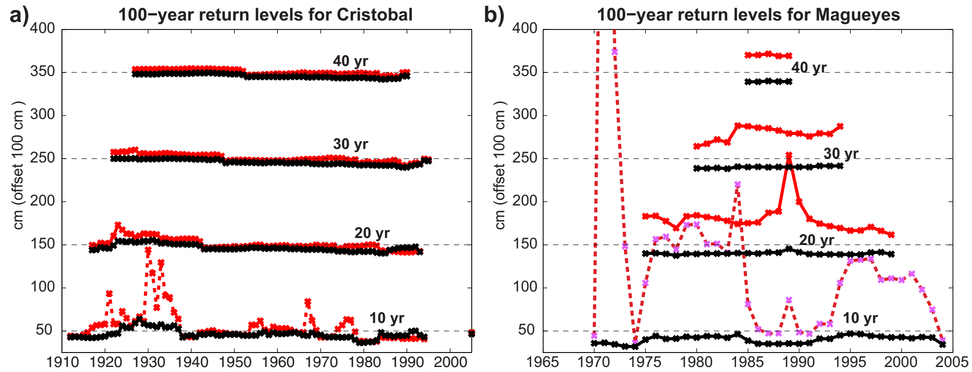

Figure 3. The 100 year return levels estimated using overlapping 10, 20, 30, and 40 year segments for (a) Cristobal and (b) Magueyes using Annual Maxima Method-AMM r = 1 (red) and R-Largest Method-RLM (black) with r = 5 extremes per year. Each curve above the 10 year segments has been offset by 100 cm.

"diff" in Table 2) is the smallest (3.6 cm). As the number of annual extremes (r) increases, the 95% error reduces (not shown) but the mean difference increases. When r = 2, the mean difference is 6.5 cm, when r = 5 the mean difference is 9.5 cm, and when r = 10 the mean difference is 11.9 cm. For example, in Cristobal with r = 1, the 94 year return level is 51 ± 12 cm, thus equal to the maximum observed sea level value in the same period (54 cm; Table 2). However, if r = 5 is used, the 94 year return level is 47 ± 4 cm, significantly lower than the observed value. Thus, it seems that the Annual Maxima Method yields better results than the R-Largest Method in the Caribbean Sea, suggesting that when two or more largest sea level values are used per year, from a statistical point of view, the data samples contain nonextreme values. Similar results were found when return levels were assessed from the nontidal residual with different number of extremes per year. The results found are not sensitive to changes in the storm length. We assumed that 72 h separation between extremes was required for the extremes to be independent.

To assess the fit of the observed annual maxima sea level extremes to the GEV model, quantile plots were used. A quantile plot is a graphical technique used to compare two probability distributions. Departures from linearity are indicative of model failure [*Coles*, 2001]. This seems to be the case in Magueyes and Lime Tree (Figure S1 in the supporting information), the two stations where large hurricane-induced surges were recorded, as the quantile plots have the largest differences between the model and empirical values in the upper quantiles (16 and 8 cm, respectively). The fit is good in all other stations. However, we believe that the good fit of the statistical model at the stations which are known to be regularly affected by tropical cyclones (Guantanamo, P. Royal, P. Pitre, and Le Robert) does not assure accurate return levels because of the shortness of the records and the fact that hurricane-induced surges were not captured over the available sea level record. At these stations, return levels (shown in Table 2) are probably underestimated.

The dependence of return sea level estimates to the length of record is assessed. We present the estimates for 100 year return levels using r = 1 and r = 5 extremes per year at two stations: Cristobal can be taken to represent the behavior in the South Colombian Basin; while Magueyes the performance in the Antilles, where hurricane-induced surges are more intense and frequent. Overlapping 10, 20, 30, and 40 year segments are used. The 100 year return sea levels estimated depend on the record length used (Figure 3). At Cristobal, return levels with r = 1 are only stable if more than 30 years are used (mean 100 year return level 50.5 cm). The downward trend that appears will be discussed later. At Magueyes, stable values with the annual maxima are obtained with time series at least 40 year long (mean 100 year return level 70.1 cm). When the five largest extremes per year are used (black lines in Figure 3), the range of the values obtained by using different parts of the record reduces in comparison with the Annual Maxima Method but they all indicate lower values. Thus, the R-Largest Method (RLM) provides more stable but smaller return levels. For example, in Magueyes, the maximum RLM 100 year return level is 47 cm when a 10 year segment is used; however, over the span of the data (44 years), the maximum observed sea level extreme is 71.2 cm.

Assuming that the results found at the two stations analyzed are representative for the whole region, it is concluded that when the Annual Maxima Method is used, the estimates of return levels acquired from the shortest tide gauge time series cannot be considered as stable as at least 30 or 40 years of data are required

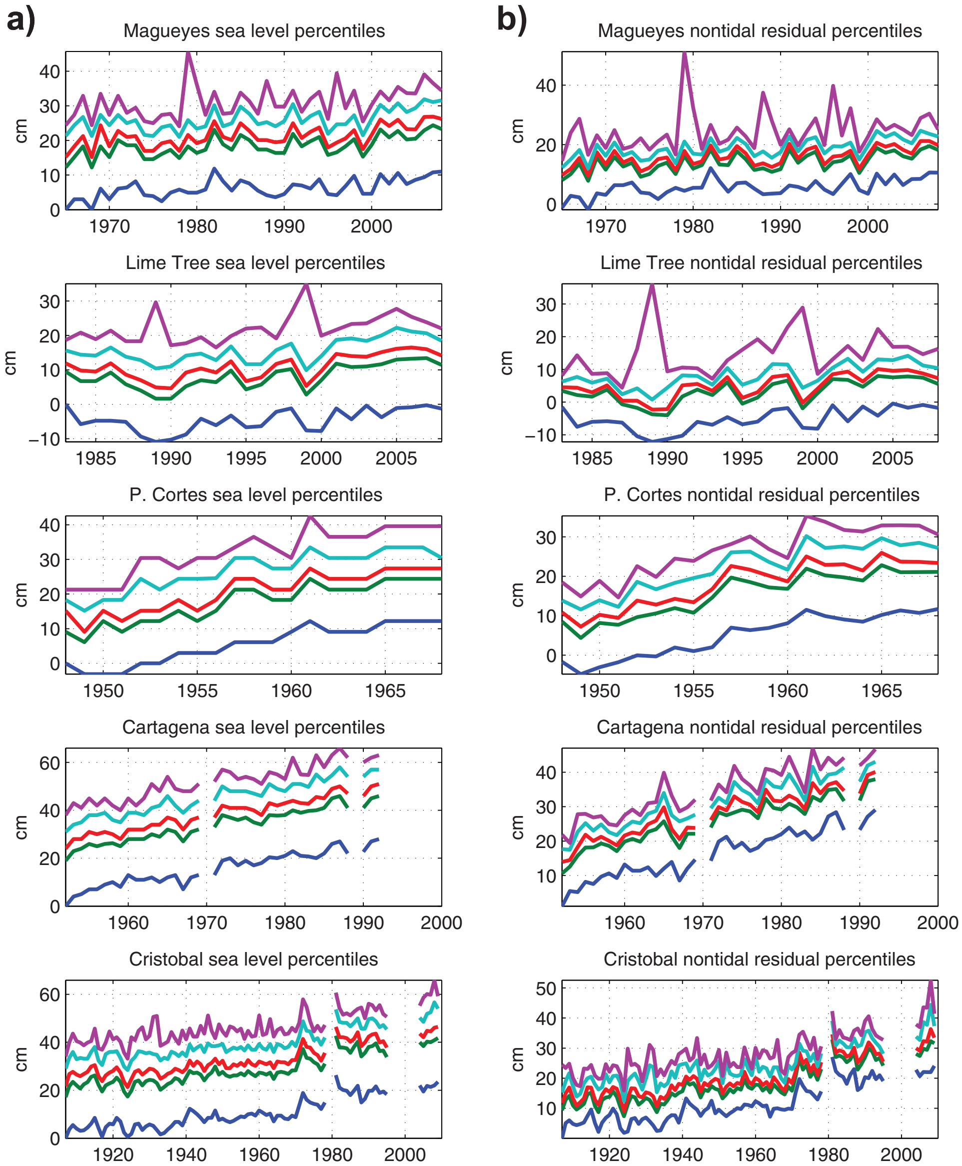

Figure 4. The 50th, 90th, 95th, 99th, and 99.9th percentiles from bottom to top in each plot, computed with (a) observations and (b) nontidal residuals in Magueyes, Lime Tree, P. Cortes, Cartagena, and Cristobal. Time series referenced to the first year mean sea level.

for stable results in the south or north of the basin, respectively. The error associated with the shorter stations can be estimated to be, on the basis of Figure 3 (red line) around 31 cm for stations in the south and as much as 92 cm for stations in the north of the basin when 20 years of data are available. When 10 years of data are used, the error is much larger. The estimates for Magueyes, Cristobal, and Cartagena are thus reliable while for the other stations it is impossible on the basis of the present data to provide accurate return levels. Besides, note that the quantile plot in Magueyes indicates the statistical model's failure. This means that the reliability of the return periods for this station is questionable.

3.3. Sea Level Extremes Temporal Variability

Temporal variability of the extremes is assessed for the records of Magueyes, Lime Tree, P. Cortes, Cartagena, and Cristobal, the five stations with over 20 years of sea level data. The 50th, 90th, 95th, 99th, and 99.9th sea level and nontidal residual percentiles are presented in Figure 4. For this assessment, only the 1951–1993 segment in Cartagena is used due to a lack of datum continuity with a shorter segment available for the period 1994–2000.

Table 3. Linear Trends and 95% Error of the 50th, 90th, 95th, 99th, and 99.9th Percentiles From the Five Stations With Over 20 Years of Data

	Sea Level Trends (mm yr^{-1})					Nontidal Residual Trends (mm yr^{-1})				
Station	50th	90th	95th	99th	99.9th	50th	90th	95th	99th	99.9th
Magueyes[a]	1.3 ± 0.5	1.5 ± 0.6	1.4 ± 0.6	1.3 ± 0.6	1.5 ± 1.0	1.4 ± 0.6	1.4 ± 0.6	1.5 ± 0.6	1.7 ± 0.6	1.3 ± 1.6
Lime Tree[a]	2.1 ± 1.6	2.9 ± 1.5	2.9 ± 1.5	2.9 ± 1.5	2.6 ± 2.1	2.6 ± 1.6	3.0 ± 1.6	3.1 ± 1.6	3.2 ± 1.4	2.7 ± 3.7
P.Cortes[a]	8.5 ± 1.3	8.9 ± 1.7	8.5 ± 1.8	8.4 ± 1.8	9.9 ± 2.2	8.4 ± 1.3	8.5 ± 1.7	8.6 ± 1.9	9.0 ± 1.9	9.1 ± 2.3
Cartagena[a]	5.6 ± 0.6	5.7 ± 0.5	5.8 ± 0.5	5.8 ± 0.5	5.8 ± 0.8	5.7 ± 0.6	5.4 ± 0.6	5.4 ± 0.7	5.5 ± 0.7	5.6 ± 0.9
Cristobal[a]	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2	1.9 ± 0.3	2.0 ± 0.2	2.0 ± 0.2	2.0 ± 0.2	1.9 ± 0.2	1.9 ± 0.3
	Sea Level Trends (mm yr^{-1})					Nontidal Residual Trends (mm yr^{-1})				
Station	50th	90th	95th	99th	99.9th	50th	90th	95th	99th	99.9th
Magueyes[b]		0.1 ± 0.3	0.0 ± 0.4	0.0 ± 0.4	0.2 ± 1.0		0.1 ± 0.4	0.1 ± 0.4	0.3 ± 0.4	0.0 ± 1.6
Lime Tree[b]		0.7 ± 0.7	0.7 ± 0.8	0.6 ± 1.0	0.3 ± 2.8		0.7 ± 0.9	0.8 ± 1.1	1.0 ± 1.2	0.4 ± 4.4
P.Cortes[b]		0.4 ± 1.0	0.0 ± 1.0	−0.1 ± 1.2	1.4 ± 1.9		0.0 ± 0.8	0.1 ± 0.9	0.4 ± 1.1	0.6 ± 1.5
Cartagena[b]		−0.1 ± 0.2	−0.1 ± 0.3	−0.1 ± 0.4	−0.1 ± 0.6		−0.1 ± 0.3	−0.2 ± 0.4	−0.1 ± 0.5	0.0 ± 0.6
Cristobal[b]		0.0 ± 0.1	0.0 ± 0.1	−0.1 ± 0.1	−0.2 ± 0.2		0.0 ± 0.1	0.0 ± 0.1	−0.1 ± 0.2	−0.1 ± 0.2

[a]Computed from the observed sea level and nontidal residual time series with annual mean sea level.
[b]Computed from the observed sea level and nontidal residual time series without annual mean sea level.

The 99.9th percentile shows larger variability than the lower percentiles. Interannual variations of the upper sea level percentiles are in general significantly correlated (coefficient >0.8) with mean sea level changes (50th percentile). The exception is the 99.9th percentile at Lime Tree, where the correlation coefficient is 0.09 and is statistically insignificant. We believe this to be due to the intermittent occurrence of hurricane-induced values. For the same reason in Magueyes, the 99.9th percentile has the smallest significant correlation with mean sea level (0.47).

Due to the poor time coverage and lack of common periods among the time series in the region (Figure 1b), we do not compare between stations. At each station, sea level and nontidal residual trends in the percentiles do not differ significantly (Table 3). Thus, the tidal signal in the Caribbean does not influence the linear trends of extremes or of any other of the trends in the percentiles used. In addition, the trends of the five percentiles assessed at each station are not statistically different. Therefore, the trends in the extremes (99.9th percentile) as well as the other percentiles are driven by mean sea level changes (50th percentile). This is true for all stations and all percentiles except the nontidal residual 99.9th percentile in Magueyes and Lime Tree (Figure 4b), which show insignificant trends. This is probably caused by the large hurricane-induced extremes which increase the variance and obscure the mean sea level trends effect on the extremes.

Significant positive trends (up to 9.9 ± 2.2 mm yr^{-1}) are found in the sea level extremes (99.9th percentile) at the five stations. Trends are computed from the available record at each station. Linear sea level trends of the 50th percentile vary between 1.3 ± 0.5 mm yr^{-1} in Magueyes and 8.5 ± 1.3 mm yr^{-1} in P. Cortes (Table 3), and in all cases are insignificantly different from the mean sea level trends found by *Torres and Tsimplis* [2013]. Differences in the trends among the stations are due to the different time periods covered by the records (Figure 1b) and the large spatial and temporal variability in the Caribbean mean sea level trends [*Torres and Tsimplis*, 2013].

In Figure 5, the 90th, 95th, 99th, and 99.9th percentiles from the sea level and nontidal residual, relative to the annual mean sea level are shown. These percentiles do not include the mean sea level variability. Cartagena's entire record (Figure 1b) is used in this case because the annual mean sea level is subtracted from each calendar year before computing the percentiles and as a result any datum discontinuity between years does not matter.

Observed sea level and nontidal residual extremes (99.9th percentile) without the annual mean sea level show large interannual variability (Figure 5). In general, sea level percentiles are higher than the nontidal percentiles as the former includes the tidal signal. The exceptions are the hurricane-induced extremes (Magueyes and Lime Tree) when the maximum surge occurred at low tide. Note the influence of the tidal nodal cycle in the Cristobal's sea level percentiles (Figure 5a), which does not appear in the nontidal percentiles as the tidal signal has been removed.

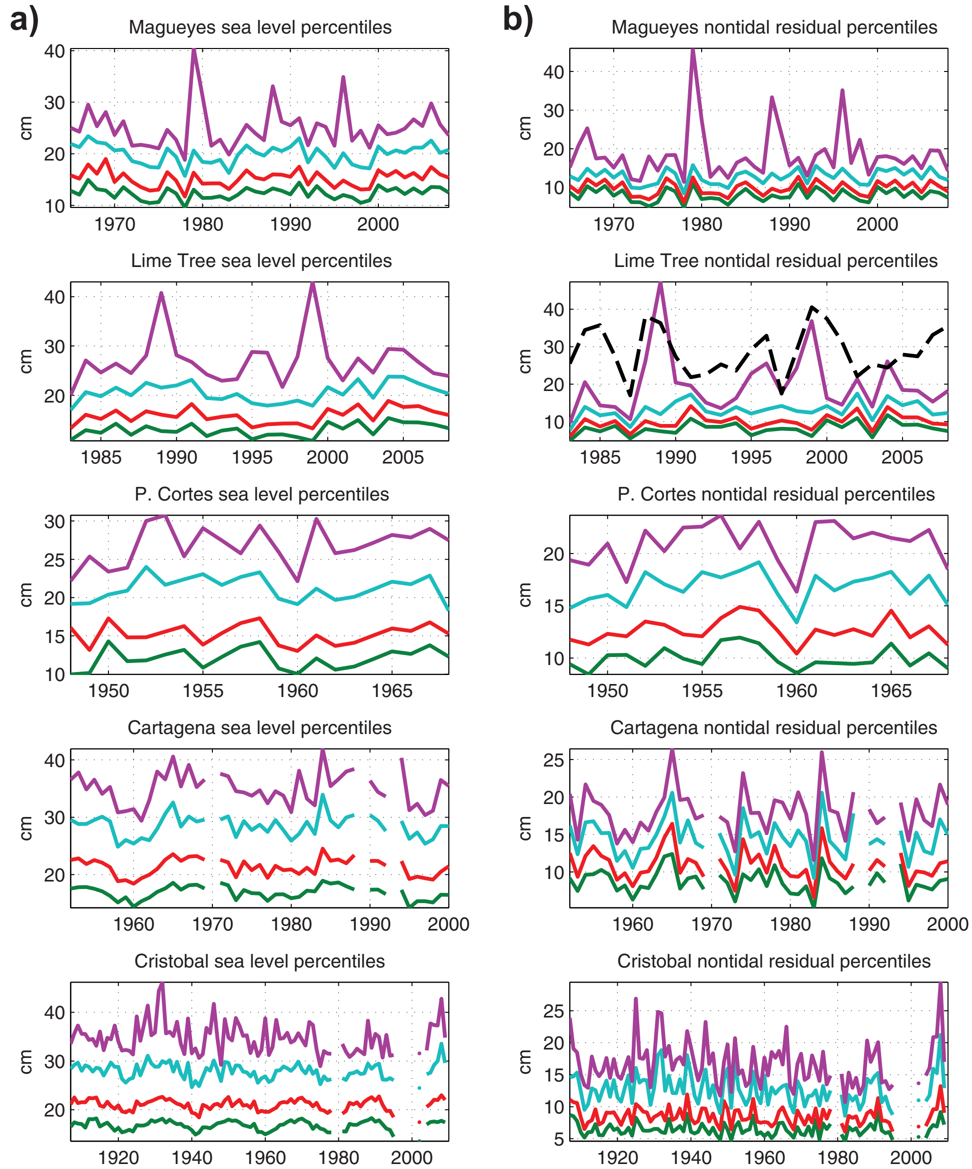

Figure 5. The 90th, 95th, 99th, and 99.9th percentiles from bottom to top in each plot, computed with (a) observations and (b) nontidal residuals in Magueyes, Lime Tree, P. Cortes, Cartagena, and Cristobal. Percentiles referenced to the annual mean sea level. Black dash line in Lime Tree nontidal residual corresponds to Niño3.4 times (−10) and 30 cm offset.

Linear trends have been estimated from the sea level and nontidal residual upper percentiles (Figure 5) to assess secular changes in extremes not related to mean sea level change (Table 3). Significant trends for the entire period are not found at any station regardless of the percentile used. However, Figure 5b shows a negative nontidal trend in Cristobal (-0.7 ± 0.4 mm yr^{-1}) for the period 1925–1995 in the 99.9th percentile. Smaller significant negative trends are also found in the 95th and 99th nontidal percentiles at the same station. Trends in the nontidal extremes are likely to be due to secular changes in the storm surges, as trends in the seasonal cycle were not found [*Torres and Tsimplis*, 2012]. If the annual mean sea level is not removed in Cristobal for this 71 year period (Figure 4), the upper nontidal residual percentiles show significant positive trends; thus, the mean sea level positive trend prevails over the negative trend in the nontidal residual.

The 99.9th percentile of the sea level record in Cristobal also shows a negative trend (-0.7 ± 0.4 mm yr^{-1}) for the period 1925–1995 (Figure 5a), probably as consequence of the significant trend in the nontidal residual percentile in the same period. Such reduction in the sea level extremes also explains the negative trend found in Cristobal's 100 year return levels (Figure 3a) because as the overlapping 20, 30, and 40 year segments move from left to right, smaller extremes became available in the observational segment which consequently produce smaller 100 year return level estimates.

The nontidal residual 99.9th percentiles (Figure 5b) from the five stations were correlated with climatic indices to assess the relation between the extremes and climate variability. No correlation with the NAO was found. Significant correlations (~ -0.5) are found at Lime Tree with Niño 3 and Niño 3.4 (Figure 5b). A significant correlation (-0.3) is found in Cartagena's 99.9th percentile with Niño 4, where all ENSO indices used show significant correlation (~ -0.4) with the 99th percentile. Negative correlation between the ENSO index and the cyclone activity was reported by *Klotzbach* [2010]. *Torres and Tsimplis* [2013] found a positive correlation between interannual sea level variability and ENSO with a time lag of 3 months. Thus, a positive phase of ENSO seems to be related to an increase in the mean sea level but to a decrease in the extremes at two of the stations assessed in the Caribbean Sea. The lack of a significant relationship between ENSO indices and nontidal extremes at the other stations is probably because the 99.9th nontidal residual percentile variability do not indicate exclusively and accurately the cyclone activity variability in the basin due to two reasons: first, nontidal extremes result from the combination of storm surge, the seasonal cycle and eddies (section 3.4), and not only from hurricane-induced surges; second, as discussed in section 3.1, large hurricane-induced surges are not frequently recorded in the available time series in the basin.

3.4. Nontidal Extremes Contributors

When a powerful hurricane crosses nearby a station, it will generate a large sea level extreme distinguishable from any other extremes in the tide gauge record (e.g., Magueyes or Lime Tree 99.9th percentile in Figure 5). Detailed inspection of the hourly time series during the quality control process showed that hurricane-induced surges, recorded at the tide gauges, are not always large enough to become the annual maxima nontidal extreme. Thus, for most years when no large hurricane-induced surges happen, nontidal extremes are caused by a combination of various other contributing components.

Extremes in nontidal residuals result from the combination of: (i) the seasonal sea level cycle; (ii) storm surges due to atmospheric pressure and wind effects on sea level; and (iii) eddies. Tsunamis or seiches can also produce extreme values but these will not be discussed in this paper.

3.4.1. Sea Level Seasonal Cycle

The annual maxima nontidal extremes distribution through the year, before and after removing the mean seasonal cycle is shown at 12 stations in Figure 6 (black and light ochre bars, respectively). The largest occurrence of annual maxima nontidal extremes in the Caribbean Sea is from August to November (black bars in Figure 6). This is partially due to the seasonal cycle contribution, which peaks in the second part of the year especially during September and October [*Torres and Tsimplis*, 2012]. The distribution of the annual maxima extremes through the year after the seasonal cycle has been removed is more uniform. This indicates the significant contribution of the seasonal cycle to the annual maxima in the Caribbean Sea. For example, in Cartagena, after the seasonal signal is removed, the annual extremes distribution shifts from September, October and November (black bars in Figure 6) to January and February (light ochre bars).

The removal of the seasonal cycle reduces the maximum nontidal residual at 10 of the 13 stations shown in Figure 2c. The largest reduction is 8.5 cm in P. Pitre. The removal of the seasonal cycle also reduces at all stations the average annual nontidal residual maxima. For example, in Cartagena, the average of the 46 annual maximum values reduces by 3.3 cm from 19.9 cm (Table 1) to 16.6 cm when the seasonal cycle is removed.

3.4.2. Storm Surges

In Figure 7, nontidal records of storm surges produced by a hurricane and by a cold front in the Caribbean are shown. The hurricane David (1979) storm surge recorded at Magueyes the 31 August is the largest nontidal residual recorded in the time series used in this study (76 cm in Figure 2c). Note the steep rise and drop of the large nontidal residual. By contrast, the maximum nontidal residual in the 94 years assessed at Cristobal is much smaller (32.1 cm); it took place the 22 November 2008 and it is not linked to a tropical cyclone but to a cold front intrusion which was tracked and reported by local and regional meteorological agencies. The position of the cold front in the Caribbean Sea can be inferred from the GOES-12 infrared image (Figure 7); it was located in the boundary between the low pressure (observed cloudiness) in the Western Caribbean and the cloud-free area in the Cayman Sea.

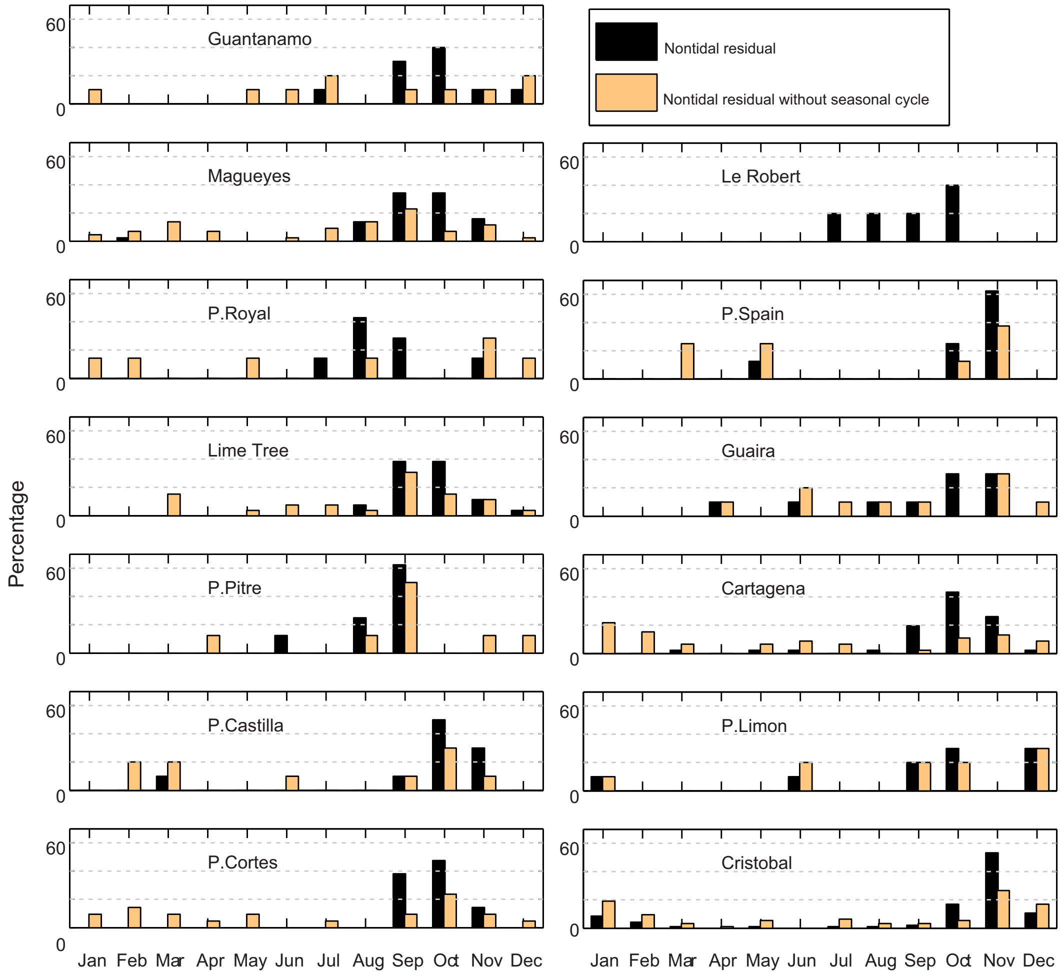

Figure 6. Annual maxima nontidal distribution through the year (black bars) and after the mean seasonal cycle has been removed (light ochre bars). It shows the percent of annual maxima occurrence in each month.

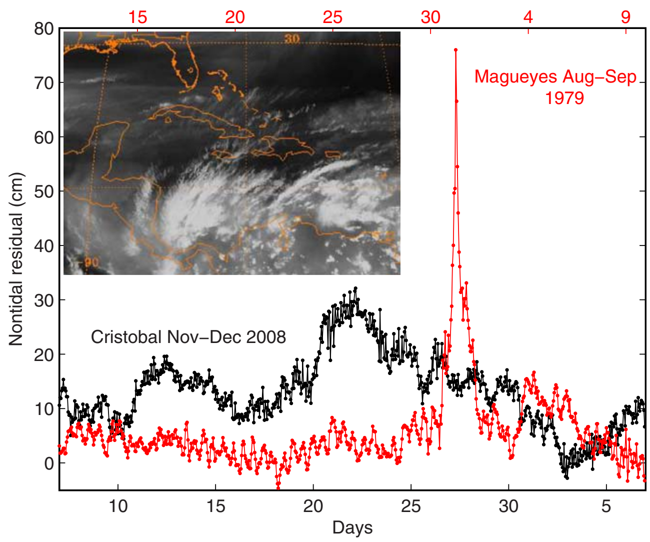

Figure 7. Nontidal residual time series referenced to the annual mean sea level from Magueyes (red) in 1979 (16 August to 14 September); and Cristobal (black) in 2008 (7 November to 6 December). Section of the GOES-12 IRWVP (5.72–7.34 μm) image from 21 November 2008 at 17:45 UTC is included.

Once the seasonal contribution has been removed, the distribution through the year of the annual nontidal residual extremes (Figure 6) can give information about the prevailing type of meteorological event that caused them at each station. Cold fronts move over the basin from October to March but it is primarily between January and March, when they can become stationary [*DiMego et al*., 1976], that they become more likely to produce large storm surges. The hurricane season is from June to November, with a peak from mid August to late October (National Hurricane

Center—http://www.nhc.noaa.gov/climo/). Note that the hurricane season coincides with the peak of the seasonal contribution (September-October), while the months with large probability of stationary cold fronts coincide with the seasonal trough (January-March) [*Torres and Tsimplis*, 2012].

At Magueyes and Lime Tree, after the seasonal correction, the mode of the distribution of the annual nontidal extremes is September (ochre bars in Figure 6), indicating the prevalence of tropical cyclones in the forcing of annual nontidal extremes. By contrast, at P. Cortes and Cartagena, annual nontidal extremes from January to March become more frequent after removing the seasonal cycle, indicating a contribution of large surges induced by cold fronts. Nontidal extremes that occur in October and November may be forced by either tropical cyclones or cold fronts.

3.4.3. Eddies

Figure 8 shows the eddy-related sea level variability at two stations: P. Pitre in the Lesser Antilles and Magueyes in the Greater Antilles (Figure 1a). The positive (red) or negative (blue) Sea Surface Height-SSH variations in the Hovmoller diagrams (Figures 8a2 and 8b2) and regional view (Figures 8a3 and 8b3) are mainly due to anticyclonic-cyclonic eddies, respectively. The trend and the seasonal cycle have been removed from the weekly altimetry time series.

At P. Pitre's longitude (61.3°W), the RMS varies between $\pm$4 cm across all latitudes (Figure 8a4). The range, which is the difference between the maximum and the minimum weekly SSH, is around 30 cm. At Magueyes' longitude (67°W), there is larger variability both in the range and the RMS (Figure 8b4); however, at Magueyes' latitude (18°N), the range is $\sim$30 cm. The eddy-related variability calculated near to Port Royal (not shown) has a range of 40 cm. Note that the SSH range in the open sea, nearby to these stations, is of the same order of magnitude of the tide, and nontidal residual 98% percentile (Table 1); thus, the sea level variability induced by eddies can be an important contribution to the annual nontidal extremes in the Caribbean Sea when coincides with positive anomalies in the other sea level components. Such contribution at intra-annual scales seems to vary from offshore to the coast and from one station to the other (Figure 8). Altimetry measures sea level accurately at distances larger than 30 km from the coast. Thus, the suggestion made depends on whether the signal measured by altimetry is the same as that measured at the tide gauge.

Figures 8a1 and 8b1 compare the sea level time series from the nearest to the tide gauge altimetry point (blue line) and the tide gauges (red line) at P. Pitre and Magueyes, respectively. The tide gauge records have been filtered by a 7 days moving average filter; the altimetry time series correspond to the latitudes indicated by a black line in the Hovmoller diagram (Figures 8a2 and 8b2). The good correspondence between the altimetry and tide gauge time series indicate that the mesoscale eddies observed in the open ocean affect coastal sea level. In Figures 8a3 and 8b3, a SSH regional view show the spatial eddy variability for (a) 3 September 1997 and (b) 5 August 2003. The black arrow in Figures 8a1 and 8b1 indicates the week of the regional view. A positive SSH anomaly (altimetry) is also evident in the tide gauge records. In 1997, the annual maxima nontidal residual in P. Pitre was on the 6th of September. It is likely that the positive sea level anomaly ($\sim$20 cm) of the anticyclonic eddy observed east of the station (Figure 8a3; which later entered the basin), combined with the seasonal sea level cycle and the surge to create this annual nontidal maxima.

4. Summary and Conclusions

Hourly values from 13 tide gauges in the Caribbean Sea have been used to analyze the distribution and range of extremes. Sea level extremes range from 38 cm in Le Robert to 83 cm in P. Spain. Extremes without the annual mean sea level range from 36 cm in P. Cortes to 79 cm in P. Spain. After the annual mean sea level and the tidal signals are removed from the time series, the nontidal extremes range from 20 cm in Le Robert to 76 cm in Magueyes (Figure 2). The largest value in Magueyes is forced by hurricane class 5 David in 1979. Sea level extremes are more frequent in September-October when the peak of the seasonal cycle, tropical cyclones, and spring tides coincide. Some sea level extremes occur in January-March caused by cold fronts which are moderated by the seasonal cycle trough.

The analysis of sea level extremes in the Caribbean is made difficult because of two factors. First, there are only five time series with more than 20 years of data and only three with more than 40 years of data. The

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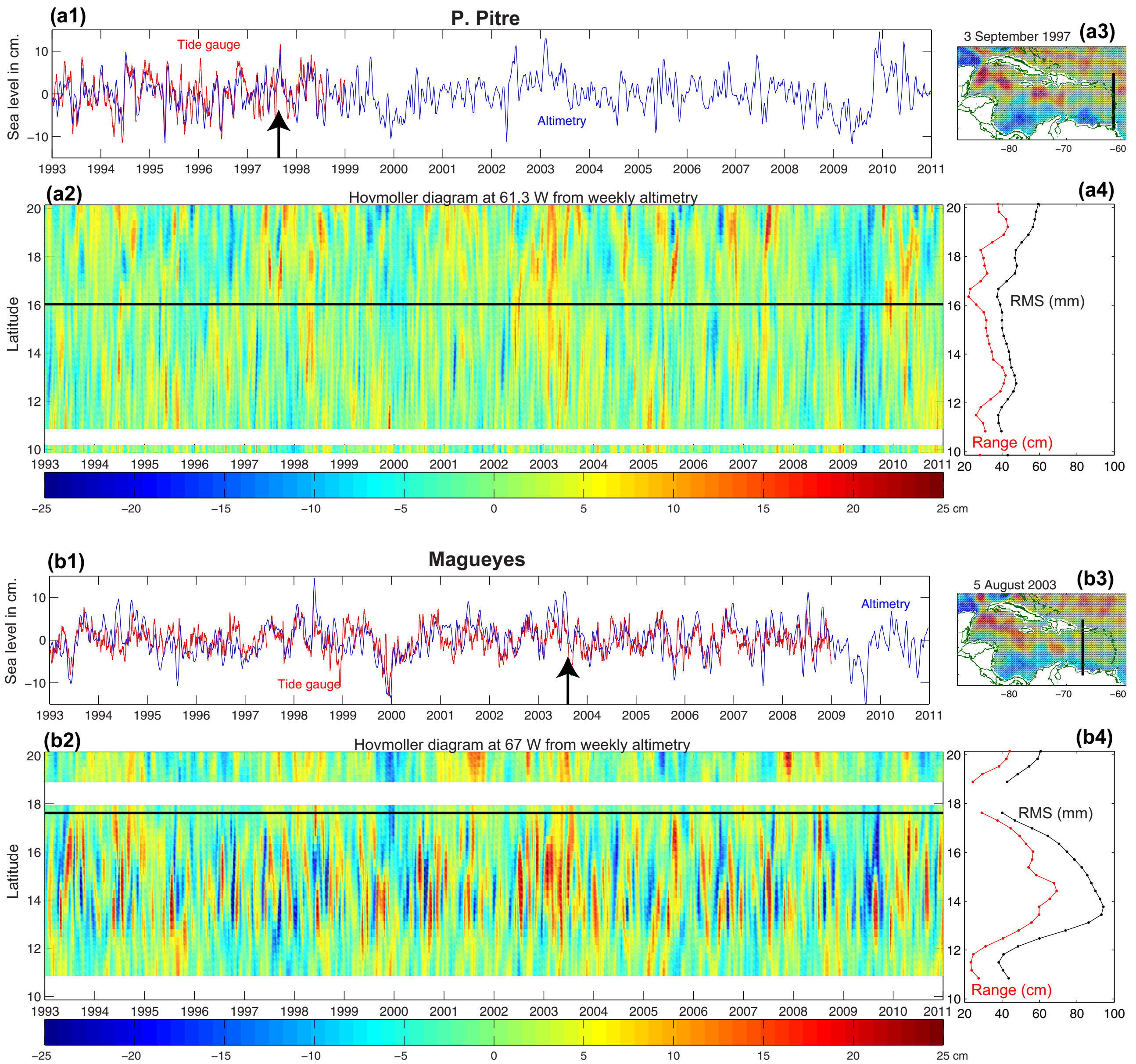

Figure 8. Eddy-related sea level variability at (a) P. Pitre and (b) Magueyes. All time series without the mean, trend, and seasonal cycle. The hourly tide gauge time series after a 7 days moving average (red) and the weekly altimetry time series from the nearest grid point (blue) in cm are shown in (a1)/(b1). Hovmoller diagrams of latitude-time with the weekly altimetry Sea Surface Height-SSH in cm are presented in (a2)/(b2); the black horizontal line indicates the time series of the closest grid point to the tide gauge. A regional view of the SSH in (a3)/(b3) illustrates the spatial eddy variability in a specific week which coincides with the black arrow in (a1)/(b1). It includes a vertical line of the section that corresponds to the Hovmoller diagram. In (a4)/(b4), a meridional distribution of the range (cm) and RMS (mm) of the SSH is shown.

other eight time series have between 5 and 10 years of data thus making any analysis based on them uncertain. However, they have provided interesting information on the forcing of extremes.

Second, conventional extreme value methods have limited use in estimating return levels in the Caribbean Sea due to the undersampling of hurricane-induced surges in the available sea level records. Only for Cristobal and Cartagena, the Annual Maxima Method appears reliable and this is because of their location in the southern boundary of the basin which is not significantly affected by hurricanes. In this case, at least 30 years of data are needed. This condition is satisfied by these two stations. For the north of the Caribbean basin, the sporadic occurrence of hurricanes requires at least 40 years of data for the method to work. Only Magueyes has such a long record but even there the statistical model fails due to the occasional occurrence of hurricane-induced extremes.

Sea level extremes (99.9th percentile) have increased during the last century in the five stations with long records by a rate between 1.5 ± 1.0 mm yr^{-1} in Magueyes (44 years) to 9.9 ± 2.2 mm yr^{-1} in P. Cortes (21 years; Table 3). Increases in the extremes are consistent with the mean sea level trend at each station, thus at least 40 years of data [*Torres and Tsimplis*, 2013] are needed to obtain temporally stable trends in the extremes. In Cartagena (43 years) the sea level extremes secular trend is 5.8 ± 0.8 mm yr^{-1} (Table 3); thus in a century, the maximum observed sea level extreme (46 cm in Figure 2b) can double its height as consequence of mean sea level rise alone. Contrary, there are no significant trends in the extremes when the annual mean sea level is removed from each year prior to the estimation of extremes. There is, however, a downward trend in the extremes during a 71 year period in the record of Cristobal. Overall, there is no evidence of regional changes in the storm activity.

The significant negative correlation between the nontidal high percentiles and ENSO indices supports at two of five stations assessed the reduction of the cyclone activity in the Caribbean Sea during a positive ENSO event as suggested by *Klotzbach* [2010].

The average annual sea level maxima range from 29.6 cm in Magueyes to 68.9 cm in P. Spain (Table 1). Annual maximum water levels are small in the Caribbean Sea when compared with global behavior [*Merrifield et al.*, 2013], partially because tidal amplitudes are small in the basin. Besides, the tidal and nontidal residual contributions to sea level (98% percentiles) are the same order of magnitude in the Caribbean Sea (Table 1).

The average annual nontidal residual maxima range from 16.9 cm in Le Robert to 31.2 cm in P. Spain (Table 1). The nontidal residual in the Caribbean Sea includes the contribution of the seasonal cycle, storm surges and mesoscale eddies. Estimating the contributions to sea level extremes form each signal is challenging. The mean seasonal sea level cycle in the Caribbean is unsteady in time [*Torres and Tsimplis*, 2012]. This influences coastal flood risk [*Wahl et al.*, 2014]. Storm surges cannot be accurately forecasted for more than a couple of days and the additional contribution of mesoscale eddies makes accurate flood risk estimates and appropriate planning for coastal protection a challenging task that needs further work.

However, the largest sea level extremes in the Caribbean Sea are caused by hurricane-induced storm surges. Although hurricanes are frequent in the basin [*Klotzbach*, 2010], the large surges are not frequently recorded in the available time series. Within nearly 300 years of analyzed sea level data from 13 stations together, only two nontidal extremes (99.9th percentile) associated to hurricanes larger than 45 cm were recorded (Figures 2 and 5). Larger values than these observed are likely to occur. A crude estimate of the storm surge as function of the square wind stress, blowing distance and depth [*Pugh*, 1987] at the north to south oriented coast of Nicaragua, where the continental shelf extends for about 146 km and has depths shallower than 30 m (Figure 1a), gives for a category 2 hurricane approaching to the coast with wind speed of 46 m s^{-1} a sea level increase of ~2 m. The sparse tide gauge data set and the shortness of many of the available records make the need of development of an appropriate measuring network and a suitable numerical modeling program essential for the basin. It is very clear that the development of a dense network of tide gauges which will be operational for several decades is needed to improve the understanding of extremes in the basin.

Coastal communities in the Caribbean Sea are especially vulnerable to hurricane-induced surges for three reasons. First, coastal morphology and infrastructure are adapted for small sea level variations (mean 98% sea level percentile of 69 cm—Table 1). Second, basin-wide return levels of hurricane-induced surges are not possible to obtain on the basis of the presently available observations. Third, the small islands and the developing countries in the basin have constraints on adaptive capacity [*Nicholls et al.*, 2007]. In the future, vulnerability to storm surges will increase in this area due to population growth [*Pielke et al.*, 2003], and due to increased exposure of the population and coastal infrastructure brought about by sea level rise. Therefore, awareness of the actual and future hazards for the coastal environment must be raised so that planning and adaptation responses will start developing sooner than later.

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References

Alvera-Azcarate, A., A. Barth, and R. H. Weisberg (2009), The surface circulation of the Caribbean Sea and the Gulf of Mexico as inferred from satellite altimetry, *J. Phys. Oceanogr.*, *39*(3), 640–657, doi:10.1175/2008JPO3765.1.

Andrade, C. A., and E. D. Barton (2000), Eddy development and motion in the Caribbean Sea, *J. Geophys. Res.*, *105*(C11), 26,191–26,201, doi:10.1029/2000JC000300.

Andrade, C. A., Y. F. Thomas, A. N. Lerma, P. Durand, and B. Anselme (2013), Coastal flooding hazard related to swell events in Cartagena de Indias, Colombia, *J. Coastal Res.*, *29*(5), 1126–1136, doi:10.2112/jcoastres-d-12-00028.1.

Chan, J. C. L. (2006), Comment on "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment", *Science*, *311*(5768), 1713, doi:10.1126/science.1121522.

Chelton, D. B., M. G. Schlax, R. M. Samelson, and R. A. de Szoeke (2007), Global observations of large oceanic eddies, *Geophys. Res. Lett.*, *34*, L15606, doi:10.1029/2007GL030812.

Church, J., J. Hunter, K. McInnes, and N. White (2006), Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events, *Aust. Meteorol. Mag.*, *55*, 253–260.

Church, J. A., et al. (2013), Sea level change, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., Cambridge Univ. Press, Cambridge, U. K.

Coles, S. (2001), *An Introduction to Statistical Modelling of Extreme Values*, 207 pp., Springer, London.

DiMego, G. J., L. F. Bosart, and G. W. Endersen (1976), An examination of the frequency and mean conditions surrounding frontal incursions into the Gulf of Mexico and Caribbean Sea, *Mon. Weather Rev.*, *104*(6), 709–718, doi:10.1175/1520-0493(1976)104<0709:AEOT-FA>2.0.CO;2.

Emanuel, K. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*(7051), 686–688. [Available at http://www.nature.com/nature/journal/v436/n7051/suppinfo/nature03906_S1.html.]

Enfield, D. B., and D. A. Mayer (1997), Tropical Atlantic sea surface temperature variability and its relation to El Niño-Southern Oscillation, *J. Geophys. Res.*, *102*(C1), 929–945, doi:10.1029/96JC03296.

Feng, X., and M. N. Tsimplis (2014), Sea level extremes at the coasts of China, *J. Geophys. Res. Oceans*, *119*, 1593–1608, doi:10.1002/2013JC009607.

Firing, Y. L., and M. A. Merrifield (2004), Extreme sea level events at Hawaii: Influence of mesoscale eddies, *Geophys. Res. Lett.*, *31*, L24306, doi:10.1029/2004GL021539.

Grinsted, A., J. C. Moore, and S. Jevrejeva (2012), Homogeneous record of Atlantic hurricane surge threat since 1923, *Proc. Natl. Acad. Sci. U. S. A.*, *109*(48), 19601–19605, doi:10.1073/pnas.1209542109.

Grinsted, A., J. C. Moore, and S. Jevrejeva (2013), Projected Atlantic hurricane surge threat from rising temperatures, *Proc. Natl. Acad. Sci. U. S. A.*, *110*(14), 5369–5373, doi:10.1073/pnas.1209980110.

Gumbel, E. J. (1958), *Statistics of Extremes*, 375 pp., Columbia Univ. Press, New York.

Haigh, I., L. MacPherson, M. Mason, E. M. S. Wijeratne, C. Pattiaratchi, R. Crompton, and S. George (2013), Estimating present day extreme water level exceedance probabilities around the coastline of Australia: Tropical cyclone-induced storm surges, *Clim. Dyn.*, *42*, 139–157, doi:10.1007/s00382-012-1653-0.

Haigh, I. D., R. Nicholls, and N. Wells (2010), A comparison of the main methods for estimating probabilities of extreme still water levels, *Coastal Eng.*, *57*(9), 838–849.

Hanley, D. E., M. A. Bourassa, J. J. O'Brien, S. R. Smith, and E. R. Spade (2003), A quantitative evaluation of ENSO indices, *J. Clim.*, *16*(8), 1249–1258, doi:10.1175/1520-0442(2003)16<1249:aqeoei>2.0.co;2.

Jones, P. D., T. Jonsson, and D. Wheeler (1997), Extension to the North Atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland, *Int. J. Climatol.*, *17*(13), 1433–1450, doi:10.1002/(sici)1097-0088(19971115)17:13<1433::aid-joc203>3.0.co;2-p.

Jouanno, J., J. Sheinbaum, B. Barnier, J.-M. Molines, L. Debreu, and F. Lemarié (2008), The mesoscale variability in the Caribbean Sea. Part I: Simulations and characteristics with an embedded model, *Ocean Modell.*, *23*(3-4), 82–101.

Jouanno, J., J. Sheinbaum, B. Barnier, and J.-M. Molines (2009), The mesoscale variability in the Caribbean Sea. Part II: Energy sources, *Ocean Modell.*, *26*(3-4), 226–239.

Klotzbach, P. J. (2010), The influence of El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean Tropical Cyclone Activity, *J. Clim.*, *24*(3), 721–731, doi:10.1175/2010jcli3705.1.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi (2010), Tropical cyclones and climate change, *Nat. Geosci.*, *3*(3), 157–163. [Available at http://www.nature.com/ngeo/journal/v3/n3/suppinfo/ngeo779_S1.html.]

Kuleshov, Y., L. Qi, R. Fawcett, and D. Jones (2008), On tropical cyclone activity in the Southern Hemisphere: Trends and the ENSO connection, *Geophys. Res. Lett.*, *35*, L14S08, doi:10.1029/2007GL032983.

Landsea, C. (2007), Counting Atlantic tropical cyclones back to 1900, *Eos Trans. AGU*, *88*(18), 197–202, doi:10.1029/2007eo180001.

Lerma, A., Y. Thomas, P. Durand, R. R. Torres, and C. Andrade (2008), Sea-level variability from 1950 to 2000 and hazards linked to storm surge episodes in Bocagrande and Castillogrande peninsulas, Cartagena de Inidias, Colombia, *Boletin Cientifico CIOH*, *26*, 72–85.

McInnes, K. L., K. J. E. Walsh, G. D. Hubbert, and T. Beer (2003), Impact of sea-level rise and storm surges on a coastal community, *Nat. Hazards*, *30*(2), 187–207, doi:10.1023/a:1026118417752.

Merrifield, M. A., A. S. Genz, C. P. Kontoes, and J. J. Marra (2013), Annual maximum water levels from tide gauges: Contributing factors and geographic patterns, *J. Geophys. Res. Oceans*, *118*, 2535–2546, doi:10.1002/jgrc.20173.

Mooers, C. N. K., and G. A. Maul (1998), Intra-Americas Sea circulation, in *The Sea*, vol. II, edited by K. R. Brink and A. R. Robinson, pp. 183–208, Wiley, N. Y.

Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe (2007), Coastal systems and low-lying areas, in *Climate Change, 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry et al., pp. 315–356, Cambridge Univ. Press, Cambridge, U. K.

Pawlowicz, R., B. Beardsley, and S. Lentz (2002), Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE, *Comput. Geosci.*, *28*(8), 929–937, doi:10.1016/S0098-3004(02)00013-4.

Pielke, R., J. Rubiera, C. Landsea, M. Fernández, and R. Klein (2003), Hurricane vulnerability in Latin America and The Caribbean: Normalized damage and loss potentials, *Nat. Hazards Rev.*, *4*(3), 101–114, doi:10.1061/(ASCE)1527-6988(2003)4:3(101).

Pugh, D. T. (1987), *Tides, Surges and Mean Sea Level*. 488 pp., John Wiley, Chichester, U. K.

Reading, A. J. (1990), Caribbean tropical storm activity over the past four centuries, *Int. J. Climatol.*, *10*(4), 365–376, doi:10.1002/joc.3370100404.

Richardson, P. L. (2005), Caribbean Current and eddies as observed by surface drifters, *Deep Sea Res., Part II*, *52*(3-4), 429–463.

Smith, R. L. (1986), Extreme value theory based on the r largest annual events, *J. Hydrol.*, *86*(1–2), 27–43, doi:10.1016/0022-1694(86)90004-1.

Tawn, J. A. (1988), An extreme-value theory model for dependent observations, *J. Hydrol.*, *101*(1–4), 227–250, doi:10.1016/0022-1694(88)90037-6.

Torres, R. R., and M. N. Tsimplis (2011), Tides and long-term modulations in the Caribbean Sea, *J. Geophys. Res.*, *116*, C10022, doi:10.1029/2011JC006973.

Torres, R. R., and M. N. Tsimplis (2012), Seasonal sea level cycle in the Caribbean Sea, *J. Geophys. Res.*, *117*, C07011, doi:10.1029/2012JC008159.

Torres, R. R., and M. N. Tsimplis (2013), Sea-level trends and interannual variability in the Caribbean Sea, *J. Geophys. Res. Oceans*, *118*, 2934–2947, doi:10.1002/jgrc.20229.

Torres, R. R., L. Otero, F. Afanador, and L. Marriaga (2008), Sea level behaviour on Colombia's Caribbean coast line, *Boletin Cientifico CIOH*, *26*, 8–21.

Wahl, T., F. M. Calafat, and M. E. Luther (2014), Rapid changes in the seasonal sea level cycle along the US Gulf coast from the late 20th century, *Geophys. Res. Lett.*, *41*, 491–498, doi:10.1002/2013gl058777.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*(5742), 1844–1846, doi:10.1126/science.1116448.

Zhong, L., M. Li, and D.-L. Zhang (2010), How do uncertainties in hurricane model forecasts affect storm surge predictions in a semi-enclosed bay?, *Estuarine Coastal Shelf Sci.*, *90*(2), 61–72, doi:10.1016/j.ecss.2010.07.001.