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Original Article

The coastal flood regime and its climate tendencies at the Havana City shore area

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ABSTRACT: The coastal flood behavior and its trends at Havana City shore area is analyzed, using archive information from some Cuban institutions and other sources. The weather events that have generated these floods (hurricane and cold fronts) from 1901 to 2015 are studied, taking into account the ENOS event influence on the winter floods and the thermohaline structure changes at the end of the XX Century, favorable to increase the destructive hurricane power, which were determined using oceanographic expedition data, obtained in deep waters around Cuba. The coastal flood behavior shows an increase in frequency and intensity in the last 40 years, as a consequence of the severe event frequency rise, under the influence of an increase of sea surface temperature, mixed layer depth and salinity in the Cuban surrounding waters. Their maximum values were located around the Cuban Western Region, which is the most favorably area to the hurricane development. Moreover, the extreme value of the sea level rise by the expected climate change, around 1 meter according to IPCC [2013], could bring the wave breaker line up to 11 meters in the Havana Seafront area, which lead to an increase of the flooding damages in the area.

Keywords: Havana City, coastal floods, climate tendencies.

INTRODUCTION

The most beautiful place at Havana City is an avenue, locating along a solid wall, which was constructed in 1919 over the Havana shore line. It is known as Malecon Habanero (Havana Seafront) and it is often affected by extreme meteorological events, such as hurricanes and frontal systems, which produce severe coastal floods in this place. To protect the local population and social-economical objects of this zone, it is necessary to investigate the temporal and spatial behavior of the coastal floods, the events that generate them and their trends. Of particular interest is the ENOS event effect and the thermohaline structure evolution, given its influence on the tropical cyclone season behavior.

Some research results about the Havana Seafront shore floods and its particularities are described at the present text, which were obtained during the execution of several scientific projects during the last 15 years, having the Cuban Meteorological Institute as the leader.

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INFORMATION SOURCES AND METHODS

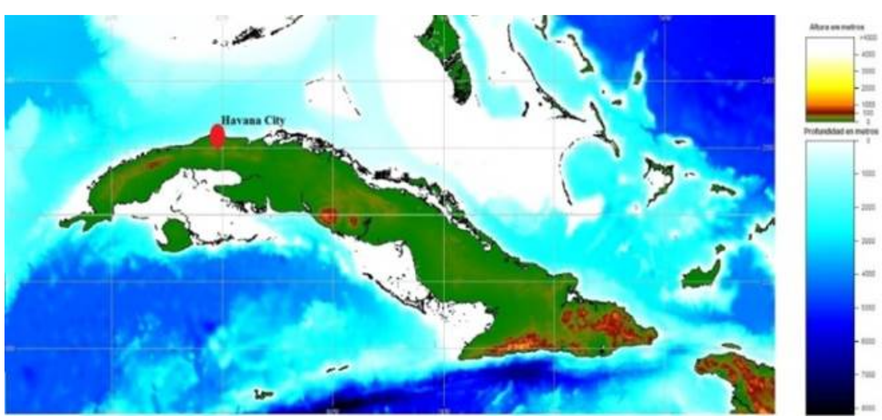
The Climate in Cuba and Havana city

The Cuban archipelago is located in the Tropical Zone of the North Atlantic Ocean, in a neighbourhood of the big continental mass of North America and inside the coordinates 74º07'-84º58' West and 19º 49'-23º 18' North (Figure 1). Havana City is located in 22°58'-23°10' North and 82°30', 82°06' West . Thus, the climate of Cuba may be classified as "tropical seasonally rainy, with semi-continental temperature regime and strong influence of surrounding seas" [Iníguez & Mateo, 1980].

The surface wind regime in Cuba, is basically composed by the permanent action of the warm oceanic Azores-Bermuda anticyclone (Trade Winds) and local winds (orographic, land-sea and sea-land winds). Prevailing winds (from the E, mostly) blow with a mean speed of 3,7 m/s, while the general mean speed is about 2,8 m/s, based on tri-hourly observations [Vega et al. 1990]. Over the Havana City, prevail winds from the North North East to East direction, with speed average of 4 to 5 m/s. A wind diurnal cycle is observed in not-disturbed conditions. The wind is weak in the morning and blows from the East-South-East, but around 10:00 am its direction changes to the North-West and its speed increase to its maximum force between 14:00 and 15:00. After that, the wind speed decreases and return to East direction; around the 21:00 hours, the South component appears.

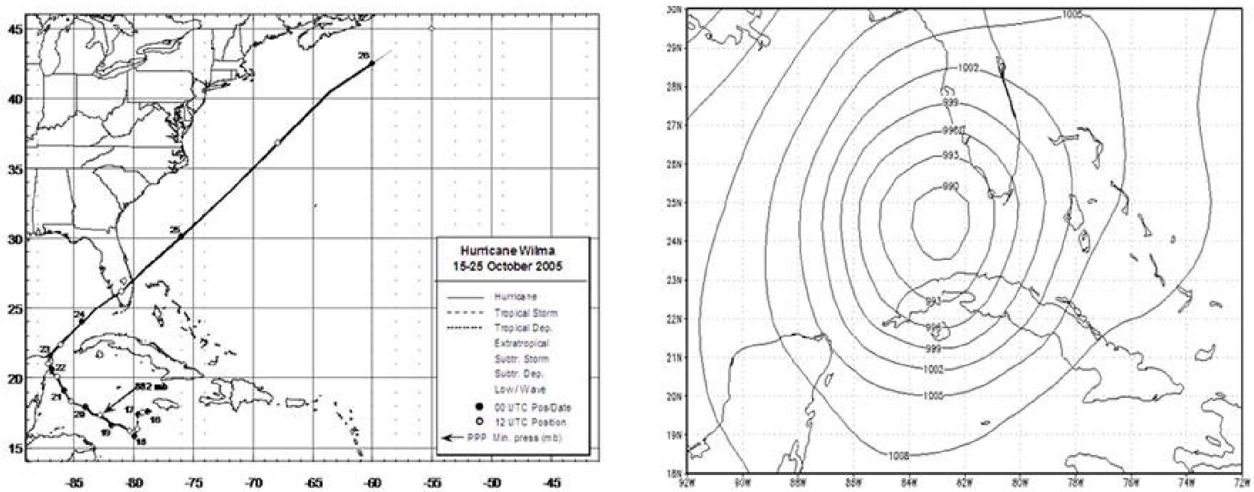
The normal wind regime in Cuba, is occasionally perturbed by the occurrence of migratory synoptic scale phenomena such as frontal systems (cold fronts and extratropical centres of low pressure) during the North Hemisphere winter season (comprising the dry season November-April), and tropical disturbance (Hurricanes, storms, depressions, easterly waves) during the summer season (comprising the rainy season May-October). Severe local thunderstorms (most frequent in the summer month of July and August), tornadoes, water spouts and troughs are also reported. Furthermore, significant values of wind speed in Cuba are generated also by the complex action of low pressure centres in the Westerns Caribbean Sea and high pressure centres in the Gulf of Mexico and the Atlantic Ocean [Vega et al. 1990]. In particular, coastal flooding has been reported, mainly on the northern coast of the western provinces and especially, on the Havana City, due to strong North-Western winds, generated by tropical cyclones (Figure 2 a, b) and frontal systems, moving over the Gulf of Mexico (Figure 3).

The Havana Seafront is located between the Havana Bay channel and the Almendares River mouth, with an extension of 5556 Km (Figure 4). The shore area is rocky and its profile is very abrupt, so it is favourable to the sea level increase by wave setup and the effect of the hurricane storm surges is smaller. It´s open to the North-West



[GEBCO, 2009]

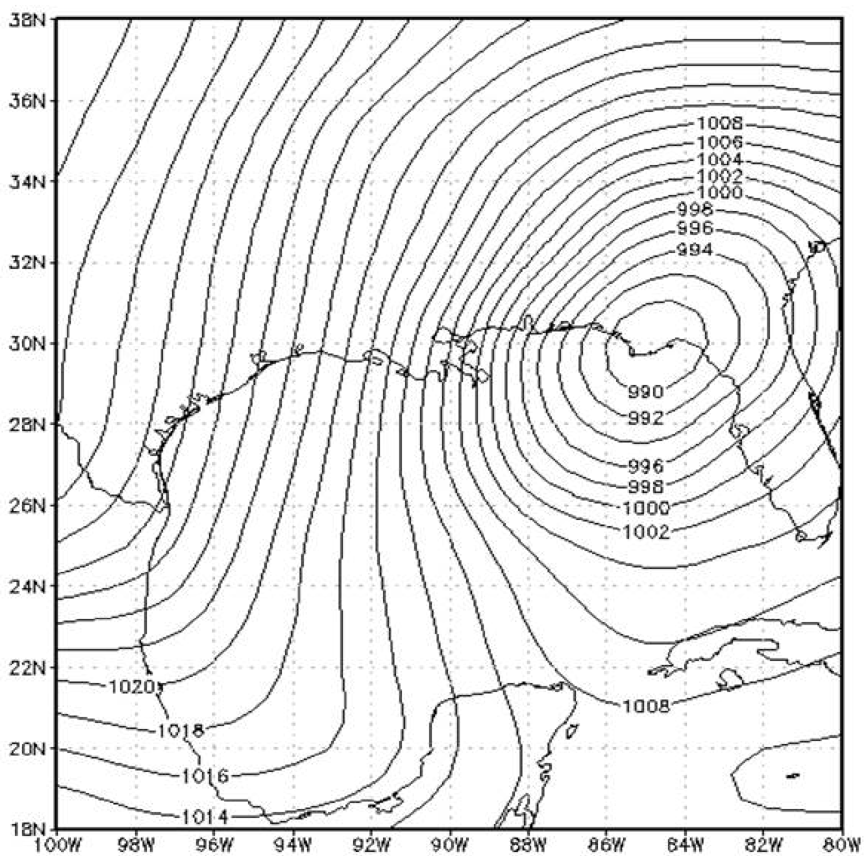
Figure 1. The Cuban Archipelago and Havana City location



a) b)

[NOAA-NOMADS 2012]

Figure 2. a)The track of the hurricane Wilma, b) The sea level pressure field on October 24/ 2005, at 06 hours UTC, when it was affecting the Havana Seafront, generating an extreme severe coastal flood



[NOAA -NOMADS 2012]

Figure 3. The extra-tropical cyclone circulation of March 13 /1993 at 00 hours UTC, when it was affecting the Havana Seafront, generating an extreme severe coastal flood

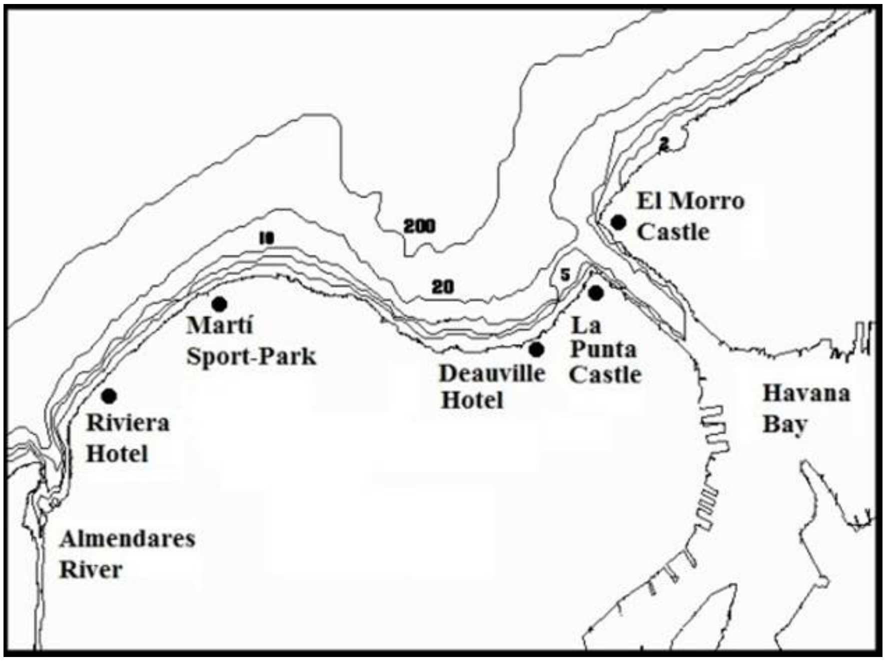


Figure 4. The Havana Seafront area

direction, in coincidence with the longer geographical fetch between Mexican and Cuban territory, so with the North-West wind speed around 15 m/s and persistence over 12 hours, the significant wind wave height on deep water can be over 4 m and this is the critical moment to begin a coastal flood in this area [Perez & Lezcano, 1993].

On the basis of spatial distribution of hurricanes tracks (the probability of occurrence is higher in western provinces and lesser in eastern provinces) and the geographical configuration of the island of Cuba (long and narrow), three maximum wind zones are defined by means of 70º and 80º meridians [Vega et al., 1990]. The zone I (Western zone) is located to the west of 80º W. Taking in account hurricanes with crossing tracks, the spatial medians of moderate and great intensity hurricanes (82º W and 83º W, respectively), belong to this zone (also the spatial median of all cases: 81º30' W). This fact shows the high density of hurricanes tracks lying on the western region of Cuba (deducted from data of the period 1886-2015, 129 years), where Havana City is located.

Used data and applied methods

To make a chronological data of the coastal floods events at the study area, diverse information sources were used. The most important, are the data files (period 1901-2015) from the Center of Marine Meteorology (CMM) at the Cuban Meteorological Institute (INSMET), the meteorological synoptic maps (1919-2013) from the INSMET Archive, the NOAA re-analysis maps [NOAA-NOMADS, 2013] and the information from the National Hurricane Center [NHC, 2014]. To confirm the occurrence of some coastal flooding events before the INSMET foundation, some newspaper testimonies, collected by Torrens [1993], were consulted.

The CMM official classification of the Havana Seafront floods, was used. It is showed on Table 1. The wind wave significant height was obtained, taking into account a lot of visual observations, making by the CMM specialists during the last 40 years from the higher buildings at the Havana City; it is in correspondence with the mean wind wave height at the generation area, so it is possible to deduce a mitigation effect of 40% on the significant wind wave, when it is moving from the generation area, in the Gulf of Mexico, to the Havana Seafront zone. The sea level increase was deduced from the altitude of the point, located at the end of the larger incursion distance.

All the data were carefully checked, submitted to standard statistical processing, and settled in tables

Table 1. Coastal flood classification for the Havana Seafront, where (δz)-Sea level increase , (h_{sig})-Significant wind wave height in deep water, just before its transformation and (d)-Incursion distance

Classification	δz [m]	h_{sig} [m]	d [m]	Observations
Severe	$\delta z \geq 2$	$h_{sig} > 6$	$d \leq 900$ m	The flood invades the Linea Ave.
Between moderate and severe	$1{,}5 \leq \delta z < 2$	$5 < h_{sig} \leq 6$	$d \leq 700$ m	The flood invades the Calzada Ave.
Moderate	$1 \leq \delta z < 1{,}5$	$4 < h_{sig} \leq 5$	$d \leq 300$ m	The flood invades the 3rd Ave.
Weak	$\Delta z < 1$	$2.5 < h_{sig} \leq 4$	$d < 50$ m	The flood invades only the Havana Seafront Ave.

and graphs. The ENOS behavior influence was also analyzed, using the ENOS index and the ENOS chronology, analyzed by Cárdenas & Naranjo [1998]

There don´t exist sea level rise and wind-wave observational records for the Havana Seafront, so to obtain the return period to characterize the coastal flooding regime, it was necessary to use an element, which was possible to calculate and compare with any real records. Taking into account that the most frequently form of sea level rise in the study area is the wave setup, the select element was the significant wind wave height (h_{sig}) at the wind wave generation area over the longer geographic fetch between Havana and Mexican shore lines; there is locate the buoy station 42003 from NDBC/NOAA [2013], with coordinates 26,0044 North and and 85,612 West .

The wind wave mean parameters on their generation area, were calculated by Mitrani et al. [2001], for all the hurricanes that affected the Havana shore zone from 1919 to 1998, using the information of the synoptic maps from the INSMET archive and applying a very simple method, recommended by GOSTROI [1982]. The map, where is showed the most dangerous situation, is selected. A quasi-stationary approximation of the wind is obtained and after that, the mean wind parameters are determinate. The following relation were use, to obtain the significant wind wave height from the mean one [WMO, 1998]:

$$h_{sig} = 1{,}59\, h_m,$$

A comparison among the obtained results, the buoy station record (Buoy 42003) and some visual ship observations, carried out in the wind wave generation area, shows a relative error less than the 10% as average, so a combination of the calculated values (from 1919 to 1994) with the observed ones (after 1994), were used to obtain the return function for a longer data from 1919 to 2015.

The obtained results for quasi-stationary wind and wind wave elements were organized in decreased order, one sequence for hurricanes and other for the cold front systems. The return function was calculated by the following relation:

$$F\ [\text{case/years}] = (n.m) / (N.M)$$

in which:

n -Number of cases that moved over Havana city and the sea, on a distance of 250 km over the coastal area.

m -Order number for each case

N -Total number of cases that affected the Cuban territory and the surrounding waters, on a distance of 250 km of the shore line, during the study period

M -Number of years

To make the adjustment for the hurricane wind wave height, all the hurricane that moved over the Cuban Archipelago and surrounding waters, from January/1919 to December/2017 were analysed, so the values of each term are: N= 105; n=55 ; M=98

To make the adjustment for the frontal system wind wave height, all the frontal system that moved over the Cuban Archipelago and surrounding waters, from 1980 to 2017 were analysed. All these systems affected the sea area near Havana City, so the values of N and n are equivalents and are the following: n=N =701 and M= 47

An observational records from oceanographic cruises, carried out in national waters by Cuban and foreign institutions, which is conserved at the INSMET too (period 1966-2001; Figure 5), were used to analyze the thermohaline structure influence on the hurricane evolution.

RESULTS AND DISCUSSION

The most significant coastal floods, occurred at the Havana City, during the period (1901-2015)

From the available information about the coastal floods that affected Havana City on the period 1901-2015, it was possible to identify those meteorological situations that are considered by the authors as the most significant of the chronological record. They are the following:

- **The hurricane of September 9, 1919**, during which the waters destroyed the newly constructed wall of the Havana Seafront and sidewalks. Fell blocks on the tram line, at the foot of the stump where the National Hotel is today.
- **The hurricane of October 20, 1926**. It is estimated that the water level in Maceo Park, the gardens of the House of Charity and other buildings, reached a height of up to two meters.
- **The hurricane "Juan", on October 29, 1985**. The flood lasted three days (29, 30 and 31 October; 72 hours of affectation) and the water level was over two meters in the lower points of the city. There was even one deceased, due to the collapse of a wall in the Hotel Riviera.
- **The extratropical low of 13 March 1993**, known as Storm of the Century, which although it is a winter time system, the consequences were similar to those of intense hurricanes due to the rapidity of its development and speed of translation.
- **The hurricane "Wilma", on October 23-25, 2005**, which has been identified as the most intense in the history of the Western Hemisphere. After its turn on the Yucatán Peninsula, it moved to the Havana City shore line, on the 23rd and 24th. Great swells occurred, that produced water accumulation by wave setup on the low areas of the city. Combined with the effect the hurricane surge and the increasing tide phase, there were strong coastal floods that covered five of the six coastal Havana municipalities. It is estimated that the total sea level rise was over two meters, with greater or lesser value in some points, depending on the local geographical configuration, bathimetry and topography. The flood lasted until the morning of the 25th and in some points, until the afternoon.

The most interesting period is 1985-2017. The most lasting event (Hurricane Juan, in 1985), the most intense winter storm (Storm of the Century, in 1993) and the two most intense hurricanes of the

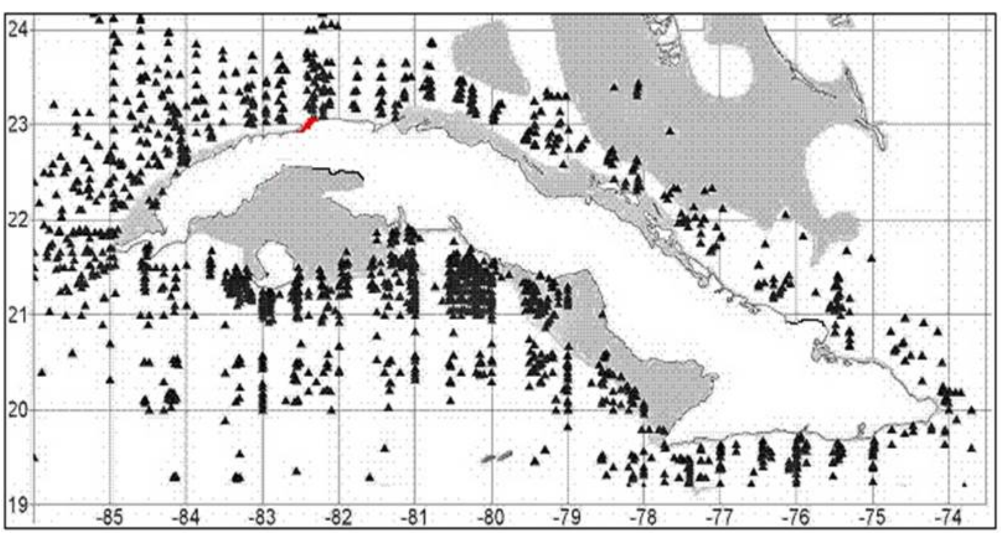


Figure 5. Ship-expedition stations around Cuba (1966-2000)

last 117 years (Wilma and Irma), occurred in these 33 years.

The return function

The best adjustment for the return function of the mean wind-wave height were obtained with the Weibull function, with a correlation coefficient R=98.9% and standard deviation σ=0.006 for hurricane cases, and R=99.8% and standard deviation σ=0.2 for the cold front system ones. The return periods, the wind wave heights at the generation area and the coastal flood classification are showing on Table 2. It is observed from this table, that a coastal flood at the Havana Seafront occurs at less one time in a year as average and a severe case, at less one in 10-25 years.

The coastal flood behavior tendency

The chronological data, for period 1901-2017 shows more flooding cases after 1980. This situation generates some doubts about the influence of the expected climate change on the last 50 years, so it was necessary to clean the data, taken into account the following facts:

a. There are more cases after 1980, but the majority are weak.
b. The CMM was funded in 1975, so it is possible that before this year, there were only registered the most intense cases on the meteorological historical records.

At the end, only the moderate and strong cases (more than 1 m of sea level rise), identified as all the severe cases, were conserved in the data by the authors of the present text.

The coastal flood behavior is better looking, when all the data is organized by decade, as it is showed on Figure 6 and 7. These graphical representations include the lineal tendencies, which show a clear increase for both kind of cases (by frontal systems and by hurricane) , with a frequency increase of the last ones at the beginning of the XXI Century.

Some simulations of the wind wave transformation at the Havana shore zone were made by Juantorena et. al [2000], using some values of the possible sea level rise by climate change. The obtained results showed that during the flooding occurrence at the study area, the vertical dimension will not substantial change, although with the scenario of 1m for the year 2100, in coincidence with the last IPCC [2013] report; the problem is with the horizontal dimension, because the wind wave break line could move 11 m to the shore line, so with wind wave height of 4 m, it would be possible the occurrence of moderate floods. This is a fact that will negative influence on the coastal flood regime at the Havana Seafront.

The 5th order polynomial tendencies, with correlation coefficients of 84% and 60%, show the althernancy of 30 - 40 years of low and high activity. An opposing behavior between the coastal flood generated by hurricane and those, generate by frontal systems, is observed too. In this case, one of the reasons, is the ENOS influence.

When the ENOS event is occurring, the North-continental circulation moves to the Southern latitudes, so the extratropical cyclone centers are located nearest the Cuban territory and it is the reason of an intensity and frequency wintry flood increase. At the same time, an inhibition of the hurricane activity is observed. It is a good relation between the ENOS index of Cardenas and Naranjo

Table 2. The particularities of the coastal flood regime at the Havana Seafront $\bar{h}$ - Mean wind wave height; h_{sig} - Significant wind wave

Return period	$\bar{h}$ [m] at the generation area	h_{sig} [m] at the generation area	Flood classification
1 case/1 year	4	6.4	From weak to moderate
1 case/5 years	4.2	6.7	Moderate
1 case /10 years	4.7	7.5	Moderate to severe
1 case /25 years	5.3	8.42	Severe
1 case /50 years	6.7	10.7	Very severe
1 case /100 years	7.5	12.0	Very severe

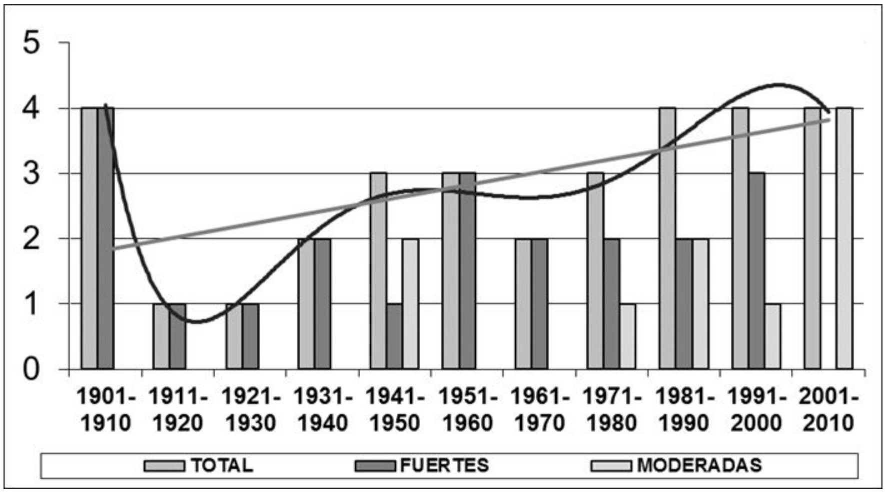


Figure 6. The wintry coastal flooding tendencies on the Havana Seafront (1901-2015)

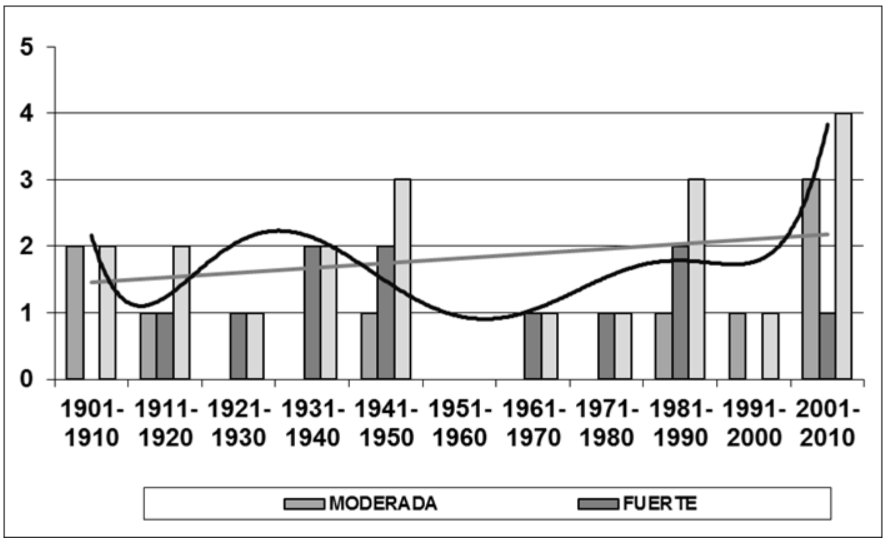


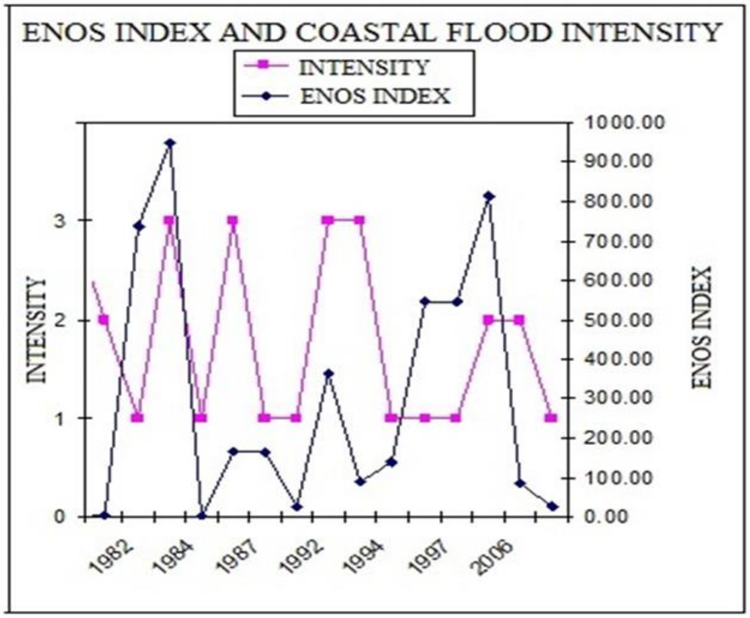
Figure 7. The hurricane coastal flooding tendencies on the Havana Seafront (1901-2015)

[1998] and the coastal flood occurrence, as it is described by Hernández & Garcia [2011]; a graphical representation is showed on Figure 8 and it is the possible explanation of the wintry flood activity increase at the end of the XX Century, when the ENOS influence was intensified too.

The changes on the thermohaline structure

The graphical representation of the vertical TS-water mass analysis is showed on Figure 9. Some change on the thermohaline structure parameters were detected during the last 36 years of the XX Century, from the surface to 500 m depth (Table 3), favorably to the energy accumulation on the sea and, as a consequence, to the increase of the hurricane destructive power. The most important changes, were the following: a) An increase of the sea surface temperature in 0,7 C^0, b) An increase of the salinity maximum, located between 200 and 300 depth, in 0,1 psu, c) An increase in some tens on meters, of the mixed layer depth. The salinity maximum increase is indicating a salinity rise in the surface and sub-surface water masses; it could attribute to the diminution of the rainfall volume over the study area in combination with the decrease of the Amazonas river contribution to the Central Atlantic and Caribbean stream system [Mitrani et al., 2014].

The maximum values of all the studied thermohaline parameters are located around the Cuban Western Region, in coincidence with the most favorably area to the tropical cyclone intensification (Figure 10 a, b, c).



Obtained by Hernandez and Garcia 2011

Figure 8. The ENOS index and the coastal flood occurrence (1980-2013)

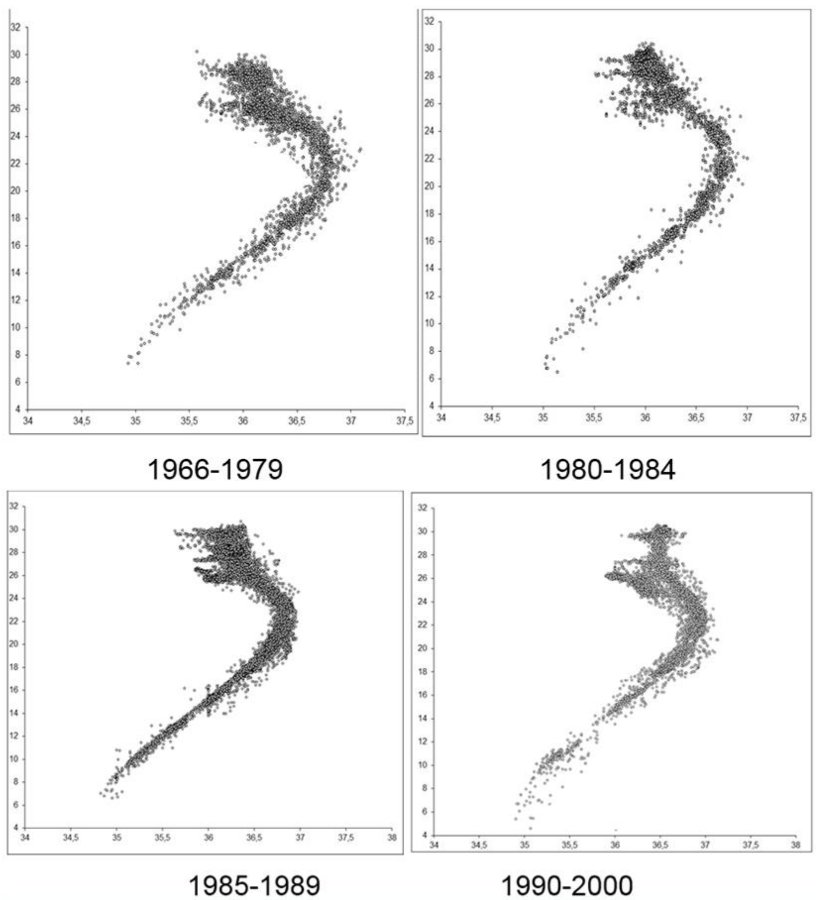
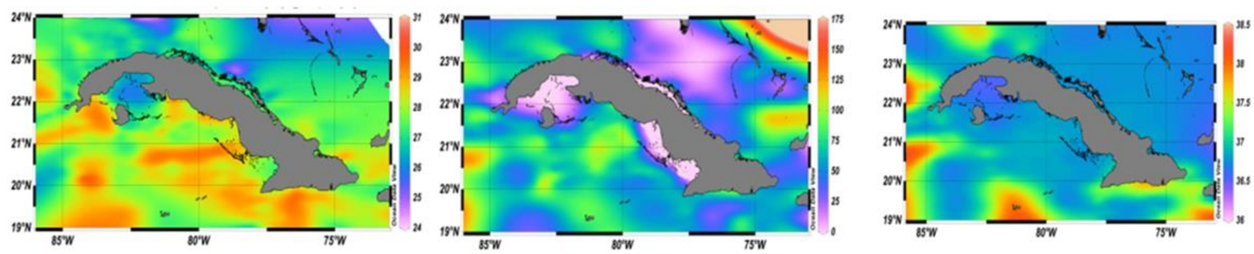


Figure 9. TS-analysis of the sea water mass around Cuba (The salinity was plotted on the X direction and the temperature, on the Y one)

Table 3. Temperature and salinity at the surface and sub-surface ocean levels, according to the TS-analysis of the sea water mass around Cuba, in different time periods.

		1966-1979		1980-1984		1985-1989		1990-2000	
Water mass	**Depth [m]**	**T [°C]**	**S [psu]**	**T [°C]**	**S [psu]**	**T [°C]**	**S [psu]**	**T [°C]**	**S [psu]**
Local surface	0-100	24-29	35.9-36.5	25-30	35.8-36.6	25-30	35.9-36.7	25-30	35.9-36.6
Subtropical North Atlantic	100-250	20-24	36.8-36.6	21-25	36.7-36.8	22-25	36.7-36.9	22-25	36.7-37
Western North Atlantic Central	250-800	8-20	36.6-35.0	21-8	36.6-35.1	21-8	36.7-35.1	8-22	35.1-36.7



a) b) c)

[Rodriguez & Mitrani, 2013]

Figure 10. The annual average of the a) sea surface temperature, b) isothermal layer thickness and c) salinity maximum around Cuba

CONCLUSIONS

The Havana Seafront is affected by a coastal flood at less ones a year and it is probable the occurrence of an important flood at less one in ten years. An increase in frequency and intensity tendencies of the coastal floods are observed during the study period (1901-2015), with intervals of low and high activity phases of 30-40 years. It exits a link with the ENOS event occurrence; when the ENOS is activated, the coastal floods occurrence increase during the winter. Observed changes on the thermohaline structure around the North-Western region of the Cuban Territory are favorable to the increase of the hurricane destructive power, so these facts have a positive influence on the coastal flood occurrence too.

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