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Consequences of sea level variability and sea level rise for Cuban territory

MARCELINO HERNÁNDEZ[1], CARLOS A. MARTÍNEZ[1] & ORLANDO MARZO[2]
1 Institute of Oceanology, 18406 1st Avenue, Flores, Playa, Havana, Cuba
marcel@oceano.inf.cu
2 National Tide Gauge Network, Geocuba Geodesia, Loma and 39, Plaza, Havana, Cuba

Abstract The objective of the present paper was to determine a first approximation of coastal zone flooding by 2100, taking into account the more persistent processes of sea level variability and non-accelerated linear sea level rise estimation to assess the main impacts. The annual linear rate of mean sea level rise in the Cuban archipelago, obtained from the longest tide gauge records, has fluctuated between 0.005 cm/year at Casilda and 0.214 cm/year at Siboney. The main sea level rise effects for the Cuban coastal zone due to climate change and global warming are shown. Monthly and annual mean sea level anomalies, some of which are similar to or higher than the mean sea level rise estimated for halfway through the present century, reinforce the inland seawater penetration due to the semi-daily high tide. The combination of these different events will result in the loss of goods and services, and require expensive investments for adaption.

Key words sea level rise; flooding; climate change; global warming; tides; climate change; tide gauge; global warming; coast; Cuba

INTRODUCTION

The Cuban archipelago extends from east to west between the Gulf of Mexico, Florida Straits and the canals of St. Nicholas and Old Bahamas to the north; the western Caribbean Sea and Columbus Strait to the south, and the Yucatan Channel and Windward Passage to the west and east, respectively. It is located between latitudes 19°49′36″ and 23°17′09″ north, and longitudes 74°07′52″ and 84°54′57″ west. The Island of Cuba is long and narrow, with 1250 km from Cabo de San Antonio at the western end, to the easternmost point, Punta Maisí. The maximum width is 191 km and the minimum only 31 km. The archipelago consists of the Island of Cuba, the Isle of Youth, and more than 1600 islands, islets and keys, amounting to a total surface area of about 110 922 km^2. An area of approx. 105 007 km^2 corresponds to the Island of Cuba, and 2200 km^2 to the Isle of Youth. The remaining keys and islets cover 3715 km^2, while the insular shelf spans 67 832 km^2 (Furrazola and Nuñez, 1997). There are four types of coast: iron-shore low terrace, mangrove swamps, beaches and coastal cliffs (Toledo *et al*., 2005), with four corresponding shelf areas, separated by coastal sectors where the shelf edge is close to the coast.

Sea level rise has been identified as the main threat to the Cuban archipelago (Centella *et al*., 2001; Hernández-González *et al*., 2012). The objective of the present paper was to determine the first approximation of possible coastal zone flooding by 2100, taking into account the more persistent processes of sea level variability and non-accelerated linear sea level rise estimation to assess the main impacts, from direct measurements at 39 temporary and permanent tide gauges of the National Tide Gauge Network and from a geographic information system.

DATA AND METHODS

Sea level hourly height time series from 38 permanent and temporary tide gauges of the National Tide Gauge Network plus Guantanamo tide gauge were used as primary information (Fig. 1 and Table 1). The National Tide Gauge Network was created in 1966, and its measurements and analysis are governed by a unique documented methodology (Geocuba Geodesia, 2004) that takes into account international standards (IOC, 2006). Equipment used for measurements have the characteristics recommended by the Intergovernmental Oceanographic Commission (Hernández-González *et al*., 2010). Monthly and annual mean values from six Cuban tide gauges are sent to GLOSS.

Table 1 Characteristics of hourly data series and flooding estimation.

Tide gauges	Latitude	Longitude	Date From – To	HAT & (Sa+Ssa) (cm)	HAT + MSLA (cm)	Perm. flooding (cm)	Flooding by 2100 (cm)
Los Morros	21 54,0	84 54,4	1971–2012	22	59	5	64
La Fé	22 02,5	84 16,5	1971	33	70	33	103
Los Arroyos	22 21,1	84 22,8	1971	41	78	33	111
Santa Lucía	22 40,5	83 58,0	1971	40	77	33	110
Bahía Honda	22 56,1	83 11,1	1971	32	69	33	102
Cabañas	22 59,4	82 58,6	1971	32	69	33	102
Mariel	23 01,2	82 45,4	2001–2012	45	82	33	115
Siboney	23 05,5	82 28,5	1966–2005	34	71	33	104
La Habana	23 08,9	82 21,2	1970–2012	37	74	33	107
Matanzas	23 03,5	81 33,2	1973	37	74	33	107
Punta Hicacos	23 11,6	81 07,6	1971–1972	33	70	33	103
La Isabela	22 56,4	80 00,8	1973–2012	30	67	12	79
Cayo Francés	22 38,5	79 14,0	1972	42	79	12	91
Bufadero	21 33,6	77 14,2	1992–2008	37	74	12	86
Punta de Prácticos	21 36,2	77 05,9	1992–2012	47	84	12	96
Manatí	21 21,4	76 49,5	1971–1972	68	105	23	128
Puerto Padre	21 12,1	76 36,0	2001	40	77	23	100
Gibara	21 06,5	76 07,5	1976–2012	42	79	23	102
Banes	20 55,1	75 42,4	2002–2005	55	92	23	115
Preston	20 46,0	75 39,4	1972	41	78	23	101
Saetía	20 46,6	75 34,7	1972	70	107	23	130
Levisa	20 42,9	75 33,0	1972	70	107	23	130
Tánamo	20 40,7	75 20,1	1972	62	99	23	122
Moa	20 39,2	74 54,6	1989–1990	63	100	23	123
Baracoa	20 21,1	74 30,1	1973–1978	62	99	23	122
Maisí	20 14,8	74 08,7	1995	56	93	23	116
Guantánamo	19 53,6	75 09,9	1937–1971	34	64	12	76
Santiago de Cuba	19 59,1	75 52,5	1992	27	62	12	74
Pilón	19 54,0	77 19,1	1972	25	57	12	69
Cabo Cruz	19 50,4	77 43,7	1992–2012	20	82	12	94
Manzanillo	20 20,4	77 08,8	1992–2012	45	77	12	89
Santa Cruz del Sur	20 42,0	77 58,6	1994–2001	40	61	12	73
Casilda	21 45,2	79 59,5	1972–2012	24	54	12	66
Punta Los Colorados	22 02,0	80 26,6	1971	17	57	12	69
Cayo Loco	22 09,1	80 27,3	1992–2012	20	56	12	68
Playa Girón	22 03,9	81 02,2	1971	19	59	12	71
Cayo Largo	21 37,3	81 33,9	1983–1984	22	57	12	69
Carapachibey	21 26,9	82 55,3	1977	20	56	12	68
La Coloma	22 14,2	83 34,3	1991–2001	19	37	12	49

Perm. flooding, value of relative mean sea level increase by 2100; MSLA, the highest monthly mean sea level anomaly; HAT & (Sa + Ssa), the value of the highest astronomical tide that includes sea level seasonal variations; Flooding by 2100, sea level flooding by 2100.

Bathymetry and altimetry data were obtained from the GEBCO System (General Bathymetric Chart of the Oceans) available on the Internet at: http://www.gebco.net/data_and_products/gridded_bathymetry_data/, and SRTM v. 4: http://www.cigar.gov, using the WGS84, EPSG: 4236. To develop the layer that represents the flooding of low lying areas by 2100, GIS Mapinfo 10.5 and Discover 12 were used, following the same steps as those used to obtain the layers corresponding to the bathymetric and altimetric data, and to socio-economic and ecological information (human settlements, roads, industries, agricultural and forest areas, and other).

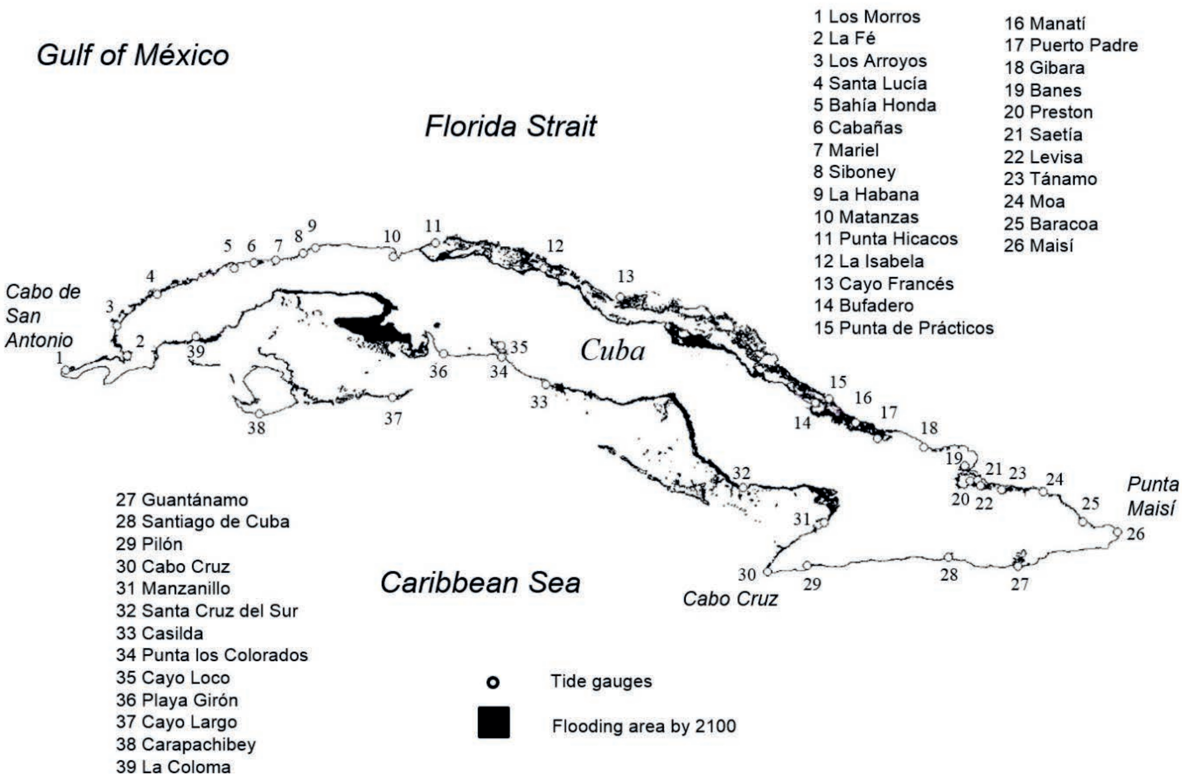

Fig. 1 Geographical distribution of tide gauges and estimated sea level flooding by 2100.

Sea level rise calculation

Restitution of absent data in the series of observed sea level hourly heights, the calculation of annual mean values and of trend, estimated as a linear adjustment of the annual mean values from a first grade linear equation, were performed according to Hernández-González *et al*. (2010). The calculation of the annual linear rate of relative mean sea level was done from the tide gauges with longer measurements: Los Morros, Siboney, La Isabela, Gibara and Casilda (Table 1). The annual mean value series of tide gauges from Guantanamo to La Coloma were averaged, because trends are very mild or almost null on the southern coast of Cuba, especially in the longest data series (Hernández-González *et al*., 2010), and taking into account the existence of a high linear correlation between monthly mean value series and the determination coefficient values, R between 0.76 and 0.90 (Hernández-González and Marzo, 2009). From the new series obtained, a single annual linear rate for the entire south coast was calculated. Then, five values of the annual linear rate of relative mean sea level were calculated, and with these, the values of relative mean sea level increase by 2100 (Table 2).

Sea level flooding by 2100 (Flooding area by 2100) was calculated as the sum of permanent flooding, represented by the value of relative mean sea level increase by 2100 (Perm. flooding), the highest monthly mean sea level anomaly (MSLA), and the value of the highest astronomical tide that includes sea level seasonal variations (HAT & Sa + Ssa) (see Table 1).

Table 2 Application of relative mean sea level value and increase per Cuban coastal sectors by 2100.

	Reference tide gauge	Coastal sector	Perm. flooding
1	Los Morros	Cabo de San Antonio	5.43 cm
2	Siboney	Cabo de San Antonio – Cárdenas	33.40 cm
3	La Isabela	Cárdenas - Punta de Prácticos	11.99 cm
4	Gibara	Punta de Prácticos – Punta Maisí	22.70 cm
5	Average for south coast	South coast of Cuba	12.12 cm

The linear increase in relative mean sea level by 2100 (Perm. flooding) was applied to the coastal sectors of Cuban territory according to Table 2.

RESULTS

Astronomical tides

Mixed semi-diurnal tide prevails in Cuban waters, except for some small coastal sectors where diurnal and mixed-diurnal tides occur. Tide mean amplitude varies between less than 25 cm and 65 cm, and is bigger on the north coast than on the south (Rodríguez and Rodríguez, 1983). For the present work, the highest astronomical tide (HAT) values were used, according to the updated information reported annually for each tide gauge (SHG, 2012).

Annual mean cycle and monthly anomalies

The maximum values of the sea level annual mean cycle (AMC) are located between September and October, and the minimum values between January and March (Hernández-González and Marzo, 2009). Long-term solar annual (Sa) and solar semi-annual (Ssa) components determine the seasonal variability, with values comparable to those of the main semi-diurnal lunar wave, M_2. For this reason, the resultant of the Sa + Ssa component at each tide gauge was added to HAT values, according to the updated information reported annually by the Hydrographic and Geodetic Service (SHG, 2012).

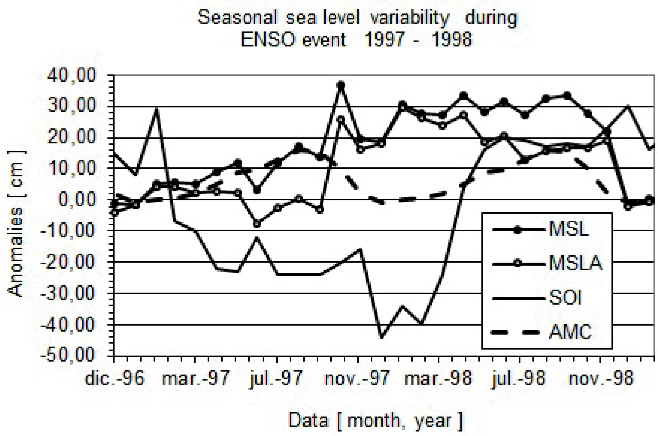

Fig. 2 Sea level monthly anomalies. MSL – monthly sea level; MSLA - monthly sea level anomalies; SOI - Southern Oscillation Index; AMC – annual mean cycle.

It has been proven that remarkable positive anomalies of monthly and annual mean sea level are recorded during ENSO events in all Cuban tide gauges (Fig. 2), with important alterations of annual mean sea level cycle during one year and more (Blázquez, 1989; Hernández-González & Díaz-Llanes, 2001; Hernández-González and Marzo, 2009; Hernández-González *et al*., 2012). Some of the monthly mean sea levels recorded are comparable in magnitude with some of the estimates of the relative mean sea level increment for halfway through the present century because of climate change. Therefore, these extreme monthly levels were taken into account when mapping floods by long-term mean sea level rise. In the present work, the monthly mean sea level of 36.8 cm recorded at La Isabela tide gauge in November 1997 (Fig. 2) was used.

The annual linear rate of relative mean sea level in the Cuban archipelago

The highest value in the annual linear rate of relative mean sea level was obtained at Siboney (2.14 mm/year) on the coast of Havana, and the lowest at Casilda (0.05 mm/year) on the south coast of Cuba. Los Morros (0.37 mm/year), and La Isabela (0.34 mm/year) only showed a slight linear trend to increase.

Sea level flooding by 2100 and consequences

According to these results, the total flooded area would be 8.24% of Cuban territory (Fig. 1; Table 1), assuming that all or most of the keys and islands will be flooded or seriously affected. Most of the flooded areas coincide mainly with mangrove swamps on the south and northeastern coasts of Cuba. Mangrove swamps, of great economic and ecological importance, occupy 4.8% of the Cuban land area. Since they are open ecosystems, with a constant flow of matter and energy, they will exercise a strong influence on the adjacent land and sea ecosystems (Leda and Guzmán, 2002).

Ecological and human settlement studies foresee that keys and islands of the archipelago will be lost. Marshes occupied by mangrove forest formations and grasslands will be affected, as well as low coastal areas, river deltas, tidelands and sandy dunes on the beaches. A permanent flood of approximately 30 cm would affect more than 70 coastal settlements and cause the disappearance of 15 of them. Seawater intrusion in rivers and aquifers will increase. This process will cause subsequent salinization of agricultural land, mainly in the dry season. Therefore, it is considered more viable to relocate towns and economic activities (Rodríguez *et al*., 2010; Planos *et al*., 2012). The more evident consequences of relative mean sea level increase for the Cuban archipelago are:

- Gradual increase in submerged areas at the expense of emerged areas.
- Gradual increase in the median plane of monthly and annual mean sea level anomalies.
- Seawater intrusion in rivers and aquifers will increase.
- Gradual increase in coastal flooding.
- Need for costly investments in coastal protection structures and relocation of human settlements.

CONCLUSIONS

- The annual linear sea level rise rate in the Cuban archipelago, obtained from the longest tide gauge records, fluctuated between 0.214 cm/year at Siboney and 0.005 cm/year at Casilda.
- Monthly and annual anomalies of mean sea level, some of which are similar to or higher than the mean sea level rise estimated for halfway through the present century, reinforce the inland penetration of seawater due to the semi-daily tide run-up.
- The total flooded area would be 8.24 % of Cuban territory.
- The combination of these different events will result in the loss of goods and services, causing expensive investments for adaption.

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