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Original Article

Coastal flood forecast in Cuba, due to hurricanes, using a combination of numerical models

Pronóstico de inundaciones costeras en Cuba por huracanes, utilizando una combinación de modelos numéricos

http://opn.to/a/WBJb9

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ABSTRACT: A regional model combination (WRF+ROMS+WW3+SWAN), identified as SPNOA (Numeric Ocean-Atmosphere Forecasting System), was applied for coastal flood forecast in Cuban coastal zones. A module to predict sea level rise by wave setup was added. Nested domains were used, covering the Inter-American Seas, Cuban surrounding waters and shore areas. Several hurricanes were considered as study cases in the experimental work to test the system effectiveness. The following procedures were utilized to evaluate the obtained results: A) WRF output circulation patterns were compared with NOAA re-analyses, and hurricane trajectories with NHC best tracks. B) The records of meteorological stations and buoys were compared with punctual model outputs. C) Storm tide forecast, given by ROMS and wave setup modules at the shore line, were evaluated in comparison with tide gauge records at some points of the Cuba coastal zone, near or located in the flooding areas. Some local testimonies about flooding intensity were also analyzed. It was concluded that SPNOA system is efficient in terms of up to 72 hours for the representation and prediction of wind waves and sea level rise, under the influence of hurricanes; therefore, its use in the Cuban meteorological service is recommended.

Keywords: Numerical models, coastal floods, hurricanes.

RESUMEN: Se presenta la aplicación de los modelos combinados (WRF+ROMS+WW3+SWAN) dentro del Sistema SPNOA (Sistema de Pronósticos Numéricos Océano-Atmósfera), en la representación y predicción de las inundaciones costeras en Cuba, para uso del servicio meteorológico nacional. Se añade un módulo para el cálculo del aumento de nivel por rompiente de oleaje (*wave setup*). Se utilizan dominios anidados que cubren los mares Interamericanos, las aguas aledañas y las costas cubanas. Para comprobar la efectividad del sistema en la representación y pronóstico de las inundaciones, se analizan varios estudios de caso de huracanes. Se comparan los patrones de circulación de salida de WRF con los re-análisis NOAA y las trayectorias de los huracanes con las mejores trayectorias (*Best track*) de NHC. Posteriormente, se comparan los registros de estaciones meteorológicas y de boyas, de las variables viento, presión atmosférica y elementos de ola, con las salidas de WRF, WW3 y SWAN. Las salidas de sobreelevación del nivel del mar, dadas por ROMS +wave setup, se evalúan en comparación con registros de mareógrafos en algunos puntos de las costas de Cuba, cercanos o localizados en las áreas de inundación. Se concluye que el sistema SPNOA es eficiente en plazos de hasta 72 horas para la representación y predicción de oleaje y sobreelevación del nivel del mar, al paso de huracanes, por lo que se recomienda su uso en el servicio meteorológico cubano.

Palabras clave: Modelos numéricos, inundaciones costeras, huracanes.

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INTRODUCTION

Cuban Archipelago is frequently affected by coastal floods, generated by tropical cyclones. To mitigate the possible damages, it is necessary to increase the quality and anticipation of weather, wind wave and sea level rise forecasts, which is efficiently achieved using numerical models.

In Cuba, the first experiences in numerical modeling were acquired using the MM5V3 (Mesoscale Model Fifty generation, Version 3), which has been operationally installed at INSMET since 2005. Three nested domains were used, centered on the Republic of Cuba and with the most appropriate parameterizations for this tropical region, following the recommendations of MM5V3 manuals (PSU/NCAR, 2000; 2006) and of other INSMET specialists (Mitrani *et al.*, 2003; Mitrani and González, 2005). Subsequently, the combinations MM5V3 + WW3 (Mitrani *et al.*, 2011), WRF + WW3 (Mitrani *et al.*, 2012 a) and WRF+WW3+SWAN (Pérez *et al.*, 2013 a) were assimilated for the prediction of weather and waves in deep and shallow waters, with emphasis on the presence of tropical cyclones.

SPNOA system (Numeric Ocean-Atmosphere Forecasting System) was created by Pérez Bello *et al.* (2013 b) and consists of a combination of atmospheric, wind wave and ocean circulation models, which allows obtaining in a fully automated way the space-temporal representation and forecast of atmospheric circulation, oceanic circulation, wind waves and sea level increase in Cuban coastal areas and adjacent seas. These characteristics make it a very practical tool, to increase the quality of coastal flood forecast; but it is necessary to assess the possibilities and limitations of the system.

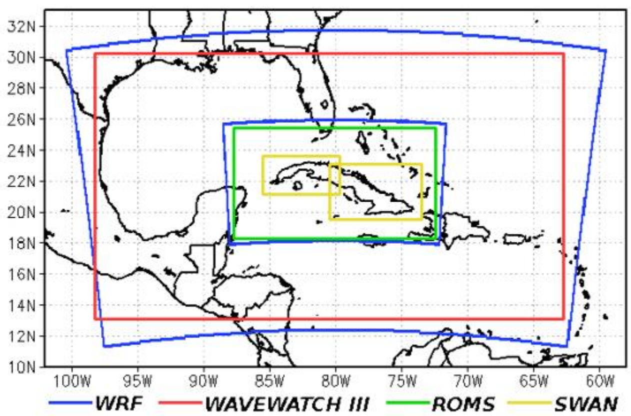
The general objective of the present work is to develop weather, wind wave and sea level increase forecasts in presence of hurricanes on Cuban territory and surrounding waters, as generators of coastal flooding, using high-resolution atmospheric and marine models. The following actions are necessary to achieve this objective: a) Application of a combination of numerical models for weather and sea surface state forecast, in presence of tropical cyclones. b) Addition of a wave setup calculation module to the model system used. c) Verification of the model outputs, in comparison with synoptic re-analyses and records of meteorological stations, oceanographic buoys and tide gauges.

MATERIALS AND METHODS

The work domains cover the areas of the Inter-American Seas, the Cuban Archipelago and adjacent seas (Figure 1a).

Numerical model description

The SPNOA system, developed by Pérez *et al.* (2013), includes the combination of the numerical models WRF, ROMS, WW3 and SWAN. The wave setup calculation module (WST) was added, following the recommendations of CEM (2006). The incorporation of a wind setup module was not considered necessary, since this calculation is included in ROMS model. Figures 1.1 a, b show the work domains and SPNOA model chain scheme.



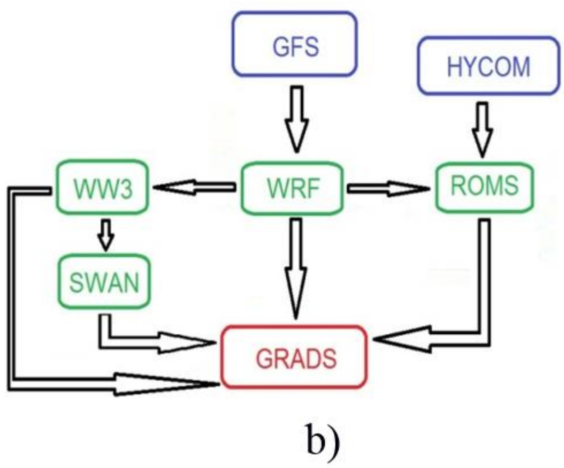


Figure 1. SPNOA work domains and model chain scheme (Pérez *et al.*, 2013)

The WRF model

A variant of WRF 3.5.1 (Weather Research and Forecast model, version 3.5.1) was applied, according to the description and recommendations of WRF User Page (WRF, 2008-2012) and taking into account the national experiences on the application of MM5V3 and WRF in previous research (Mitrani *et al*., 2011; 2012 a, b). Two nested domains were used, covering the area of interest for Cuban meteorological service at regional and local scale. The model was developed on LINUX support and run on a cluster of personal computers, which allows faster data assimilation and appropriate graphic presentation graphic outputs for users. The working language is FORTRAN-90/95 and graphic outputs are produced in Grads.

Taking into account the physical - geographical characteristics of Cuba and its position in the central zone of the Inter-American Seas, as well as previous Cuban experiences (Mitrani *et al*., 2011), two nested domains were defined in Lambert projection, with central coordinates at 22° N and 80° W. This point is approximately towards the center of the area, so that meridian 80 practically divides the island in half, as defined by Lecha *et al*. (1994). The outer domain covers the Inter-American Seas with a total of 26257 mesh points (217x121) and with space steps of 18 km. The inner domain occupies Cuban Archipelago and surrounding waters, with steps of 6 km and a total of 40600 mesh points (280x145). In both domains, 30 vertical levels were used (Fig. 3.1).

The following diabatic process parameterization schemes were utilized:

a. Eta-Mellor-Yamada boundary layer, as described in WRF (2008).

b. RRTM long-wave radiation (Mlawer *et al*., 1997)

c. Dudhia short-wave radiation (Dudhia, 1989)

d. Lin microphysics scheme (Lin, Farley and Orville, 1983)

e. Kain-Fritsch cumulus clouds (Kain, 2004)

GFS (Global Forecast System) outputs, with space resolution of 0.25 degrees (approximately 28 km), available on the website http://www.nco.ncep.noaa.gov/pmb/products/gfs/, were used every 6 hours as input to the atmospheric model WRF (Weather Research and Forecast system) http://www.nco.ncep.noaa.gov/pmb/products/gfs/. The meteorological variables were: sea level pressure, air temperature, relative humidity and wind components, from the surface, 1000, 850, 700, 500, 400, 300, 200, 150 and 100 hPa levels; as well as the geopotential heights. Sea surface temperature was determined from the input data at the initial moment, remaining constant throughout the forecast period.

The WW3 model

Version 2.22 of the wind wave model Wave Watch III (Tolman, 2002; 2006) was assimilated, which is freely available on INTERNET (the later variant requires a license by now). It has a 6-km space step and a total of 176368 mesh points (604x292) over the second WRF domain. This domain was chosen, because it covers the entire area of the Inter-American Seas, where a predominance of natural land borders reduces the use of simulated borders over the sea.

Tolman (2002) recommends not to use WW3 in areas where the main limiting factor for wind wave development is sea depth. In addition, the space step should not be less than ten kilometers. These recommendations, confirmed at the model website (WW3, 2010), exits because local details of the coastal zone are not well treated inside the model algorithm. Therefore, fine-tuning the resolution may be unnecessary, because it does not provide better results. For this reason, WW3 should be combined with a coastal model that takes into account all the details of bathymetry, bottom relief, coastal configuration and land use, such as the SWAN model.

To preserve WW3 mathematical stability, it must be satisfied the condition that $C_g = (\delta t/\delta s) < 1$ must be satisfied, where C_g is the wave group speed and the expression $(\delta t/\delta s)$ refers to the relationship between the spatial and temporal steps of model integration. According to the classic trochoidal wind wave representation, the ratio between wave length and period is taking as $\lambda = 1.56\ \tau^2/g$, but the wind wave length can be greater than 100 m under the action of hurricane winds, with a period over 10 s, so the relationship between the temporal and spatial steps in the model integration must be quite less than 0.1. For this reason, the appropriate integration time step was 300 seconds in the current work.

As WW3 input data, WRF wind outputs every three hours were used, and a bathymetry matrix in combination with the coastal topography and inclusion of small islands, with a mesh size of 6 km. These data were taken from GEBCO Atlas (2003), for the area that is observed in Figure (1.2). Wind and bathymetry meshes were made to coincide by linear interpolation. At the end, WW3 outputs were available every one hour with a space step of 6 km.

The parametrization schemes recommended by Mitrani *et al*. (2012 a, b; 2016) were used, as they are described below:

a. JONSWAP spectrum of limited fetch. It was selected for the spectral approximation of sea surface state. It was considered the most appropriate due to the peculiarity of the study area, which is enclosed by land in three of its borders, so that fetch is effectively limited by geographical conditions.
b. Propagation scheme described by Tolman (2002). It is used because it includes techniques that soften the "sprinkler" effect of the wind, which when overestimated produces excessive deformation in the direction of wave propagation, especially when it is generated by hurricane winds.
c. The dissipative term parametrization of Tolman-Chalikov (1994, 1996), improved by Tolman (2002). This parameterization represents in detail the swell formation, propagation and mitigation in time and space. This detail is important, given the frequency of flooding in the northwestern part of Cuba by a combination of sea and swell surface states, with predominance of swell.

As output options, significant wave elements (height, period, wavelength), the wind field and special outputs are offered at points of interest for the forecaster.

The ROMS model

ROMS (Regional Oceanic Modeling System) is a three-dimensional numerical model for ocean circulation, as it is described by Shchepetkin and McWilliams (2005). This model has been specially designed to improve the precision of simulations in regional ocean systems. The tidal data used to run the model were obtained from the global model TPXO7 (Egbert and Erofeeva, 2002), of Oregon State University, with 0.25 degrees of spatial resolution. In the present work, an space resolution of 3 km is used, with a total of 139264 mesh points (544x256) and 16 vertical levels, from surface to the seabed.

Three data groups were used as ROMS input information:

a) HYCOM (HYbrid Coordinate Ocean Model) global ocean model output every 24 hours, available at the website https://hycom.org/dataserver/, with space resolution of 1/12 latitude degree (approximately 12 km)

The oceanographic variables were: temperature, salinity and speed components of marine currents at the standard sea levels: 0, 10 25, 50, 100, 125, 150, 200, 250, 300, 500, 1000, 1500 and 2000 m.

b) Bathymetry from a Digital Atlas (GEBCO, 2003), with a resolution of 30 seconds (approximately 900 m)

c) Astronomical tide components, as output of TOPEX07 model

The SWAN model

SWAN (Simulating Waves Near shore) is a wind wave numerical model, developed to obtain realistic estimates of wave parameters in coastal areas, lakes and estuaries for given conditions of wind, currents and bathymetry. This model was developed by specialists from the Technological University of Delft, The Netherlands (Booij *et al*., 1999).

In this work, version 40.81 was used, with two domains on a local scale of 1.5 km of spatial resolution, one for the western region of Cuba with a total of 73216 mesh points (416x176) and another for the eastern region with a total of 126976 mesh points (496x256). L"Ike" in the application of WW3, JONSWAP spectrum with limited fetch was chosen for the spectral representation of sea surface state with limited fetch was chosen. The model algorithm includes all the shallow water deformations of wind waves under the influence of the seabed, as shoaling effect, refraction, reflection and diffraction.

As a limitation, the used mesh is rectangular, thus coastline irregularities were not represented with high fidelity; but the available bathymetry (with a space step of 900 m) would not have allowed a significant improvement.

Three groups of data were used as input:

a. Wind field output from the atmospheric model WRF
b. Bathymetry from GEBCO Atlas (2003), with a resolution of 30 seconds (approximately 900 m)
c. WW3 wave element output, as wind waves that were coming from deep waters.

The Wave Setup module (WST)

This operation was carried out for those cases where the hurricane moved over or in the vicinity of steep coastal slope. Wind wave outputs from SWAN model were used, following the recommendations of the Shore Protection Manual (SPM, 1984), the Costal Engineering Manual (2006) and the proceedings of the World Meteorological Organization (WMO, 1998; 2012):

$$\delta_b = \frac{g^{0.5}(h\acute{_0})^{2.5}\tau}{64\pi(H_r)1.5}$$

where:

δ_b - Sea level rise by wave setup at shore line

$h'_0=0.82h_0$ - Wave height at breaking point. It was defined, using the criterion of Komar and Gaughan (CEM, 2006) for steep slopes, where h_0 is the significant wave height coming from deep water. Its ratio with the wavelength at that point is $h_0/\lambda_0=1/7$

λ_0 - Is the average wave length in deep water

τ_0 - Average wave period, which is conserved from deep waters (WMO, 1998)

H_r - Breaking point depth, taken as 0.25 λ_0 by recommendation of WMO (1998)

Since wave height output in SWAN and WW3 models is known as significant height, it does not correspond to the average length and the average period. For this reason, it was necessary to rectify the final value of δ_b as "over-elevation of the significant height" and the whole expression was multiplied by a numerical coefficient B =(tan α^{-1}) $(1.59)^2$, where α is the shore line slope and it was around 0.1.

Study cases

The study cases (Table 1.) were selected from the coastal flood chronology, available at the Marine Meteorology Center of the Institute of Meteorology (CMM/INSMET), taking into account two aspects:

a. Those hurricanes that affected the Cuban territory and adjacent seas, generating coastal flooding.
b. Existence of sufficient information, for both model inputs and output assessment.

A total of 56 experiments were carried out, which included in each case the days before, during and after coastal flood occurrence, until its mitigation.

Data sources for model output assessments

The data used for model evaluation assessments were taken from INSMET archive, the national tide records and some INTERNET freely available sources.

Assessment of atmospheric model outputs

The meteorological elements that produce the greatest influence on coastal flooding intensity are sea level pressure and wind components, which make up the circulation patterns of synoptic systems. This is essential to evaluate hurricane tracks.

WRF wind and wind wave field outputs were vivified, using the following information:

a. Re-analyses of meteorological fields, located on the Operational Model Archive Distribution System-3 website (NOMAD3, 2013). As the spatial resolution of these re-analyses is approximately 220 km, while that of the WRF model is 18 km, the image is used only to

Table 1. Study cases analyzed in the present research.

“Charlie” (August 2004)	“Hanna” (September 2008)
“Ivan” (September 2004)	“Ike” (September 2008)
“Dennis” (July 2005)	“Paloma” (November 2008)
“Wilma” (October 2005)	“Sandy” (October 2012)

evaluate the position of the synoptic scale systems.

b. Data from some buoys of the National Data Buoy Center (NDBC, 2013), which are shown in Figure 2 and Table 2, to evaluate wind speed and wind wave height.

To represent the hurricane track forecast, hurricane centers were located in the sea level pressure, wind and stream function fields from WRF outputs. Hurricane tracks were assessed, using NHC (National Hurricane Center) "best tracks". This information has been published by several authors on NHC website (NHC, 2016).

Assessment of wave model outputs

Only deep-water wind wave records are available, derived from buoy data of the National Data Buoy Center (NDBC, 2013), which are mainly installed in the Gulf of Mexico (Figure 2); therefore, only WW3 outputs can be safely evaluated. Table 2 shows the coordinates of the buoys coordinates, used in this work.

Assessment of sea level increase forecast

Sea level rise forecasts were assessed using three fundamental means:

a. A comparison between tide gauge records of the National Network and ROMS output values at the location points of these equipment (Table 3, Figure 3).

b. Descriptions of the floods, kept in the archives of the Marine Meteorology Center at INSMET and in hurricane cyclone season summaries, prepared by the National Forecast Center at INSMET and available at its website (http://www.insmet.cu).

c. Some testimonies of workers from local meteorological stations.

Criteria for assessing each element

Following the recommendations of Guo et al. (2003) and Zhong and Fast (2003), the forecast errors were analyzed in terms of 12, 24, 36, 48 and 72 hours, in those points where the buoys are

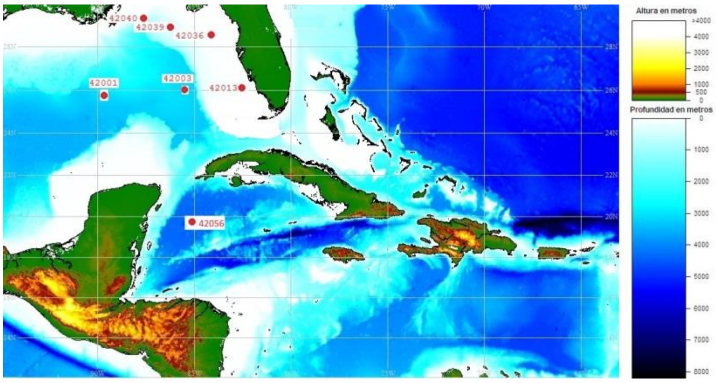


Figure 2. Bathymetric and topographic map (GEBCO 2003). The NBDC buoy positions were include.

Table 2. List of NOAA buoys, installed in waters adjacent to Cuba, whose records were used in this work.

	CODES	LATITUDE	LONGITUDE
1	42001	25.900° N	89.667° W
2	42002	26.092° N	93.76° W
3	42003	26.0044° N	83.667° W
4	42013	27.169° N	82.926° W
5	42036	28.500° N	84.510° W
6	42039	28.791° N	86.008° W
7	42040	29.210° N	88.200° W
8	42056	19.874° N	85.059° W
9	42057	16.750° N	81.550° W
10	42058	14.923° N	74.918° W
11	42059	19.250° N	67.510° W

located, including their temporal behavior. The results were graphically presented, for those cases in which sufficient information was available.

RESULTS AND DISCUSSION

Hurricane tracks

Track forecast errors were calculated as the distance between the real and WRF output position of the hurricane center. Table 4 shows the errors in comparison with the results of the official NHC hurricane track forecast (NHC, 2016), and Figures 4a-h are the graphs of the real and predicted tracks.

The efficiency of WRF model in hurricane track prediction is great, especially for terms of up to 48 hours. This advantage allows to provide high quality data as input in the marine models of waves, ocean circulation and sea level rise. However, it remains a limitation that for periods longer than 72 hours, the forecasts show a discrete improvement in several cases. Forecast efficiency decreases in cases of very slow hurricane movements, or when the track makes a

Table 3. Coordinates of the tide gauges used in this work.

	NAME	STARTING YEAR	LATITUDE	LONGITUDE
1	Los Morros de Piedra	1971	21° 54, 0´	84° 54, 4´
2	Siboney	1966	23° 05, 6´	82° 28, 2´
3	La Isabela	1972	22° 56, 4´	80° 00, 8´
4	Punta de Nuevitas de PPPrácticos	1992	21°36, 2´	77°05, 9´
5	Gibara	1971	21° 06, 5´	76° 07, 5´
6	Santiago de Cuba	1992	20° 01,0´	75°50,2´
7	Cabo Cruz	1992	19° 50, 4´	77°43, 7´
8	Manzanillo	1992	20° 20, 4´	77°08, 8´
9	Casilda	1972	21° 45, 2´	79° 59, 5´

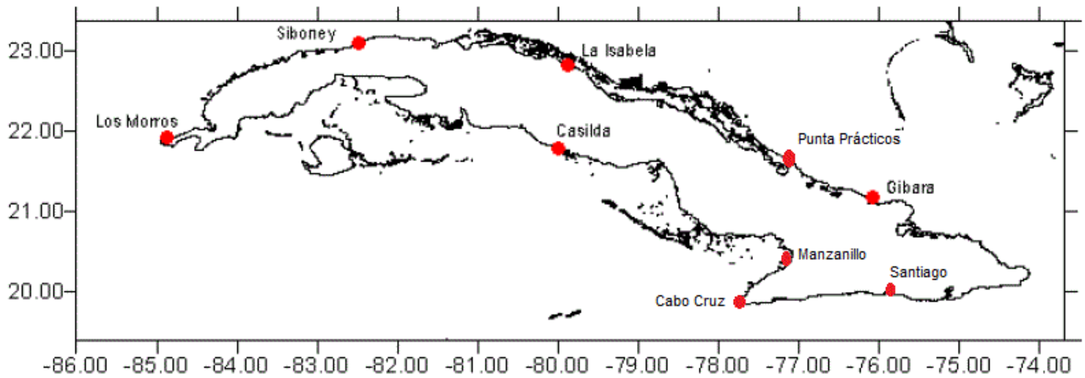
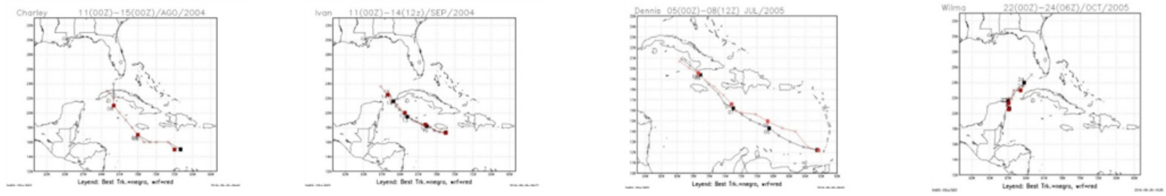


Figure 3. Location of the tide gauges used in this work.

Table 4. Hurricane track forecast errors, in Km.

Range (hours)	12	24	36	48	72
NHC - Official track forecast errors (Average from 2010 to 2014)	52.97	73.34	92.79	117.05	149.64
WRF-track forecast error:					
“Charley” (2004)	15.38	21.51	66.22	78.58	584.69
“Ivan” (2004)	7.68	19.56	19.88	24.70	57.63
“Dennis” (2005)	16.81	48.92	48.38	40.59	47.14
“Wilma” (2005)	15.33	32.37	52.55	98.29	448.94
“Hanna” (2008)	38.59	127.23	266.89	255.62	390.75
“Ike” (2008)	34.55	107.43	177.76	121.72	105.72
“Paloma” (2008)	11.81	56.13	115.26	138.70	134.98
“Sandy” (2012)	31.02	20.91	9.1	30.51	59.19

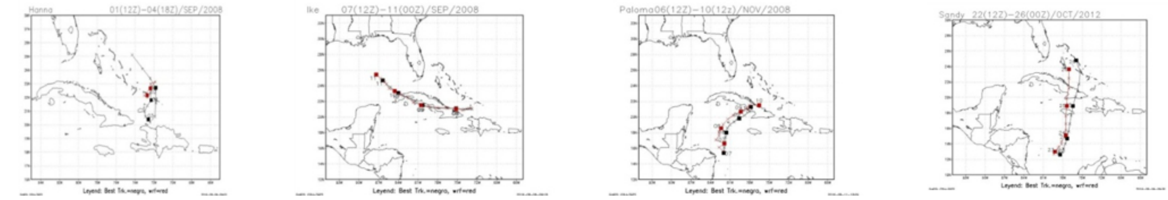


a) Hurricane "Charley". Track forecast from 11/08/2004, 00 UTC.

b) Hurricane "Ivan". Track forecast from 11/09/2004, 00 UTC.

c) Hurricane "Dennis". Track forecast from 05/07/2005, 00 UTC.

d) Hurricane "Wilma". Track forecast from 22 /10/ 2005, 00 UTC.



e) Hurricane "Hanna". Track forecast from 01/09/ 2008,12 UTC.

f) Hurricane ""Ike"". Track forecast from 07/09/2008, 12 UTC.

g) Hurricane "Paloma" Track forecast from 06/11/2008, 12 UTC.

h) Hurricane "Sandy". Track forecast from 22/10/2012, 12 UTC.

Figure 4. Comparison between NHC hurricane "best tracks" (in black) and those predicted by WRF (in red).

loop, as it could be observed in the cases of "Wilma", near Yucatan Peninsula, and "Hanna" North off the eastern northeastern Cuban coasts, as well as when the movement is on land.

Circulation patterns

The comparison of WRF outputs with the real circulation patterns, coming from the NOAA re-analyses, generally shows an excellent correspondence, especially in forecast terms of less than 48 hours, which is a guarantee of the correct location of the wind wave generation area and its displacement over deep waters in the seas adjacent to Cuba, as shown in WW3 outputs (Figures 5, 6).

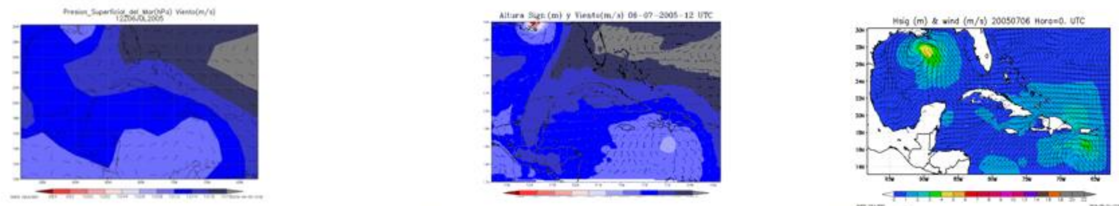
As examples, circulation patterns are shown in Figures 2.2 a, b, c and 2.3 a, b, c showed circulation patterns from the sea level pressure re-analyses (NOMAD3, 2013), in comparison with WRF outputs for sea level pressure, wind and wave height fields in presence of hurricanes "Dennis" and ""Ike"" for 24, 48 and 72-hour forecasts.

It is presented as a limitation that in the presence of slow movement or loops, or when the hurricane center is on land, the wind wave forecast quality decreases, because the quality of the hurricane track forecast also decreases. That kind of movement also influences on the lower quality of the output wind and sea level pressure fields with respect to the real patterns.

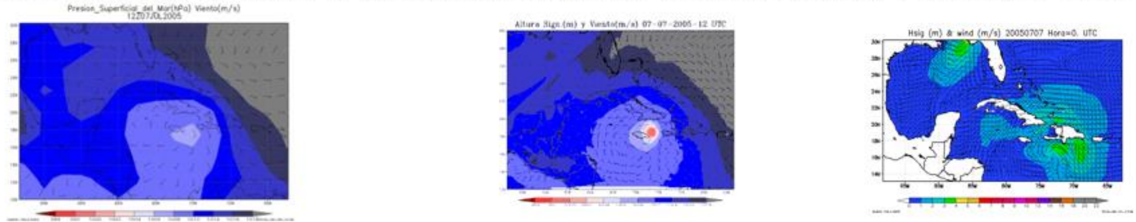
Comparison of wind and wind wave model outputs with NOAA buoy records

Wind forecasts, compared to buoy records, show that errors are, on average, less than 20%; but they increase in extreme values, when the weather is close to calm or during storm, with very intense winds. Although the absolute error is rarely greater than one meter and the relative one is generally between 20 and 25%, in the evolution of wave height in deep water as WW3 output, the relative error increases for very low values, of the order of centimeters, because the model does not forecast values close to zero. To improve the quality of the first hours, a pre-forecast was applied, which reduces errors in the first hours of the model forecast. However, the influence of the self-education period is preserved, so that the optimum period of highest quality forecast is recorded from 12 to 48 hours, and after this interval the prediction quality again decreases, because the hurricane track forecast error increases.

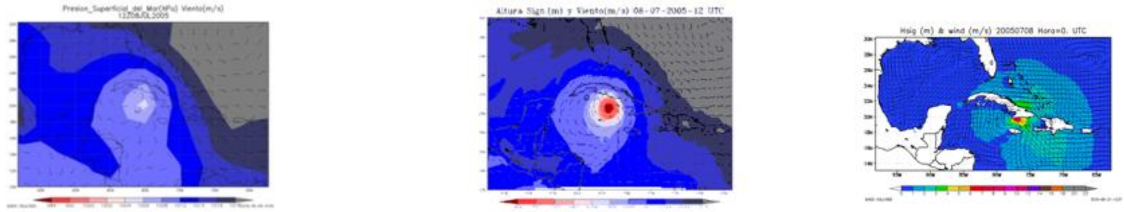
Wind speed records show a great dispersion with respect to the values that have a certain persistence over time, which is really the wind that generates waves. Wind speed absolute errors, in general, are below 2 m/s, but the relative error oscillates around 30%. Here, the influence of hurricane track forecast errors is also present.



a) NOAA pattern, WRF and WW3 output fields in a 24-hour forecast (July 6th, 2005, 00 UTC).

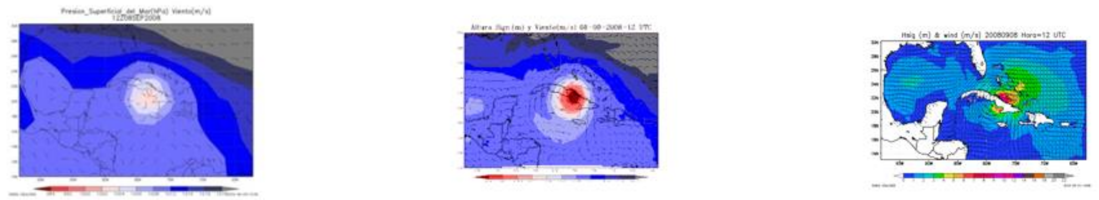


b) NOAA pattern, WRF and WW3 output fields in a 48-hour forecast (July 7th, 2005, 00 UTC)

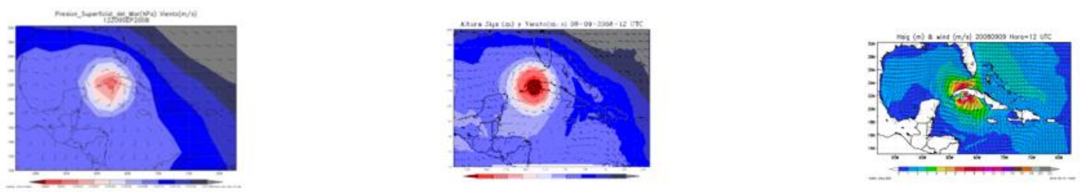


c) NOAA pattern, WRF and WW3 output fields in a 72-hour forecast (July 8th, 2005, 00 UTC)

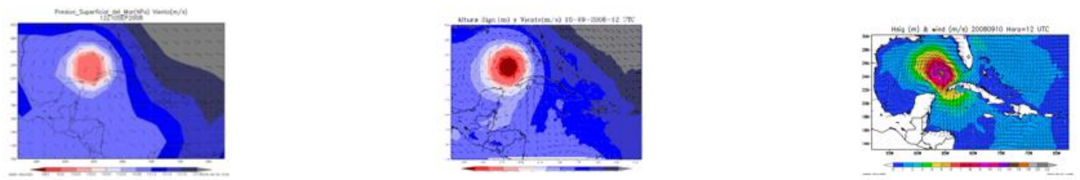
Figure 5. Comparison among NOAA circulation patterns, WRF and WW3 output fields (sea level pressure, wind and wind wave height) in presence of Hurricane "Dennis". Forecast from July 5th, 2005, 00 UTC.



a) NOAA pattern, WRF and WW3 output fields in a 24-hour forecast (September 8th, 2008, 12 UTC).



b) NOAA pattern, WRF and WW3 output fields in a 48-hour forecast (September 9th, 2008,12 UTC)



c) NOAA pattern, WRF and WW3 output fields in a 72-hour forecast (September 10th, 2008, 12 UTC)

Figure 6. Comparison among NOAA circulation patterns, WRF and WW3 output fields (sea level pressure, wind and wind wave height) in presence of Hurricane "Ike". Forecast from September 7th, 2008,12 UTC.

As an example, Figures 7 and 8 show the comparison of wave heights and wind speed values recorded in buoys with those forecasted in the presence of hurricanes "Dennis" and "Ike" on Figures 7 and 8.

Sea level increase as an output of ROMS model, in comparison with testimonies and tide gauge records

Given the fine resolution of ROMS model, with a space step of 2 km, it seems that it is not necessary to introduce a parametric cyclone or a

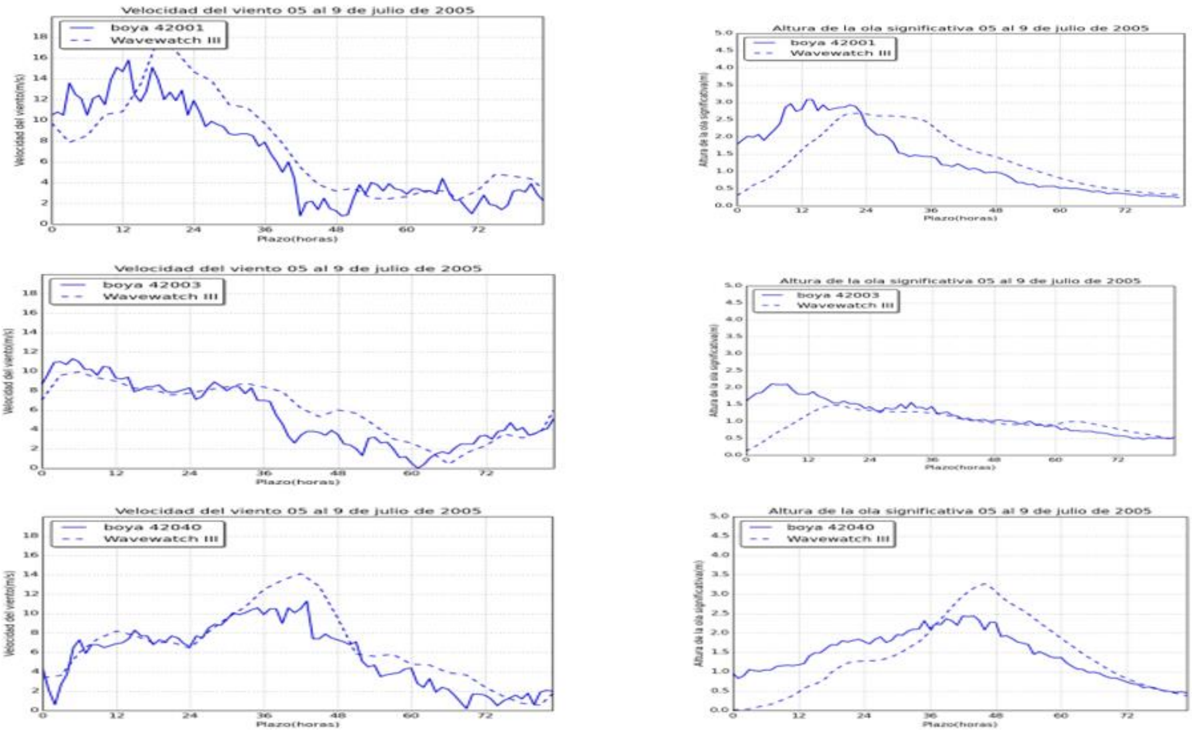


Figure 7. Comparison between some buoy records (broken lines) and WW3 outputs for wind and wind wave height (solid lines) in the presence of Hurricane "Dennis" from July 5th to 9th, 2005, during a 72-hour forecast.

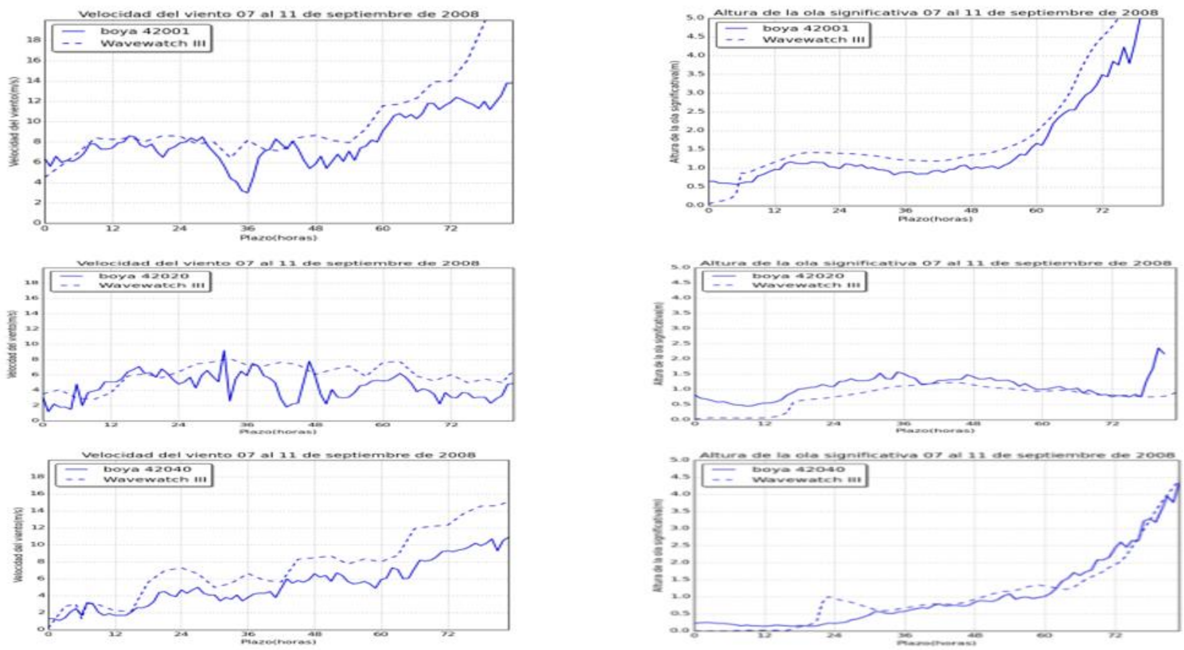


Figure 8. Comparison between some buoy records (broken lines) and WW3 outputs for wind and wind wave height (solid lines) in the presence of Hurricane "Ike" from September 7th to 11th, 2008, during a 72-hour forecast.

mobile mesh for the efficient representation of sea level increase in shallow water areas. This advantage is observed in Figures 9 (a-h), when hurricanes “Charley”, “Ivan”, “Dennis”, “Ike” and “Paloma” were located near the shore line, generating a sea level increase by storm surge. The maximum values of the sea level increase correspond to those reported in the hurricane season summaries (Ballester and Rubiera 2005,2006, 2009), prepared at INSMET.

At the pass of “Charley”, the highest sea level increase, of 3.84 m, was predicted at El Cajio, while the reported value in the Hurricane Season Summary (Ballester and Rubiera, 2005) was 4 m. As shown in Figure 9 a, the graph of the model result shows more than 3.5 m for this area. At Surgidero de Batabano, the model shows an elevation between 2.5 and 3 m, while the reported value was 2.8 m. It was also possible to forecast the behavior of a moderate flooding that occurred in Havana, in the order of 0.5 to 0.8 m, when “Charley” entered the Gulf of Mexico.

In the case of “Ivan” (Fig. 9 b), significant values of sea level rise appear in low-lying areas of the southern coast of Havana and Pinar del Rio provinces, from 1.5 to 3.5 m, corresponding with the reports published in the Season Summary (Ballester and Rubiera, 2005).

As regards "Dennis" (Fig. 9 c), the model shows the area of maximum impact to the south of the central provinces; sea level rise was between 1.5 and 2.5 m, while to the south of Camagüey an increase of up to 1 m can be observed, in correspondence with the report by Ballester and Rubiera (2006).

Hurricane "“Ike”" caused flooding in several coastal zones. Figures 9 d,e,f show that, in the Gibara - Baracoa section, sea level rise was over 1 m, while on the coasts of Granma province it reached from 1 to 2 m. To the south of Camaguey, Ciego de Avila and Sancti Spiritus provinces, values of 1 to 1.5 m were observed, and l”Ike”wise to the south of Cienaga de Zapata.

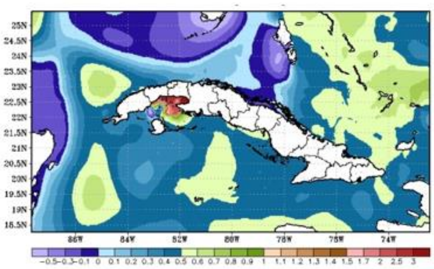
For “Paloma” (Fig. f,g), ROMS hourly outputs were obtained and the experiment lasted up to 96 hours, in order to follow the flood with enough detail, since this has been a very controversial case for the authors. Graphic outputs showed the sea level rise to the south of Sancti Spiritus, Ciego de Avila and Camaguey, and later also in Las Tunas, with values of 60 to 70 cm. However, it is known that the flood had devastating effects. The season summary (Ballester and Rubiera, 2009) stated that waters penetrated 1.5 km inland in Santa Cruz del Sur; while in Guayabal, Las Tunas, it reached up to 700 m. It is known from previous research (UNDP, 1998; Mitrani *et al.*, 2000 a) that these are roughly the distances between the coastline and 1-m elevation above sea level. Thus, it is perfectly possible that a sea level increase in less than one meter can cause serious damage, it is also n taking into account that floods occur together with heavy rains, strong winds and wind waves moving above sea level, throwing all kinds of objects. After this consideration, the authors consider that the model results for hurricane “Paloma” are satisfactory.

Table 5 shows a comparison between ROMS outputs for sea level rise and some visual testimonies, taken from hurricane season summaries (Ballester and Rubiera 2005,2006, 2009) and from the archives of the Marine Meteorological Center (CMM) and the Meteorological Center of Holguin Province (CMPH).

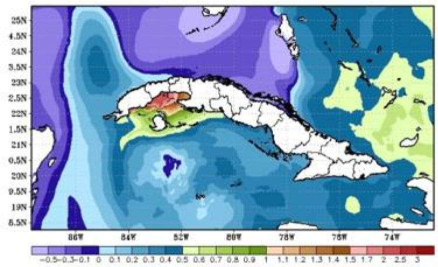
Below, specific ROMS outputs are compared with the tide gauge records provided by the Institute of Marine Sciences. seen that The model outputs have a high correspondence with the rhythm of sea level oscillations recorded by tide gauges, especially those on the northern coast (Figure 10, 11, 12), like Siboney and Los Morros, but with errors of the order of 20 to 30 cm. On the southern coast, Cabo Cruz is the one that best corresponds to the model outputs, also with higher errors in the moments of maximum sea level increase. However, as in these cases the error is systematic and of the order of 25 cm, on average, it is possible to make a rectification simply by subtracting this value from the forecast that exceeds 50 cm.

Sea level increase by wave setup, in comparison with testimonies and tide gauge records

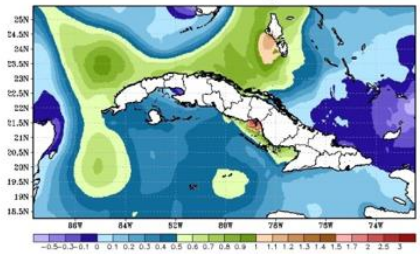
The wave setup phenomenon is best observed on steep coasts that favor its occurrence. In the present work, these effects are shown in the presence of hurricanes “Wilma” (in Havana seafront), “Hanna”(in Gibara) and “Sandy” (in



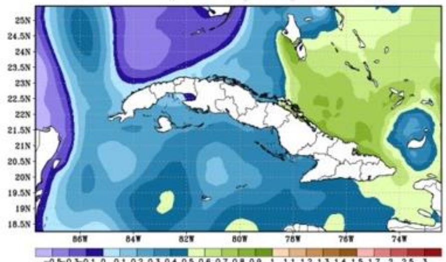
a) Hurricane “Charley” (sea level increase, 11/08/2004 at 9 UTC, 57 hours forecast)



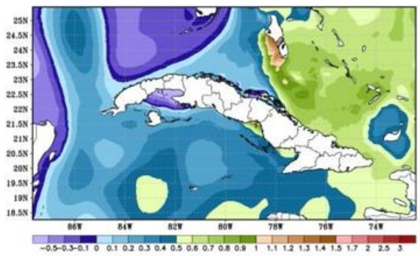
b) Hurricane “Ivan” (sea level increase, 11/09/2004 at 9 UTC, 57 hours forecast)



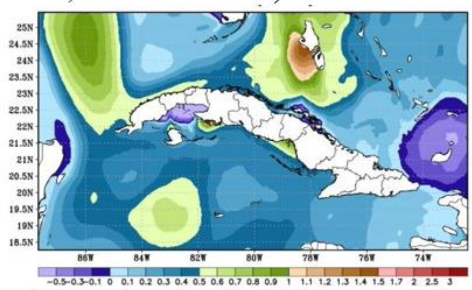
c)Hurricane “Dennis” (sea level increase, 08/07/2005 at 9 UTC, 63 hours forecast)



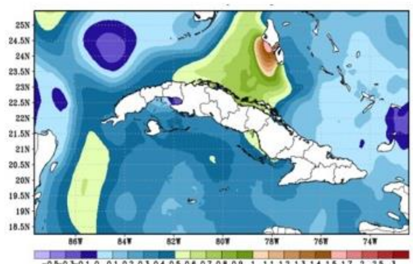
d) Hurricane “Ike” (sea level increase, 07/09/2008 at 00 UTC, 12 hours forecast)



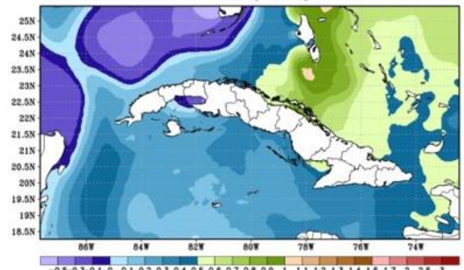
e) Hurricane “Ike” (sea level increase, 08/09/2008 at 00 UTC, 36 hours forecast)



f) Hurricane “Ike” (sea level increase, 08/09/2008 at 10 UTC, 46 hours forecast)



g)Hurricane “Paloma” (sea level increase, 09/11/2008 at 00 UTC, 72 hours forecast)



h)Hurricane “Paloma” (sea level increase, 09/11/2008 at 10 UTC, 82 hours forecast)

Figure 9. Sea level increase forecast, using ROMS model, in presence of hurricanes “Charley”, “Ivan”, Dennis, “Ike” and “Paloma”

the surroundings of Santiago de Cuba Bay). In these cases, tide gauges cannot register the wave setup effect in the flooding areas, because they are installed in other locations; therefore, the most real data are some local visual testimonies. But it is important to validate the astronomical tide contribution, especially in the eastern regions, where the tide maximum values of Cuban territory are registered. For this reason, Figures 14, 15, 16, 17 show the calculated wave setup values, and these values plus those of the astronomical tide ones.

The sea level rise by wave setup in Havana seafront, under the influence of Hurricane “Wilma”, was calculated as above 1.5 m. This value is characteristic of severe floods, with more than one meter of increase at the time of maximum impact; although the watermarks in some buildings of the city indicated more than 2 m of water boarding (in Havana Aquarium, for

Table 5. Comparison between ROMS outputs for sea level increase and some testimonies taken from hurricane summaries, CMM and CMPH archives

	Localities	Visual Testimonies	ROMS
Charley	El Cajío Surgidero de Batabanó La Habana	Sobreelevación de hasta 4 m Sobreelevación de hasta 2.8 m Inundación de ligera a moderada (Sobreelevación de < 1m)	3.84 m De 2,5 a 3 m De 0,5 a 0,8 m
Iván	Prov. Habaneras y sur de Pinar del Río	De 1.5 a 3.5 m	De 1.5 a 3.5 m
Dennis	Sur de Santi Spíritus, Ciego de Ávila, Camaguey, Las Tunas	De 1.5 a 2.5 m Hasta 1m	De 1.5 a 2.5 m Hasta 1m
Ike	Gibara Baracoa Sur de Santi Spíritus, Ciego de Ávila, Camaguey, Ciénaga de Zapata	Entrada del mar Entrada del mar más 400m Entrada del mar de 400 a 500 m	Hasta 1m De 1 a 2 m De 1 a 1,5 m
Paloma	Santi Spíritus, Ciego de Ávila, Camaguey, Las Tunas	De 0.7 a 1,5 Km tierra adentro (cota de 1 m)	De 0.6 a 1 m

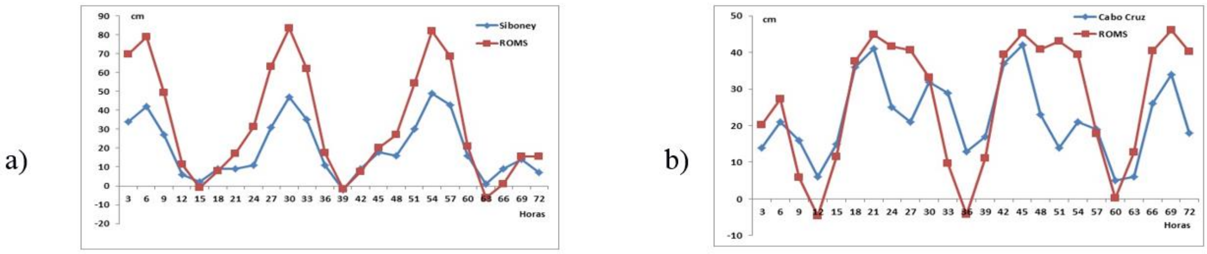


Figure 10. Comparison between tide gauge records of sea level increase and ROMS outputs during a 72-hour forecast in the presence of Hurricane "Charley", from August 11th, 2004, 00 UTC. Locations: a) Siboney b) Cabo Cruz

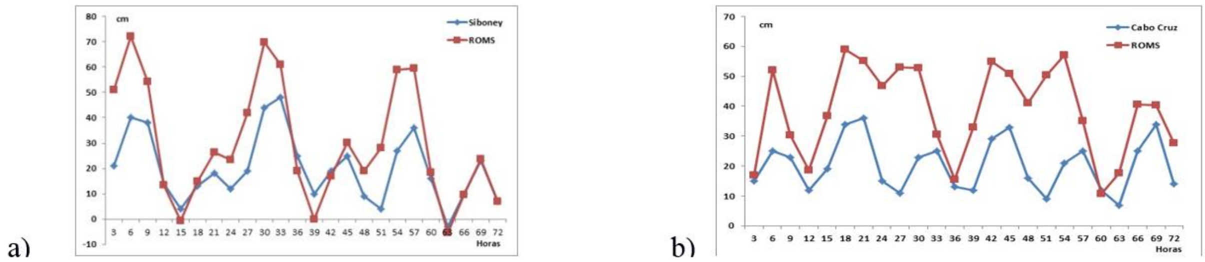


Figure 11. Comparison between tide gauge records of sea level increase and ROMS outputs during a 72-hour forecast in the presence of Hurricane "Ivan", from September 11th, 2004, 00 UTC. Locations: a) Siboney b) Cabo Cruz

example, according to the testimony of its Director at that time, Dr. Guillermo Garcia). But it should be noted that urbanization makes it difficult for the water to return to the sea.

Hurricane "Hanna" mainly affected Gibara, where, as MSc. Axel Hidalgo stated in his testimony, the flood was from moderate to strong, almost 1 m high over mean middle sea level. The calculation of wave setup effect indicated around 1 m too. Here the tide component was important, because it was of the same order as the flood.

The wave setup was calculated when "Sandy" moved over Gibara and Santiago de Cuba. In both cases, the behavior was similar to the previous hurricanes ("Wilma" and "Hanna") with

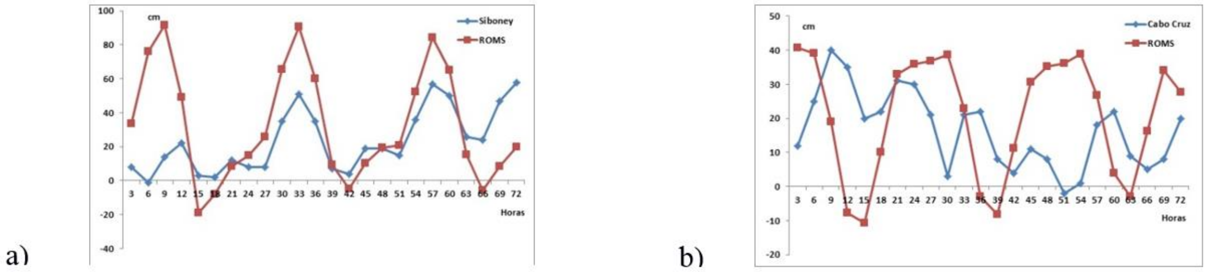


Figure 12. Comparison between tide gauge records of sea level increase and ROMS outputs during a 72-hour forecast in the presence of Hurricane "Dennis", from July 6th, 2004, 12 UTC. Locations: a) Siboney b) Cabo Cruz

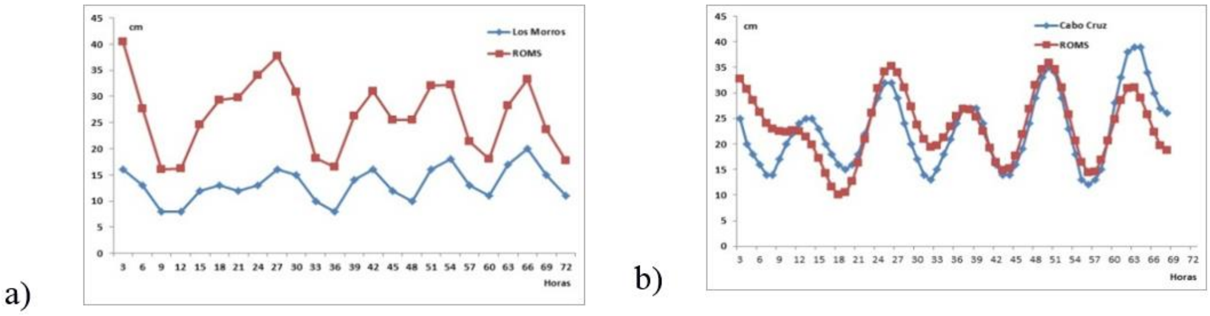


Figure 13. Comparison between tide gauge records of sea level increase and ROMS outputs during a 72-hour forecast in the presence of Hurricane "Paloma", from November 9th, 2008, 00 UTC. Locations: a)Los Morros b) Cabo Cruz

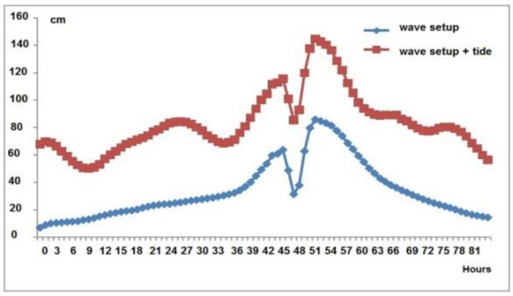


Figure 14. Sea level increase by wave setup (blue line) and by wave setup plus astronomical tide in Havana seafront. Forecast from October 23rd, 2005 at 00 UTC ("Wilma")

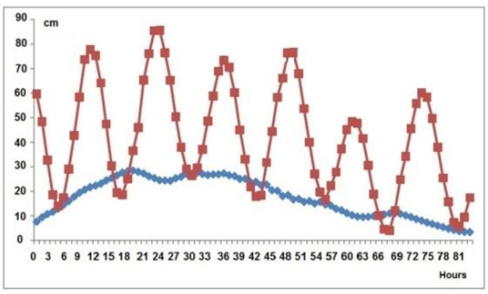


Figure 15. Sea level increase by wave setup on WW3 wave output, and by wave setup plus the tide components in Gibara, under the influence of hurricane "Hanna". Forecast from September 1st, 2008, at 00 UTC.

respect to the tidal component, where the contribution was considerable.

A comparison between testimony values and sea level increase, calculated as wave setup, is showed on Table 6. It is observed that the possible error is less than 25%.

During the experimental work, it was evident that ROMS model is efficient to forecast sea level increase in shallow water areas, which are flooded mainly by wind setup and hurricane

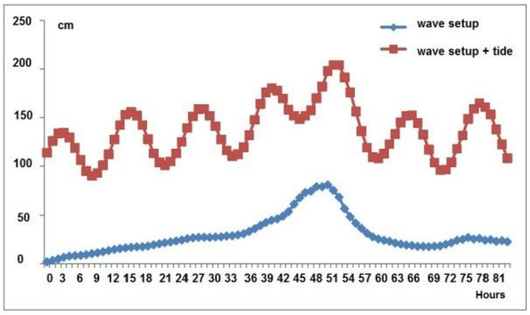


Figure 16. Sea level increase by wave setup, based on WW3 wave output, and by wave setup plus the tide components in Santiago de Cuba. Forecast from October 22nd, 2012 at 12 UTC (Hurricane "Sandy").

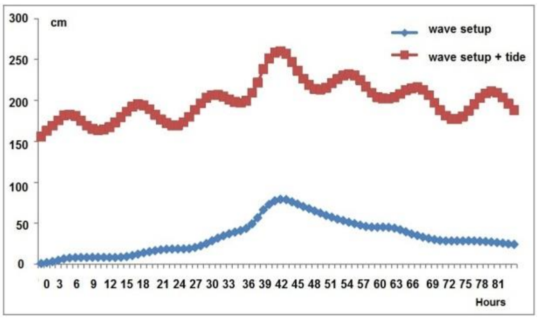


Figure 17. Sea level increase by wave setup, based on WW3 wave output, and by wave setup plus the tide components in Gibara. Forecast from October 23rd, at 12 UTC (Hurricane "Sandy").

Table 6. Comparison between calculated wave setup and some testimonies of sea level increase, taken from hurricane summaries, CMM and CMPH archives

	Localities	Visual Testimonies	Wave setup forecast + astronomical tide value
Wilma	Havana seafront; the water covered the roof of some cars in front of the Melia Cohiba Hotel	Up to 1.7	Up to 1,5
Hanna	Gibara	Up to 1 m	Up to 0.9
Sandy	Gibara	Up to 1,5 m	Up to 2 m
	Bahía de Santiago de Cuba	Up to 2,5 m	Up to 2.8 m

storm surge. In this case, the tide gauge records are generally compatible with ROMS outputs, giving small errors for the low values of sea level oscillations, but they increase in the maximum records, generally in those that exceed 40 centimeters. It is observed that, although at times the error could be high with respect to the records, it is almost systematic and on average equals 25 centimeters above the tide gauge value. However, for areas of severe flooding (more than 1 meter), this relative error is not important because it does not exceed 25% and, as it could be seen in ROMS graphic outputs, there is a good correspondence with the reports made to of the hurricane season summaries prepared at INSMET.

For those floods that occur due to wave breakers, it is recommended to use wave setup formulations to calculate sea level rise, supported by the good quality of wave forecasts, as shown in the analysis of WW3 outputs, and adding the tide component, which in some places is essential.

CONCLUSIONS

a) The necessary premises for the efficient forecast of coastal floods are given by the high quality of model outputs in the prediction of:

- Tracks of tropical cyclones
- Atmospheric circulation patterns
- Wind field on the marine surface

- Wave elements in deep water
- Sea level oscillations

The combination of WRF + WW3 + SWAN + ROMS models, integrated in the SPNOA system and including the calculation of wave setup, shows suitable quality in weather prediction for periods up to 72 hours, especially under the influence of hurricanes moving over the Cuban territory or surrounding waters that generate great wind waves and coastal flooding.

b) ROMS model output shows satisfactory results in the prediction of sea level rise over shallow waters, while the wave setup module is more efficient in cases of steep coastal zones.

c) Relative errors in wind waves and sea level rise forecasts are around 25%; therefore, the applied forecasting methods are considered adequate.

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The authors of this work declare no conflict of interest.