Coastal Risk Assessment in Central America: from Deep Waters to Nearshore Regions

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COASTAL RISK ASSESSMENT IN CENTRAL AMERICA: FROM DEEP WATERS TO NEARSHORE REGIONS

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KEY POINTS

- *An unstructured wavel model in Central America is developed*
- *The hindcast models allows to assess the coastal risk due to wave storms in the region*
- *Sea wave records are used to validate the developed spectral wave model*
- *Storm surge is considered in risk index, taking into account the event duration*

1 INTRODUCTION

Wave climate and atmospheric behaviour in the Pacific Ocean is quite different from that of the Mediterranean sea, and the phenomena which occur along the Pacific Basin influence the state of other oceans around it. The waves that reach the coasts of the American continent are mainly influenced by events such as storm surges, ENSO phenomena, low pressure systems and climate change. However, scarce studies have been carried out around the assessment of wave storm risk in the Central American coastal regions, which still suffer flooding and coastal erosion events.

In the Pacific of Central America, activities such as environmental conservation, fishing, international trade and mainly tourism are carried out. Moreover, the Panama Canal which connects the Caribbean sea with the Pacific Ocean is located in the Central American region, thus, there is a significant amount of maritime traffic. On the other hand, the shoreline morphology presents a high marine and terrestrial vegetation cover, with a predominance of slightly steep sandy beaches (*Lizano*, 2013). These factors are in constant change throughout the year and it is interesting to study the risk of storms that occur in the Pacific Ocean and that have repercussions on the activities that take place in this region.

Wave models forced by atmospheric conditions are crucial to increase our understanding of wave climate in a given region. Studies have revealed that the wave estimated by numerical models arriving on the Pacific coast of Central America is underestimated and the wave statistics need to be recalibrated, or a recalibration of the global wave model to handle this deficiency must to be carried out (*Alfaro, et. al*., 2019).

One of the main reasons of the accuracy shortcoming of the numerical models in this region is partly due to the lack of field-recorded wave data, or the low temporal resolution with which these models work. Recently, Acoustic Doppler Current Profilers have gone into operation in the region, which combined with satellite data, it has been used in this investigation.

In this study the configuration, calibration and validation of the an unstructured wave numerical model were developed by using Wavewatch III (*The WAVEWATCH III ® Development Group*, 2019) from the Pacific basin to the Central American shoreline. Then, the Storm Power Index, Costal Vulnerability Index and Risk Index have been estimated for several coastal regions in the Central American Pacific coast.

2 METHODS AND MATERIALS

The first stage of this study corresponds to the generation of the wave hindcast. The spectral model used is Wavewatch III (hereinafter WW3) which is based on the wave action balance equation:

$$\frac{\partial}{\partial t}N + \nabla_x \dot{x}N + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial \theta}\dot{\theta}N = \frac{S_{tot}}{\sigma} \tag{1}$$

where N is the wave energy spectrum, k is the wavenumber, $\dot{x}$ corresponds to the 2D spatial coordinates, θ represents the wave energy direction and σ is the wave frequency. The WW3 model was evaluated with several tunning configurations which were mainly determined by the source terms e.g. the one proposed by *Ardhuin et. al*. (2010) and *Rogers, et. al.* (2012) , wave interaction, unresolved obstacles (*Mentaschi, et. al.*, 2018), and the numerical methods required for propagations in space and time. The wind forcing used was ERA-5 global climate reanalysis (*Hersbach et. al.*, 2018). Moreover, after testing with unstructured grids of different resolutions, the chosen grid resolution ranges from 150 km offshore up to 1 km nearshore, as shown in Figure 1.

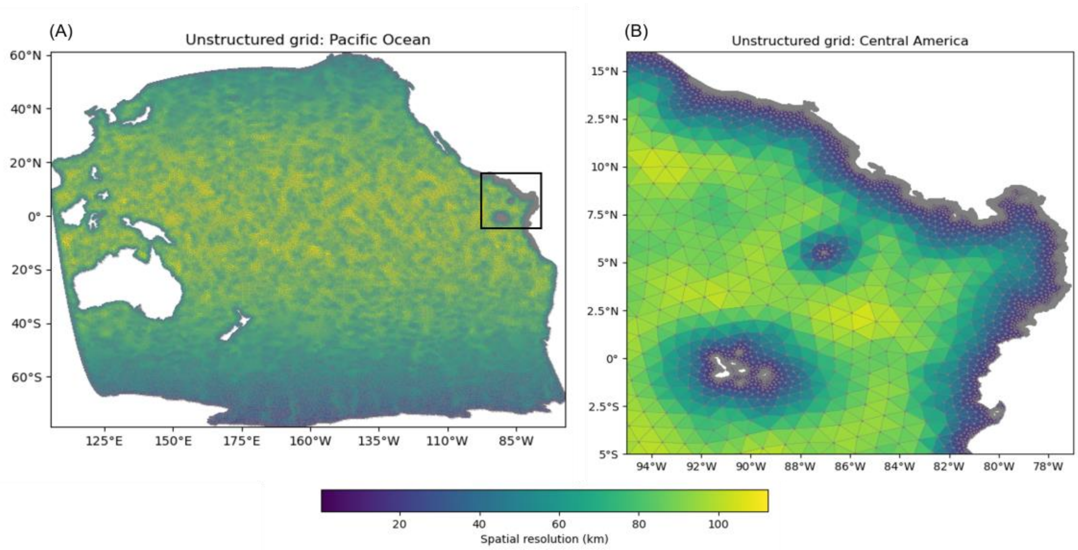

Figure 1. Unstructured grid used in WW3 model for: (A) Pacific ocean., (B) Central American Pacific region.

After calibration and validation of the WW3 model, the wave outputs from the nearshore nodes were used to estimate the Wave Storm Power P, which is defined by the eq. (2):

$$\mathrm{P}=\int_0^{t_d} \mathrm{E}\cdot\overrightarrow{C_g}\;\; dt_d=\int_0^{t_d}\left(\frac{1}{16}\rho g\mathrm{H}^2\right)\cdot\left[\frac{1}{2}\left(1+\frac{2kh}{\sinh(2kh)}\right)\sqrt{\frac{g}{k}\tanh(kh)}\;\cdot\cos(\theta_n)\right]dt_d \qquad (2)$$

The eq.(2) considers the energy flux per unit wave crest length occurring in the direction perpendicular to the coast and propagating at the wave group velocity *Cg* (*Postacchini & Brocchini*, 2014). The parameter θ_n indicates the angular dephasing between the predominant wave direction and the perpendicular direction to the section of the coastline closest to the point where the wave assessment is conducted.

The wave storm power is numerically integrated over the time taken by the storm period t_d. For this study t_d was defined as the time span in which the wave height (or wave statistics) of consecutive sea states exceed a threshold. However, it has been considered that the definition of t_d is interdependent on the minimum storm duration, and interarrival time between successive storms. (*Lira-Loarca*, 2020). Then, it is possible determine the storm power index (SPI), either based on the storm power values for each storm, or by means of equations such as the one presented by *Dolan & Davies* (1992).

$$SPI=\begin{cases} SPI \leftarrow \mathrm{H}^2 t_d \quad [Dolan\ and\ Davis\ 1992] \\ SPI \leftarrow Classification\ by\ cumulative\ probability\ of\ storm\ power \end{cases} \qquad (3)$$

According to the SPI value obtained, a criterion for classifying the storm wave hazard can be established. In this study there were defined five categories from SPI=1 (very low) up to SPI=5 (very high). On the other hand, coastal vulnerability in the Central American region is mainly determined by the sensibility of the coastal area to wave hazard and it measures the capability to cope and withstand to storm events and their impacts (*Gilard & Givone*, 1996; *Weichselgartner*, 2001).

The coastal vulnerability was assessed by means of the coastal vulnerability index (CVI) defined as the lowest values equal to 1, while values of CVI equal to 5 correspond to the highest CVI value. The classification of CVI levels is described in Table 1.

Coastal Vulnerability Index CVI	**Description**
1. Very low	Natural coastal plain: Abscence of transportation infrastucture or urban areas and/or turistic places.
2. Low	Protected littoral transportation infrastructure with hard protection infrastructure or artificial gravel beaches. Presence of urban areas and/or turistics places are not considered.
3. Medium	Unprotected littoral transportation infrastructure. Presence of urban areas and/or turistics places are not considered.
4. High	As level 2 but considering urban areas and/or turistic places.
5. Very high	As level 3 but considering urban areas and/or turistic places.

Table 1. Determination of the Coastal Vulnerability Index, under conditions of Central American nearshore regions.

Once the CVI and SPI have been determined for a given location nearshore, the risk index (RI) is calculated as follows:

$$RI = CVI \cdot SPI \tag{4}$$

Thus, for a storm level defined by the SPI classification by cumulative probability of the wave storm power from eq.(3), and according to the coastal vulnerability in the regions of interest, a risk category based on the RI can be determined. Hence, the RI categorization established for the Pacific coastal region of Central America is shown in Figure 2.

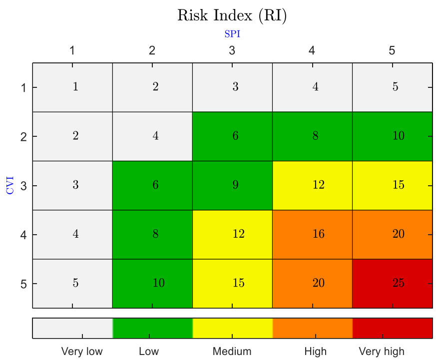

Figure 2. Classification of the Risk Index. The number inside each cell indicates the given RI value.

3 RESULTS AND DISCUSSION

The validation and calibration test runs of the WW3 model have been carried out from the year 2006 to 2016. Calibration has been done against satellite data and validation has been done against buoy records, obtaining RMSE values close to 0.215 and Pearson correlation coefficient of 0.805. According to the evaluations carried out using different calibration scenarios, a calibrated model was optimized which produced a linear correlation coefficient linear of 0.79 between the modeled zeroth order moment wave height (H_{m0}) and satellite data employed. With respect to the estimation of storm risk, the period analyzed corresponds to the period from January 1st, 2006, to December 31st, 2016, with hourly output results from the WW3 model. Figure 3 (A) firstly presents the nearshore WW3 nodes where wave storm power estimations is carried out. The red dot marks a sample node, at which the timeseries of the H_{m0} was produced using the WW3 model. The above timeseries is shown in Figure 3 (B) and in addition the H_{m0} associated to the 95 % exceedance probability was estimated, when the H_{m0} threshold was exceeded storm wave periods occurred.

The empirical cumulative distribution function (ECDF) of the storm powers is presented in Figure 3 (C). A very low value of SPI is shaded in dark green color, a low SPI in light green, a medium SPI in yellow, a high SPI in red and finally, if the exceedance probability is greater than 0.99 the scenario is a very high SPI and it is shaded in dark red color. For the time span analyzed in chart (C) of Figure 3, wave storms were found, mainly between the months of July and September, whose storm powers are greater than 850 kW h/m, Besides, considering that the community of Santa Teresa in the North Pacific of Costa Rica obtained a CVI equals to 4, then a high risk (RI equal to 4 according to Figure 2) is reached, and this fact could impact negatively in the economic activities such as tourism and cabotage.

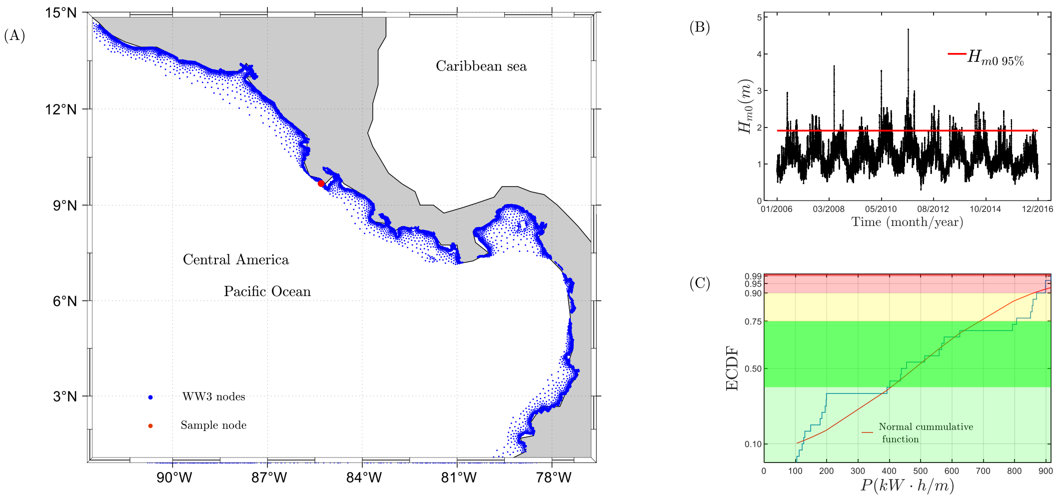

Figure 3. Storm wave power: (A)WW3 Nodes and sample, (B) Timeseries of H$_{m0}$ and storm threshold associated with the 95 % of probability of exceedance, and (C) the empirical cumulative distribution function (ECDF) of wave storm power for the timeseries in presented in (B).

Likewise, as shown for the sample node in Figure 3, this risk assessment was conducted for multiple coastal locations along the Pacific coast of Central America, offering findings of high importance for the coastal communities, socio-economic activities and coastal infrastructure as well.

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