Storm characterization in the Yucatan Peninsula

E.Tonatiuh Mendoza, Christian M. Appendini, Paulo Salles, Jose López, Alec Torres-Freyermuth

Laboratorio de Ingenieria y Procesos Costeros, Instituto de Ingeniería, Universidad Nacional Autónoma de México,Sisal, Yucatan, Mexico

Correspondence to: E.T. Mendoza (emendozap@iingen.unam.mx)

Abstract

This work presents an intensity scale for storm waves in the Yucatan (Mexico) coast. The storm characterization in the study area is based on deep-water wave hindcast information obtained from 4 nodes covering the period 1979-2008. Storms events were defined based on statistical wave properties (i.e., μ+2σ) being defined for a 2 m wave height threshold occurring for a minimum duration of 12 hours. Subsequently, the storms were catalogued in five classes by means of cluster analysis and supervised classification, each class was defined as a function of mean values of wave height, period, and duration. Finally, a preliminary assessment of the storm-induced inundation hazard was carried out for each class in order to characterize the potential risk in the area.

1 Introduction

A storm can be defined as an intense atmospheric perturbation accompanied by strong winds among other elements. Its occurrence causes an increase in wave height and in some cases in sea level (storm surge). These events drive a series of morphodynamic responses such as beach and dune erosion, overwash, and flooding of low-lying areas with important consequences upon the coastal geomorphology. The magnitude of these processes and responses is proportional to the storm energy content and, in this sense; high-energy storms can significantly accelerate existing rates of shoreline erosion (Morton and Sallenger, 2003).

The practical consequences of these processes are large damages in existing infrastructures, affectation of coastal uses and disturbance of coastal ecosystem services. Therefore, importance of storm events and their induced hazards are explicit in Integrated Coastal Zone

Management (ICZM) Protocols (PAP/RAC, 2007). These protocols include specific chapters dealing with natural hazards, where parties are advised to undertake vulnerability and hazard assessments of coastal zones and take prevention, mitigation and adaptation measures to address the effects of natural disasters.

One of the simplest approaches to estimate the impact of these events is based on the use of an intensity storm scale where each storm is associated to a given class in terms of a variable characterising its hazardous potential. Examples of such approaches are the Saffir-Simpson scale for hurricanes (Simpson, 1971; Saffir, 1979), the scale proposed by Dolan and Davis (1992) for Atlantic storms and Mendoza and Jimenez (2008) for the NW Mediterranean.

Within this context, the main aim of this work is to obtain an intensity scale for storm waves storms in the Yucatan coast (Gulf of Mexico). This will result in a storm classification where each class is characterized in terms of wave height, wave period, duration and energy content.

2 Study area and wave data

The study area is situated in the northern coast of the Yucatan Peninsula (Figure. 1). It has a coastline of about 360 km long and it is characterized by coastal lagoons with barrier islands and sandy beaches.(CINVESTAV, 2007). In terms of wave conditions there are two types of meteorological systems that create wave storms in the area: mid latitude anticyclonic systems generating cold fronts known as *Nortes* (characterized by polar winds blowing from the Northern region); and tropical cyclonic systems that create tropical depressions tropical storms and hurricanes.

The historical wave information employed in this study to characterize storms was obtained from a 30-year (1979 to 2008) wave hindcast (Appedini et al, 2011) with an output every three hours which include, the significant wave height, Hs, the peak period, Tp and direction θ. This work uses 4 different nodes (LIPC-01 to LIPC-04 in Figure 1) located along the Yucatan coast at an approximate depth of 40 m within the Gulf of Mexico which permit to cover the spatial variability in wave conditions.

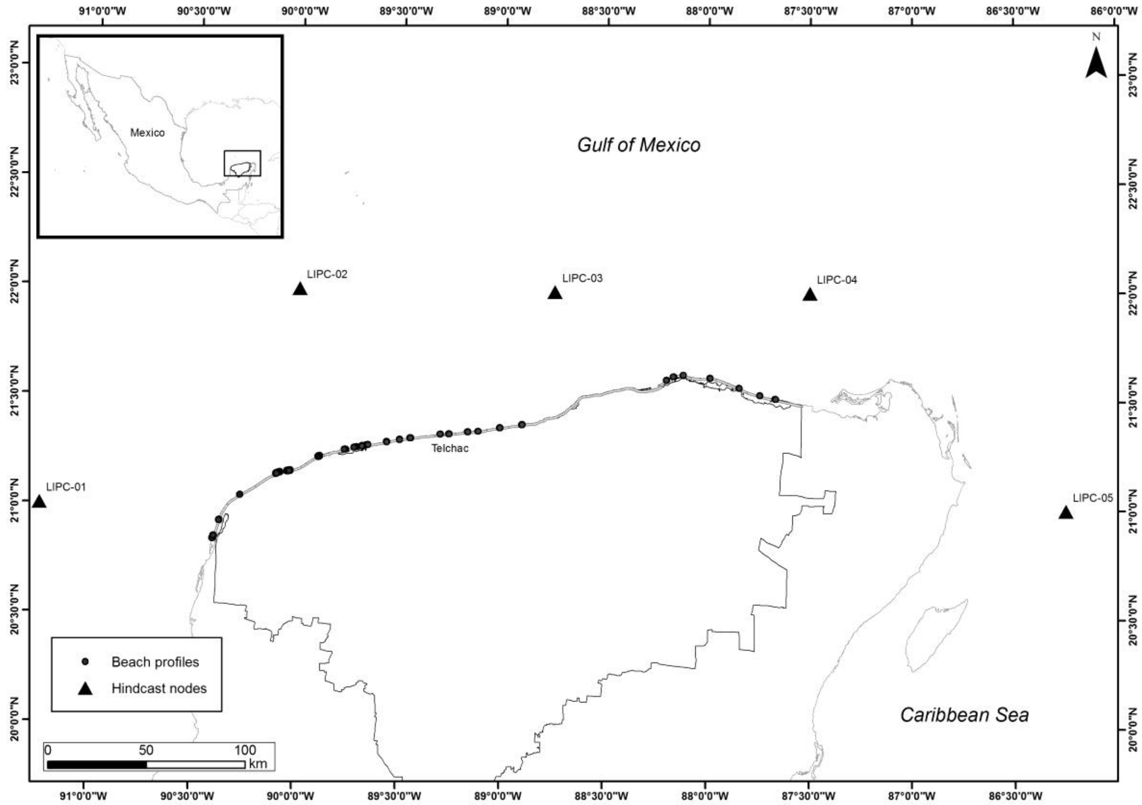

Figure 1. Study area and location of wave data nodes.

3 Methodology

In order to develop a storm classification, three main steps have to be done: (1) storm definition and identification, (2) selection of the parameter to characterize them according to a given criteria, and (3) selection and application of a classification method.

A storm is defined as a wave event in which the wave height exceeds a given threshold during a certain time period; therefore the first step is the definition of the wave height threshold. This can be done as a function of the local wave climate characteristics or based on some robustness criteria, especially when they are going to be used in extreme wave analysis (see e.g. Pandey et al., 2004). In this work we follow the criteria used by the United States Army Corps of Engineers which define the threshold as the mean long term *Hs* plus two standard deviations (http://frf.usace.army.mil/storms.shtml). Table 1 presents these values for the different nodes employed in this work (see Figure 1).

Table 1. Long term mean and stdv. Hs values along with Hs storm thresholds for the 4 nodes along the Yucatan Peninsula for the period 1979-2008.

	Long term Hs		Hs storm
NODE	mean	stdv	threshold
LPIC-01	1.01	0.54	2.09
LPIC-02	1.1	0.57	2.24
LPIC-03	1.04	0.55	2.14
LPIC-04	1.06	0.57	2.2

Given these values, a storm is defined as a wave event exceeding an Hs value of 2 m, during a minimum time of 12 hours. The duration criteria are usually designated in order to assure that the identified event has the sufficient time to induce the erosion and inundation processes. Thus, for example in the structure design methods, the duration of a storm is considered in terms of the number of waves (see Van der Meer, 1989).

Because one of the main objectives of the classification is to provide an idea about the potential hazards induced by the storms, the classification variable should reflect their intensity. To this end, we use the storm "energy content", *E*, which is given by

$$E = \int_{t1}^{t2} Hs^2 dt \qquad (1)$$

where t_1 and t_2 define the storm duration (*Hs* > *Hs* threshold). The solely use of the wave height value to characterize the storm (e.g. storm-averaged *Hs* or *Hs* at the peak of the storm) might result in an underestimation or overestimation of the actual wave storm energy.

Once the storms were identified and characterized by its energy content at the different locations, they were integrated into a single storm data set. The practical result of this integration is that one meteorological event can be represented in the dataset by different wave values reflecting the spatial variability of the event. This is clearly illustrated in Figure 2, where wave records at different locations along the Yucatan coast during hurricane Isidore (September 2002) show very different *Hs* values. With this approach, we are able to take into account different energy contents for different locations along the coast during the same meteorological event.

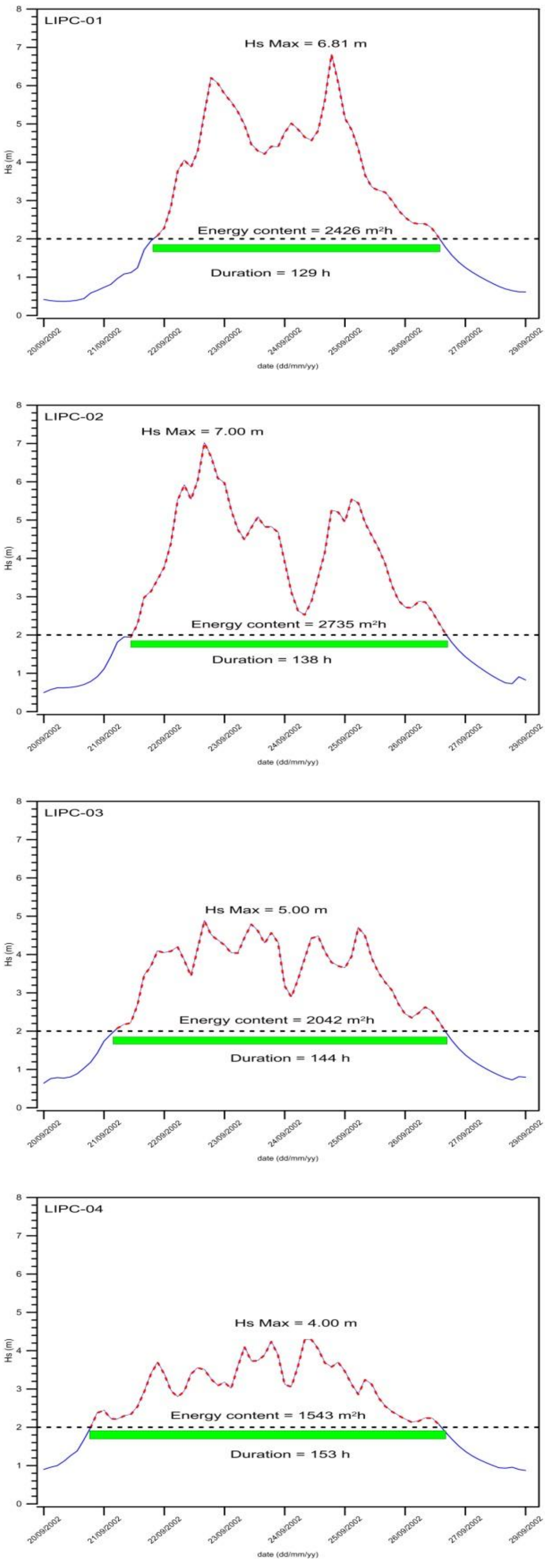

Figure 2. Spatial variability along the Yucatan coast coast during Huricane Isidore in September 2002.

Finally, the classification process was carried out by means of cluster analysis, which permits the reduction of the amount of data by categorizing or grouping them in terms of similarity. The average linkage method was then used which consists of creating a hierarchical cluster tree using the single linkage algorithm. Although it tends to produce a great number of small groups, it is generally superior to other clustering methods and it has been successfully used in climate studies (see Bunkers et al., 1996).

In order to reduce the tendency to produce a large number of groups, a supervised classification was applied to resulting clusters to produce a 5 category classification considering the obtained dendrogram partition, the cluster consistency and the energy content variation within each group. The selection of a 5 categoy scale was made to maintain the analogy with existent storm scales (Simpson, 1971; Saffir, 1979; Dolan and Davis, 1992; Mendoza and Jimenez, 2008). The selected scale categorizes the storms into: I-weak, II-moderate, III-significant, IV-severe, and V-extreme.

As an example of potential management applications, the inundation magnitude caused by the wave-induced maximum water level at the shoreline (wave run-up) is assessed using the model proposed by Stockdon et al. (2006). In order to cover the variations in hazard intensity due to existing differences in beach characteristics along the Yucatan coast, 25 representative beach profiles have been selected (Figure. 1). The run-up estimation for each class has been calculated by averaging all the values calculated for each storm belonging to the corresponding class for each profile. Since the main interest is assessing the contribution of the forcing (storm) to the flooding process, we use the induced run-up as a proxy of the inundation potential of the considered storms.

4 Results

4.1 Storm classes

The application of the selected *Hs* threshold (Table 1) criteria resulted in a total number of 1541 storm records in the four analyzed nodes from 1979 to 2008. It is important to notice that this number does not correspond to the number of meteorological events since in most of the cases; the same forcing event is usually recorded as a storm wave in different locations (nodes) with different characteristics (e.g. Figure 2). These 1541 storm records along the coast correspond to approximately 362 *Nortes* and 20 tropical cyclonic systems -2 extra-tropical storms, 5 tropical depressions,7 tropical storms, and 6 (1 category-I, 1 category-III, 3 category

IV and 1 category V) – and correspond, on average, to 14 events per year during the study period (1978-2009).

The application of the clustering analysis is shown in Figure 3 and the resulting class-averaged values of *Hs*, *Tp*, duration and energy content for each storm type can be seen in Figure 4 and Table 2. As observed, the increase in storm category is accompanied by an increase in all wave variables at different rates. It must be stresses that having a classification based on the storm energy content is that to properly classify a given event it is necessary to take into account the two variables controlling its magnitude (eq 1): wave height and duration.

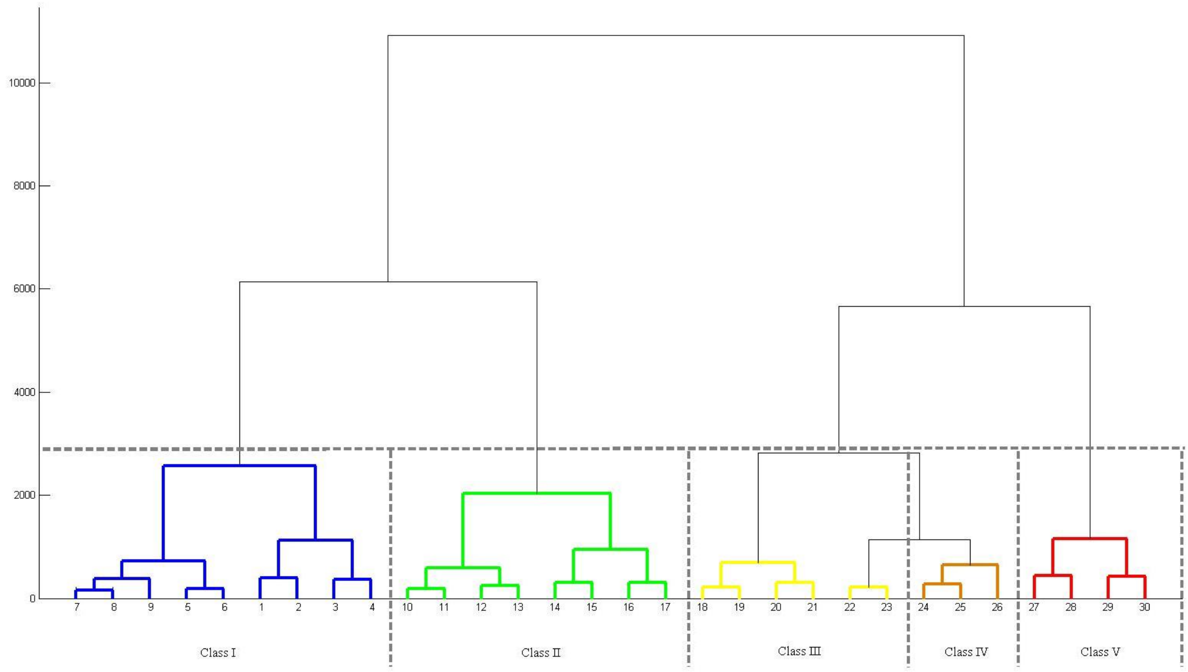

Figure 3. Storm classification using cluster analysis (solid lines) and supervised classification (dashed lines). Numbers in the x-axis are clusters' identifiers.

Figure 4 shows the class-averaged values for each intensity level. It is observed that the wave period is the variable with the smallest variation with storm category. Thus, although it increases for more intense categories, it only varies about 3.2 s over the full range. It has to be considered that this sea environment is characterized by the presence local waves with maximum *Tp* values of about 14 s. The wave height at the peak of the storm increases about 2.3 times in the full range of categories whereas the duration increases about 6 times. Finally, the largest increase in magnitude was observed for the energy content in such a way that, the energy content of category V storms is 16 times larger than category I events. These results indicate that the produced classification clearly reflects the variations in storm waves magnitude. In particular, the increase from one category to the upper levels will reflect a significant increase in the energy content and, in consequence, its hazard potential.

Table 2. Averaged characteristics of storm classes recorded during the period 1979-2008.

Storm class	**Hs max (m)**	**Tp max (s)**	**Duration (h)**	**Energy (m^2h)**
I	2.8	9.3	23	150 (48-300)
II	4.0	10.6	45	418 (301-600)
III	4.7	11.6	74	812 (601-1100)
IV	5.9	12.3	97	1321(1101-1600)
V	6.5	12.5	146	2480 (>1601)

In terms of frequency of occurrence, the smaller the storm category is, the most frequent the event will be. Thus, from the 1541 storm records, 72 % fall into class I-weak, 22 % are class II-moderate-, 5 % are class III-significant, 1.5 % are class IV-severe and, only 0.5 % belong to class V-extreme. This can also be expressed in terms of probability of occurrence (or the equivalent return period, T_R, obtained after fitting an extreme distribution). Thus, for instance, the estimated return periods of each class: (I) < 1 year; (II) ~ 1 year; (III) ~ 3 years; (IV) ~ 5 years; (V) ~ 10 years. It has to be considered that the probability of occurrence of each storm category varies along the coast. In this sense, the eastern part of the Yucatan Peninsula (LIPC_01 in Figure 1) can be classified as the mildest zone in terms of the storms energetic content thus, it is the area with the smallest number of recorded storms of highest categories.

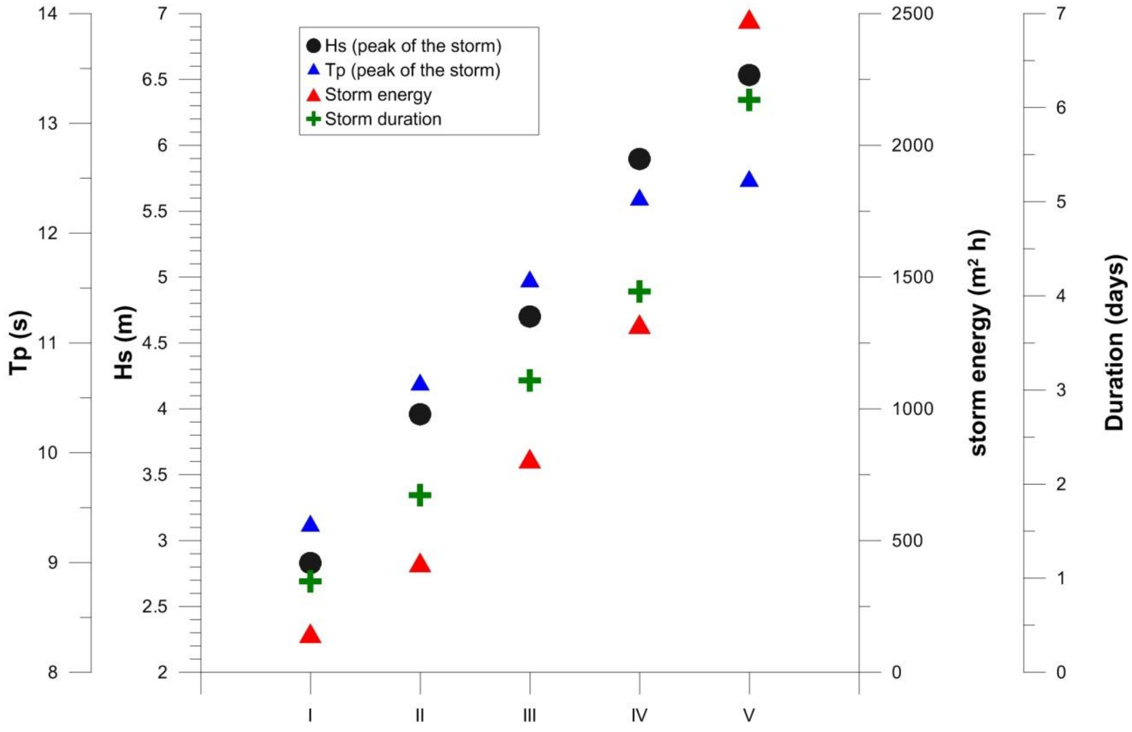

Figure 4. Class-averaged values of wave storm properties in the Yucatan coast.

4.2 Direction and seasonality

Figure 5 shows the directional distribution of storm waves during the analyzed period for each category, where North (N), North-western (NW) and North-eastern (NE) are the main components identified representing 95% of the total number of storms. In addition the most energetic storms registered (belonging to class IV and V) are associated to these directional sectors The Eastern sector is represented by 4%, followed by the Western sector with a 1% of occurrence.

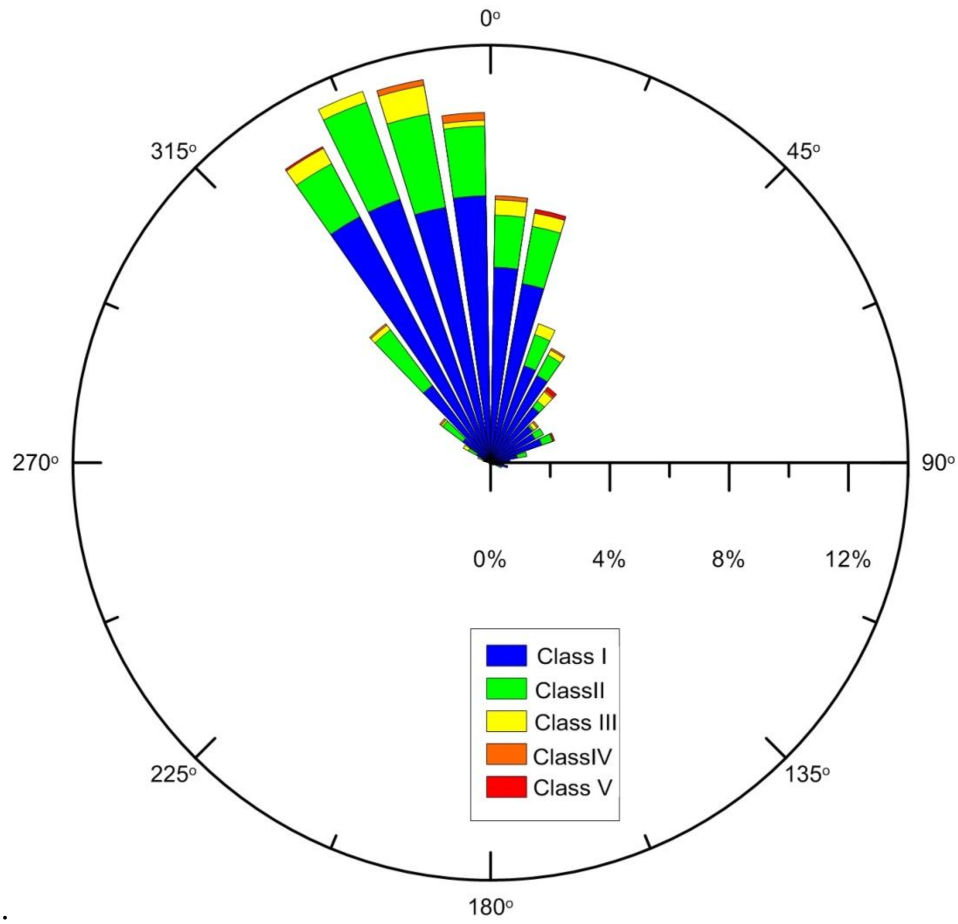

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Figure 5. Directional distribution of storms during the period 1988/2008.

Figure 6 shows the seasonal distribution of storms during the analyzed period. This distribution reflects a mean climatic year with two seasons according to the storm regime: The storm season from September to April and, the calm season from May to August. The limits of both seasons are defined by months with storm activity (May and September) although normally restricted to low energy events. The storms type I and II are present throughout the year although with higher frequency in the stormy season. The storms that belong to the most energetic classes (III, IV and V) mainly verify from September to March and are associated to tropical cyclonic systems that create tropical depressions tropical storms and hurricanes from June through November and mid latitude anticyclonic systems generating cold fronts October to March

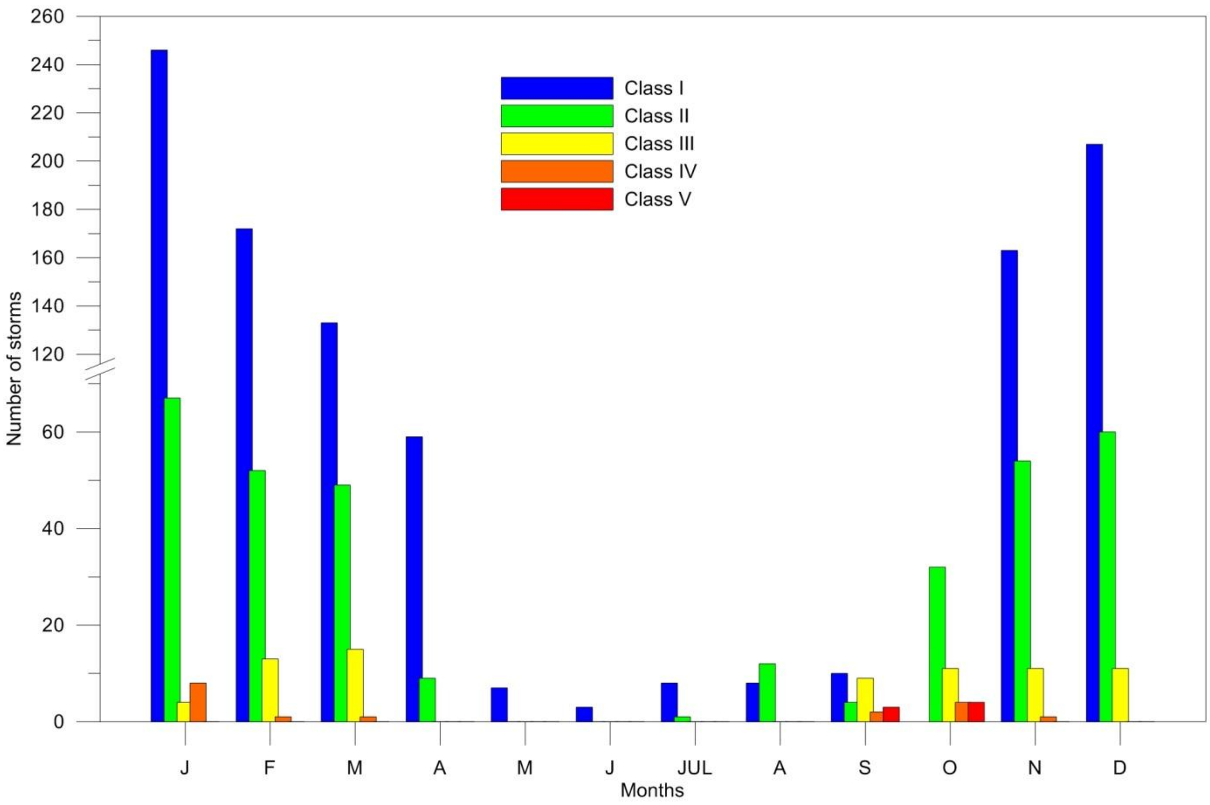

Figure 6. Seasonal distribution of storms during the period 1988/2008.

4.3 Potential Hazards

Figure 7 shows the estimated class-averaged representative potential run-up values for different beach profiles along the Yucatan coast. As expected, the higher the intensity of the storm, the larger the run-up magnitude. In terms of potential hazard the highest values are present in the Hunucma region and San Felipe.

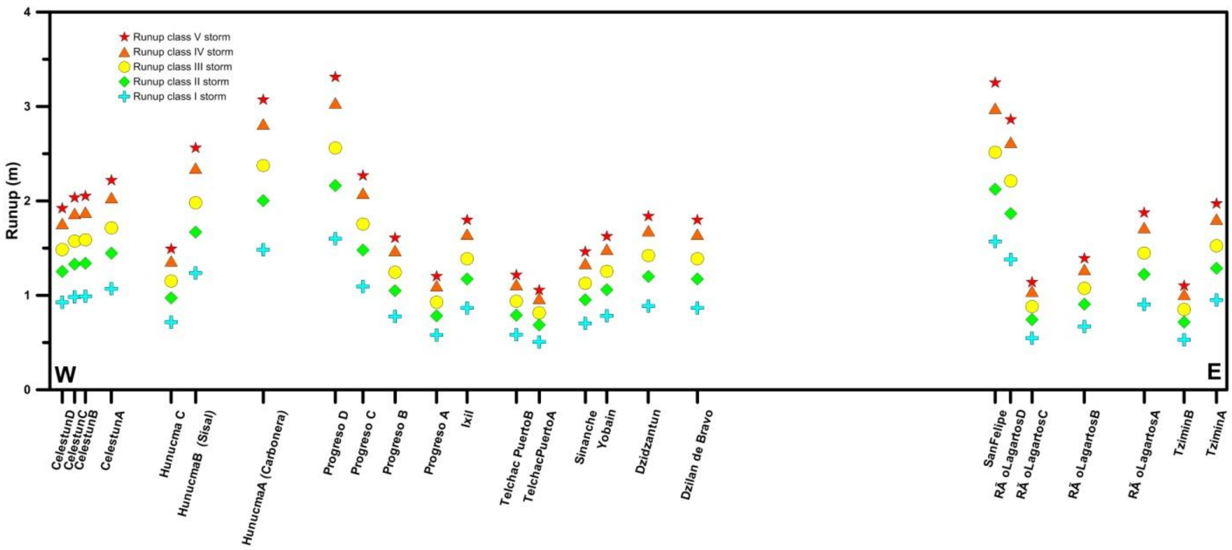

Figure 7. Averaged-class induced run up in different beach profile locations (from West to East).

5 Summary

In this work we have presented a 5-classes intensity scale for wave storms in the Yucatan coast. This has been done by using a wave hindcast data sets from 4 slected nodes within the Gulf of Mexico for the 1979-2008 period. Covering the Yucatan coast from E to W. In this sense, the obtained classification resolves the spatial and temporal variability of wave storms in the area.

The obtained classification (Table 2 and Figure 4) clearly reflects the increase in wave storm properties as storm category increases. Moreover, because the selected classification parameter was the energy content, the most sensitive parameter to changes in storm classes is the energy. Since this variable is a good proxy of induced hazards, the observed increase in energy content for higher classes should reflect a significant increase in the intensity of the expected hazards for categories IV and V. In any case, the real magnitude of the hazard is affected or controlled by the coastal geomorphology.

Acknowledgements

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