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Coastal Vulnerability to Storms in the Catalan Coast

Memoria presentada por

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Chapter 3

Storms[a]

3.1 Introduction

A storm can be defined in a simple manner as a violent atmospheric perturbation accompanied by strong winds, among other elements. When this happens in the sea, the most immediate effects are the increase in wave height and sea level (storm surge). Storms have important consequences upon the coastal geomorphology, particularly large storms, due to the fact that the wave power is a quadratic function of wave height; therefore, they have the ability to rapidly redistribute large volumes of sediment, accelerate rates of erosion or accretion, and control short-term shoreline movement (Morton *et al.*, 1995). It is also frequent that storms cause an abnormal elevated water level (storm surge), which raise the level of wave attack on the shore; higher water levels enable waves of a given size to shoal and penetrate farther landward; setup, runup, overtopping, and overwashing are enhanced during storms.

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[a] Edited version of MENDOZA, E. T. & JIMÉNEZ, J. A. 2008 Clasificación de tormentas costeras para el litoral Catalán (Mediterráneo NO). *Ingeniería Hidráulica en México*, **23**, 2.

For this reason, when storms are characterized on the coastal zone, these are referred to wave heights and storm surge which are the intrinsic marine agents that will induce the majority of damages with the exception of the wind. From now on, whenever a storm or event is referred, it will be with the coastal marine meaning and using the waves and storm surge elements for its definition.

Although the response of a beach to a large storm involves rapid erosion followed by slow recovery, it is unclear how beaches behave under the impact of a variety of different kinds of storms of varying intensity. Additional factors such as dune breaching and overwash may cause the shore to be more sensitive to subsequent storm events, even storms of lesser intensity might cause great changes, if the interval between storms is insufficient for rebuilding the pre-storm dune or barrier crest morphology (Forbes *et al*., 1995).

Storms have also human and economic effects. According to the reinsurance companies (Munich Reinsurance Group, 2004; Swiss Reinsurance Company, 2004), these events are responsible for a large number of deaths every year (35,000 in 2003), and significant annual costs (about 49, 5 billions euros in 2003) in damage to harbour facilities, coastal tourism infrastructures, and private homes. A growing concern has risen toward the effects of global warming which includes the possible increase in the severity of mid-latitude storms (Lambert, 1995; McLean *et al*., 2001.).

This situation arise the need to know the storm regime of the affected area, in terms of its meteorological-marine characteristics as well as the expected impacts. This need is evident especially for coastal managers that must adequately recognize the source of the possible risks and also the expected magnitude of the processes that will determine the damages along the coast.

The first step to develop a storm classification essentially consists in a categorization as a function of a representative parameter of the interested process. In this sense there are some classification proposals based on wind intensity and duration (Simpson, 1971; Saffir, 1979; Allen, 1981) (see Table 3.1.1) or wave characteristics (Bryant, 1988; Dolan & Davis, 1992) (see Table 3.1.2).

Table 3.1.1: The Saffir-Simpson scale for hurricanes.

Category	*Pressure (mb)*	*Winds (m/sec)*	*Surge (m)*	*Damage*
1	≤980	32 42	1.32	Minimal
2	965 - 979	42 -49	2.13	Moderate
3	945 - 964	50 -57	3.20	Extensive
4	920 -944	58-68	4.57	Extreme
5	>920	>69	5.49	Catastrophic

Table 3.1.2: The Dolan-Davis scale for Atlantic Coast Northeast Storms.

Category	Hs *(m)*	*Duration (hr)*	*Power (m^2/h)*
1	2.0	8	32
2	2.5	18	107
3	3.3	34	353
4	5.0	63	1455
5	7.0	96	4548

Although some of these intend to be generic; its global application is not always possible. This will happen when the proposed scale evaluates the induced impacts while including the coastal response given that, the local characteristics and the type of coastal response play an important role.

Based on the previous information, the objective of this chapter is to present a coastal storm classification developed for the Catalan coast. Given the wave characteristics of the area, it is expected that the classification will be valid for the North western Mediterranean. Equally, the followed methodology is valid for every area and its use will allow to obtain similar classifications in any coast for the same purposes.

3.2 Methodology

3.2.1 Storm classification

The buoy used to characterize the storms is located in Cap Tortosa (see Figure 2.2.1 and subsection 2.2.1) at a depth of 50 m and at approximately 8 km off the coastline, the used data covers a period of 14 years from June 1990 to December 2004.

Although a series of gaps are present in the data series due to punctual malfunctioning problems, these were not frequent in the stormy season, thus in principle it can be assumed that the obtained results will be characteristic of the storm regime of the area. The data used in this chapter are wave height (Hs), peak period (Tp) and mean direction (θ) obtained from the spectral wave data calculated for 20 minute recordings taken every hour, with a sampling frequency of 1.38 Hz.

The development of the storm classification covers three principal aspects: (1) definition and storm identification, (2) selection of the storm characterization parameter and (3) classification method.

A storm is defined as a wave event in which the wave height exceeds a determined threshold for a certain time period; therefore the first step is the definition of the wave height threshold. Traditionally this selection is done taking on account the local characteristics of the wave regime or based on robustness criteria if the events are going to be used in a statistical analysis (see Pandey *et al*., 2001).

As mentioned before, the final objective of this classification is used to foresee the generated impact by a storm in the coast. In this sense, the selection of the variable was aimed at the description of the erosion potential; this variable was the *energy content* “E” defined in equation (3.2.1).

$$\mathrm{E} = \int_{t1}^{t2} Hs^2 \, dt. \tag{3.2.1}$$

where t1 and t2 define the storm duration (*Hs* > *Hs* threshold). A similar approach was used by Dolan & Davis (1992) in a storm classification based on the relative storm energy, although using a single wave height -mean *Hs* or max *Hs*- consequently over or underestimating the actual storm energy.

Once the storms were identified and having calculated the *energy content*, the classification process was carried out by means of cluster analysis using the *energy content* as the classification variable. The cluster analysis reduces the amount of data, by categorizing or grouping in terms of similarity. This study employed the average linkage method, although this technique tends to produce a great amount of small groups, this process is generally superior to the existing clustering methods (see Bunkers *et al*., 1996).

In order to reduce the tendency to produce a large number of groups, a supervised classification was applied to the resulting groups which derived into a five category classification considering the obtained dendrogram partition, the cluster consistency and the *energy content* variation within each group. The five category scale was made in order to keep the analogy with the other existent scales (Simpson, 1971; Saffir, 1979; Dolan & Davis, 1992). The final selected scale categorizes the storms into: I-weak, II-moderate, III-significant, IV-severe and V-extreme.

3.3 Results

3.3.1 Storm class

At the time to distinguish the presence of a storm, it was first selected a threshold of *Hs* = 1.5 m (Figure 3.3.1), this value corresponds to approximately twice the yearly averaged significant wave height and was previously used by Jiménez *et al*. (1997b) when analyzing the waves in the area.

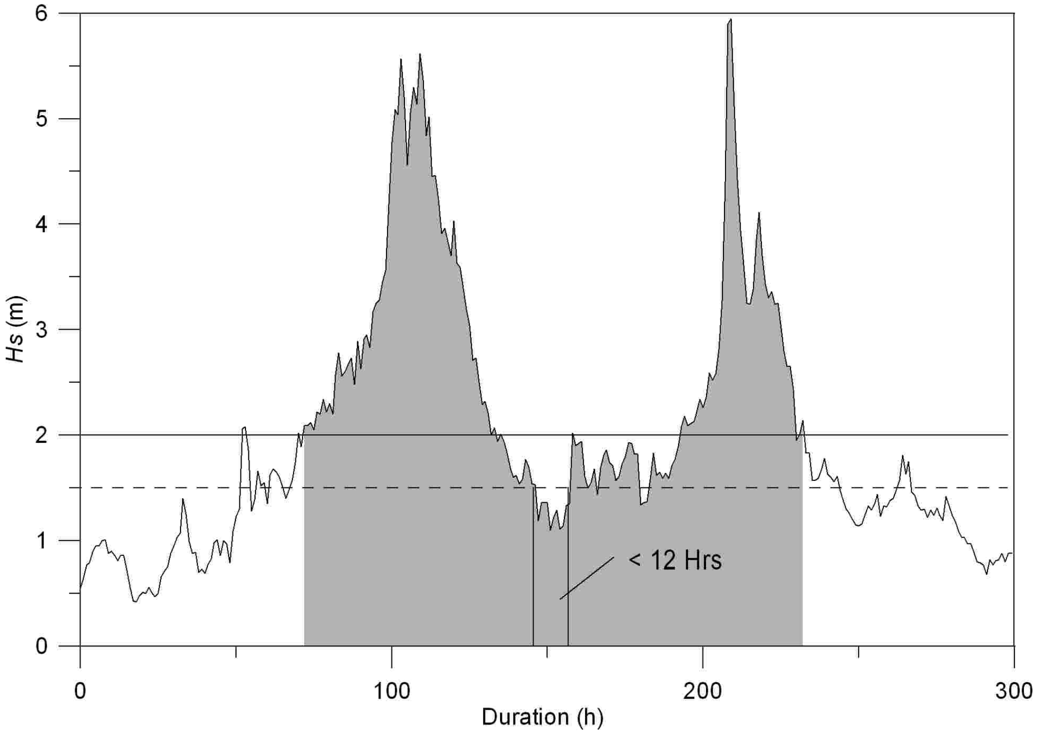

Figure 3.3.1: Storm definition using the 1.5 m (dashed line) and 2 m threshold (line).

The condition of minimum duration was selected to be 6 hours in which the wave height had to be equal of higher than the established threshold. This minimum duration criterion is usually imposed to assure that the identified event has enough acting time to induce the processes of interest. As an example, in the design of maritime structures it is usual to consider storm duration in terms of number of waves (see e. g. Van der Meer, 1988).

Similarly the maximum time between consecutive storms was established for 12 hours, to avoid counting those events associated with single unique meteorological situation as different storms. Figure 3.3.2a, shows the dendrogram partition and the supervised classification when using the storm definition threshold of *Hs* = 1.5 m. where a total of 316 storms were obtained.

Type I-weak storms resulted in a large number (155 storms), with a mean short duration (12 hours) and a mean *Hs* of approximately 2 m. Type II-moderate-storms were also quite frequent (91 storms) and a mean duration which doubles the previous class (29 hours). The number of storms of class III storms -significant- is maintained relatively high -61 storms- with a mean duration of 52 hours. Group IV -severe- was integrated by only eight storms, with a mean duration of 3.5 days and a mean maximum *Hs* value of about 4 m. Lastly class V –extreme was formed by a single storm with a duration of eight days and a maximum wave height of 6 m. This event was associated to the presence of an intense stormy winds in the Mediterranean which in a recent cyclone intensity analysis for the Mediterranean since 1958 was ranked seventh place (Genovés *et al*., 2006) and generated numerous damages along the Spanish Mediterranean coast (Gracia & Jiménez, 2004). The 5 obtained groups presented a good linear relation between the mean values of *Hs* in the peak of the storm and duration (Figure 3.3.3).

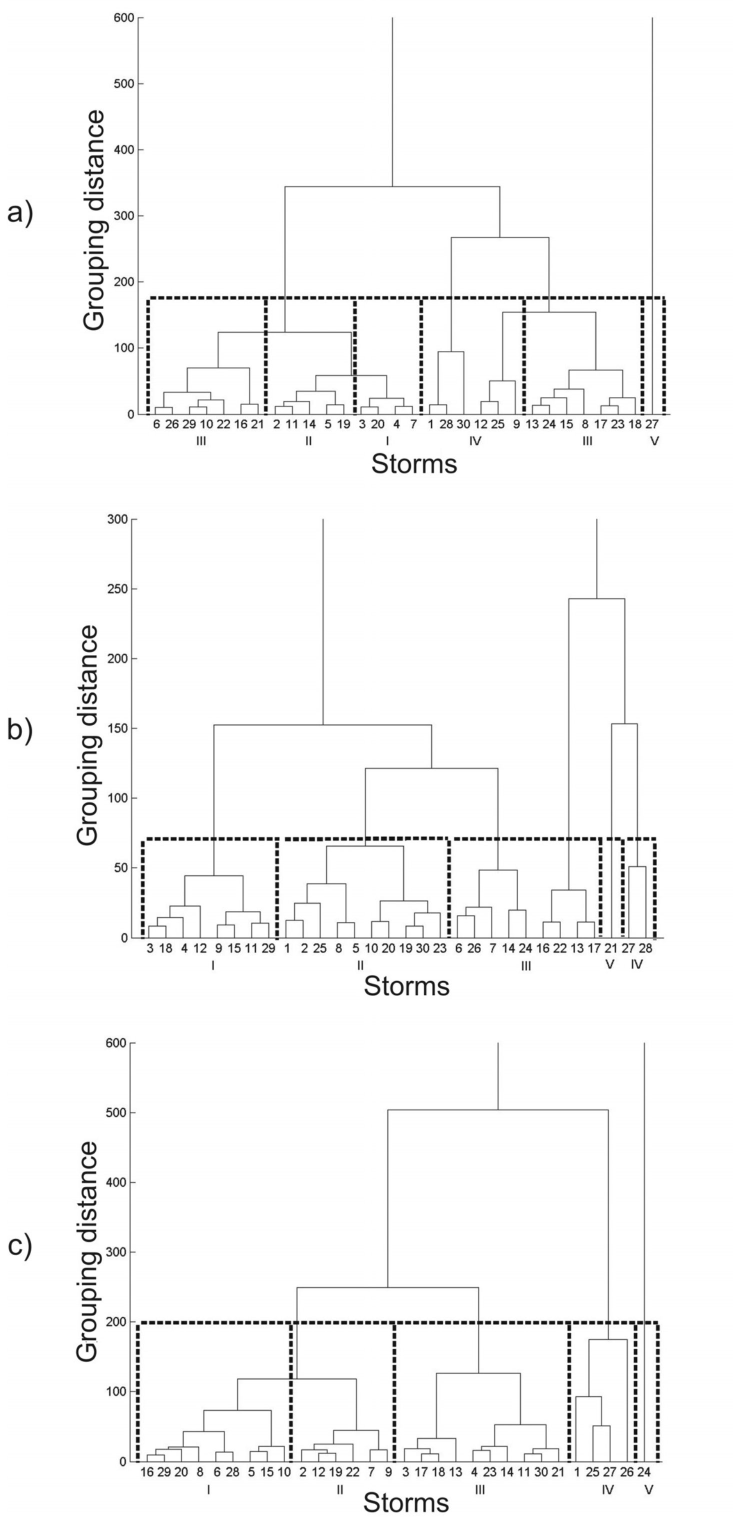

Figure 3.3.2: Storm classification by means of cluster analysis (solid lines) and supervised classification (dashed lines) using the 1.5 m (a), 2 m (b) thresholds and combining the 2 m threshold and the double peak criteria (c).

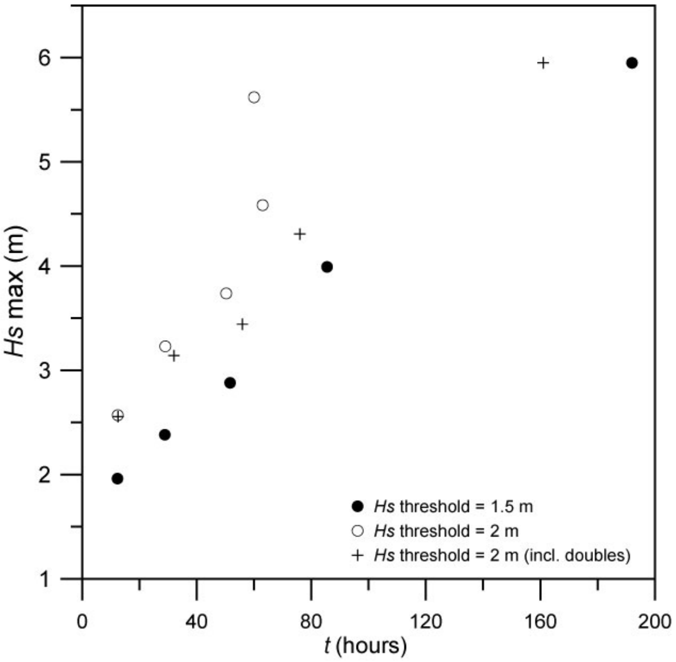

Figure 3.3.3: Relation between mean values of *Hs* max and duration of each storm group obtained through the three classification methods.

The resulting storms classified as type I (less energetic) were analyzed in terms of the induced beach response (eroded volume). The beach volume change was simulated by these events in the two representative beach profiles of the Catalan coast mentioned in subsection 2.2.3, dissipative and reflective beaches. The calculations were done using the Sbeach model (Wise *et al*., 1996) which was fed with data from local Catalan beach profiles and wave time series of the corresponding storms. The obtained results showed the inability of the less energetic storms to produce important erosion on the beach profiles (Mendoza & Jiménez, 2005). As a result of this and because the purpose the analysis is to characterize/study storms as drivers for impulsive coastal changes, they were excluded. Thus, although from the statistical point they can be considered as events, from a morphodynamic standpoint they are not.

Taking into account the previous results, the threshold was increased to *Hs* = 2 m (Figure 3.3.1) which coincides with the recommended value for the analysis and design of coastal structures of the Spanish East coast (EPPE, 1991). When increasing the threshold storm value to *Hs* = 2 m the number of storms decreased as it was expected, resulting in a total of 116 events (Figure 3.3.2b). Because the grouping methodology classifies the groups in relative terms taking on account the total available data, the increase of the threshold meant a redefinition of all the groups and not only the less energetic groups.

The mean durations of each storm group were slightly inferior to the ones obtained with the previous classification, with the exception of the higher *energy content* categories, IV and V that are significantly reduced, particularly in the case of category V (Figure 3.3.3). This is due to the occurrence of double peak storms, in other words, events that are separated by less than three days and the wave direction remains constant. The majority of the double peak storms belonged to both categories and as a consequence of the threshold change switched from being a single storm in the previous case (Hs = 1.5 m) into two storms of less duration with the new criterion. The most extreme example is the only registered class V storm which changed from a eight day duration according to the previous classification into two of approximately 3 days according to the *Hs* = 2 m criterion. This effect is reflected in the *Hs* and duration relation for this classification which looses the well defined linear pattern which was found in the previous case (Figure 3.3.3).

The presence of double peak storms (events separated by less than three days and the wave direction remains constant), was relatively frequent during the period of the study with about 16% of the total number of storms (115). Of the 18 double peak storms, 12 were Eastern storms which are the most energetic in the area and are produced under the presence of wind gusts over the NW Mediterranean (Sánchez-Arcilla & Jiménez, 1994; Jiménez *et al*., 1997b; Cateura *et al*., 2004). The frequency of these double events as well as the expected morphological consequences of their impact on the coast (consecutive action of two storms in a short time period) make advisable for these storms to be taken in a specific manner in this analysis. If the *Hs* = 2 m criterion was applied, these double events would be classified as two individual storms. Therefore and for the purposes of this analysis, a specific criterion for double peak storms was included. In the first place a maximum time of three days between events is considered. If the wave height during this time is below the secondary threshold of 1.5 m for a time lapse grater than 12 hours, the event will be considered as two independent storms, in other case it will be considered as a sole event (Figure 3.3.1).

When including the additional criteria with the presence of double peak storms along the 2 m threshold, the number of storms is reduced, as some events which were classified as two before they are now considered as single storms, leaving a total of 105 storms. In this case, the resulting cluster analysis is more consistent in terms of grouping and facilitates the supervised classification (Figure 3.3.2c). The basic characteristics of the resulting storms using this categorization are presented in Table 3.3.1. The mean values of *Hs* and duration from this classification show a strong linear dependence with a monotonous increase of both variables as the energetic storm category increases (Figure 3.3.3).

According to the objectives of this analysis, we is proposed the use of the definition of a storm based on the 2m threshold including the double peak storms and the storm classification obtained through these two criteria (Table 3.3.1).

Table 3.3.1: Mean characteristics of the five class storm categories. ([%]: frequency percentage; n: number of storms; *Hs* max: wave height in the peak of the storm; *Tp* max: peak period associated to the *Hs* max; Energy: defined in Eq. 3.2.1.

Storm Class	*Direction*	*Storms [%] n*	*Duration (hrs)*	*Hs max. (m)*	*Tp max. (s)*	*Energy (m^2 h)*
I	All	[56] 59	13	2.6	7.3	57
I	E	[42] 25	12	2.5	8.4	56
I	S	[22] 13	13	2.6	7.4	62
I	Other	[36] 21	13	2.6	6.1	56
II	All	[25] 26	32	3.1	8.3	175
II	E	[77] 20	31	3.1	8.4	176
II	S	[07] 02	26	3.5	10.3	173
II	Other	[16] 04	45	3.3	6.7	171
III	All	[14] 15	56	3.4	8.2	343
III	E	[80] 12	53	3.5	8.6	346
III	Other	[20] 03	70	3.0	6.5	328
IV	All E	[04] 04	76	4.3	9.9	643
V	All E	[01] 01	161	6.0	11.1	1369

3.3.2 Direction and seasonality

Given that wave direction and the seasonal distribution are important when assessing the impact on the coast, both variables were analyzed. The storm wave direction has an important influence on the spatial variability of the magnitude of the impact because the relative orientation of the coast with respect to storm waves and the geomorphologic configuration (e.g. indented coast with promontories) will determine the degree of exposure. On the other hand, the storm seasonal distribution determines the type and intensity of the impact to be expected in some places, because the use of the beach use varies with the seasons and in consequence, the occurrence of the storms in different moments of the year might generate different impacts in terms of the affected beach use.

An example of this interaction occurs when in a climatic year some "*late*" storms take place (out of the normal stormy season) in beaches with tourist use that need a given beach width at the beginning of the vacational season and therefore will not be efficiently used because of the loss of the necessary beach width (see Valdemoro & Jiménez, 2006). In this case, the knowledge of the storm occurrence probability of a determined intensity during the year, will allow the managers to identify the possible interactions with the beach use or determine the season of the year in which he would have to ensure the protection function of the beach bearing in mind the buffering of the impact over the existent infrastructure.

Figure 3.3.4 illustrates the directional distribution of the storms in the study area, where it can be identified the presence of three principal divisions: East-Northwest (E), Northwest (NW) and south (S). From these, the East direction corresponds to the highest number of storms, congregating 59% of the total number of storms including the ones belonging to class IV and V. This result is consistent with previous observations that classified the E storms as the most energetic in the Catalan coast due to the fetch and the wind regime of the area (García *et al*., 1993; Jiménez *et al*., 1997b).

The second sector in numerical importance is the one associated with the NW direction with a 27% of the registered storms. However, these storms are not relevant for coastal impacts, since these correspond to storms generated by winds that blow from land (Mistral) and considering the general orientation of the Catalan coast, these are waves that do not have any effects on the beach.

The wave storms with S direction are the less frequent in the area, with an occurrence of only 14% in the analyzed time period. Asides this low incidence, the wave storms associated to this direction presented low *energy content*, and have only been registered in the class I and II levels. However this does not mean that their effect should not be taken on account, when these occur in the Catalan coast mainly when these are present in an accumulative way, in other words, in seasons without E storms, some embayed beaches have registered important beach rotation (see Jiménez *et al*., 2003).

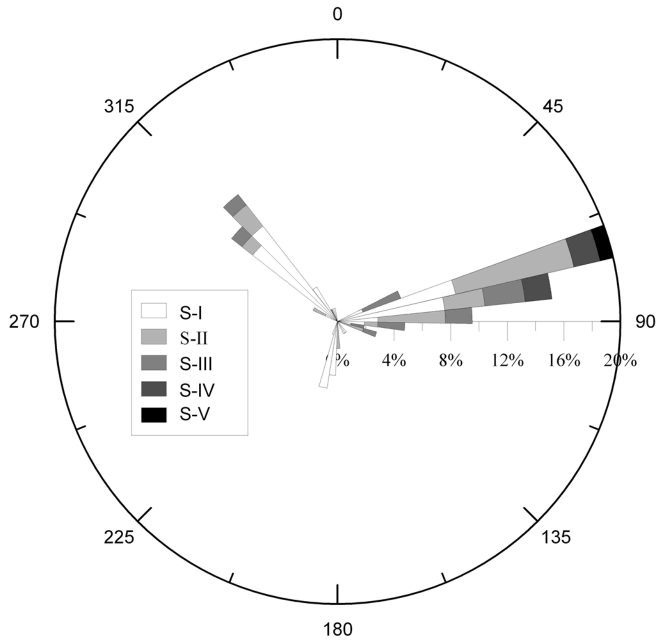

Figure 3.3.4: Directional distribution of the storms according to the energy classification.

The seasonal distribution of the registered storms in the area allows to define a mean climatic year with two seasons as a function of the dominant wave storms: the stormy season which would extend from October to April and the calm season from May to September (Figure 3.3.5). Type I and II storms are present all year round with higher frequency in the stormy season. On the opposite side the most energetic classes (type III, IV and V) have only been registered during the stormy season. Lastly the single event classified as extreme (type V) occurred in November. Even though a unique event was registered in this category an therefore, the record has no statistical significance in order to deduct its representativity, if associated to the meteorological conditions that generate it, this type of intense storms/squalls are produced in the Mediterranean mainly from November to March (see Genovés *et al*., 2006).

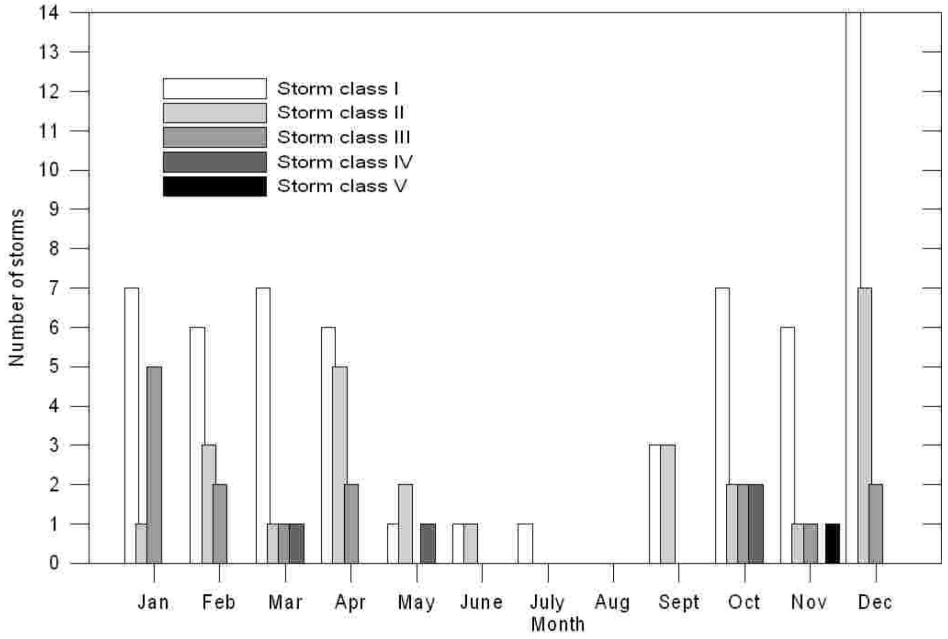

Figure 3.3.5: Temporal distribution of the different storm types along a climatic year.

3.3.3 Storm classification based on *Hs*

As seen previously on subsection 3.3.1 the storms were characterized and classified based on the storm *energy content*, which was acquired using a combination of wave height and duration. Despite the fact that this variable is the best option to produce a classification from a technical point of view, it is hard for coastal managers and officials to actually calculate the energy of the storm in a quick manner. The most immediate information usually given by meteorological reports is based on the use of wave height, for this reason and for the practical use of the given storm classification, a new adapted categorization range is proposed based on Table 3.3.1. This new classification was made taking into consideration exclusively the mean *Hs* max values from the previous categorization, which was divided in regular intervals to define the new categories.

The wave height range values between the different storm classes can be seen in Table 3.3.2 The usefulness of this classification can be seen when a coastal manager or state official receives a wave forecasting report which mainly consists in the prediction of bulk parameters of the wave field (*Hs*, T,θ), which can be fitted in a simple manner into the storm classification and can be used in real time. Once the wave height is fitted within the respective group, the classification provides the most probable storm duration which will be the one corresponding to that class.

Table 3.3.2: Five class storm categories based on the *Hs*.

Storm Class	*Hs range (m)*				
I Weak	2.00	≤	*Hs*	≤	2.75
II Moderate	2.76	≤	*Hs*	≤	3.50
III Significant	3.51	≤	*Hs*	≤	4.25
IV Severe	4.26	≤	*Hs*	≤	5.00
V Extreme			*Hs*	>	5.01

3.3.4 Long term storm characterization

The characterization was obtained using the HIPOCAS wave data which were adjusted to the wave heights given by Cap Tortosa buoy by means of regression analysis, using equation A.5 (detailed description can be seen in Annex A). The resulting storms were used to obtain the temporal variability of storms in time and classified using Table 3.3.2 for each of the selected nodes in Figure 3.3.6.

Figure 3.3.6. also presents the frequency of occurrence of the most energetic storms (type III, IV and V) along the entire Catalan coast, from 1958 to 2001, considering the storms that are coast bound (E and S). From the obtained spatial distribution it can be seen that the northernmost area (sectors 1 and 2) is subject to a higher number of storms; further south the frequency of these high energy storms decrease progressively, being the southern area the least impacted area by storms.

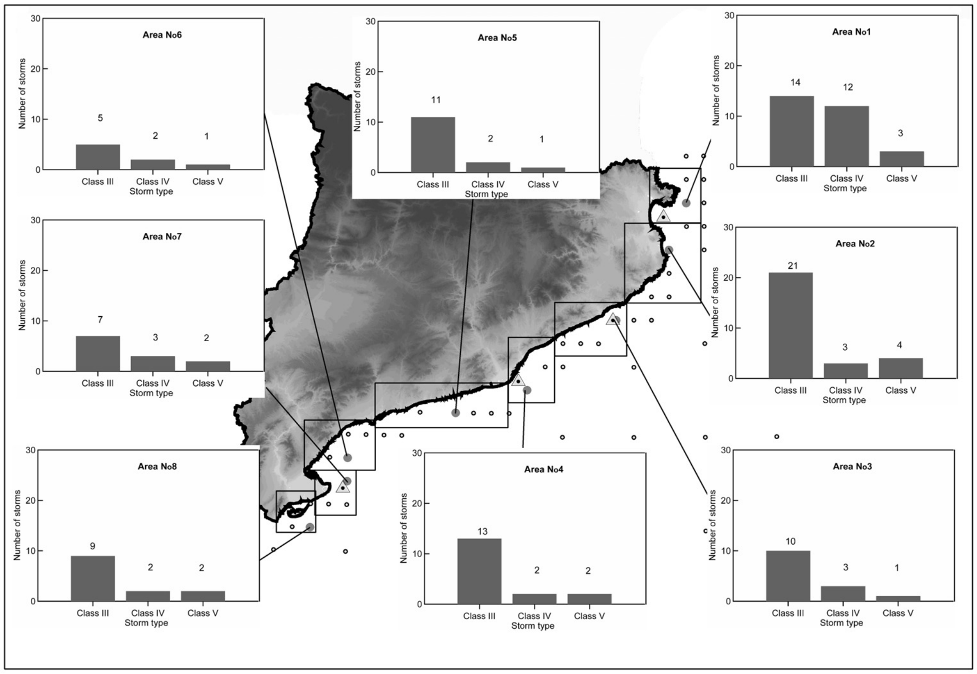

Figure 3.3.6: Frequency of the most energetic storms (type III, IV and V) along the Catalan coast for the 1958-2001 time period, considering E and S storms.

Within the same example of specific application, the temporal variation of the frequency was analyzed for a specific area. Figure 3.3.7 represents the number of total storms and the most energetic ones (category II and above), grouped in periods of time of 5 years since 1958 to 2001 for the geographical area assigned as No.2 (see Figure 3.3.6). It can be seen that the number of total storms fluctuated between 16 and 32 storms with an approximate mean value of 14 storms for the entire time period. The most energetic storms (type III, IV and V) fluctuated between 0 and 7 storms, having a mean of approximately 3 storms.

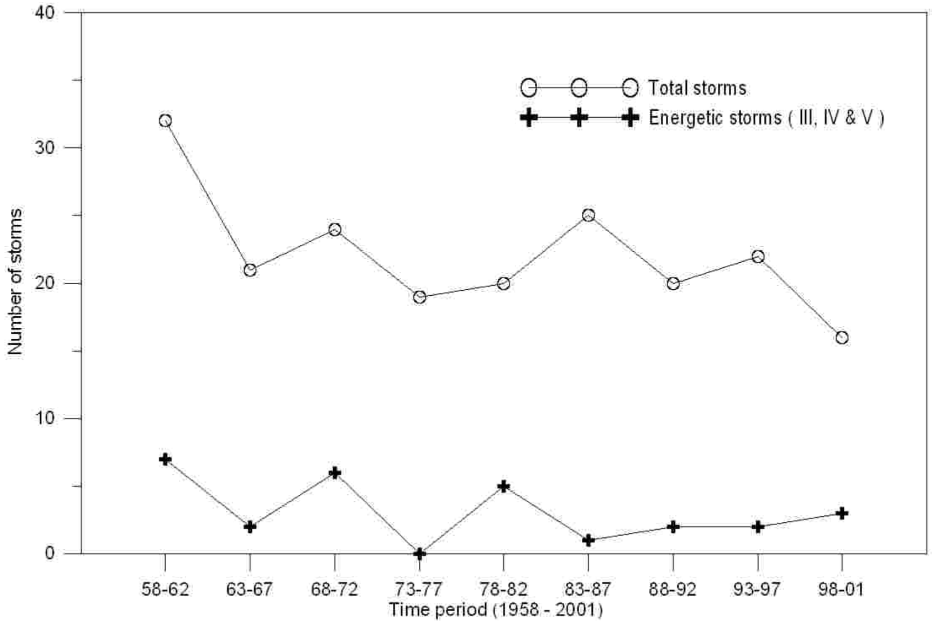

Figure 3.3.7: Variation of number of total storms (dots) and most energetic (cross) in Area No.2, grouped in periods of time of 5 years from 1958 to 2001 considering only the Eastern and Southern directions.

3.4 Conclusions

This chapter presents a storm classification for the Catalan coast (NW Mediterranean) using the wave *energy content* as the characteristic variable. Although developed for a specific area, the followed methodology can be easily applied to other coastal zones. When selecting the threshold value to define the existence of a storm three different criteria were tested. Based on the climatic characteristics of the area and bearing in mind that the principal objective of this classification is the use to analyze the impact over sedimentary coasts. The significant wave height exceeds the 2 m threshold during a minimum time of 6 hours. The double peak storm criteria was also considered, which were relatively frequent in the area, especially in the case of the most intense events. Once the storms were defined, a five level classification procedure was implemented using the *energy content* as the characteristic variable. The groups were defined based on a cluster analysis of the registered storms. If the storms of each group is defined based in the mean values of Hs at the peak and the duration of the event, a strong linear relation has been found, so as the as the *energy content* -intensity- increases so does the Hs and the duration (Table 3.3.1). Once the classification was established, the direction and seasonality of each storm type were studied, given that these are important parameters when assessing the response of the coast and the associated impacts. For this specific case it was observed that the dominant E, occurring between the months of October and April.