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ORIGINAL RESEARCH ARTICLE

Statistical analysis of Mediterranean coastal storms

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Abstract Coastal storms as extreme hydrometeorological events have severe impacts on the coasts and consequently affect the coastal communities, attracting considerable research interest nowadays. Attempting to understand the risk of these extreme events, a coastal storm analysis is accomplished by studying the parameters which define a coastal storm and their properties, such as the wave height, the wave period, the duration, the calm period, and the storm energy. The frequency of occurrence of coastal storms, the thresholds of storm parameters and the way they are interrelating with each other draw a rough outline of wave climate during coastal storm events for a specific location. This information is valuable afterwards for the design of coastal structures and the coastal zone management. In this work, buoy datasets from 30 locations in the Mediterranean Sea are analysed for describing coastal storm activity. A sample of 4008 coastal storms is identified. Each location faces around 10—14 coastal storms per year, with most of them to occur in winter months and their characteristics to be site-dependent. Their average duration is lower than 30 hours, and 25% of them are consecutive events which hit the same location in less than a day. Furthermore, the wave period and the main direction present no remarkable fluctuations during a coastal storm. With this analysis, a

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deeper understanding of coastal storm severity is pursued, gaining knowledge about their past activity, in order to be prepared in the future and to protect the coastal areas.

1. Introduction

Researchers all over the world are focused on coastal storms to study their impacts and learn more about their severity. Considering the coastal storms as storm events with impacts on coastal areas, they can cause serious problems such as coastal flooding, beach erosion, and damages on ports. The management of such events, the preparedness, and an informed coastal community are of great importance and more urgent, especially nowadays in a changing climate.

Climate change and related extreme events causing infrastructure damages and resulting in human losses, have turned coastal communities and consequently coastal storms into the centre of attention over the past decades. In this context, the latest reports of the Intergovernmental Panel on Climate Change (IPCC, 2018, 2019), the United Nations Framework Convention on Climate Change (UNFCCC) meetings, such as the well known Paris Agreement (UNFCCC, 2016) and the Fourth National Climate Assessment of U.S. Global Change Research Program (2018), give an incredible boost to the field of science communication regarding the climate change. On the other hand, many extreme events hit coastal communities causing losses of billions of euros in the last two decades. The hurricane Sandy (22 October—2 November 2012) (Binder et al., 2015; Rosenzweig and Solecki, 2014), the cyclone Xynthia (27—28 February 2010) (Bertin et al., 2012; Ferreira et al., 2017), the hurricane Katrina (23—31 August 2005) (Irish et al., 2008; Kates et al., 2006) are some of the most recent and among the costliest and deadliest storms in human history, which have changed the way the humans act, protect and prepare themselves within an everchanging environment.

Many research projects have also focused on the hazards and the risk management of extreme events for coastal communities. PEARL (Karavokiros et al., 2016), RISC-KIT (Van Dongeren et al., 2014), MICORE (Ciavola et al., 2011b), and THESEUS (Zanuttigh, 2011) are typical examples of this progress for European seas, while their deliverables stand as a significant source of information for any researcher.

Storm identification can be carried out by using the important storm parameters and their thresholds, such as the significant wave height (H), the duration of a storm event (D), and the calm period (I). The significant wave height should exceed a certain threshold and remain over this for a time period (De Michele et al., 2007; Li et al., 2014). The clusters of these exceedances are considered as storm events and the storm duration is defined as the time period in which the significant wave height remains over the threshold (Boccotti, 2000). The minimum duration is also defined, discarding all the events that last a shorter time. The calm period, or the inter-arrival time according to Corbella and Stretch (2013) and De Michele et al. (2007), is the time period between the start of the upcoming event and the end of the previous event. If the calm period is too short, then the neighbouring storm events could be considered as one, prolonging in this way the storm event and consequently extending the duration. For example according to Figure 1, which is based on previous work of Wahl et al. (2016) and Li et al. (2014), the consecutive events over the threshold have duration D_1, D_3 and D_5. The first two of them could be considered as one storm event, due to their short calm period (D_2), with final storm duration $D = t_4 - t_1$. The next event with duration D_5 is independent from the previous, due to the long calm period (D_4), but it is not considered as a storm event because of its short duration (D_5). The calm period threshold is essential for the identification of consecutive coastal storms. A sequence of storm events, cause extensive damages on coastal zones, affecting the coastal morphology and could be more destruc-

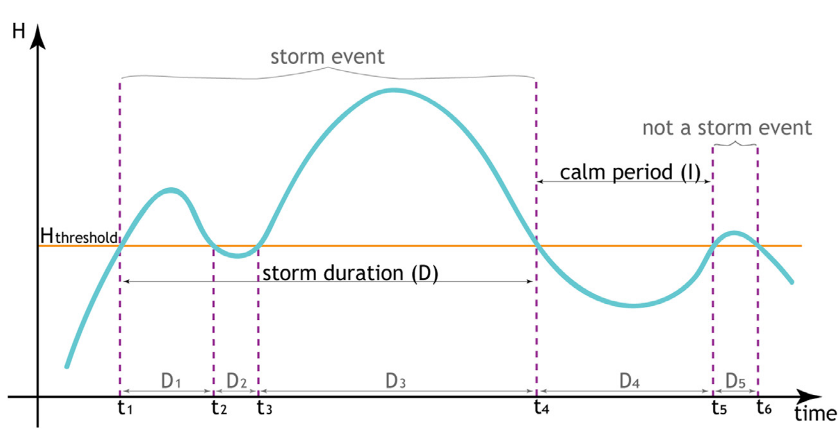

Figure 1 Definition of the storm event and the description of important parameters.

tive than isolated events in many cases (Dissanayake et al., 2015; Ferreira, 2005; Sénéchal et al., 2017).

The coastal storm thresholds are site-specific and they depend on the synoptic systems, the bathymetry, the local characteristics, and the exposure of a location to the winds and the big waves (Harley, 2017). Other parameters which are taken into account in such analyses are the main direction of coastal storms and their energy. Moreover, the mean, the maximum or the peak value of the important parameters (Dissanayake et al., 2015; Lin-Ye et al., 2016) are also used in coastal storm analysis.

Trying to understand the storminess, which denotes the frequency of occurrence of coastal storms and their severity, a large dataset of wave climate is required. However, the time series of storm characteristics, acquired from buoys measurements, are rarely used, mainly due to their spatial availability and their limitation about temporal data coverage. The majority of the data are not available before 1978 (Caires and Sterl, 2005). Data are not available everywhere, even nowadays, but only for specific locations. For instance, in the Mediterranean Sea, Spain and France have a dense network of buoys to record the wave climate of their seas, in contrast with the other European countries, which have very few (i.e. Greece, Italy, Bulgaria and Romania) and other countries that have none at all. However, the buoys are frequently out of order, or they are moving over the years, changing their position. The available datasets are usually non-continuous and with many gaps. Hence, a lot of research is based on model and satellite data before or after a reanalysis (Dee et al., 2011; Kistler et al., 2001; Sartini et al., 2017), which are operationally more efficient and cost-effective.

Up to now, significant research has been conducted for the wave climate and storm events along European coasts. Usually, it is not limited in the Mediterranean Sea (Almeida et al., 2011; Ciavola et al., 2011a), it is based on model data (Androulidakis et al., 2015; Lionello et al., 2012, 2008; Vousdoukas et al., 2016) and often examines storms from the climatology viewpoint, investigating the characteristics and the frequency of occurrence for cyclones or medicanes in the Mediterranean region (Cavicchia et al., 2014; Emanuel, 2005; González-Alemán et al., 2019; Lionello et al., 2006; 2016) .

This work is based on buoy wave measurements, presents a coastal storm activity over the Mediterranean Sea, through the frequency of storm occurrence and the statistical analysis of their parameters. The purpose is to gain a deeper understanding of coastal storm severity, their past activity, and their seasonal variation over the years in a changing climate.

Based on many works cited above which are usually focused at a specific area, an extensive database of wave measurements at 30 coastal locations is analysed. The data consist of buoys measurements and not of model simulations. As a follow-up of previous works, a general methodology for coastal storm identification is described here and a coastal storm analysis is presented.

In the following sections, the data and the study area are described, the methodology for the identification of coastal storm events and the estimation of storm characteristics are presented. Information about the coastal storm thresholds, the descriptive statistics of important parameters, the coastal storm duration and the calm period, the variance of the wave period and the direction, are also included. Finally, the results draw conclusions about the different locations and the variation of storm parameters in the Mediterranean Sea.

2. Data and study area

A dataset from wave recordings from buoys at 30 locations over the Mediterranean Sea, in Greece, Italy, France and Spain, is analysed. The data were obtained by the databases of Puertos del Estado (www.puertos.es), Copernicus (www.copernicus.eu) and EMODnet (www.emodnet.eu), covering in general, a time period since the 1980s. The 30 locations are selected because the buoys are close to the coast (Figure 2), in order to analyse coastal storms. A brief description of these stations is presented in Table 1, including sampling and regional details. The temporal data coverage — or the period for which data are available — de-

Figure 2 Regional description of the buoys' location over the Mediterranean Sea. The squares indicate buoys which are out of order (last check October 13, 2020).

Table 1 Coordinates and sampling details of buoys stations for 30 locations in the Mediterranean Sea.

Location		Coordinates [Longitude, Latitude]	Depth [m]	Distance from coast [km]	Covering Period	Duration of record [months]	Sampling Interval [hr]
				Greece			
1	Athos	[24.73°E, 39.97°N]	215	27.7	25/05/2000–31/05/2017	181	3.0
2	Lesvos	[25.80°E, 39.15°N]	120	4.5	29/05/1999–28/07/2012	133	3.0
3	Skyros	[24.46°E, 39.11°N]	83	14.4	28/08/2007–18/07/2012	57	3.0
4	Mykonos	[25.46°E, 37.51°N]	80	5.3	27/05/1999–30/04/2017	132	3.0
5	Santorini	[25.50°E, 36.26°N]	286	9.2	28/05/1999–27/07/2012	141	3.0
6	Heraklion	[25.07°E, 35.43°N]	170	5.1	15/07/2016–31/05/2017	8	3.0
7	Kalamata	[22.09°E, 36.97°N]	290	4.2	17/10/1999–17/05/2011	57	3.0
8	Pylos	[21.60°E, 36.83°N]	3016	7.2	09/11/2007–30/06/2016	92	3.0
9	Zakynthos	[20.60°E, 37.96°N]	297	7.5	08/11/2007–23/01/2012	47	3.0
				Italy			
10	Venice	[12.66°E, 44.97°N]	33	7.3	01/06/2013–01/01/2015	18	0.5
11	Crotone	[17.22°E, 39.02°N]	37	1.3	04/06/2013–10/12/2014	17	0.5
12	Catania	[15.15°E, 37.43°N]	45	5.3	06/01/2013–01/01/2015	14	0.5
13	Palermo	[13.33°E, 38.26°N]	135	6.9	01/06/2013–30/10/2014	8	0.5
				France			
14	Alistro	[9.64°E, 42.26°N]	116	6.7	29/10 2013–01/06/2017	16	0.5
15	La Revellata	[8.65°E, 42.57°N]	194	5.6	30/10 2013–30/06/2017	8	0.5
16	Nice	[7.23°E, 43.64°N]	45	1.7	22/06/2010–07/03/2016	38	0.5
17	Porquerolles	[6.21°E, 42.93°N]	347	5.4	24/04/2008–24/08/2012	44	0.5
18	Marseille	[5.23°E, 43.21°N]	30	8.9	17/04/2011–30/06/2017	61	0.5
19	Sete	[3.78°E, 43.37°N]	34	6.2	06/10/2009–30/06/2017	88	0.5
20	Leucate	[3.12°E, 42.92°N]	43	4.8	06/10/2009–30/06/2017	82	0.5
21	Banyuls	[3.17°E, 42.49°N]	15	3.2	06/10/2009–19/05/2017	83	0.5
				Spain			
22	Cabo Begur	[3.65°E, 41.92°N]	1200	34.6	27/03/2001–31/03/2019	170	1.0
23	Barcelona	[2.20°E, 41.32°N]	68	2.5	08/03/2004–31/03/2019	152	1.0
24	Tarragona	[1.19°E, 41.07°N]	15	0.8	12/11/1992–22/12/2017	283	1.0
25	Valencia	[0.20°W, 39.51°N]	50	9.1	08/06/2005–30/10/2013	97	1.0
26	Cabo De Gata	[2.32°W, 36.57°N]	536	20.1	28/04/2003–23/03/2018	137	1.0
27	Malaga	[4.42°W, 36.69°N]	15	1.5	19/11/1985–31/03/2019	382	1.0–3.0
28	Dragonera	[2.10°E, 39.56°N]	135	17.5	29/11/2006–31/03/2017	136	1.0
29	Capdepera	[3.49°E, 39.65°N]	48	3.1	01/01/2000–01/04/2014	163	1.0
30	Son Bou	[4.06°E, 39.90°N]	5	0.5	5/10/2011–31/01/2016	52	1.0

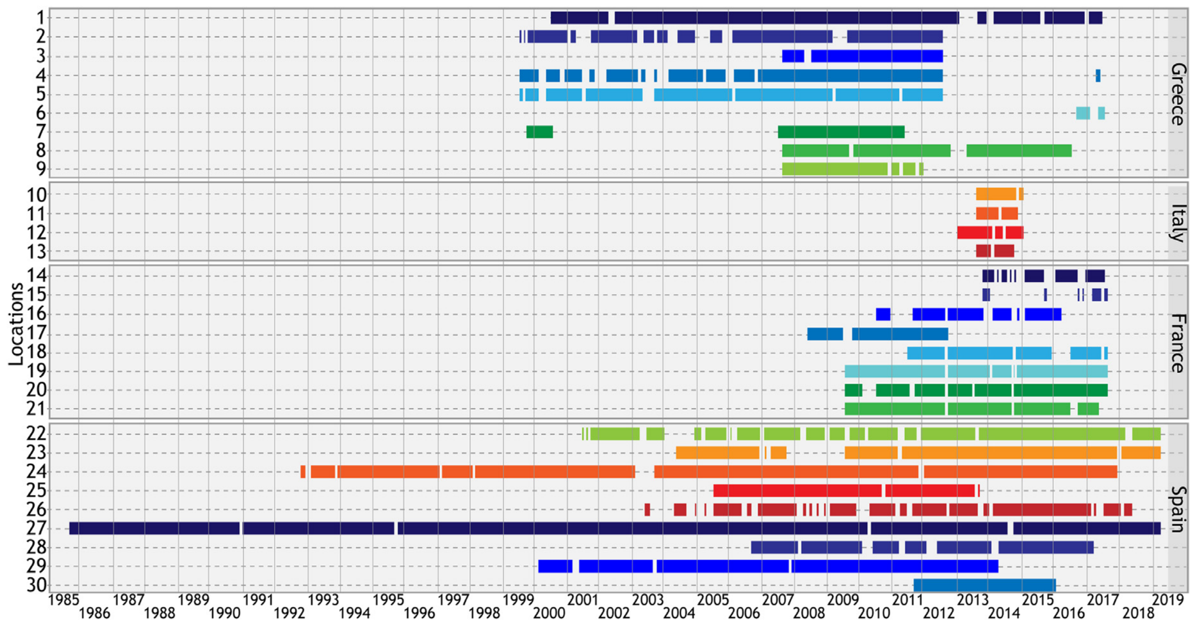

Figure 3 Temporal availability and coverage of historical data.

pends on the operation period of buoys, with most of them to be examined until 30/6/2017. Wherever more data were available, the examined period is extended up to 31/3/2019 (Figure 3). According to the database of EMODnet, in Italy, only a few buoys are nowadays in operation, and most of the Greek buoys are out of order at this moment (see also Figure 2).

This analysis is mainly based on the wave height and the wave period. These critical parameters have been estimated by the operational centres of data providers, following a spectral analysis or zero-crossing method (Copernicus Marine In Situ Tac Data Management Team, 2018; OceanSITES, 2015). However, the spectral significant wave height (H_{m0}) and the wave period at the spectral peak, also known as peak period (T_p), are preferred, and hereinafter referred to as H and T for brevity.

All the errors and the missing values which can often happen are rejected, through a data cleaning process. The events with a measurement gap greater than 18 hours are also excluded, considering that the specific buoy might be out of operation for a while. The elapsed time between consecutive measurements, also known as the sampling interval, mostly varies from 0.5 to 3 hours (Table 1).

3. Methodology

Considering coastal storms as extreme hydrometeorological or meteo-oceanic phenomena, the Extreme Value Theory (EVT) is applied for the analysis and the description of such events. The EVT is widespread in the last decades and becoming increasingly popular by work of Coles (2001) which described thoroughly the theoretical background of this field. Since then, numerous works and applications in EVT had a high impact on coastal engineering (Caires and Sterl, 2005; Mazas and Hamm, 2011; Menéndez et al., 2009; Méndez et al., 2006; Ruggiero et al., 2010; Vinoth and Young, 2011). The Block Maxima (BM) and the Peak Over Threshold (POT) methods are both the fundamental approaches in EVT, which are quite different in their application (Arns et al., 2013; Bezak et al., 2014; Jarušková and Hanek, 2006). In brief, the BM method is based on the analysis of maximum values of a dataset or within a specific block. However, it is also very common, as an alternative method, to take the r-largest order statistics (Coles, 2001; Dey et al., 2015). Therefore, the BM is not recommended when the reference period is only a few years or decades (Caires and Sterl, 2005). On the other hand, the POT method analyses time-series that extracted from the initial dataset when they exceed a specific threshold (Coles, 2001; Ferreira and Guedes Soares, 1998).

Following the definitions of Harley (2017) and Ciavola et al. (2014), the coastal storm is defined as “any meteorologically-induced disturbed sea state that causes changes and damages to the coastal zones, impinging the coastal morphology and the infrastructure”. For the definition of coastal storms, the closest buoys from the coast are considered and the events with a measurement gap greater than 18 hours are discarded (at the phase of data cleaning). The coastal storms are identified by applying the EVT for the definition of H threshold and using the thresholds of duration and calm period. Finally, the storm characteristics and storm activity are investigated. The methodology which is adopted here is presented in Figure 4. All the estimations are performed in R language (R Core Team, 2020).

3.1. Coastal storm identification

The identification is conducted at each location, through the thresholds of the significant wave height, the duration, and the calm period. In literature, storm thresholds are defined in different ways and mostly depend on the available data. The threshold of significant wave height is the primary threshold in this procedure and is used to extract the most

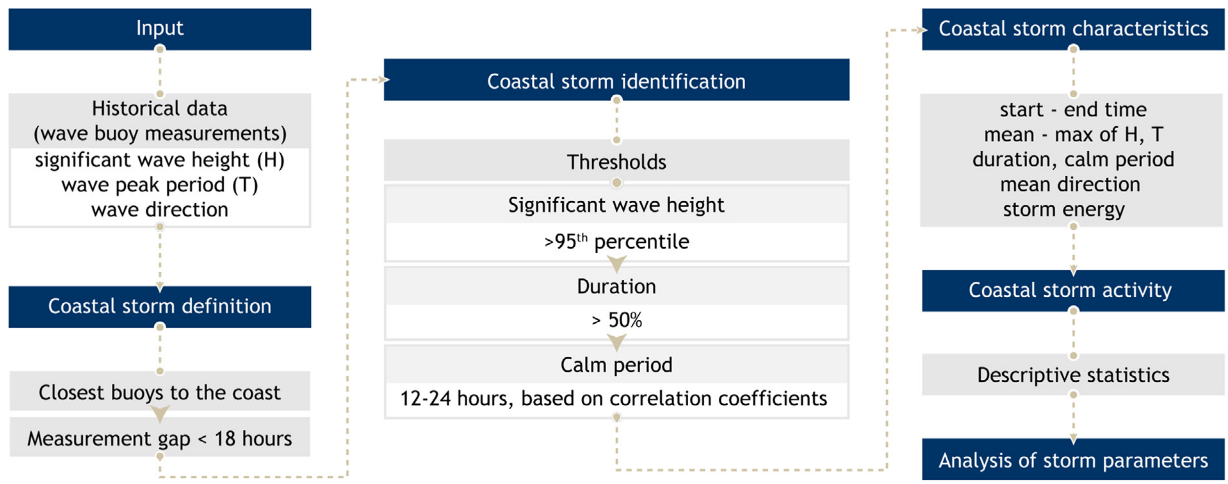

Figure 4 Description of the methodology.

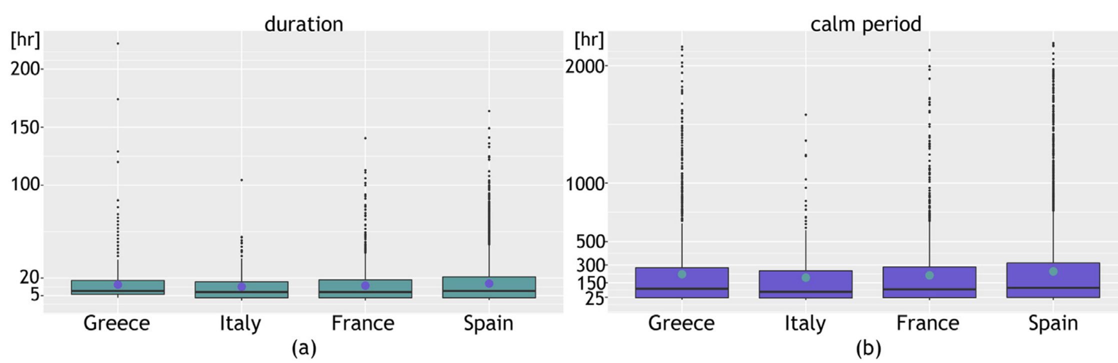

Figure 5 Boxplots for the range of the duration of storm events (a) and the calm period between two consecutive storm events (b), when it does not exceed three months (in approximately 2190 hours).

extreme values. Consequently, the data are filtered by the thresholds of duration and calm period.

3.1.1. Significant wave height threshold

The threshold of significant wave height H_{thr} could be selected inter alias by a) defining a specific value as representative for a specific location (Corbella and Stretch, 2012b), b) following the stability check for the parameters of extreme value distribution as it was proposed by Coles (2001) and also used by Bernardara et al. (2014) and Martzikos et al. (2018), c) using a high percentile of the data set, usually over 90 or 95%, to describe and analyse only the most extreme events (Davies et al., 2017; Masselink et al., 2014; Rangel-Buitrago, 2011; Tsoukala et al., 2016), or d) taking a linear equation between the mean value and the standard deviation of an important parameter. The last methodology was proposed by Yevjevich (1967) for the drought analysis but is also used similarly by Almeida et al., (2011) for the storms.

Given the short reference period of data, the POT method is used in this analysis. Hence, the H_{thr} is taken as the 95th percentile of the significant wave height at each location. Starting with this threshold, exceedances over this are extracted and are grouped, representing the coastal storm events.

3.1.2. Duration and calm period thresholds

Taking for each country a sample of storm duration and calm period, both thresholds of the minimum duration and the calm period (I_{thr}) of consecutive coastal storms are decided based on the range of these parameters. The boxplots of Figure 5 illustrate the full range and the distribution of these parameters, without significant divergences between countries. The rectangles of boxplots correspond to the interquartile range (75th—25th percentile), while everything out of this range is considered an outlier. Inside the rectangle, the dot represents the mean value, and the horizontal line shows the median.

Regarding duration (Figure 5a), the upper side of the rectangles is almost 20 hours, which means that 75% of events last less than 20 hours. So, the minimum storm duration has no meaning to be set higher than this value. The average duration (internal dot) is almost 10 hours, for all the countries, while the median and thus 50% (horizontal line) of events last less than 7.5 hours. Trying to analyse the most severe events, the minimum duration is considered appropriate to be higher than the median, investigating the upper 50% of events, but without exceeding the mean value. The minimum coastal storm duration is set at 9 hours for all the examined locations, which is also multiple of 3 hours based on the longest sampling interval.

Hence, the events with a duration of less than 9 hours are ignored.

The calm period is essential for the separation of coastal storm events and their independence. Coastal storms with a long calm period might occur in different seasons and they are certainly not related to each other. The short calm period means more dependent events that usually could be unified. For the investigation of the calm period, we focus only on the closest consecutive events which have a calm period of less than three months (approximately 2190 hours). Following the boxplots of Figure 5b, the examined events have an average calm period around 200 hours (internal dots), and 50% of them usually occur in less than 87.5 hours from the previous event. The lower side of rectangles shows that 25% of storms are consecutive events which hit the same location in a row in less than 24 hours.

From a meteorological perspective, two coastal storm events are independent if they are developed in different synoptic systems. On the other hand, the consecutive coastal storms which belong to the same synoptic system, could have similar characteristics and be dependent. It is quite rational to have dependent events into the same weather system, but it is conceivable that this may happen in different systems also. The threshold of calm period I_{thr} can be determined better in a physical way, as the mean calm period between consecutive synoptic systems (tropical or extratropical cyclones). The concurrent weather satellite images and the weather maps could be very useful, but up to now, all this information is difficult to get. Corbella et al. (2015) link the atmospheric circulation patterns with the spectral characteristics of ocean waves trying to improve the identification of statistically independent storm events. In extreme value analysis of rainfall and flooding events, the independence of consecutive events is ensured by using the minimum inter-event period (Freitas et al., 2020; Jean et al., 2018). Similarly, the independence of coastal storms is usually approached by taking a fixed value of calm period (e.g. 12, 24, 36 hours) between coastal storms.

Here, based on wave measurements, the independence of coastal storms and the definition of the calm period threshold is approached by the estimation of correlation coefficients. More specifically, the coefficients of Spearman's rho (ρ), Kendall's tau (τ), and Pearson's (r) are estimated, trying to understand the behaviour of H and T within consecutive coastal storms.

The Spearman's rho (ρ), Kendall's tau (τ), and Pearson's (r) coefficients measure the association strength between two numeric variables. The three coefficients are usually used for the independence of different variables (Kereszturi et al., 2016; Williams et al., 2016) or the correlation between different samples of the same variable. Two samples are strongly associated when ρ, τ, *and* r values are close to 1 or −1. On the contrary, both samples are considered independent when the coefficients are close to zero. The correlation coefficients vary in their effectiveness and usually one of them is more appropriate than the other (Ferguson et al., 2000), thus all of them are estimated to get a better overview.

The Spearman's rho (ρ), when the samples have no ties, is estimated based on Eq. (1) (Hollander et al., 2015). The R_i and S_i are the ranks of X_i and Y_i variables (when both samples are on ascending order). Here, X_i and Y_i represent the H or T of consecutive coastal storm events.

$$\rho = 1 - \frac{6\sum_{i=1}^{n}(S_i - R_i)^2}{n(n^2-1)} \tag{1}$$

The Kendall's tau (τ) statistic, or the Kendall rank correlation coefficient, is used primarily when the data do not necessarily come from a bivariate normal distribution. The estimation is done according to Eqs. (2) and (3) (Hollander et al., 2015) for two different samples, with the same length n and without ties.

$$\tau = \frac{2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} Q((X_i, Y_i), (X_j, Y_j))}{n(n-1)} \tag{2}$$

$$Q((X_i, Y_i), (X_j, Y_j)) = \begin{cases} 1, & if\ (Y_j - Y_i)(X_j - X_i) > 0 \\ -1, & if\ (Y_j - Y_i)(X_j - X_i) > 0 \end{cases} \quad for\ 1 \le i \le j \le n \tag{3}$$

The Pearson's (r) statistic is given by the Eq. (4) for two samples or variables $X=(X_1,..,X_n)$, $Y=(Y_1,..,Y_n)$, with mean values $\overline{X}$, $\overline{Y}$.

$$r = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \tag{4}$$

The above coefficients are estimated for H and T for all the consecutive events at each location. The correlation coefficients ρ, τ, and r which are close to zero, are only taken into consideration. It is optimum to analyse the longest coastal storms, working with a lot of data, but quite often coastal storms consist of short length time-series. Hence, for the best performance, a small extension is accomplished whenever an event consists of less than 10 values, by taking some additional values of H or T, before the first event and after the end of the second event.

Given that the calm period threshold usually ranges around 24 hours in literature, the above analysis provides more information for selecting the optimum threshold. The calm period threshold is set as the minimum calm period, which ensures a weak correlation of H samples, based on ρ, τ, and r, for the most consecutive coastal storms (and similarly for T).

The results are classified by the calm period into 15 classes, from 12 to 96 hours. The representative of each class is the upper boundary and is set as multiple of 6, dividing a day into quartiles. However, the first class is 12 hours, and all the previous cases are merged into one, setting a half-day milestone for the calm period. For instance, all the above statistics are estimated for Barcelona and are presented in Figure 6. Based on significant wave height (Figure 6), the calm period of 12 and 42 hours are the most dominant, for all the correlation coefficients. In Figure 6b 12 and 30 hours are the prevailing calm periods, especially for Pearson's r coefficient. This finding means that the most independent consecutive events in Barcelona have a calm period of 12 or 42 hours. Hence, the twelve-hourly calm period is considered as the calm period threshold for Barcelona.

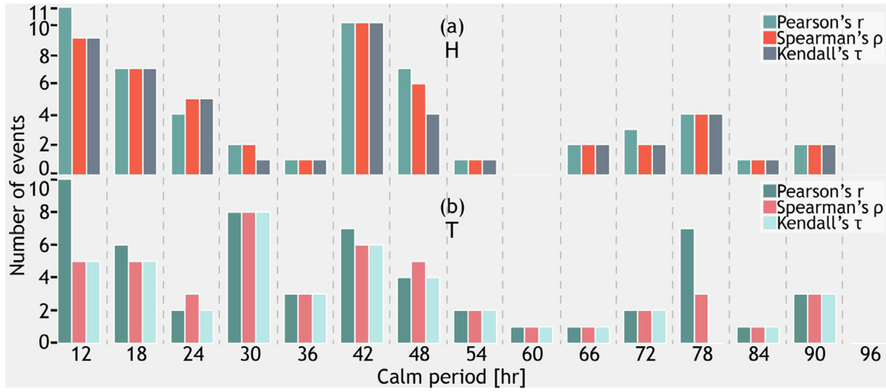

Figure 6 The number of coastal storm events in Barcelona, which are not correlated with the next event, having the Spearman's ρ, Kendall's τ, and Pearson's r coefficients close to zero, for H (a) and T (b).

3.2. Coastal storm characteristics

After the storm identification, the important storm characteristics are estimated to describe each coastal storm, namely the start and the end date, the duration, the mean and the max value of H and T, the direction, the energy, and the calm period.

The wave period and the wave direction have slight variation during a coastal storm. For this investigation, the coefficient of variation (CV) is estimated (Eq. (5)) at each coastal storm, dividing the standard deviation (s) with the mean value ($\bar{x}$) of each parameter. The coefficient of variation shows the homogeneity of wave period and the direction and how normally are spread around the mean during a storm. It should be noted that the circular mean and standard deviation have been used in the case of direction, (Jammalamadaka and SenGupta, 2001).

$$CV = \frac{s}{\bar{x}} \tag{5}$$

The coastal storm energy (E) is estimated for each event by using Eq. (6), as it was proposed by Dolan and Davis (1992), where t_1 and t_2 denote the beginning and the end of an event respectively.

$$E = \int_{t_1}^{t_2} {H_s}^2 dt \tag{6}$$

For the energy estimation, the coastal storm duration and the sampling interval may need to be corrected. Whenever the first value of H during a coastal storm is not equal to the threshold, a correction is applied for the estimation of the duration. More specifically, the properties of similar triangles from Geometry are used to approximate better the storm duration, considering a more linear shape of a storm. Following the above assumption, the H threshold is set at the first and the last value for each storm event and the duration is extended by adding a short time period s_4, following Figure 7), before and after the initially estimated duration. Consequently, the corrected duration is considered as the storm duration (D). Also, when the sampling interval (dt) is non-constant during a coastal storm, the H values are distributed uniformly according to the duration (Figure 7b), and hence the storm energy is estimated based on a new average time step (dt).

The wave energy flux (P) (Boccotti, 2014) is also estimated using Eq. (7). The wave energy (E), per unit surface area, is estimated by the Eq. (8) where g is the gravitational acceleration and ρ denotes the density of salt water. The C_g denotes the group velocity that depends on many wave parameters (e.g. wave period, wave length) and it is different for the shallow, intermediate, and deep waters. The energy flux is estimated at each hour of storm duration and then the sum of these values gives the energy flux for the coastal storm.

$$P = E \cdot C_g \tag{7}$$

$$E = \frac{1}{8} \rho \cdot g \cdot H^2 \tag{8}$$

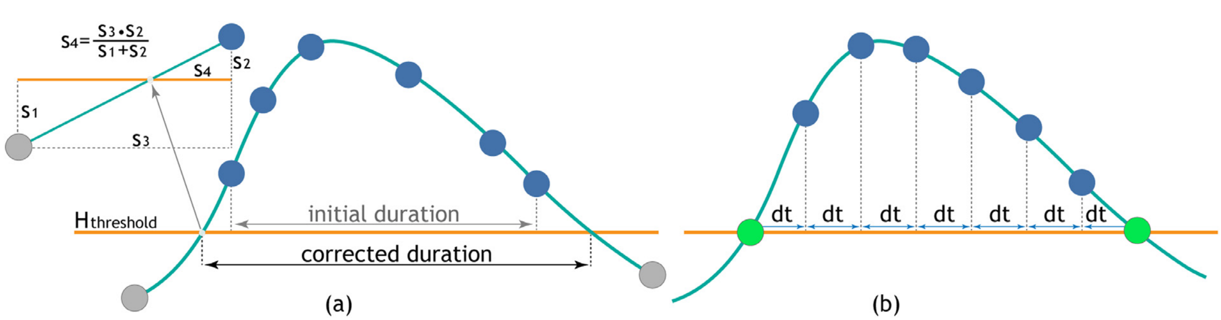

Figure 7 (a) The correction of storm duration when the first and the last value of H are not equal to the threshold, extending by s_4 the storm duration, according to properties of similar triangles. (b) The values of H are distributed uniformly by dt when the sampling interval (dt) is not constant during a coastal storm.

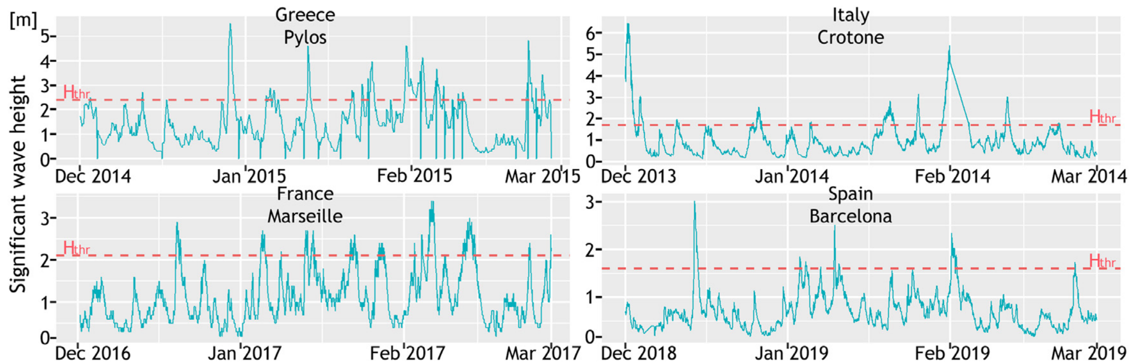

Figure 8 Illustration of significant wave height variation and their thresholds for 4 typical locations.

4. Analysis of results

The analysis of 30 different locations and their datasets, provides valuable information about the variation of important parameters (Figure 8) and the storm activity over the Mediterranean Sea during the last decades. Following the above methodology, the coastal storms thresholds are defined and subsequently, the coastal storm events are identified and analysed.

4.1. Coastal storm thresholds

For the coastal storm identification, three thresholds are considered regarding a) the significant wave height, b) the duration, and c) the calm period. As indicated previously, the threshold of minimum duration is generally set at 9 hours for all the examined locations. The H_{thr} is defined as the 95% of the sample of significant wave height per location and the I_{thr} is established according to the correlation coefficients Spearman's ρ, Kendall's τ, and Pearson's r. The general framework of this methodology is very common in literature but differs in the way the thresholds are set (Bernardara et al., 2014; Corbella and Stretch, 2013; Lira-Loarca et al., 2020; Lin-Ye et al. 2016) while sometimes they are defined based on previous studies (De Michele et al., 2007; Li et al., 2018, 2014) or without describing the following procedure. The thresholds of the significant wave height (H_{thr}) and the calm period (I_{thr}) between two consecutive events are estimated for each location (Table 2).

Similar findings are also presented in other studies. For instance, the calm period threshold of 12 hours is in agreement with the results of Lin-Ye et al. (2016) for Barcelona and the north-western Mediterranean Sea. For Marseille, Bernardara et al. (2014) identify the independence threshold at 24 hours while our results show 12 hours. For Sete in the Gulf of Lions, Gervais et al. (2012) indicate that storms with H=2.7 m or higher can cause specific impacts in beach morphology or overtopping. Here, for Sete the H_{thr} is 1.7 m, the average H of all events is 2.36 m and the average of the most extreme events is at 3.33 m, which means that concur. For all the cases, any divergences might be rational and the comparison is not indicative owing to the different reference periods and the model data that use which usually overestimate the mean value of important parameters.

Table 2 The estimated thresholds of the significant wave height (H_{thr}) and the calm period of consecutive storm events (I_{thr}), for the 30 examined locations.

Location		H_{thr} [m]	I_{thr} [hr]
	Greece		
1	Athos	2.3	12
2	Lesvos	1.9	12
3	Skyros	2.3	12
4	Mykonos	2.4	12
5	Santorini	2.0	18
6	Heraklion	1.8	18
7	Kalamata	0.9	18
8	Pylos	2.4	12
9	Zakynthos	2.0	18
	Italy		
10	Venice	1.3	18
11	Crotone	1.7	24
12	Catania	1.5	12
13	Palermo	2.2	24
	France		
14	Alistro	1.6	18
15	La Revellata	3.1	24
16	Nice	1.3	12
17	Porquerolles	2.6	12
18	Marseille	2.1	12
19	Sete	1.7	12
20	Leucate	1.7	12
21	Banyuls	1.7	12
	Spain		
22	Cabo Begur	3.4	18
23	Barcelona	1.6	12
24	Tarragona	1.1	12
25	Valencia	1.4	24
26	Cabo De Gata	2.4	12
27	Malaga	1.2	12
28	Dragonera	2.7	12
29	Capdepera	2.5	18
30	Son Bou	1.4	24

4.2. Descriptive statistics

In this work, 4008 coastal storms are analysed, corresponding to 41—127 storm events per year. Most of them (77—

Table 3 The total number of examined coastal storm events at each country and their characteristics.

	Overall	Oct.—Mar.	Apr.—Sep.	Annual average				Average temporal coverage [years]
				Overall	Oct.—Mar. %	Apr.—Sep. %	Per location	
Greece	1103	950	153	98	86	14	12	8.8
Italy	87	69	18	41	78	22	10	1.2
France	633	509	124	87	80	20	13	5.5
Spain	2185	1668	517	127	77	23	14	14.6

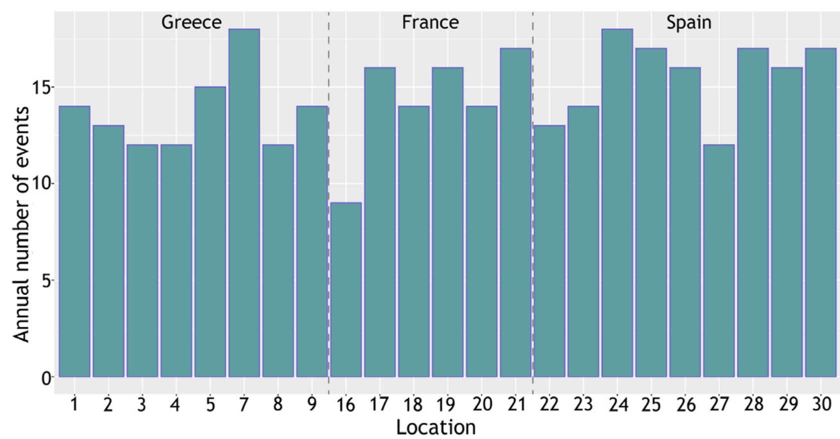

Figure 9 The annual average number of coastal storms for each location, (the locations with a short temporal coverage are not included).

86%) occur in winter months, especially from October to March (Table 3). The average temporal coverage of datasets is shorter than 15 years. Trying to understand better the frequency of storm occurrence, the annual average of coastal storms per location is also estimated, excluding the short-length datasets to avoid the underestimation (i.e. Heraklion, Allistro and La Revellata). Subsequently, 10—14 coastal storms, on average, hit the examined coastal areas annually. More specifically, the frequency of occurrence is taking into account for each location, and the annual average is presented in Figure 9. Once again, the locations with a short dataset, regarding the duration of the record, are not included in Figure 9 (i.e. Heraklion, Venice, Crotone, Catania, Palermo, Alistro and La Revellata). The percentage frequency of coastal storm occurrence at a monthly level, as presented in Figure 10, confirms that coastal storms are more frequent in the winter semester for each location. During a summer month (July, June, August) the coastal storm activity is usually less than 5% of the annual coastal storm activity, while the percentage for a winter month varies between 10% to 30%. Furthermore, it is worth mentioning that storm activity is more intense during the summer for most of the Spanish locations.

The present findings could be used in the future by any researcher who wants to pursue a coastal storm analysis at the examined locations. The annual or the monthly frequency of occurrence of coastal storms, according to Figures 9 and 10, is useful for applying extreme value analysis based on the Block Maxima or the r-largest order statistics (Coles, 2001; Dey et al., 2015). Comparatively, Bernardara et al. (2014), working with a more extended dataset, detect in Marseille 10 events per year, while the above analysis identifies 14 events. Lionello et al., (2016) describing the climatology of cyclones in the Mediterranean, present the variation of cyclones per month, with average 18 events, but this value corresponds to all the Mediterranean region; thus it is not directly comparable. Previous studies have indicated that the most active areas in cyclones in the Mediterranean Sea are the Aegean, the Adriatic, the Gulf of Genoa, the Gulf of Lion, and the Catalan Sea (Cavicchia et al., 2014; González-Alemán et al., 2019; Lionello et al., 2006). This information ties well with the findings of the present study, where the highest frequency of coastal storms as well as the highest values of *H* and *T* were identified in representative coastal locations of the aforementioned seas; namely in Athos, Pylos, La Revellata, Porquerolles, Cabo Begur.

The overview of Mediterranean coastal storms analysis is completed with the description of the different descriptive coefficients (Table 4). The mean (m_H and m_T) and the maximum (max_H and max_T) values of all significant wave heights and wave periods (m_T) are estimated at each location for all storm events. The storm energy, the wave energy flux and the storm duration of events are presented by their mean values and described respectively by m_E, $m_{P,}$ and m_D. Finally, the most extreme events are examined by taking the average of the highest 5% of all the wave heights ($m_{H5\%}$) and the wave periods ($m_{T5\%}$) that occur at a given location.

The highest significant wave heights occur at exposed locations, where the fetches are long, such as Cabo Begur in

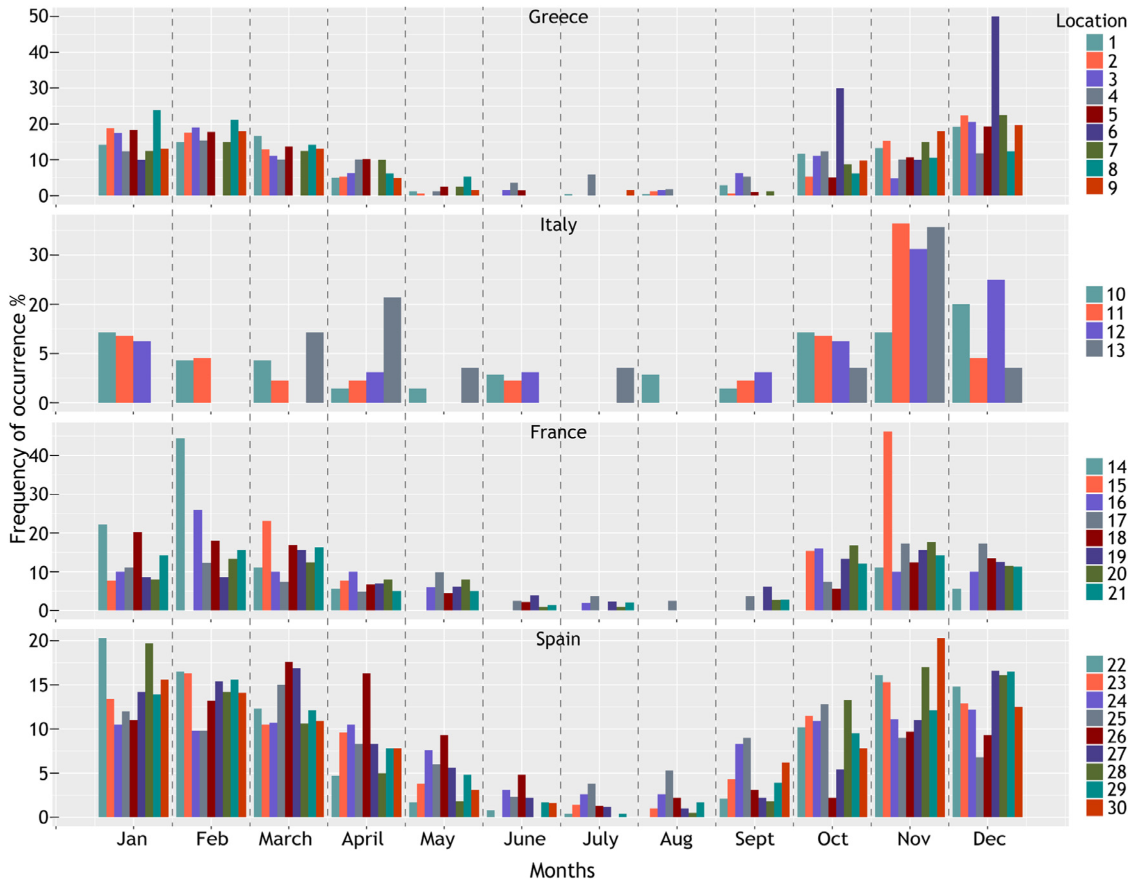

Figure 10 The percentage monthly frequency of coastal storm occurrence for each location.

Spain, La Revellata in France, Palermo in Italy and Pylos in Greece. On the other hand, the lowest wave heights appear in shallow waters and sheltered locations, such as Kalamata (Greece), Venice (Italy), Nice (France) and Tarragona (Spain). This analysis is of essential importance for buoys very close to the coasts (i.e. Tarragona, Malaga and Son Bou in Spain) and furthermore when the depth is increasing (i.e. Crotone and Nice). For the above cases, the waves travel to the coasts preserving their characteristics, contrary to the buoys in deep waters where many processes (e.g. refraction, shoaling or breaking) induce significant changes to incident waves.

The highest values of T and E also appear to the most exposed locations, as previously. For the most extreme events, the analysis reveals that $m_{H5\%}$ and $m_{T5\%}$ are approximately 12% higher than m_H, m_T respectively, giving valuable information for each location. The coastal storm energy varies between 38 and 447 m^2 hr and given its dependence on the H and the D, is high when these parameters have also high values. Coastal storms with the highest energy occur in Pylos, Palermo, La Revellata and Cabo Begur, locations in deep waters. Moreover, it could be stated that coastal storms in Greece have higher energy than those of the other countries, followed by Spain, France and Italy. The wave energy flux at each location varies between 1014.57 and 37867.01 Whr/m having similar trends with the coastal storm energy. Given that the coastal storm impacts are not clearly associated with the storm energy and the energy flux, the information about energy could be used for the determination of storm severity.

4.3. Duration and calm period

The examined coastal storm events have a mean duration between 18 to 31 hours, while the shortest events occur in Palermo, Italy and the longest in Malaga, Spain (Table 4). Additional analysis for the duration is accomplished by taking the events which exceed the significant wave height threshold, before rejecting some of them due to the threshold of minimum duration of 9 hours as described in 3.1.2. The boxplots of Figure 11a show the full range of the storm duration. The average duration is lower than 30 hours, and according to the median, 50% of coastal storms last less than a day.

Moreover, it is shown that the variation of the median is very small for Greek and Spanish locations. The upper quartile (75%) is almost the same for Greek locations which are not in the centre of Aegean Sea, as well as for Leucate, Sete and Banyuls in France. The highest upper quartiles and the most outliers of duration occur in Spain. In the same context, Lionello et al. (2006) state that the shortest cyclones in Mediterranean last lower than 12 hours and the most severe cyclones have an average duration 18—24 hours. It could be said that the coastal storm duration has the same characteristics, according to Figure 11, and it is a rational

Table 4 Basic statistics of the most important parameters during a coastal storm event for the examined locations.

	Location	m_H [m]	max_H [m]	m_T [s]	max_T [s]	m_E [m^{2}hr]	m_P [Whr/m]	m_D [hr]	$m_{H5\%}$ [m]	$m_{T5\%}$ [s]
	Greece									
1	Athos	3.01	5.99	7.57	19.99	243.84	19850.37	27.06	4.01	9.05
2	Lesvos	2.52	14.71	7.30	19.32	169.71	14645.21	24.13	4.33	10.58
3	Skyros	3.01	5.45	7.82	10.04	248.04	20495.81	28.10	3.75	8.81
4	Mykonos	3.10	5.76	7.87	11.36	234.35	20860.71	27.38	5.13	9.47
5	Santorini	2.46	4.92	7.37	13.82	143.32	10966.83	24.51	3.08	9.16
6	Heraklion	2.47	4.25	7.33	10.04	191.64	16720.21	31.13	2.77	7.61
7	Kalamata	1.28	3.28	7.37	11.13	38.93	3049.20	24.31	1.76	9.13
8	Pylos	3.10	7.57	8.95	13.71	273.69	25949.15	28.64	4.05	10.21
9	Zakynthos	2.68	9.37	9.49	24.37	219.77	13874.17	28.82	4.62	18.37
	Italy									
10	Venice	1.67	3.77	6.39	10.53	57.91	3956.21	20.23	2.34	8.34
11	Crotone	2.34	6.46	8.26	13.33	178.60	12565.84	29.09	3.41	9.67
12	Catania	2.21	4.96	8.57	12.50	131.63	10365.29	24.03	3.92	10.33
13	Palermo	2.85	5.49	8.99	13.33	152.46	15581.80	18.50	3.73	11.90
	France									
14	Alistro	2.25	5.80	7.45	11.80	128.61	11851.22	23.31	3.45	9.12
15	La Revellata	3.94	7.70	9.65	13.30	374.49	33189.66	22.57	5.32	10.88
16	Nice	1.73	4.00	7.23	13.30	69.23	5042.72	22.45	2.24	10.82
17	Porquerolles	3.06	6.20	8.52	12.10	175.94	14482.73	19.09	3.85	10.07
18	Marseille	2.47	8.60	7.45	25.00	123.21	7947.60	20.57	3.10	8.94
19	Sete	2.36	5.90	7.41	11.80	162.38	10889.63	27.70	3.33	9.34
20	Leucate	2.33	9.10	7.40	28.60	164.50	11851.71	27.74	3.57	9.56
21	Banyuls	2.15	12.80	7.27	25.00	127.29	3901.43	25.77	3.17	9.80
	Spain									
22	Cabo Begur	4.05	7.40	8.06	12.70	446.36	37867.01	26.98	5.11	9.91
23	Barcelona	2.03	5.20	7.56	12.30	118.88	10077.18	27.49	2.83	9.46
24	Tarragona	1.39	3.90	6.97	12.20	52.57	2024.92	25.02	1.81	7.09
25	Valencia	1.80	4.50	7.35	12.50	101.38	7684.43	29.51	2.42	9.57
26	Cabo De Gata	2.94	6.60	7.42	10.60	205.07	16190.26	23.47	3.76	8.77
27	Malaga	1.69	4.70	6.94	15.60	98.79	3720.91	30.37	2.47	6.83
28	Dragonera	3.27	6.30	8.24	12.80	269.30	26876.39	24.97	4.03	9.93
29	Capdepera	3.16	7.00	8.88	12.80	264.94	21296.32	25.88	4.16	10.09
30	Son Bou	1.73	4.98	5.33	8.52	89.94	1014.57	28.98	2.25	6.30

outcome since coastal storms originate from cyclones and synoptic systems.

The average calm period of coastal storms is shorter than 625 hours, or less than one month, according to Figure 11b. Most events (75%) have calm period less than 750 hours, while 25% of events have calm period almost 150 hours, hitting consecutively the same location in less than a week. In general, the variation of the calm period is higher than the duration. The median is around 190 hours for most Greek locations and around 250 hours for Spain. The highest upper quartiles belong, again, in Spain and the average calm period of 500 hours is the most common in Spanish locations. The results about the mean storm duration and the calm period are also important for the coastal erosion (Callaghan et al., 2008; Corbella and Stretch, 2012a; Dissanayake et al., 2015), the vulnerability of coastal structures and their design (Lira-Loarca et al., 2020; Salvadori et al., 2014). Consecutive storm events and events with long duration are responsible for significant loads in the coastal structures as a well as for the short time for beach recovery.

4.4. The variance of the wave period and the direction

Another issue that emerged from the data analysis is that the wave period (T) and the main direction (D_{ir}) are usually quite stable during a coastal storm. To understand the level of dispersion around the mean (or the circular mean), the coefficient of variation (CV) of these parameters is estimated for each coastal storm (Figure 12). Regarding the wave period, no significant patterns are detected between locations, but it can generally be stated that 75% of storm events have the CV usually less than 0.15 and for 25% of them the CV is even less than 0.05 (Figure 12a).

Similarly, Figure 12b shows the range of CV for the coastal storm direction (wherever is available), which is shorter than the wave period. The upper boundary of boxplots shows that 75% of coastal storms have the CV less than 0.08. Following the boxplots, it is shown that there is no high dispersion for T and D_{ir} during a coastal storm. The values of T and D_{ir} are normally spread around the mean during

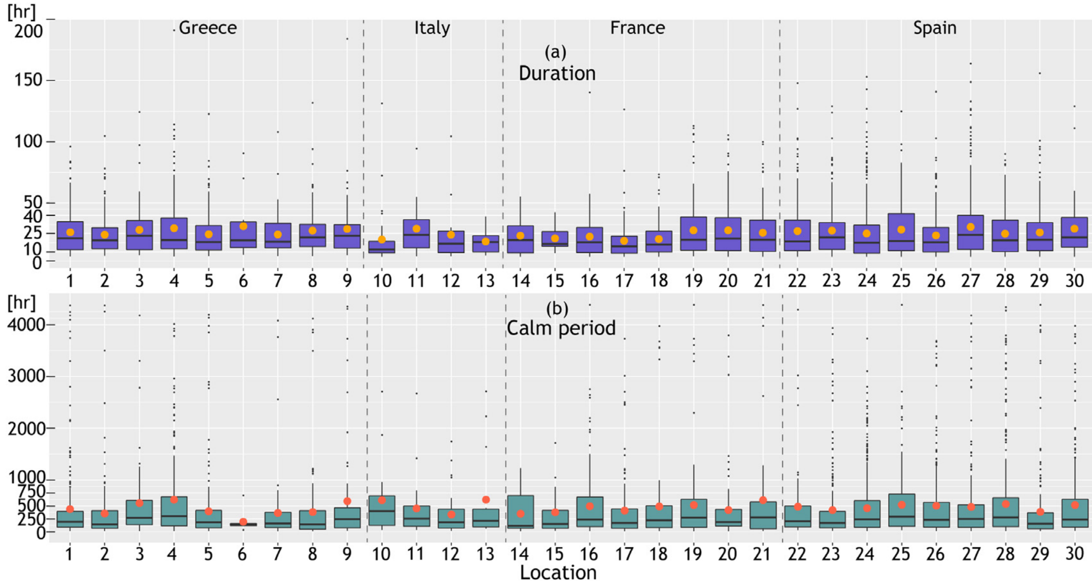

Figure 11 Boxplots for the full range of variation of coastal storm duration (a) and the calm period between two consecutive events (b).

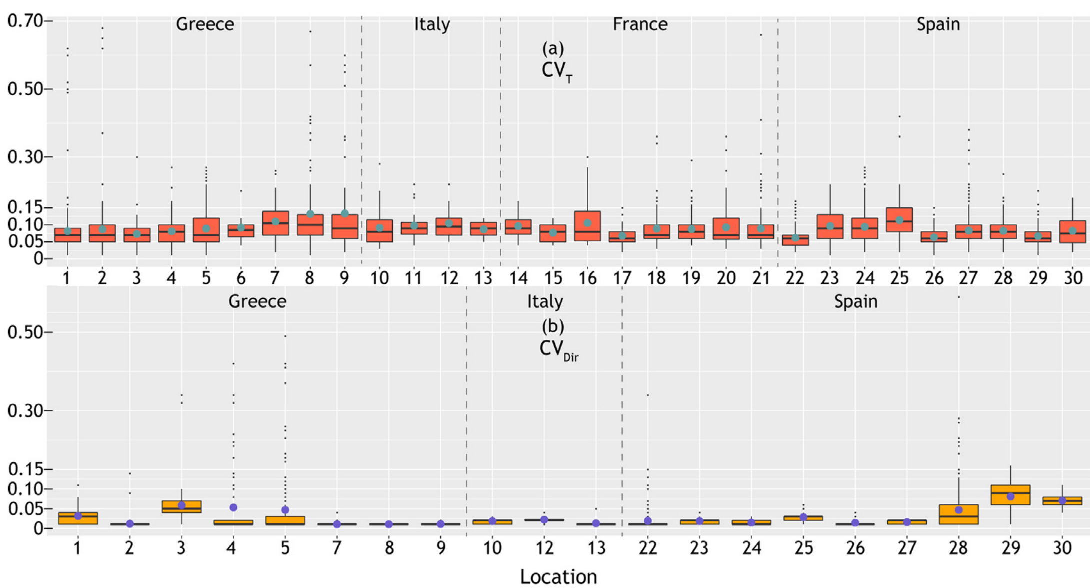

Figure 12 Boxplots for the full range of the coefficient of variation for (a) the wave period and (b) the wave direction.

a coastal storm for the majority of storm events and thus the mean value can represent efficiently the coastal storm wave period and the direction.

5. Conclusions

In the context of this work, a deeper understanding of coastal storms is pursued, providing knowledge on the coastal storms in the Mediterranean Sea, as well as on the variation of their parameters, and their characteristics. The novelty lies on the analysis of big datasets from buoys measurements at various coastal locations in the Mediterranean. A general methodology for coastal storm identification is described thoroughly. All this information could be useful to researchers, engineers, organisations, or stakeholders on their effort to understand better the coastal storms, to protect and inform the coastal communities from coastal storm impacts in a changing climate.

The coastal storm events are studied and analysed based on their characteristics and not on their impacts on coastal morphology and infrastructure. To achieve this, the coastal storm is defined by taking the closest buoys from the coast and by applying the 95th percentile of H as the primary threshold for storms identification. Furthermore, two more thresholds are used for the storm identification (minimum duration and calm period).

A dataset of wave buoys measurements from 30 different locations over the Mediterranean is analysed, and a total amount of 4008 storm events are identified, covering coastal areas in Greece, Italy, France, and Spain for the period 1985—2019. A detailed descriptive analysis is provided, which includes the mean and the maximum value of storm parameters. The range of storm parameters is site-specific since storm characteristics depend on the water depth and the bathymetry. Their extreme values and the intense coastal storm activity occur in areas that have also significant cyclonic activity. The exposure of coastal areas is inherently linked to the wave height and wave period. Indeed, the most exposed locations are associated with the most extreme values of wave height and wave period, whereas the most sheltered ones are identified where the lowest values of H and T occur. According to the results, 10—14 storm events occur per year in a Mediterranean coastal area, and most of them span from October to March. The examined events have an average duration lower than 30 hours, and 25% of them are consecutive events which hit the same location in less than a day.

Another concluding remark of this work is that the wave period and the wave direction present no remarkable fluctuation during a coastal storm event, according to their coefficient of variation. Therefore, the mean values of T and D_{ir} describe sufficiently the wave period and the direction of a coastal storm.

The limitations are mainly related to the sampling interval of buoys measurements (0.5—3 hours). In addition, the temporal data coverage is also very short and different for few locations. The latter is restrictive on providing a more general overview of coastal storm activity. Such technical barriers, including the collection of the respective data and the encoding of different data (i.e. file formats, variables' names) make this work more demanding and time-consuming, especially during the process of data mining. In this context, all Italian and some French locations with short coverage are excluded from the annual frequency of occurrence (Figure 9). For these reasons, it is quite difficult to conclude about climate change and how it affects the frequency of coastal storms over the years.

For future research, a more extensive database, with the shortest possible sampling interval, is essential to avoid the use of general thresholds. The thresholds for the significant wave height, storm duration and calm period could be redefined for each location, through the consideration of smaller values compared to ones used here. The satellite data, the information about synoptic systems, and other parameters such as atmospheric pressure should be included for a more detailed coastal storm analysis. For such analyses, a denser network of buoys and increased data availability are also needed to identify the storm activity for more locations and assess their relationship. At a next level, this analysis and its findings could be used, as the basis for the development of synthetic storms and the storm modelling at the examined locations.

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