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Review

The Imprint of Recent Meteorological Events on Boulder Deposits along the Mediterranean Rocky Coasts

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Abstract: In this review, the potential of an emerging field of interdisciplinary climate research, that is the Coastal Boulder Deposits (CBDs) as natural archives for intense storms, is explored with particular reference to the Mediterranean region. First, the identification of the pertinent scientific articles was performed by using Web of Science (WoS) engine. Thus, the selected studies have been analysed to feature CBDs produced and/or activated during the last half century. Then, the meteorological events responsible to the literature reported cases were analysed in some details using the web archives of the Globo-Bolam-Moloch model cascade. The study of synoptical and local characteristics of the storms involved in the documented cases of boulder production/activation proved useful to assess the suitability of selected sites as geomorphological storm proxies. It is argued that a close and fruitful collaboration involving several scientific disciplines is required to develop this climate research field.

Keywords: Coastal storm; Wind wave; Storm surge; Extreme coastal water level; Boulder dynamics; Geomorphological proxy; Interdisciplinary climate research

1. Introduction

Coastal boulder deposits (CBDs) are often signatures of high energy waves on coastal environments. They are widespread along marine coasts and have distinctive geomorphological imprints because their transport and emplacement are restricted to the duration of tsunami and storms [1,2]. Clustering of boulders lying on the coast can be produced also by other natural processes such as gravitational landslides or weather waterspouts. However, CBDs produced by high energy wave have some peculiar characteristics (see Section 2), thus geomorphological survey is usually enough to recognize their origin with high confidence [3–5]. Boulder production and deposition by wave quarrying are strictly related to coastal erosion and flooding hazard. This explains the increasing interest on the subject in various scientific and engineering disciplines [6–9].

Since the 1960s it is become increasingly recognized that storms are capable of significant bounder dynamics activation especially in tropical - subtropical (e.g. [10–12]) and in middle - high latitudes (e.g. [13–15]). This recognition in the Mediterranean region and, more generally, in medium-low latitudes took place only subsequently ([16,17] and [18], respectively). For what concerns the Mediterranean, the interest on the dynamics of CBDs to improve the knowledge in coastal hazards is currently growing especially because of possible changes in the storm climatology, with an increase of the energy release by storms [19,20].

The suitability of CBDs as geomorphological storm proxies (i.e. preserved physical characteristics of a number of storms in deposits and landforms) has been recently stressed for macrotidal high-energy rocky coasts [21,22]. Although the reconstruction of mid- (i.e. (multi-decadal) and long-term (i.e. secular or millennial) storminess record is hampered by complexities in dating and identifying individual events inside the boulder clusters [23], CBD studies is becoming an emerging field in interdisciplinary climate research. As a matter of fact, several scholarly disciplines recently try to bring own epistemology, theories, methods, and practices from across the range of each research sector toward a common research perspective. The efforts made to avoid a failure of such an interdisciplinary work are noticeable taking into account the first results [8,17,21]. Geomorphologists, atmosphere

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physicists, physical oceanographers, and hydrodynamics researchers were the first players in this process, but other expertises (such as optical luminescence and lichenometry dating) are required to establish solid foundation for this issue.

The main goal of this paper is to explore the potential of CBDs as natural archives for Mediterranean storms. First, a scientific articles identification was performed by using Web of Science (WoS) engine. Thus, the selected articles have been analysed to feature CBDs produced and/or activated during the last half century. Then, the meteorological events responsible to the founded cases of CBDs production and/or activation were examined using the web synoptic maps of the Globo-Bolam-Moloch model cascade [24]. Finally, the suitability of selected sites as geomorphological storm proxies is considered in the perspective to advance the interdisciplinary climate research.

2. Basic Concepts

According to the sedimentological nomenclature, boulders are fragments of rock (i.e. clasts) with intermediate axis from 0.256 to 4.096 m long (larger clasts are named blocks and megaclasts) and weight usually from tens of kilograms to several tonnes [25]. They are the size class most represented in CBDs. For the mode of boulder/block transport, morphometry parameters such as shape and roundness are important determinants [2,26]. In what follows, unless otherwise specified, the treated clasts fall within the class of boulders; in case of belonging to the block class this will be specified.

Coastal boulders/blocks are originally produced by the detachment from the bedrock. The area of clast detachment is termed socket [27]. Any further movement of previously uprooted clasts due to the action of high energy wave are referred as activation [21]. Boulder dynamics is herein used for both the processes. CBDs form the following sedimentary assemblages types: isolated boulder; field of scattered boulders; boulder clusters (spaced, stacked or imbricated); boulder ridges (Figure 1). From a theoretical point of view, the assemblage structure of the deposits should change from isolated boulders to large-scale boulder ridges with the number of high energy wave events [21,22]. However, this is only a rough indication since each CBD has its own depositional history due to local conditions.

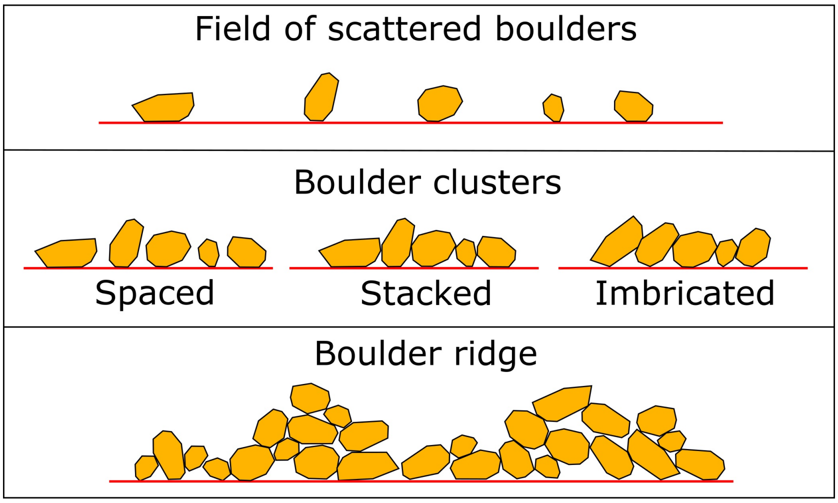

Figure 1. Schematic cross sections (normal to the coastline) of the CBD assemblages types placed on shore platform (red line) and produced/activated by high energy waves.

A large number of CBDs described in literature are placed on shore platforms, in both the intertidal and supratidal zones. However, they are also present offshore in the subtidal zone, as well as over the top of the coastal cliffs. CBDs produced by high energy wave usually have sedimentological evidence of landward transport, thus their origins mechanisms are readily identified. However, ascribing one of the two specific wave process (tsunami or coastal storm) to CBD of unknown date of deposition is often quite difficult [5,22]. This problem does not exist for the purpose of this review as it deals with the

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activation of boulders during recent storms, while the occurrence of tsunamis can be excluded.

Before addressing Section 3, some basic features on the concepts of coastal storm and storminess must be given. Coastal storms may alter the geomorphological features of the coasts and affect the coastal zones with flows and flooding. They are usually identified using basic parameters and the associated thresholds, such as significant wave height, duration of the meteorological event, and calm period [28]. Thresholds are site-specific and depend mainly on synoptic systems, bathymetry, topography, exposure to wind waves, direction and energy of coastal storm [29]. The duration of a storm is the time period in which significant wave height remains over the established threshold. The storminess of a stretch of a coast denotes frequency and energy (severity) of the impacting storms. However, each discipline uses a specific epistemological approach to measure the storminess. In atmosphere sciences, it is calculated by means of climatological and statistical approaches [30]. In oceanology and coastal engineering, storminess is defined using dataset of wave climate acquired from buoys measurements [31,32]. Finally, in geomorphology storminess is evaluated from physical footprints (defined through fieldwork) that a series of storms have left in deposits and landforms [33,34]. The need to build a common epistemology perspective among the involved disciplines is apparent.

3. Materials and Methods

To guarantee a review suitable to users, a clear account of why the review has been performed, what it did and what it found must be done [35,36]. As above stated (section 1), the primary objective pursued herein is the evaluation of CBD as geomorphological storm proxies for the Mediterranean rocky coasts. It therefore aims to provide a synthesis of the state of knowledge in this interdisciplinary topic, from which to infer what to be expected from the next studies. For the scientific validity of the review, it was considered appropriate to limit the search field to indexed articles subjected to peer review.

Three stages were performed to found and examine the studies relevant for the aim of this study: identification, selection, and review. The screening was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [35,36] and using Web of Science (WoS) engine search [37–39] as primary platform for “title/abstract/author keywords/Keywords Plus”. No time period was specified. A limitation of the adopted procedure is that it only includes items written in English (at least the abstract). However, careful exclusion procedures were adopted in stage 2, both for abstract check and full-text articles assessment for eligibility. Articles dealing with storms that hit rocky coasts, although not reporting "boulder(s)" in the abstract, have nevertheless passed the first screening to be fully evaluated later. In stage 3, the main analysing criterion has been the accuracy in the identification of the storm event causing production/activation of boulders.

4. Review Results

WoS engine allowed the identification of 153 records. No duplicates have been found. The abstracts screening has determined the exclusion of 119 articles for being apparently irrelevant to the review purpose and belonging to different subject areas (i.e. biology, zoology, ecology, sedimentary geology, beaches dynamics, paleoclimate, paleotsunami, paleogeography, paleoenvironment, seismology, tsunami researches, engineering works, cliff stability assessment, gravitational landslides, mathematical model, wave tank experiments, other modeling) or because deal with cases out of the Mediterranean region (Figure 2).

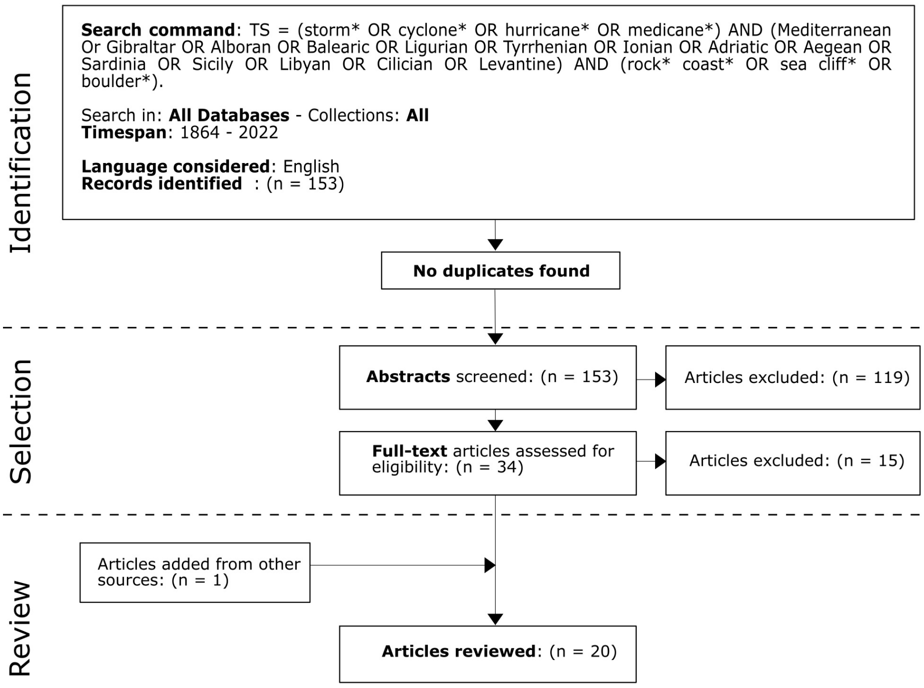

Figure 2. Flow diagram explaining the three stages screening process (see [35,36]).

15 articles were then excluded by the full-text assessment (Appendix A). These exclusions were caused by the lack in description of storm-induced dynamics on CBD, or because the article deals with CBD produced by tsunami event(s) according to the authors (Table A1). One article (Galea et alii (2018) [40]) identified by examination of the bibliography of the full-text assessed articles have been added for the review analysis. Finally, a total of 20 articles were reviewed (Table 1).

Table 1. Summary of reviewed articles.

Author (s) and Year	Location	Meteorological Event(s)
Mastronuzzi and Sansò (2004) [16]	South Adriatic	identified
Barbano et alii (2010) [41]	West Ionian	identified
Barbano et alii (2011) [42]	West Ionian	roughly identified
Hoffmeister et alii (2013) [43]	East Ionian	roughly identified
Shah-Hosseini et alii (2013) [44]	Gulf of Lion	not identified
Torab and Dalal (2015) [45]	Eastern Mediterranean	not identified
Biolchi et alii (2016) [46]	South Central Mediterranean	not identified
Causon Deguara and Gauci (2017) [47]	South Central Mediterranean	not identified
Piscitelli et alii (2017) [48]	Gulf of Lion	not identified
Roig-Munar et alii (2017) [49]	Balearic Sea	identified
Galea et alii (2018) [40]	South Central Mediterranean	identified
Pepe et alii (2018) [50]	South Tyrrhenian	not identified
Roig-Munar et alii (2018) [51]	Balearic Sea	not identified
Biolchi et alii (2019a) [17]	North Adriatic	identified
Biolchi et alii (2019b) [52]	North Adriatic	identified
Delle Rose et alii (2020) [53]	North Ionian	identified
Hoffmeister et alii (2020) [54]	East Ionian	not identified
Mottershead et alii (2020) [55]	South Central Mediterranean	not identified
Scicchitano et alii (2020) [56]	West Ionian	identified
Delle Rose et alii (2021) [57]	North Ionian	identified

Only one repetition was found among the reviewed articles: both Shah-Hosseini et alii (2013) [44] and Piscitelli et alii 2017 [48] treat the same notable case of polyphasic boulder activation happened at Martigues coast (Gulf of Lion) before December 2003. Some

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articles address two or more stretches of Mediterranean coasts [42,45,46,50,51,54,57], thus the screening process has allowed the identification of 44 sites showing evidences or clues of CBD production/activation as a results of recent (i.e. during about the last half century) storms. Many articles concern cases belonging to the central Mediterranean [16,17,40–43,46,47,50,52–57], (see Figure 3). Some studies are relative to the western Mediterranean [44,48,49,51] while only one study to the eastern Mediterranean [45].

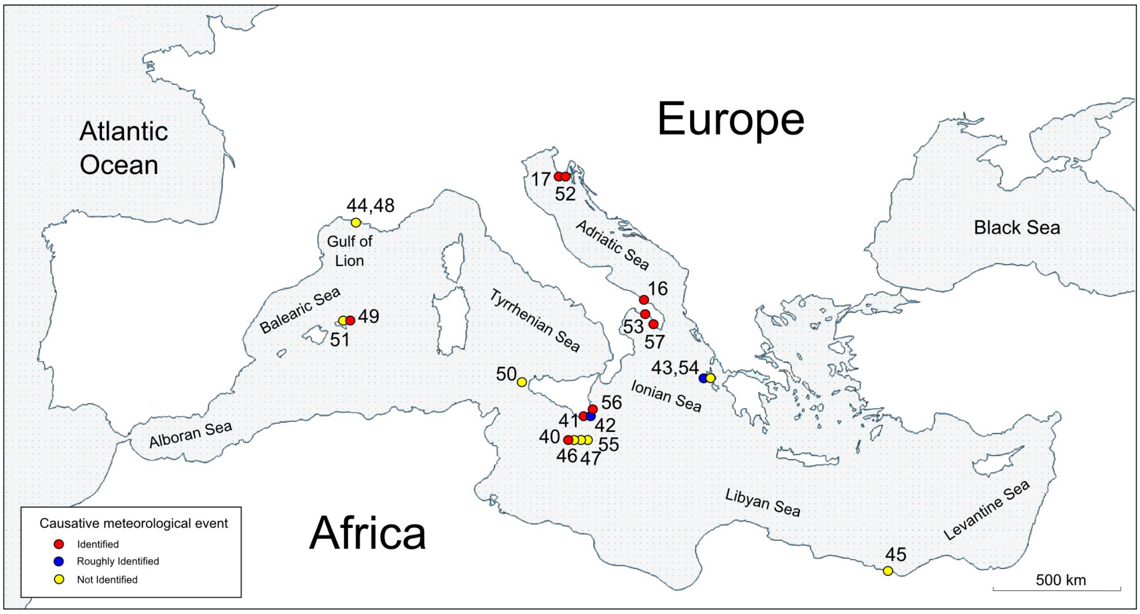

Figure 3. Location of reviewed cases study (see References numbering).

The boulder dynamics considered by all the reviewed articles were caused by meteorological events while tsunamis were explicitly or implicitly excluded as causative processes (see e.g. [17,48]). It must be also noticed that three days before the Storm Vaia (responsible for some boulder dynamics cases, see [52,57]), an earthquake occurred in the western Mediterranean. However, it caused only very small tsunami waves as registered at some tide gauge stations [58].

About the interdisciplinary contributions on CBD studies, a strong predominance of scholars in geomorphology must be underlined (see Table 2). In fact, the remainder of the researchers from other disciplines (applied physics, atmosphere physics, coastal engineering, cultural heritage, marine biology, and physical oceanography) constitutes less than 20% of the authors of the articles listed in Table 1.

Table 2. Scientific Disciplines of the authors.

Disciplines	researches
Applied Physics	2
Atmosphere Physics	1
Coastal Engineering	2
Cultural Heritage	2
Geomorphology	56
Marine Biology	3
Physical Oceanography	3

Regarding the temporal trend of the study cases, after the first pioneering study of Mastronuzzi and Sansò [16] a long stagnant period lasted until 2016 with only 6 articles published. Instead, since 2017, 14 articles have been published (Figure 4).

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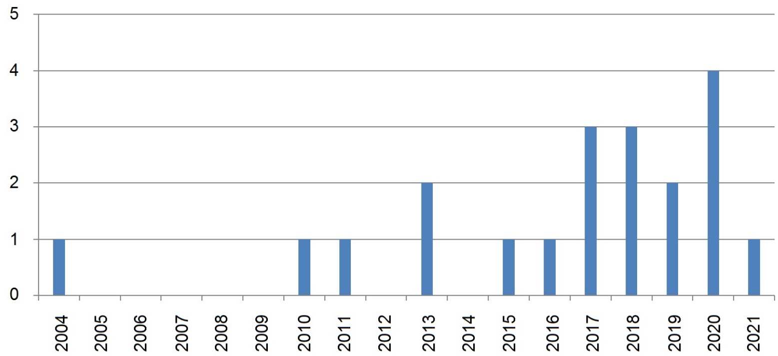

Figure 4. Number of cases studied per year.

Also the number of boulders produced and activated shows an apparent increase over time (Table 3). The use of new methods and technologies (aerial photo interpretation; camera recording analysis; drone digital photogrammetry; multi-temporal satellite imagery analysis; terrestrial laser scanning; transect photo sets) to complement the usual geomorphological fieldwork have played an important role for this trend.

Table 3. Boulders produced/activated during the selected meteorological events. U = Unspecified. Methods used by authors for CBD dynamics detection: A = geomorphological fieldwork; B = terrestrial laser scanning; C = aerial photo interpretation; D = drone digital photogrammetry; E = camera recording analysis; F = transect photo sets; G = multi-temporal satellite imagery analysis.

Storm Events	Sites Location	Boulders	References	Methods
January 4, 2002	Santa Sabina, Apulia (Italy)	1	[16]	A
January 12, 2003	Santa Sabina, Apulia (Italy)	1	[16]	A
winter 2008/2009	San Lorenzo, Sicily (Italy)	U	[42]	A
winter 2008/2009	West Cefalonia (Greece)	1	[43,54]	A,B
January 13, 2009	Maddalena, Sicily (Italy)	5	[56]	A
January 14, 2009	Vendicari, Sicily (Italy)	5	[41]	A
January 31, 2014	Kamenjak Cape, Istria (Croatia)	1	[17]	A,C
Medicane Qendresa	Maddalena, Sicily (Italy)	U	[56]	A,B,D
January 25, 2015	North Minorca (Spain)	9	[49]	A
March 5, 2015	North Minorca (Spain)	14	[49]	A
March 7, 2017	West Gozo (Malta)	U	[40]	A
Medicane Zorbas	Maddalena, Sicily (Italy)	28	[56]	A,E
Storm Vaia	Kamenjak Cape, Istria (Croatia)	14	[52]	A,D
Storm Vaia	Torre Suda, Apulia (Italy)	1	[57]	A
Storm Detlef	2 sites, Apulia (Italy)	17	[53,57]	A,F
Storms Vaia and Detlef	8 sites, Apulia (Italy)	64	[57]	A,G

Regarding the CBD assemblages treated in the reviewed studies, fields of scattered boulders and spaced boulder clusters were the most recurrent types (see Figure 1). However, sometimes also imbricated boulder clusters occurred [16,56,57]. They were almost always of boulder activation and rarely of boulder production. Special mention must be given to the cases of polyphasic activation, that is the boulders affected by the dynamics at least during two meteorological events. The most relevant are: a block twice displaced and fragmented at Martigues coast (Gulf of Lion, France) prior to December 2003 [44,48]; a seven tonnes boulder placed on the Kamenjak Cape (Istria, Croatia) and activated by the January 31, 2014 and the October 28, 2018 storms [17,52]; a block moved three times between 2009 and 2018 along the coast of Maddalena peninsula (Sicily, Italy) [56]. The case studied by [40] produced subtidal CBDs due to the collapse of a rock arch in cliff. They have not yet been analysed.

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5. Analysis of the Causative Events

5.1. Meteorological Events Description

The description of the meteorological events responsible to the more recent cases of boulder dynamics has been made mainly using information from the weather charts of the Globo-Bolam-Moloch models. Such web archives contains data from January 1, 2012. It has been used to analyze the synoptic evolution of the storms and the resulting surface wind fields. The corresponding maps of geopotential height (gph) at 500 mb, surface pressure, and windspeeed at 10 m over the sea surface are extracted from the model simulations and are available online at time intervals of three hours [24]. In what follows, some maps are used to support the descriptions. Further information were extracted from cited literature references. Moreover, estimations of the peak of the wave height distribution were made using parametric fetch-windspeed-wave height relations. These expressions relate the peak of the wave distribution to the wind speed, the oversea fetch and the duration of the high wind events (recovered from the synoptic maps), and can be used together with parametric expressions relating the increased sea level due to the storm surge to the pressure deficit and the speed and direction of movement of the cyclonic centre to estimate the sea surface characteristics from the meteorological charts of the BOLAM model. Details about these parametric expressions can be found in [59] and more details about the use of these expressions in the present context are given in [57]. Although such estimates of the peak wave height seem to give slightly higher results with respect to the significant wave height, when available from measurement/modelling, they are still in agreement with local observations of extreme waves that can be significant for the boulder activation (see below).

5.1.1. January 31, 2014

A trough elongated from the British Islands over the western Europe and the Mediterranean Sea caused cyclonic circulation over the Italian peninsula with southern winds of about 17-18 m/s persisting for about 24 hours over the Adriatic Sea (Figure 5).

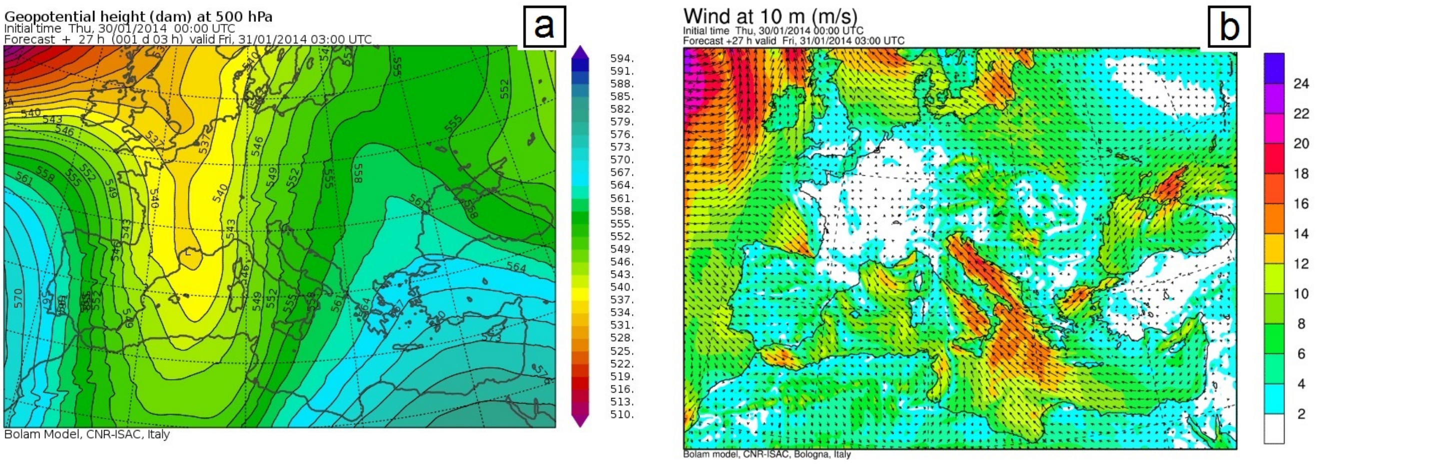

Figure 5. 31/01/2014 03:00 UTC: (a) Geopotential height (dam) at 500 hPa; (b) Wind (m/s) at 10 m (Bolam simulations).

The channeling along the Adriatic sea with a fetch of about 650 km caused development of high waves over the North Adriatic Sea. Regarding the spectral peak wave, in this case the result is an estimation of about 6-7 m impinging over the Istrian coast, while, based on the global ERA Interim reanalysis dataset [60], a significant wave height greater than 6 m was estimated by Biolchi et alii [17]. These authors also reported the activation of a boulder with a weight of about 7.65 t.

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5.1.2. November 7, 2014 (Medicane Qendresa)

The November 7, 2014 and September 29, 2018 cases (see below for the latter) are quite different from the other herein considered, as the strong winds impinging over the southern Sicily coast are due to the formation of Topical-like Cyclones in the southern Mediterranean Sea (Medicane, [61]). In November 2014, a storm originated around the Atlas promontory underwent a subsequent intensification as a medicane (later named Qendresa, [56]) in its south-eastward trajectory contouring the south-western coast of Sicily (Figure 6).

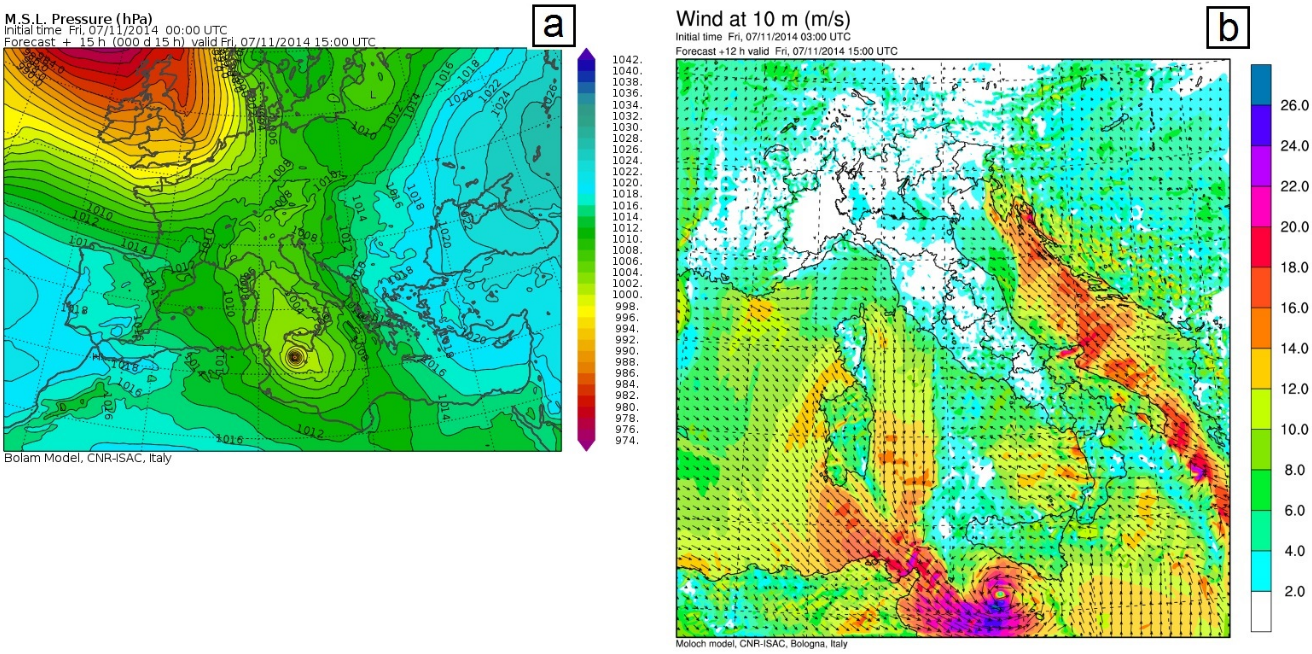

Figure 6. 07/11/2014 15:00 UTC: (a) Surface Pressure (hPa) (Bolam simulation); (b) Wind (m/s) at 10 m over the north-central Mediterranean (Moloch simulation).

Although the medicanes are able to give rise to strong winds (well over 20 m/s with gusts above 40 m/s [62] because of the deep low pressure centre, the strong cyclonic curvature results in a very variable wind direction. The small radius of curvature results in more uncertainty on the fetch required in a parameterized estimation of the wave height, than in the other cases regarding mid-latitude storms. In the Bolam-Moloch simulations average winds of about 15 m/s can be observed over south-western Sicily coast, but with a duration about half a day only during the path contouring the Sicily coast. However, winds nearest to the cyclone core and gustiness can be much stronger with high time/space variability, that cause more uncertainty in model estimations over localized sites.

Impacting on the south-eastern coast of Sicily, the medicane Qendresa caused the activation and clustering of several boulder and a block of about 41.3 t, while the closest wave buoys recorded values of significant wave height of about 4 m [56].

5.1.3. January 25, 2015

A deep trough centered in the North Europe generated a depression in the western Mediterranean Sea, causing a strong income of cold air throughout the Gulf of Lion in the Tyrrhenian Sea (Figure 7).

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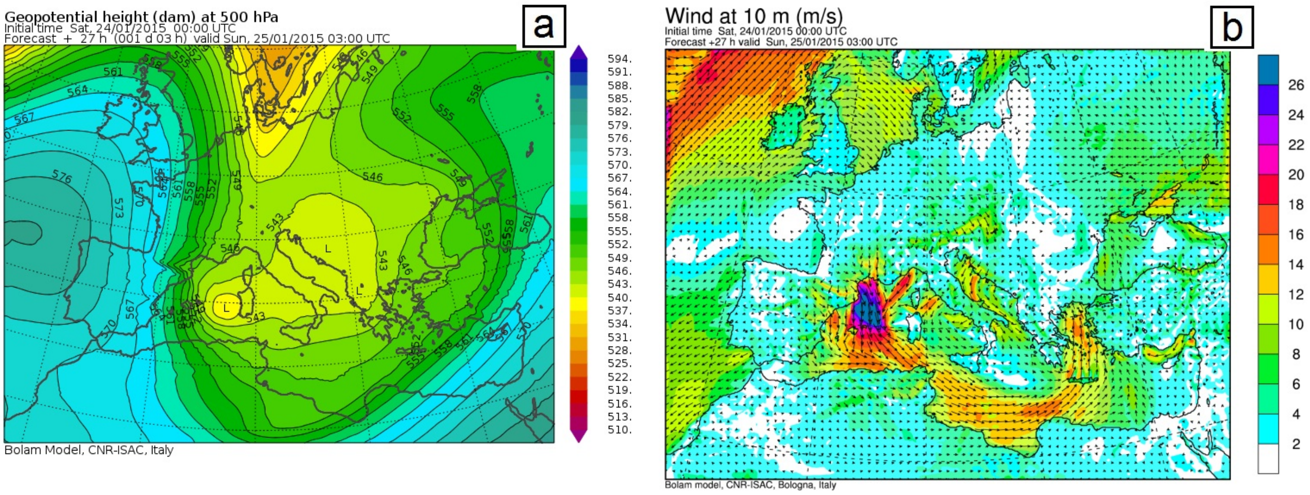

Figure 7. 25/01/2015 03:00 UTC: (a) Geopotential height (dam) at 500 hPa; (b) Wind (m/s) at 10 m (Bolam simulations).

The gustiness was very enhanced with peak winds over 25 m/s, oriented in the south-western direction and impinging for some time over the Balearic Islands. The wind speed of about 23 m/s with a fetch of about 400 km gives an estimated spectral peak wave height over 7 m near Minorca Island. For the northern Minorca coast (Table 3), Roig-Munar et alii [49] reported a maximum wave height greater than 8 m as calculated using wave buoy data and the WAM model [63].

5.1.4. March 5, 2015

In the days 4-5 of March 2015 the position of the trough of gph at 500 mb was over the north-eastern Europe, that caused the generation of a low pressure centre over the Tyrrhenian Sea. The position of this couple of low pressure centers aligned in the south-western direction caused a strong gustiness coming down from the Gulf of Lion in the direction of the Balearic Islands, with a wind speed over 20 m/s for over 20 hs (Figure 8).

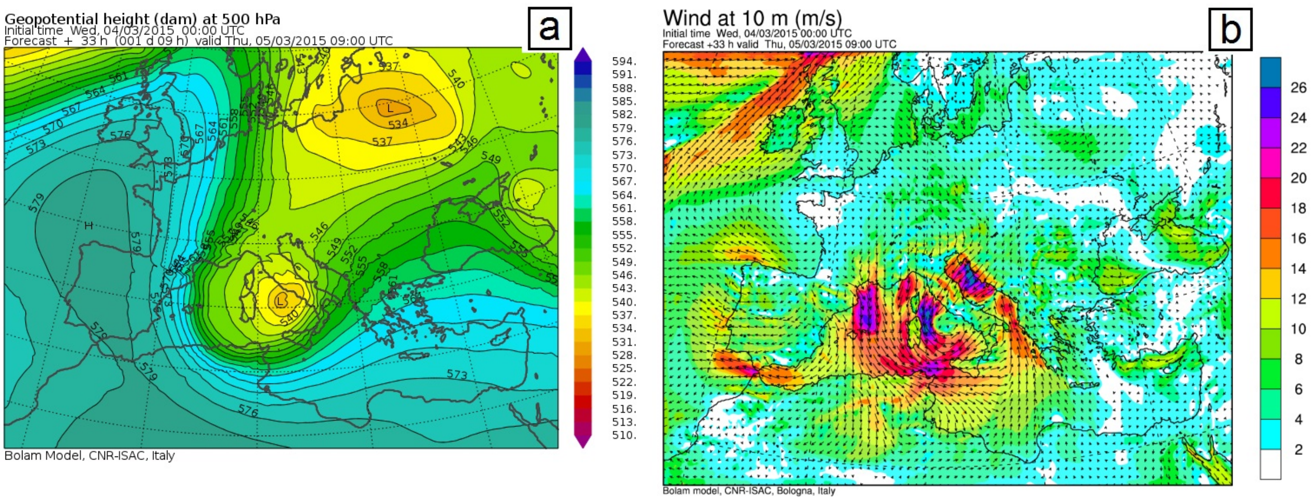

Figure 8. 05/03/2015 09:00 UTC: (a) Geopotential height (dam) at 500 hPa; (b) Wind (m/s) at 10 m (Bolam simulations).

The calculated peak wave was again over 7 m height, while a maximum wave height lower than 8 m was reported by [49].

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5.1.5. March 7, 2017

A deep trough over the north-eastern Europe elongated in the southern direction over the Adriatic Sea, generated a long cold air stream over the Tyrrhenian Sea across Sardinia and almost until the Libyan coast (Figure 9).

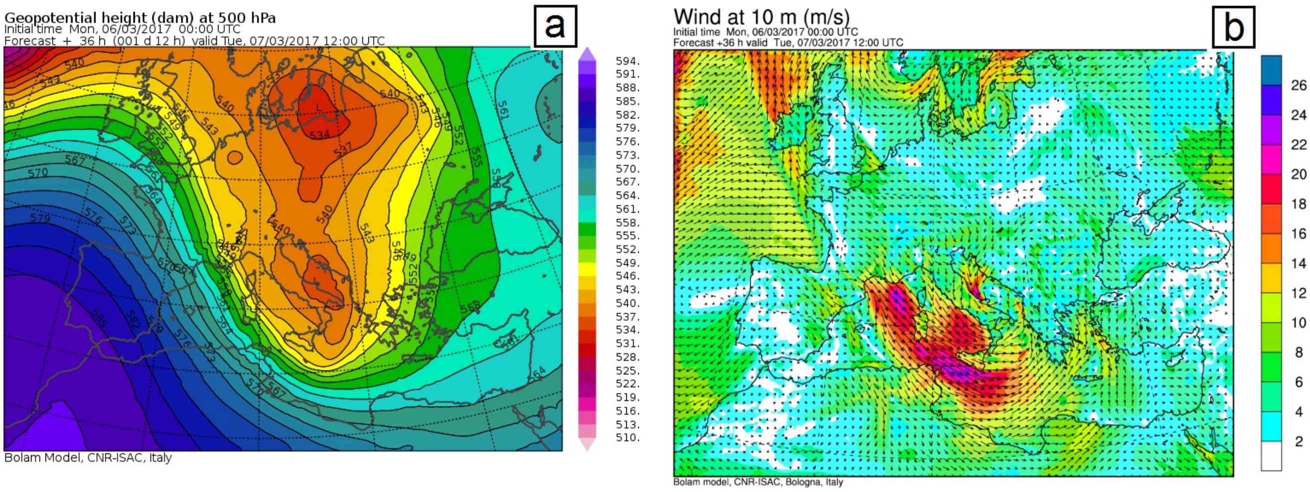

Figure 9. 07/03/2017 12:00 UTC: (a) Geopotential height (dam) at 500 hPa; (b) Wind (m/s) at 10 m (Bolam simulations).

Winds of almost 20 m/s occurred over Malta Island for about 20 hours from the north-western direction and with a minimum fetch of about 550 km northward until Sardinia Island. The calculated peak wave was about 7 m. This storm caused the collapse of Azure Window at West Gozo Island as reported by Galea et alii [40] (Tables 1,3). No wave height data are reported by these authors.

5.1.6. September 28, 2018 (Medicane Zorbas)

In September 2018 the storm originated in the Libyan Gulf. The trajectory of the forming medicane (named Zorbas) was first in the north-western direction approaching the south-western Italian coasts (Figure 10), then reversing its direction towards the Aegean Sea and the Greek coasts over which it terminated its life [64].

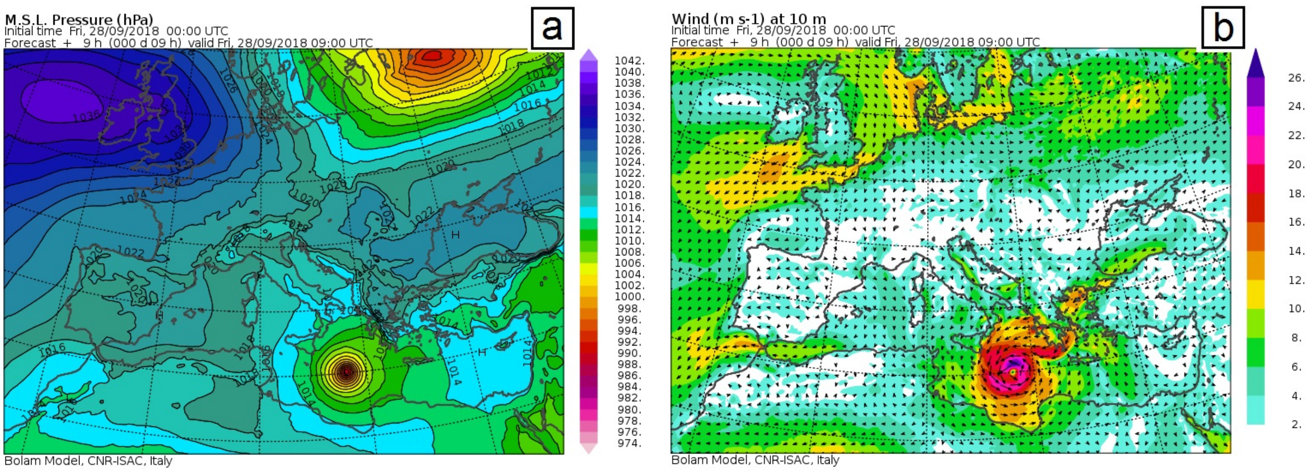

Figure 10. 28/09/2018 09:00 UTC: (a) Surface Pressure (hPa); (b) Wind (m/s) at 10 m (Bolam simulations).

In the Bolam-Moloch simulations average winds of about 15 m/s can be observed over the south-eastern coast of Sicily, again with a duration about half a day, between approaching and departing from the Sicily coast.

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For the passage of the medicane Zorbas off-shore the south-western Sicily coast, Scicchitano et alii [56] refer to a significant wave height of about 4.1 m (as reported by the site AVISO satellite altimetry data) and a storm surge up to 1 m (as measured by a local tide gauge station). As a consequence of the extreme coastal water level, the authors reported the occurring of the boulder clustering process and the activation of a 41.3 t block (see [56], Figure 10).

5.1.7. October 29, 2018 (Storm Vaia)

This is a quite well-known case of Mediterranean storm that has been studied by several authors because of strength, duration, amount precipitation and consequent damages caused mainly, but not only, in the North-East of the Italian peninsula (the Storm Vaia [57,65,66]). In this case the minimum of the 500 mb geopotential height is located at North-West with respect to the Italian peninsula, between France and Spain. The storm persisted over the Mediterranean region for a few days because of a blocking ridge over the East Europe, with intense wind channeling along the Adriatic Sea and a significant storm surge in the northern Adriatic (Figure 11).

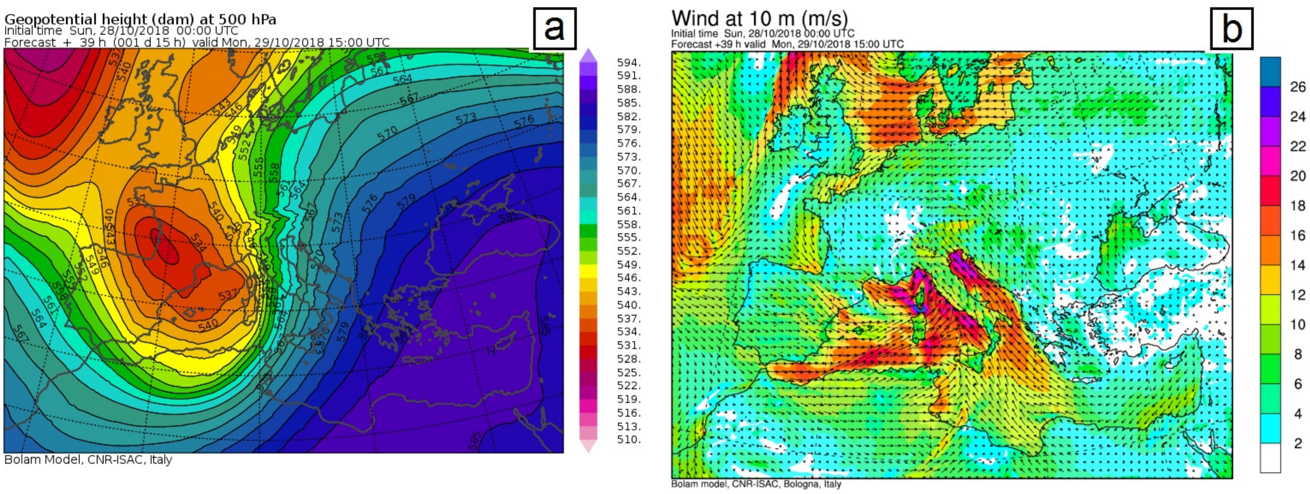

Figure 11. 29/10/2018 15:00 UTC: (a) Geopotential height (dam) at 500 hPa; (b) Wind (m/s) at 10 m (Bolam simulations).

Here, the persistence and the wind direction parallel to the coastline caused a very long fetch of at least 650 km with a wind speed of about 20 m/s that give a calculated peak wave over 7 m. The significant wave height measured in the Gulf of Venice (meteomarine tower Acqua Alta, North Adriatic) was about 6 m [67], while the maximum wave height recorded in Dubrovnik (western coast of the central Adriatic) was about 9 m [65]. The storm Vaia caused boulder activation on both the southern Istrian (Croatia) and the western Apulia (Italy) coasts (Table 3). At Kamenjak Cape even boulder clustering occurred (see [52], Figure 4). A maximum sea level height exceeding 1.5 m was measured on 29 October, 2018 by the tide gauge station Punta Salute placed in the Venice Lagoon, *"a value exceeded by only three other events in the historical series since 1872"* [52].

5.1.8. November 13, 2019 (Storm Detlef)

In November 2019 the main middle atmosphere gph minimum over the British Islands generates a new minimum that migrates to the South of Sicily acquiring new strength and vorticity around the Atlas promontory and causing southerly strong winds from the Libyan coast up to the middle Adriatic Sea (Figure 12). This storm was named Detlef [68].

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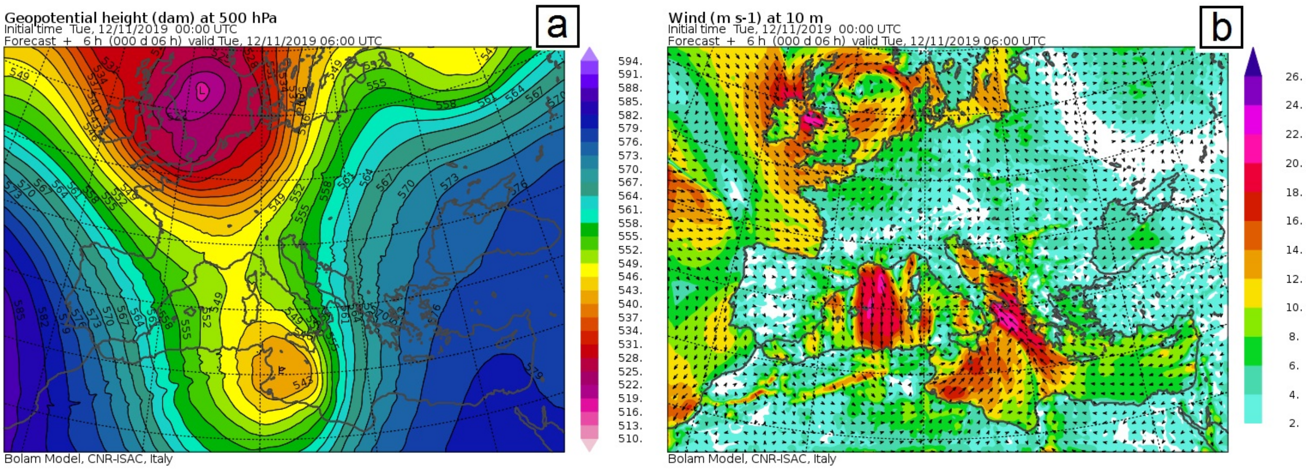

Figure 12. 12/11/2019 06:00 UTC: (a) Geopotential height (dam) at 500 hPa; (b) Wind (m/s) at 10 m (Bolam simulations).

Thus the wind fetch was quite long reaching 700-800 km with a wind speed of about 20 m/s and a duration of about 24 hours that implies a calculated peak wave height between 8 and 9 m over the Salento coast (Apulia, Italy) [57]. These exceptional wind wave conditions were confirmed by observations in the Italian Air Force S. Maria di Leuca meteomarine station [53,69]. Again, a record sea level height exceeding 1.8 m was recorded by the Acqua Alta meteomarine tower in the Venice Gulf but no wave height measurements were available there [70]. Several cases of boulder clustering have been described by [57].

5.2. Inferred General Features

From the above mentioned storm events it is possible to infer some general features about the studied sites as geographical spots for boulder displacements by storms. Indeed in limited areas or basins with an enhanced complex topography characterised by coastlines and important orographic relief, local storms tend to assume characteristics that depend not only by the synoptic meteorological conditions but also from the local topography that can give them some peculiar aspects. Some of the examined storms, and in particular those of January 2014, January and March 2015, and October 2018 show indeed a similar synoptic generation from a mid-atmospheric trough first located in the northern or north-western Europe, then generating a low pressure centre with similar wind patterns over the northern Mediterranean basin. This wind pattern has been already clearly identified and described (see Flaounas et alii [71], Figure 3).

The general feature of this wind pattern are: 1) an area of southward enhanced gustiness sided by a dry air intrusion (DI) generally placed on the Gulf of Lion and thus also forced by the local orography of the French Alps; 2) an area of northward warmer currents (warm conveyor belt, WCB) generally situated at the East of the surface low and often increased and forced northward by the channeling effect of the Adriatic Sea and the parallel orographic relief of the Apennines and the Dalmatian Mountains. These two areas are representative of the Balearic and Istrian sites, where the first was reached by a very strong gustiness from the North West in January and March 2015 and the second by the effect of the channeled WCB in the reported cases of boulder displacements of 2014 and 2018. In the first case the strong descending gustiness with winds well over 20 m/s was responsible for the wave storm, while in the second the effect of the storm over the local sea state was enhanced by the quite long Adriatic fetch, that caused high waves over the exposed Istrian peninsula.

In March 2017 the position of the trough now originating from the eastern Europe caused a prolonged DI from the Lion Gulf to an elongated strong southward current with a direct impact on the coasts of Malta, again after a very long fetch with consequent generation of high waves. On the other hand, in November 2019 (Storm Detlef), the southward displacement of baric minimum, now located at South-East of Sicily, caused a

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WCB displacement southward, down to the Lybian coast, impinging, again after a quite long fetch, the Apulia coasts. In this last case, the southward displacement of the WCB, the enhanced storm intensity around the Atlas promontory, and the long fetch in the open Ionian Sea down to the Libyan coasts, were responsible for the activation of many boulders, but only limited to the Apulia (south-eastern Italy) [57].

In addition to the sea waves, the storm surge increased the coastal water level. Indeed during the Storm Vaia the sea level registered in the Gulf of Venice, was limited to about 1.5 m only because of the negative tidal contribution [67], while the record level of more than 1.8 m was observed in 2019, because of an added positive tidal contribution [70]. Also, storm surges of the order of 1 m were estimated during the October 2018 and November 2019 near the Apulia coasts [57].

The cases of the storms Qendresa (November 2014) and Zorbas (September 2018) have a different origin, due to Mediterranean tropical-like cyclones whose peripheral winds affected the coasts of Sicily. In these cases the location of the affected coast just depends on the area of generation and the trajectory of the Medicane. Although places that favour the orographic enhancement of the cyclonic vorticity can be just identified as the Atlas and the Libyan promontories, medicanes can also develop in the north-western Mediterranean and affect the Tyrrhenian Sea. Even if the genesis of the medicanes also requires the presence of a mid-atmospheric trough over the Mediterranean, they then develop and are mainly sustained by sea surface heat and vapour fluxes [61], that make their trajectory, evolution and local effects more variable and difficult to be modelled and predicted. In this regard, the boulder activation footprints could help to trace back historical of the local intensity of these peculiar storms. An evaluation of the storm surge in these two cases, by the mentioned storm pressure deficit method [57], results in about 1 m for both the considered medicanes, thus not dissimilar from those evaluated in the other Mediterranean synoptic storms and in good agreement with that measured for Medicane Zorbas [56].

In this context it should be stressed as the effect of the storm surge is not be neglected for all the considered Mediterranean storms, and thus should be taken into account in the estimation of their coastal effects together with the wave height, and eventually possible tide effects. In [57] the surge and the tide heights were added to the average coastal sea level to obtain an effective sea level to calculate the effective wave height with respect to the coastline and the consequent boulder displacements by the flooding. It is to be noted that the storm surge and high peak waves are related to the same meteorological event, thus more likely to happen together than as statistically independent events, and generally causing increased extreme coastal water levels with a reinforcement effect as shown in [72] by a global statistical analysis of extreme coastal water levels. In the case of Mediterranean storms, in a closed limited basin in which swells are much more uncommon than wind-sea waves with respect to the open oceans, the presence of a storm surge together with high peak waves is indeed expected to be an even more probable event than in open oceans. However, the coastal storm surge depends also on the local coastal characteristics as bathymetry and coastline length and orientation, and can be different from site to site even during the same storm event. These considerations show that the assessment of a site for identifying storms from the boulder activations depend on the characteristics of the storm, but also on the geomorphology of the coast and the topography of the whole region under study. In the case of the Mediterranean region, it appears from these considerations that the Istrian peninsula and also the Balearic islands can represent hot spots for typical storms with baric centers in the northern Mediterranean Sea, while Apulia, Malta and Sicily coasts for meteorologic troughs displaced southward.

6. Discussion

Because a review has to provide *"syntheses of the state of knowledge"* and addressed *"questions that otherwise could not be answered by individual studies"* [36], it can be first noted that, if on the one hand the number of cases studied of CBDs dynamics has objectively grown in last few years (Figure 4 and Table 3), on the other hand it is necessary to understand whether this corresponds to an actual increase in the number of boulders moved by wind waves (and thus likely in the storm activity) or if this is the result of greater interest and attention of the research groups on the issue. As explained below, it is not easy to solve this problem.

Although the Mediterranean has long ago been identified as a region in the globe of frequent cyclogenesis [73], it has been mainly affected by moderate storm events throughout the second half of the 20th century. From the middle of the 70s, a moderate increasing trend in gustiness was observed [74,75]. However, as shown by bi-decadal records of several stations spread all over the Mediterranean, stormy days dwindled at the turn of 2000 [76]. Unluckily, the temporal data coverage of the measurements taken by the buoys placed within the Mediterranean is too short to statistically infer on change in storminess that could have occurred throughout the last few decades [29]. Nevertheless, using a long-term wave hindcast developed by a calibrate SWAN (Simulating WAves Nearshore) model and forcing this model with CFS (Climate Forecast System) reanalysis, some western Mediterranean coasts that have experienced increase in storm wave energy may be identified with high confidence level [77]. Again, deducing a 40-year long wave time series from the global ERA Interim reanalysis dataset [60] and performing a trend analysis through non parametric test, Caloiero et alii [78] found a positive trend for the mean value of the annual significant wave height at regional scale. A clear positive trend for the maximum value resulted only in the Algerian, Adriatic and Levantine seas, while no significant trend resulted for the Ionian Sea and the southern central Mediterranean which are the areas where the greatest number of cases of boulder activations have occurred (Tables 1 and 3).

Since the beginning of the 21th century, a particular interest on medicanes has emerged due both to the socio-economic impact of these cyclones and the implications of climate change for their intensity and location [61,71]. The current and projected coastal hazards related to such meteorological events are estimated as middle or high for many coastal stretches [79]. Where coastal flooding caused by medicanes and ordinary cyclones have been compared, the former resulted more extended [80]. Medicanes are also able to cause boulder dynamics not less than ordinary cyclones, and this is of interest for researchers [56]. Moreover, an issue that has drawn the interest of the academic world to carry out observational studies on boulders produced/activated is the identification of similarities and differences between storm and tsunami (see e.g. [6,22,81]). This may have contributed to the increase in cases studied regardless of the actual changes in frequency and intensity of coastal storms. Therefore, given the current state of knowledge, it does not seem possible to establish with certainty if the increase in boulder dynamics above discussed is real or apparent.

In this review the results of the analysis of the causative events (Section 5) for all the considered cases firstly suggest that boulder activation could be significant for intense storms capable of generating wind waves above 4-5 meters height over low rocky coasts. Also, together with the sea waves, the effect of the storm surge associated to the the causative storms in increasing extreme coastal water levels has been generally observed to be of the order of 1 m, from both estimation and local measurements. These results for the Mediterranean basin confirm those already inferred for synoptic scale storms limited to the Apulia coast, in a reviewed work (see [57], Figure 12).

As future projection, a quite reasonable agreement among different studies and climatic simulations is gaining confidence about a general increase of the storm intensity over the Mediterranean basin, but with a possible decrease in their frequency [19,71,82,83]. As the boulder activations are enhanced by storm intensity, while a single recorded track can be less identifiable after several storm events, these are expected to be more clearly and easily detected in conditions of increased storm intensity and decreasing frequency. Thus, boulder activation studies could be able to provide even better and clearer historical track of intense storm over the Mediterranean coasts in the next future. The usefulness of selected sites for geomorphological monitoring aimed to investigate the physical imprints of the storms throughout the time is thus apparent.

Currently, shorelines dynamics of sandy beaches is the main geomorphological proxy used to measure coastal storminess at decennial scale (see e.g. [84–86]). As stressed by some authors [21,87] such a paradigm is however affected by significant problems due to the concurrent processes of dune recovery and beach-dune sediment transfer. Therefore, despite of the rocky coasts have a lower suitability to undergo changes as a result of storms compared to sandy beaches, the lack of other significant sedimentological processes for the boulder dynamics can favor the former in selecting the sites to study the storminess records. If the geomorphological survey and monitoring are the basic methods for analyzing the physical effects of coming storms [52,53,56], no less important are the methods that allow to achieve data on past storms. As a matter of fact, studying CBDs "*can help gauge the intensity/frequency of extreme storm events*" also "*beyond the instrumental and historical record and provide insights on the severity of storms under warmer climates*" ([23]). Two prominent methods have recently been used to date the boulder dynamics in medium-low latitudes. Oliveira et alii [88] applied lichenometry techniques to date boulder movement on the western coast of Portugal while Brill et alii [89] used optically stimulated luminescence on CBDs placed on the Moroccan Atlantic coast, both with encouraging results.

The interaction of the different scientific disciplines involved in the study of CBDs as natural archives for intense storms is the final point here discussed. Assuming that the identification of suitable CBDs is a geomorphological expertise, the contribution of atmosphere physicists, physical oceanographers, hydrodynamics researchers, and others natural science scholars is crucial to establish the processes that determined their formation (see e.g. [8,17,21,88,89]). While the intrinsically interdisciplinary nature of such a field of research is strongly emerging, it is necessary to ensure that disciplinary differences do not hinder interdisciplinary research efforts (Sections 1, 2). Due to the preeminent role of geomorphology, the approach to foster advances in such emerging climate research topic should inevitably be top-down. However, the bottom-up-driven approach possesses various characteristics that could favor a more fruitful dialogue between the researchers [90].

To get close collaboration among scholars coming from the different core fields, the links between fieldwork and modeling should be reconsidered. This is a crucial point that has been highlighted for several decades as regards the interdisciplinary earth science in the study of storm effects (see e.g. [91]). As a matter of fact, new approaches have been recently explored. For example, exactly to model the interactions between storm waves and boulders, Cox et alii [22] employed force-balanced, dynamically scaled wave-tank experiments using a real stretch of coast as model prototype. Further insights can also be found outside the CBDs topic. It can be mentioned, for example, the study of Li et alii [92]. To evaluate the impact of Typhoon Hato (2017) on the eastern coast of China, such authors compared a surveyed inundation map with a combination of numerical models, thus simulating and reproducing the storm surge. Finally, it is worth encouraging the promotion of interdisciplinary education of young scientists on fieldwork and modeling relationship in climate research (see e.g. [93]).

7. Conclusions

The potential of the CBDs as natural archives for intense storms in the Mediterranean region (Sections 1,2), has been explored referring to literature studies [21,22]. To be suitable to the users, the search field was limited to the indexed articles subjected to peer review, according to PRISMA statement [35,36] and using WoS engine search [37–39] as primary platform (Section 3). 19 of the 153 identified articles were then examined, together with one article found by means of bibliography check (Figure 2, Table 1). The number of cases studied of CBDs dynamics has evidently grown in last few years (Figure 4). As a whole, the screening process has allowed the identification of 44 sites with evidences of boulder dynamics as a results of storms occurring during the last half century (Section 4). Many articles concern cases belonging to the central Mediterranean (Figure 3). As expected, a strong predominance of scholars in geomorphology was found among the authors of the

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reviewed articles, applied physicists, atmosphere physicists, coastal engineers, cultural heritage scholars, marine biologists, and physical oceanographers constituting less than 20% (Table 2).

The combined action of the wind waves with concurrent storm surge has been fundamental to determine the extreme coastal water levels and thus the geomorphological imprints on CBDs for the cases extracted from the scientific literature (Sections 4,5). The examined coastal storms usually tend to assume characteristics that depend not only by the synoptic meteorological conditions but also from the local topography. Instead, when the storms were originated by Mediterranean tropical-like cyclones, the location of the affected coast just depends on the area of generation and the trajectory of the Medicane. For selecting sites for geomorphological storm proxies, local and regional features are crucial. This study shows that the Istrian peninsula and the Balearic islands can represent hot spots for typical storms with baric centers in the northern Mediterranean Sea, while Apulia, Malta and Sicily coasts for meteorologic troughs displaced southwards (Section 5). Given the current state of knowledge, it was not possible to establish if the increase in Mediterranean CBDs studies was due either to an actual increase in coastal storminess or the result of greater interest and attention of the research groups on the issue (Section 6). Eventually, it is argued that a close and fruitful collaboration involving several scientific disciplines can help the development of the research on geomorphological storm proxies.

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Appendix A

In Table A1, the 15 articles excluded at the assessing for eligibility are listed (see Section 4). The causes of the exclusions are reported.

Table A1. Articles excluded from the review at the stage 2 (Figure 2).

Author (s) and Year	Main Objective	Exclusion Cause
Dominey-Howes et alii (2000) [94]	process identification	CBDs produced by tsunami
Mastronuzzi et alii (2004) [95]	vulnerability study	No CBD dynamics data are reported
Andriani and Walsh (2007) [96]	process identification	No CBD dynamics data are reported
Scicchitano et alii (2010) [97]	process identification	No CBD dynamics data are reported
Furlani et alii (2011) [98]	process identification	No CBD dynamics data are reported
Paris et alii (2011) [2]	review preface	No CBD dynamics data are reported
Mastronuzzi and Pignatelli (2012) [99]	process identification	CBDs produced by tsunami
Katz and Mushkin (2013) [100]	process identification	No CBD dynamics data are reported
Mottershead et alii (2015) [101]	process identification	CBDs produced by tsunami
Shah-Hosseini et alii (2016) [102]	hazards study	No CBD dynamics data are reported
Amores et alii (2020) [103]	storm simulation	No CBD dynamics data are reported
Ruban (2020) [3]	virtual perspective	No CBD dynamics data are reported
Ferrando et alii (2021) [104]	process identification	No CBD dynamics data are reported
Fortelli et alii (2021) [105]	process identification	No CBD dynamics data are reported
Lollino et alii (2021) [106]	process identification	No CBD dynamics data are reported

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