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*Review*

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

**Marco Delle Rose *** **and Paolo Martano**

National Research Council of Italy, Institute of Atmospheric Sciences and Climate, 73100 Lecce, Italy; p.martano@isac.cnr.it
* Correspondence: m.dellerose@le.isac.cnr.it

**Abstract:** In this review, the potential of an emerging field of interdisciplinary climate research, 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 the 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 for the literature-reported cases were analysed in some detail 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 for assessing 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

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## 1. Introduction

Coastal boulder deposits (CBDs) are often signatures of high-energy waves in coastal environments. They are widespread along marine coasts and have distinctive geomorphological imprints because their transport and emplacement are restricted to the duration of tsunamis and storms [1,2]. Clustering of boulders lying on the coast can also be produced by other natural processes such as gravitational landslides or weather waterspouts. However, CBDs produced by high-energy waves have some peculiar characteristics (see Section 2). Thus a 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 in the subject in various scientific and engineering disciplines [6–9].

Since the 1960s, it has become increasingly recognized that storms are capable of significant boulder dynamics, 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 interest in the Mediterranean, the attention to dynamics of CBDs to improve the knowledge of coastal hazards is currently growing, especially because of possible changes in the storm climatology, with an increase in the energy released 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; more conceptual details are given in Section 2) has been recently stressed for macrotidal high-energy rocky coasts [21,22]. Although the reconstruction of mid-term and long-term storminess records (i.e., multi-decadal or secular-millennial) is hampered by complexities in dating and identifying individual events inside the boulder clusters [23], CBD studies are becoming an emerging field in interdisciplinary climate research. As a matter of fact, several scholarly disciplines have recently tried to bring their own epistemology, theories, methods, and practices from 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 physicists, physical oceanographers, and hydrodynamics researchers were the first players in this process, but other expertise (such as optical luminescence and lichenometry dating) is required to establish a solid foundation for this issue.

The main goal of this paper is to explore the potential of CBDs as natural historical archives for Mediterranean storms and climatology. First, a scientific article identification was performed with the 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 for the known cases of CBD production and/or activation were examined using the synoptic web maps of the Globo-Bolam-Moloch model cascade [24]. Finally, the suitability of selected sites as geomorphological storm proxies is considered in perspective to advance the interdisciplinary climate research.

## 2. Basic Concepts

According to the sedimentological nomenclature, boulders are fragments of rock (i.e., clasts) with an intermediate axis from 0.256 to 4.096 m long (larger clasts are named blocks and megaclasts), and their weight is usually from tens of kilograms to several tonnes [25]. They are the size classes 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 the case of belonging to the block class, this will be specified.

Coastal boulders/blocks are originally produced by detachment from bedrock. The area of clast detachment is termed a socket [27]. Any further movement of previously uprooted clasts due to the action of high-energy waves is referred to as activation [21]. Boulder dynamics is herein used for both 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 a 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.

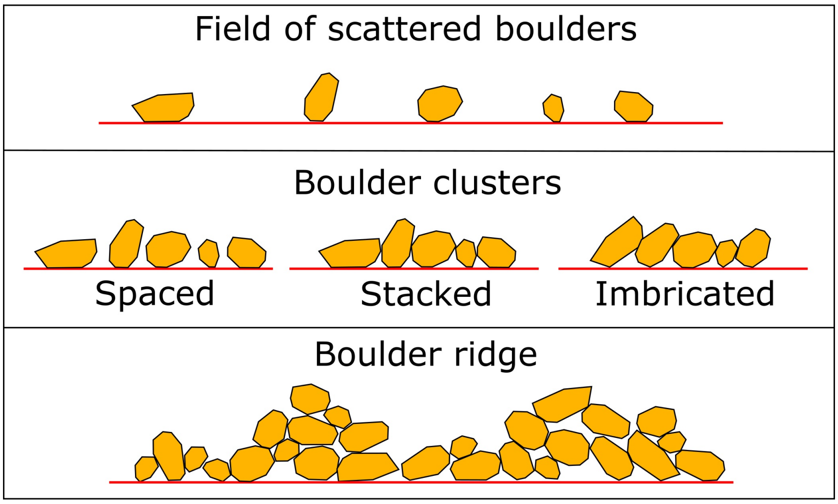


**Figure 1.** Schematic cross-sections (normal to the coastline) of the CBD assemblage types placed on the shore platform (red line) and produced/activated by high-energy waves.

A large number of CBDs described in the 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 waves usually have sedimentological evidence of landward transport; thus their origin mechanisms are readily identified. However, ascribing one of the two specific wave processes (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 activation of boulders during recent storms, while the occurrence of tsunamis can be excluded.

The insight to use CBDs as geomorphological storm proxies is quite recent and is due to Autret et al. [21]. The more general concept of "proxy data" was developed in the second half of the 20th century (see Gornitz [28] for an overview). According to the 2007 IPCC report, a climate proxy is a local quantitative record that is interpreted as a climate variable using a transfer function that is based on physical principles [29]. Proxies can be grouped into three major categories: (a) sedimentary-geological, (b) paleontological, and (c) geochemical. Chalk, dunes, lacustrine sediments, and cave concretions are some examples of "materials" belonging to the first category, which can also include the coastal boulders for the storminess as the climate variable [21]. Eventually, it must be mentioned that relevant examples of geomorphological and climatological studies are carried out on other landforms such as landslides (see, e.g., [30]) and moraines (see, e.g., [31]).

Before addressing Section 3, some basic features of the concepts of coastal storms 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 [32]. Thresholds are site-specific and depend mainly on synoptic systems, bathymetry, topography, exposure to wind waves, and the direction and energy of the coastal storm [33]. 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 the frequency and energy (severity) of the impacting storms. However, each discipline uses a specific epistemological approach to measure the storminess. In atmospheric sciences, it is calculated by means of climatological and statistical approaches [34]. In oceanology and coastal engineering, storminess is defined using a dataset of wave climate acquired from buoys measurements [35,36]. Finally, in geomorphology, storminess is evaluated from physical footprints (defined through fieldwork) that a series of storms have left in deposits and landforms [37,38]. 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 performed [39,40]. As stated above (Section 1), the primary objective pursued herein is the evaluation of the CBDs 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 is to be expected from future 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 find and examine the studies relevant to 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 [39,40] and using the Web of Science (WoS) engine search [41–43] as the 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 the production/activation of boulders.

The description of the meteorological events responsible for 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 contain data from 1 January 2012. It has been used to analyse 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 wind speed 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 was extracted from the 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). They 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, in estimating the sea surface characteristics from the meteorological charts of the Bolam model. Details of these parametric expressions can be found in Ref. [44], and more details about the use of these expressions in the present context are given in Ref. [45].

## 4. Review Results

The WoS engine search found 153 records. No duplicates have been found. The abstract screening has determined the exclusion of 119 articles as apparently irrelevant for 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, or other modelling) or because of dealing with cases outside of the Mediterranean region (Figure 2).

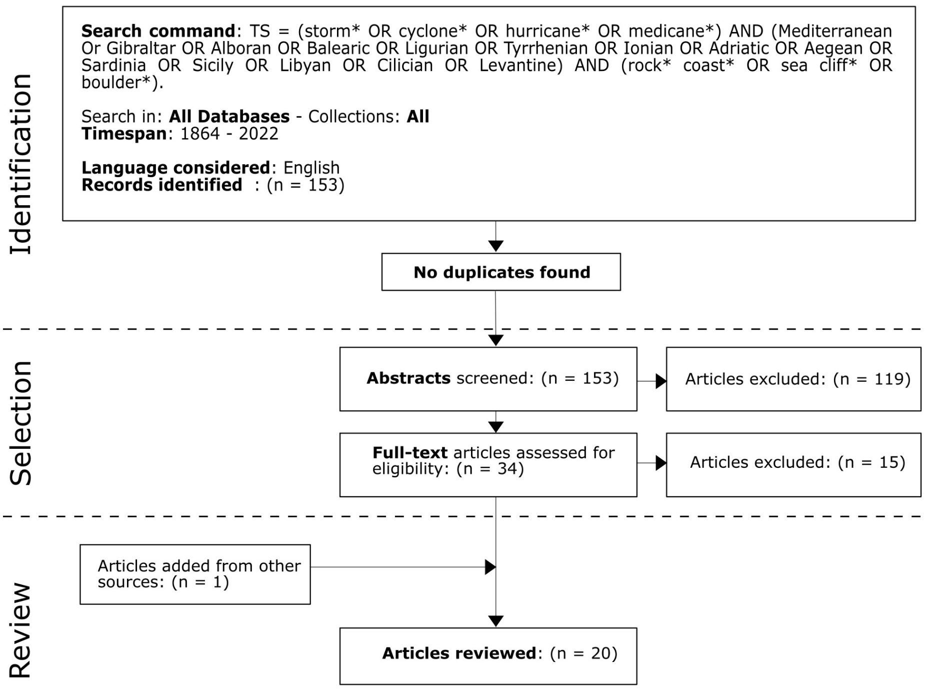


**Figure 2.** Flow diagram explaining the three stages of the screening process (see [39,40]).

A total of 15 articles were then excluded by the full-text assessment (Appendix A). These exclusions were caused by the lack of description of the storm-induced dynamics on CBD, or because the article deals with CBDs produced by tsunami event(s) according to the authors (Table A1). One article (Galea et al. [46]) identified by the examination of the bibliography of the full-text-assessed articles has 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 al. (2010) [47] | West Ionian | identified |
| Barbano et al. (2011) [48] | West Ionian | roughly identified |
| Hoffmeister et al. (2013) [49] | East Ionian | roughly identified |
| Shah-Hosseini et al. (2013) [50] | Gulf of Lion | not identified |
| Torab and Dalal (2015) [51] | Eastern Mediterranean | not identified |
| Biolchi et al. (2016) [52] | South Central Mediterranean | not identified |
| Causon Deguara and Gauci (2017) [53] | South Central Mediterranean | not identified |
| Piscitelli et al. (2017) [54] | Gulf of Lion | not identified |
| Roig-Munar et al. (2017) [55] | Balearic Sea | identified |
| Galea et al. (2018) [46] | South Central Mediterranean | identified |
| Pepe et al. (2018) [56] | South Tyrrhenian | not identified |
| Roig-Munar et al. (2018) [57] | Balearic Sea | not identified |
| Biolchi et al. (2019a) [17] | North Adriatic | identified |
| Biolchi et al. (2019b) [58] | North Adriatic | identified |
| Delle Rose et al. (2020) [59] | North Ionian | identified |
| Hoffmeister et al. (2020) [60] | East Ionian | not identified |
| Mottershead et al. (2020) [61] | South Central Mediterranean | not identified |
| Scicchitano et al. (2020) [62] | West Ionian | identified |
| Delle Rose et al. (2021) [45] | North Ionian | identified |

Only one repetition was found among the reviewed articles: both Shah-Hosseini et al. [50] and Piscitelli et al. [54] treat the same notable case of polyphasic boulder activation that happened at Martigues coast (Gulf of Lion) before December 2003. Some articles address two or more stretches of Mediterranean coasts [45,48,51,52,56,57,60], thus the screening process has allowed the identification of 44 sites showing evidence or clues of CBD production/activation as a result of recent (i.e., during about the last half-century) storms. Many articles concern cases belonging to the central Mediterranean [16,17,45–49,52,53,56,58–62], (see Figure 3). Some studies are relative to the western Mediterranean [50,54,55,57], while only one study to the eastern Mediterranean [51].

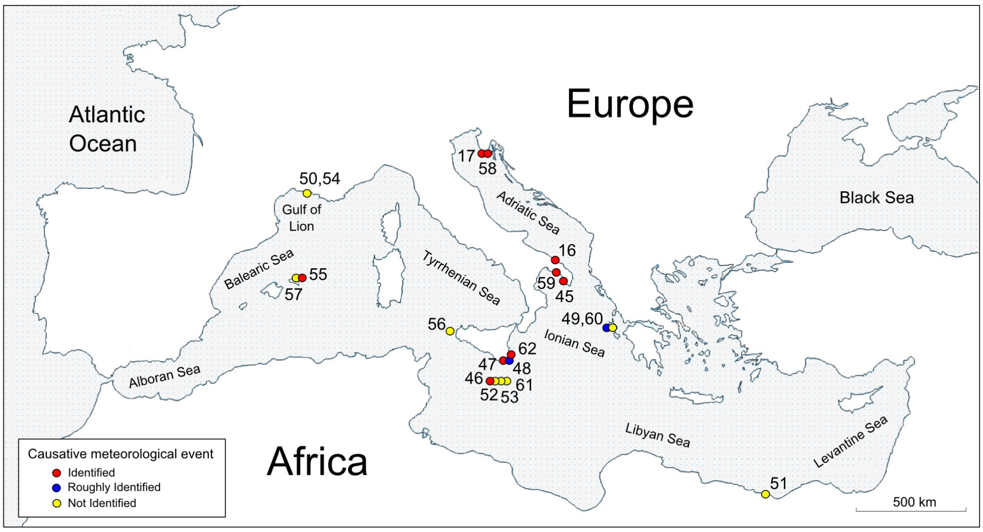


**Figure 3.** Locations of the reviewed case studies (see References numbering).

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., [17,54]). It must also be noticed that three days before the Storm Vaia (responsible for some boulder dynamics cases, see [45,58]), an earthquake occurred in the western Mediterranean. However, it caused only very small tsunami waves, as registered at some tide gauge stations [63].

Regarding the interdisciplinary contributions of 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, atmospheric physics, coastal engineering, cultural heritage, marine biology, and physical oceanography) constitute 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 six articles published. Since 2017, 14 articles have been published (Figure 4).

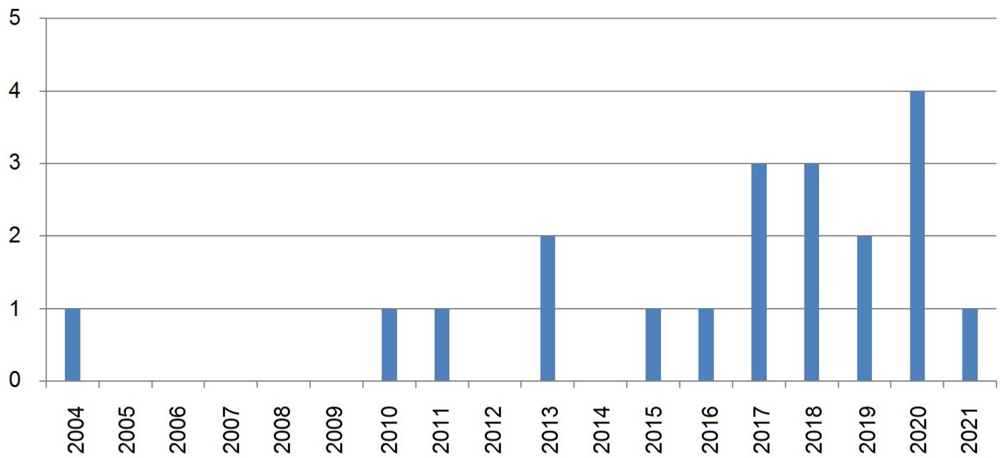


**Figure 4.** Number of cases studied per year.

The number of boulders produced and activated shows an apparent increase over time (Table 3). The use of new methods and technologies to complement the usual geomorphological fieldwork (aerial photo interpretation; camera recording analysis; drone digital photogrammetry; multi-temporal satellite imagery analysis; terrestrial laser scanning; transect photo sets) have played an important role in 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 |
|---|---|---|---|---|
| 4 January 2002 | Santa Sabina, Apulia (Italy) | 1 | [16] | A |
| 12 January 2003 | Santa Sabina, Apulia (Italy) | 1 | [16] | A |
| winter 2008/2009 | San Lorenzo, Sicily (Italy) | U | [48] | A |
| winter 2008/2009 | West Cefalonia (Greece) | 1 | [49,60] | A,B |
| 13 January 2009 | Maddalena, Sicily (Italy) | 5 | [62] | A |
| 14 January 2009 | Vendicari, Sicily (Italy) | 5 | [47] | A |
| 31 January 2014 | Kamenjak Cape, Istria (Croatia) | 1 | [17] | A,C |
| Medicane Qendresa | Maddalena, Sicily (Italy) | U | [62] | A,B,D |
| 25 January 2015 | North Minorca (Spain) | 9 | [55] | A |
| 5 March 2015 | North Minorca (Spain) | 14 | [55] | A |
| 7 March 2017 | West Gozo (Malta) | U | [46] | A |
| Medicane Zorbas | Maddalena, Sicily (Italy) | 28 | [62] | A,E |
| Storm Vaia | Kamenjak Cape, Istria (Croatia) | 14 | [58] | A,D |
| Storm Vaia | Torre Suda, Apulia (Italy) | 1 | [45] | A |
| Storm Detlef | 2 sites, Apulia (Italy) | 17 | [45,59] | A,F |
| Storms Vaia and Detlef | 8 sites, Apulia (Italy) | 64 | [45] | 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 imbricated boulder clusters also occurred [16,45,62]. They were almost always related to boulder activation and rarely to boulder production. Special mention must be given to the cases of polyphasic activation; that is, the boulders affected by the dynamics during at least two meteorological events. The most relevant are: a block twice displaced and fragmented at Martigues coast (Gulf of Lion, France) prior to December 2003 [50,54]; a seven-tonne-boulder placed on the Kamenjak Cape (Istria, Croatia) and activated by the 31 January 2014 and the 28 October 2018 storms [17,58]; a block moved three times between 2009 and 2018 along the coast of Maddalena peninsula (Sicily, Italy) [62]. The case studied by [46] produced subtidal CBDs due to the collapse of a rock arch in a cliff. They have not yet been analysed.

## 5. Analysis of the Causative Events

### *5.1. Meteorological Events Description*

The method to describe the causative events is explained in Section 3. The estimates of the peak wave heights mentioned in that section seem to give slightly higher results with respect to the significant wave height when available from measurement/modelling. Nevertheless, they are still in agreement with local observations of extreme waves that can be significant for the boulder displacements, as can be deduced from the following descriptions.

#### 5.1.1. 31 January 2014

A trough elongated from the British Islands over 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 h over the Adriatic Sea (Figure 5).

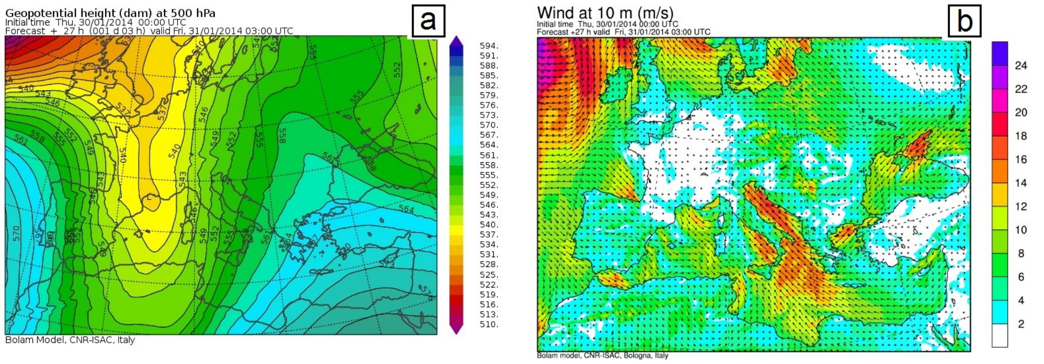


**Figure 5.** 31 January 2014 03:00 UTC: (**a**) Geopotential height (dam) at 500 hPa; (**b**) Wind (m/s) at 10 m (Bolam simulations).

The channelling along the Adriatic sea, with a fetch of about 650 km caused the 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 [64], a significant wave height greater than 6 m was estimated by Biolchi et al. [17]. These authors also reported the activation of a boulder with a weight of about 7.65 t.

5.1.2. 7 November 2014 (Medicane Qendresa)

The 7 November 2014 and 29 September 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, [65]). In November 2014, a storm originating around the Atlas promontory underwent a subsequent intensification as a medicane (later named Qendresa, [62]) in its south-eastward trajectory contouring the south-western coast of Sicily (Figure 6).

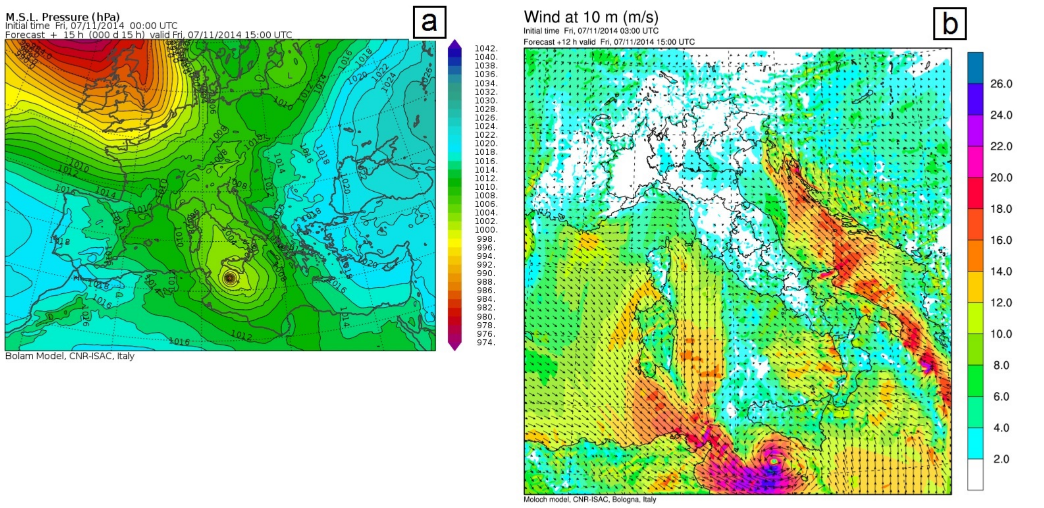


**Figure 6.** 7 November 2014 15:00 UTC: (**a**) Surface Pressure (hPa) (Bolam simulation); (**b**) Wind (m/s) at 10 m over the north-central Mediterranean (Moloch simulation).

Although medicanes are able to give rise to strong winds (well over 20 m/s with gusts above 40 m/s [66]) 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 the south-western Sicily coast, but with a duration of only about half a day 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, which causes more uncertainty in model estimations over localized sites.

Impacting on the south-eastern coast of Sicily, medicane Qendresa caused the activation and clustering of several boulders and a block of about 41.3 t, while the closest wave buoys recorded values of significant wave height of about 4 m [62].

#### 5.1.3. 25 January 2015

A deep trough centred in 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).

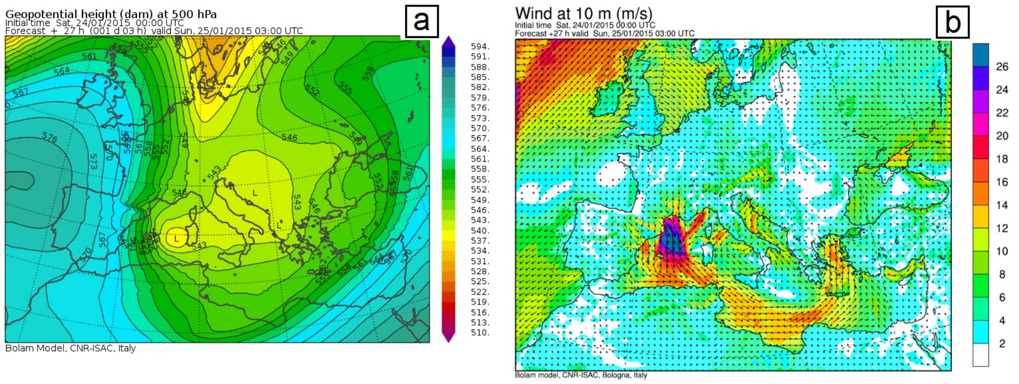


**Figure 7.** 25 January 2015 03:00 UTC: (**a**) Geopotential height (dam) at 500 hPa; (**b**) Wind (m/s) at 10 m (Bolam simulations).

The gustiness was very enhanced with peak winds over 25 m/s, oriented in the south-western direction and impinging for some time on 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 of over 7 m near Minorca Island. For the northern Minorca coast (Table 3), Roig-Munar et al. [55] reported a maximum wave height greater than 8 m as calculated using wave buoy data and the WAM model [67].

#### 5.1.4. 5 March 2015

On the 4–5 of March 2015, the position of the trough of gph at 500 mb was over north-eastern Europe, which caused the generation of a low-pressure centre over the Tyrrhenian Sea. The position of this couple of low-pressure centres 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 of over 20 m/s for over 20 h (Figure 8).

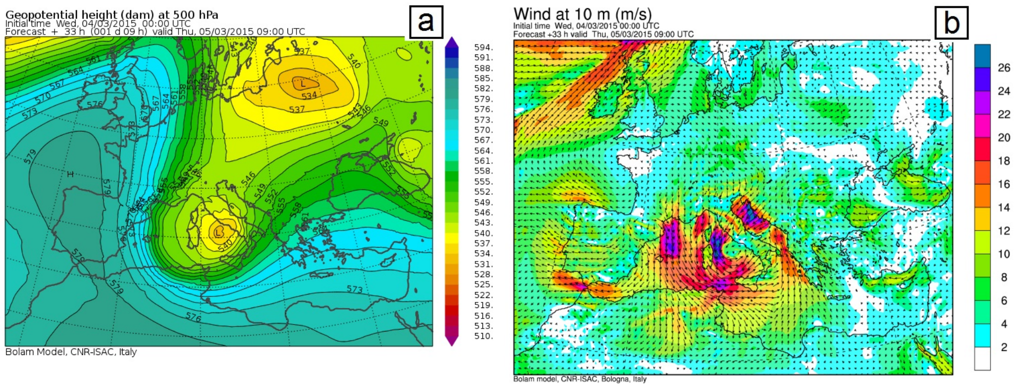


**Figure 8.** 5 March 2015 09:00 UTC: (**a**) Geopotential height (dam) at 500 hPa; (**b**) Wind (m/s) at 10 m (Bolam simulations).

The calculated peak wave height was again over 7 m, while a maximum wave height of about 8 m was reported by [55].

5.1.5. 7 March 2017

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

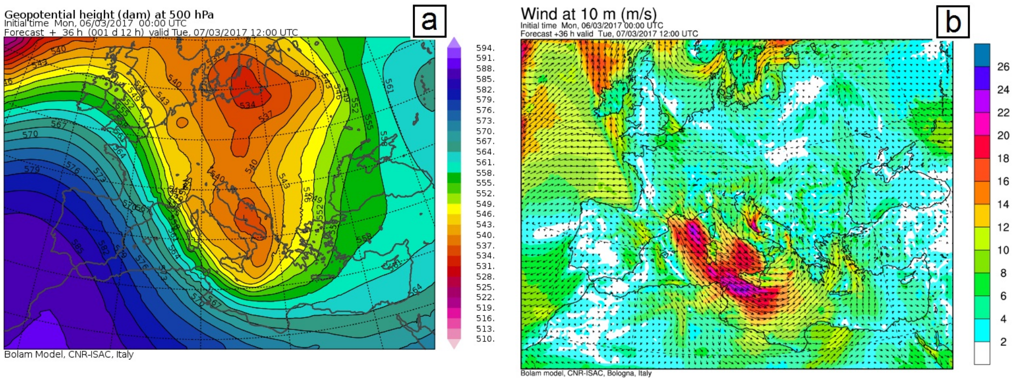


**Figure 9.** 7 March 2017 12:00 UTC: (**a**) Geopotential height (dam) at 500 hPa; (**b**) Wind (m/s) at 10 m (Bolam simulations).

Winds of almost 20 m/s occurred over Malta Island for about 20 h from the north-western direction and with a minimum fetch of about 550 km northward toward Sardinia Island. The calculated peak wave height was about 7 m. This storm caused the collapse of the Azure Window at West Gozo Island, as reported by Galea et al. [46] (Tables 1 and 3). No wave height data are reported by these authors.

5.1.6. 28 September 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 it reversed its direction toward the Aegean Sea and the Greek coast over which it terminated its life [68].

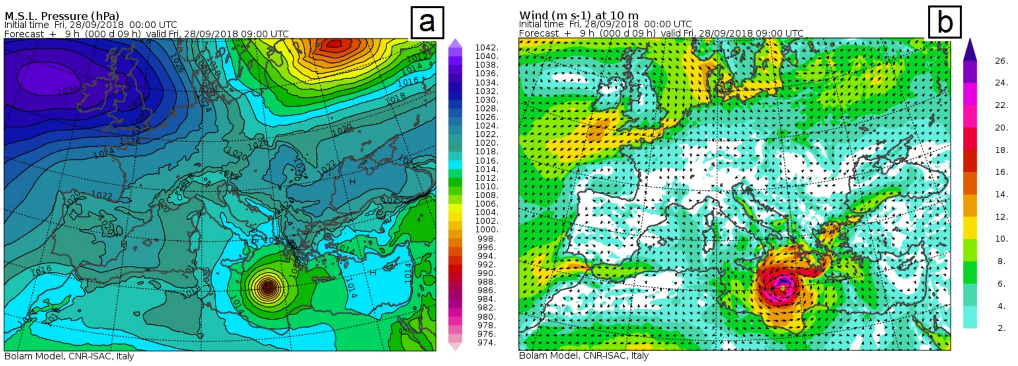


**Figure 10.** 28 September 2018 09:00 UTC: (**a**) Surface Pressure (hPa); (**b**) Wind (m/s) at 10 m (Bolam simulations).

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 of about half a day between approaching and departing from the Sicily coast.

For the passage of medicane Zorbas offshore of the south-western Sicily coast, Scicchitano et al. [62] 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 occurrence of the boulder clustering process and the activation of a 41.3 t block (see [62], Figure 10 ).

5.1.7. 29 October 2018 (Storm Vaia)

This is a quite well-known Mediterranean storm that has been studied by several authors because of the strength, duration, amount of precipitation, and consequent damage caused, mainly, but not only, in the north-east of the Italian peninsula (the Storm Vaia [45,69,70]). In this case, the minimum of the 500 mb geopotential height is located in the northwest 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 East Europe, with intense wind channelling along the Adriatic Sea and a significant storm surge in the northern Adriatic (Figure 11).

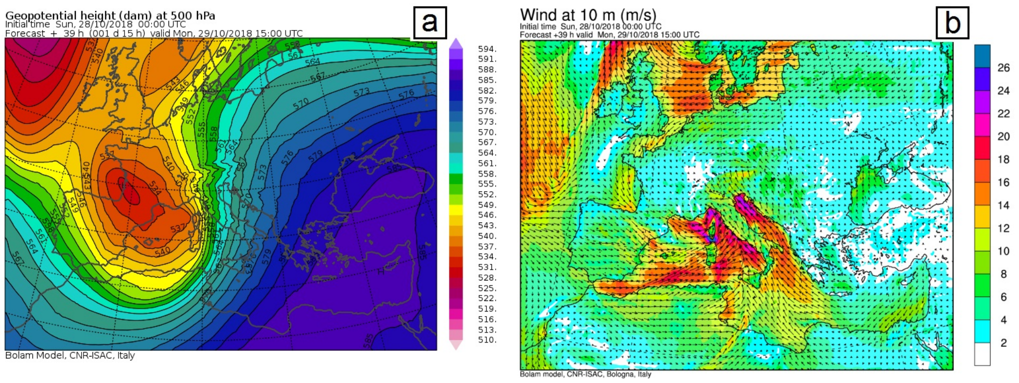


**Figure 11.** 29 October 2018 15:00 UTC: (**a**) Geopotential height (dam) at 500 hPa; (**b**) Wind (m/s) at 10 m (Bolam simulations).

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, which gives a calculated peak wave of over 7 m. The significant wave height measured in the Gulf of Venice (meteomarine tower Acqua Alta, North Adriatic) was about 6 m [71], while the maximum wave height recorded in Dubrovnik (western coast of the central Adriatic) was about 9 m [69]. Storm Vaia caused boulder activation on both the southern Istrian (Croatia) and the western Apulia (Italy) coasts (Table 3). Even at Kamenjak Cape, boulder clustering occurred (see [58], 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*" [58].

5.1.8. 13 November 2019 (Storm Detlef)

In November 2019, the main middle atmosphere gph minimum over the British Islands generated a new minimum that migrated to the South of Sicily, acquiring new strength and vorticity around the Atlas promontory. This caused strong southerly winds from the Libyan coast up to the middle Adriatic Sea (Figure 12). This storm was named Detlef [72].

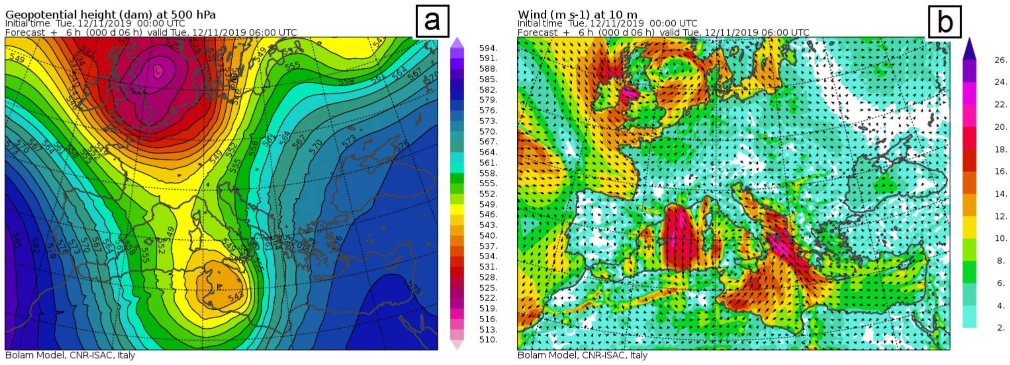


**Figure 12.** 12 November 2019 06:00 UTC: (**a**) Geopotential height (dam) at 500 hPa; (**b**) Wind (m/s) at 10 m (Bolam simulations).

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 h, which implies a calculated peak wave height between 8 and 9 m over the Salento coast (Apulia, Italy) [45]. These exceptional wind and wave conditions were confirmed by observations in the Italian Air Force S. Maria di Leuca meteomarine station [59,73]. 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 [74]. Several cases of boulder clustering have been described by [45].

### *5.2. Inferred General Features*

From the above-mentioned storm events, it is possible to infer some general features about the suitability of the studied areas as significant geographical sites for boulder displacements by storms, which is the purpose of this section. These features are discussed as:

- Regional topography in wind-wave generation;
- Storm surges, sea level, and coastal morphology;
- Locations of boulder deposits.

#### 5.2.1. Regional Topography in Wind-Wave Generation

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 on the synoptic meteorological conditions but also on the local topography. This 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, indeed show a similar synoptic generation from a mid-atmospheric trough first located in northern or northwestern Europe. This generated 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 al. [75], Figure 3 ).

The general features 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 to the east of the surface low-pressure centre and often increased and forced northward by the channelling effect of the Adriatic Sea and the parallel orographic relief of the Apennines and the Dalmatian Mountains. The Balearic and Istrian sites are representative of these two areas. The first was reached by a very strong gustiness from the northwest in January and March 2015, and the second from the effect of the channelled WCB in the reported cases of boulder displacements in 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, which caused high waves over the exposed Istrian peninsula.

In the case of March 2017, the position of the trough now originating from 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 the consequent generation of high waves. On the other hand, in November 2019 (Storm Detlef), the southward displacement of baric minimum, now located southeast of Sicily, caused a WCB displacement southward, down to the Libyan coast, impinging, again after a quite long fetch, on 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 displacement of many boulders but only limited to the coasts of the Apulia region (south-eastern Italy) [45].

#### 5.2.2. Storm Surges, Sea Level, and Coastal Morphology

In addition to the sea waves, the storm surge increased the coastal sea level. Indeed during Storm Vaia, the sea level increase registered in the Gulf of Venice; it was limited to about 1.5 m only because of the negative tidal contribution [71]. Instead, a record level of more than 1.8 m was observed in 2019 because of an added positive tidal contribution [74]. Moreover, storm surges of the order of 1 m were estimated during the October 2018 and November 2019 storms near the Apulia coasts [45].

The cases of the storms Qendresa (November 2014) and Zorbas (September 2018) have different origins; they were 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 [65] 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 the 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 [45], 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 [62].

In this context, it should be stressed that the effect of the storm surge is not to be neglected for all the considered Mediterranean storms. It should be taken into account in the estimation of their coastal effects together with the wave height and eventually, the possible tidal effects. In Ref. [45], the surge and the tidal heights were added to the average coastal sea level to obtain an effective sea level to calculate the 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. Near oceanic coasts, they generally cause increased extreme coastal water levels with a reciprocal reinforcement effect, as shown in Ref. [76] by a global statistical analysis of extreme coastal water levels. In the case of Mediterranean storms, in a limited closed 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. However, the coastal storm surge also depends on the local coastal characteristics such as bathymetry and coastline length and orientation and can be different from site to site even during the same storm event [45].

#### 5.2.3. Locations of Boulder Deposits

The above considerations show that the assessment of a site for identifying storms from the boulder displacements depends on the characteristics of the storm but also the topography of the whole region under study and the local geomorphology of the involved coastline. The regional topography has an impact on the form of the storm and the generated wind–wave patterns, while the local coastal geomorphology has an impact on the wave effects over the coastline and the coastal flooding. In the case of the Mediterranean region, the remarks in the above sections suggest that the Istrian peninsula and also the Balearic islands can represent significant hot spots of displaced boulder deposits for typical storms with baric centres in the northern Mediterranean Sea, while the Apulia, Malta, and Sicily coasts are more representative of storms with meteorological troughs displaced southward.

## 6. Discussion

Examining the results of the review (Section 4), and the causative storm events (Section 5) several themes emerged. Among these, however, three themes are fully appropriate to be discussed here. They are:

- The increase in the number of CBDs case studies;
- The suitability of rocky coasts as storm archives;
- The interdisciplinary research perspectives.

Discussion on other emerged themes, such as the technical aspects of the study of CBDs as storm archives or the differences in the impact on CBDs of medicanes compared to ordinary cyclones, is beyond the scope of this review.

### *6.1. The Increase in the Number of CBDs Case Studies*

If, on the one hand, the number of cases studied of CBDs dynamics has objectively grown in the 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 been identified as a region of frequent cyclogenesis [77], 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 has been observed [78,79]. However, as shown by bi-decadal records of several stations spread all over the Mediterranean, stormy days dwindled at the turn of 2000 [80]. Unluckily, the temporal data coverage of the measurements taken by the buoys placed within the Mediterranean is too short to statistically infer any change in storminess that could have occurred throughout the last few decades [33]. Nevertheless, using a long-term wave hindcast developed by a calibrated SWAN (Simulating WAves Nearshore) model and forcing this model with CFS (Climate Forecast System) reanalysis, some western Mediterranean coasts that have experienced an increase in storm wave energy may be identified with a high confidence level [81]. Again, deducing a 40-year long wave time series from the global ERA Interim reanalysis dataset [64] and performing a trend analysis with a non-parametric test, Caloiero et al. [82] found a positive trend for the mean value of the annual significant wave height at the 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 21st century, a particular interest in medicanes has emerged due both to the socio-economic impact of these cyclones and the implications of climate change for their intensity and location [65,75]. The current and projected coastal hazards related to such meteorological events are estimated as middle or high for many coastal stretches [83]. Where coastal flooding caused by medicanes and ordinary cyclones have been compared, the former were more extended [84]. Medicanes are also able to cause boulder dynamics even greater than ordinary cyclones, and this is of interest to researchers [62]. 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 storms and tsunamis (see, e.g., [6,22,85]). These facts may have contributed to the increase in studied cases 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.

### *6.2. The Suitability of Rocky Coasts as Storm Archives*

In this review, the results of the analysis of the causative events (Section 5) for all the considered cases first suggest that boulder production/activation can be significant for intense storms capable of generating wind waves above 4–5 m height over low rocky coasts. Further, together with sea waves, the effect of the storm surge associated with 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 whole Mediterranean basin confirm those already inferred for synoptic scale storms limited to the Apulia coast in a reviewed work (see [45], Figure 12 ) and give a general quantitative link between storm characteristics and observed boulder displacements.

As a future projection, a quite reasonable agreement among different studies and climatic simulations is gaining confidence about a general increase in the storm intensity over the Mediterranean basin, but with a possible decrease in their frequency [19,75,86,87]. As boulder production and activation 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 displacement studies could be able to provide an even better and clearer historical track of intense storms over the Mediterranean coasts in the near future. The usefulness of selected sites for geomorphological monitoring aimed to investigate the physical imprints of the storms throughout time is thus apparent.

Currently, shoreline dynamics of sandy beaches are the main geomorphological proxy used to measure coastal storminess at the decennial scale (see, e.g., [88–90]). As stressed by some authors [21,91], such a paradigm is, however, affected by significant problems due to the concurrent processes of dune recovery and beach–dune sediment transfer. Therefore, despite the fact that rocky coasts have a lower tendency to undergo changes as a result of storms compared to sandy beaches, the lack of other significant sedimentological processes for the boulder dynamics can favour the former in selecting the sites to study the storminess records. If geomorphological survey and monitoring are the basic methods for analyzing the physical effects of coming storms [58,59,62], no less important are the methods that allow the study of data from 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 al. [92] applied lichenometry techniques to date boulder movement on the western coast of Portugal, while Brill et al. [93] used optically stimulated luminescence on CBDs located on the Moroccan Atlantic coast, both with encouraging results.

### *6.3. The Interdisciplinary Research Perspectives*

The interaction of the different scientific disciplines involved in the study of CBDs as natural archives for intense storms is the final point discussed here. Assuming that the identification of suitable CBDs is geomorphological expertise, the contribution of atmospheric physicists, physical oceanographers, hydrodynamics researchers, and other natural science scholars is crucial to establishing the processes that determined their formation (see, e.g., [8,17,21,92,93]). 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 and 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 favour a more fruitful dialogue between researchers [94].

To get close collaboration among scholars coming from the different core fields, the links between fieldwork and modelling 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., [95]). As a matter of fact, new approaches have been recently explored. For example, to model the interactions between storm waves and boulders exactly, Cox et al. [22] employed force-balanced, dynamically scaled wave-tank experiments using a real stretch of coast as a model prototype. Further insights can also be found outside the CBDs topic, for example, the study of Li et al. [96]. 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 more fieldwork and modelling interchanges in climate research (see e.g., [97]).

## 7. Conclusions

The combined action of the wind waves with concurrent storm surges 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 and 5). The examined coastal storms usually tend to assume characteristics that depend not only on the synoptic meteorological conditions but also on the local topography. When the storms originated from Mediterranean tropical-like cyclones, the location of the affected coast mainly depend on the area of generation and the trajectory of the medicane. Thus, for selecting sites for geomorphological storm proxies, both regional and local features are crucial.

This study shows that the Istrian peninsula and the Balearic islands can represent hot spots for typical storms with baric centres in the northern Mediterranean Sea, while Apulia, Malta, and Sicily coasts for those with meteorological troughs displaced southwards (Section 5). Each of these areas contains stretches of rocky coasts potentially suitable to host geomorphological storm proxies, as inferred from the reviewed articles (Section 4, see Table 3 for a quick glance). In general, storms generating significant wave heights of at least 4 m appear to be responsible for boulder displacements in the studied sites, with typical storm surges of the order of 1 m.

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 al. (2000) [98] | process identification | CBDs produced by tsunami |
| Mastronuzzi et al. (2004) [99] | vulnerability study | No CBD dynamics data are reported |
| Andriani and Walsh (2007) [100] | process identification | No CBD dynamics data are reported |
| Scicchitano et al. (2010) [101] | process identification | No CBD dynamics data are reported |
| Furlani et al. (2011) [102] | process identification | No CBD dynamics data are reported |
| Paris et al. (2011) [2] | review preface | No CBD dynamics data are reported |
| Mastronuzzi and Pignatelli (2012) [103] | process identification | CBDs produced by tsunami |
| Katz and Mushkin (2013) [104] | process identification | No CBD dynamics data are reported |
| Mottershead et al. (2015) [105] | process identification | CBDs produced by tsunami |
| Shah-Hosseini et al. (2016) [106] | hazards study | No CBD dynamics data are reported |
| Amores et al. (2020) [107] | storm simulation | No CBD dynamics data are reported |
| Ruban (2020) [3] | virtual perspective | No CBD dynamics data are reported |
| Ferrando et al. (2021) [108] | process identification | No CBD dynamics data are reported |
| Fortelli et al. (2021) [109] | process identification | No CBD dynamics data are reported |
| Lollino et al. (2021) [110] | process identification | No CBD dynamics data are reported |

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