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Freak wave events in 2005-2021: statistics and analysis of favourable wave and wind conditions

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Abstract. Freak or rogue waves are unexpectedly large waves in seas and oceans, which occur without specific reasons, and cause human loss, damage of ships, oil platforms, and coastal structures. Evidences of such waves are widely spread around the globe. The present paper is devoted to analysis of the unified collection of freak wave events from different chronicles and catalogues from 2005 to 2021. The considered rogue waves are not measured in situ data, but their descriptions, which have been found in the mass media sources and scientific articles. All of them resulted in ship or coastal/offshore structure damage and/or human losses. The collection accounts for 429 events. First, the analysis based on their characteristics taken from the descriptions of the events (including locations, water depth, damages) is carried out. Second, the analysis of wave parameters taken from the climate reanalysis ERA5 is performed. Thus, the most probable background wave parameters in time of freak event (including wind speed, gusts, significant wave height, maximum wave height, peak wave period, skewness, and kurtosis) for each freak wave event are determined.

1 Introduction

Anomalously large waves in the ocean (the so-called rogue, freak or killer waves) can be dangerous for vessels including large cruise ships and small fishing boats, oil and gas pipelines and platforms. They may destroy or damage the coastal constructions, and can lead to fatal consequences for people spending time on the beach or fishing on the rocks. Rogue waves became a subject of continuous scientific investigations for more than two decades, after their existence was proven by registering a New Year Wave at the Draupner platform in the North Sea on January 1, 1995 (Sverre, 2003). The most common properties of freak waves are unusually large wave height for a given sea state, short lifetime, and unexpected formation. The mathematical definition, which is used in oceanography, is that freak waves are the waves whose height is at

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least twice larger than the significant wave height (H_s or SWH), which is itself defined as an average of 1/3 of the highest waves in the record (Massel, 1996; Kharif et al., 2009). It is believed, that the formation of a rogue wave is the result of different physical factors working together. The main reasons, which play a key role in the process of rogue wave appearance, are the following linear mechanisms: dispersive focusing, which is a time-space localization of wave train energy (Kharif and Pelinovsky, 2003; Pelinovsky et al., 2011; Fedele et al., 2016), geometrical focusing in basins of variable depth (Didenkulova and Pelinovsky, 2011; Benetazzo et al., 2017), wave-current interaction (Lavrenov, 1998; Onorato et al., 2011; Toffoli et al., 2015; Shrira and Slunyaev, 2014a; Shrira and Slunyaev, 2014b), and random superposition of steep waves (Gemmrich and Cicon, 2022). Among the nonlinear mechanisms, the most significant are the modulational instability or Benjamin–Feir instability (Slunyaev et al., 2011; Ruban, 2007; Kharif and Touboul, 2010; Onorato et al., 2006), the interaction of coherent structures as solitons and breathers (Pelinovsky and Shurgalina, 2016; Slunyaev, 2019; Gelash and Agafontsev, 2018; Akhmediev et al., 2016; Didenkulova (Shurgalina), 2019; Didenkulova, 2022), and the wave-wave and wave-coast interaction in shallow water (Didenkulova and Pelinovsky, 2011; Chakravarty and Kodama, 2014; Peterson et al., 2003). Variable wind and gust also contribute to the extreme wave formation (Pleskachevsky et al., 2016).

The study of the problem of freak waves requires a multi-faceted approach including development of analytical theories, carrying out of numerical simulations and experimental measurements. In situ measurements play an important role in the investigation of the characteristics and frequencies of the appearance of rogue waves in nature. Such in situ wave measurements are carried out in different locations of World Ocean, for example (Didenkulova and Anderson, 2010; Mori et al., 2002; Stansell, 2004; Christou and Ewans, 2014; Häfner et al., 2021). However, their amount and locations of measurements are limited.

It became obvious that freak waves may occur at any water depth and almost everywhere in the World Ocean. Thus, to get more information about them, catalogues of rogue waves started to be compiled. Some chronology of freak waves from the 16th century to the beginning of the 21st century was performed in (Liu, 2007). This catalogue includes a description of the most well-known or reliably reported freak wave encounters from the open sources. The catalogues of recent accidents associated with freak waves also include information about weather conditions and wave parameters in the region (Didenkulova et al., 2005; Nikolkina and Didenkulova, 2011; Nikolkina and Didenkulova, 2012; Liu, 2014; Didenkulova (Shurgalina), 2020; Didenkulova et al., 2022). There are also catalogues of freak waves for specific locations, for example, Ireland (O'Brien et al., 2013; O'Brien et al., 2018) or USA (García-Medina et al., 2018).

In the present article, we united and classified all the freak wave accidents from the mentioned catalogues using additional information that appeared in the literature, unifying the selection criteria and data analysis. Section 2 is devoted to the overall statistics of freak wave events during the period from 2005 to 2021, based on their descriptions. All freak wave accidents are mapped and divided by the place of their occurrence, i.e. deep/shallow/coastal events. We also consider damages caused by these events. In Section 3, we discuss and analyze the quantitative parameters of freak waves and surrounding waves, such as wind speed, gusts, significant wave height, maximum wave height, peak wave period, skewness, and kurtosis, extracted from the global atmospheric and ocean reanalysis ERA5. These data are also used for determining the most probable conditions and mechanisms of freak wave formation. Conclusions are given at the end.

2 Statistics of freak wave accidents in 2005-2021

The whole list of analyzed events, which can be considered as freak waves can be found at https://www.ipfran.ru/institute/structure/240605316/catalogue-of-rogue-waves. Most of these events are picked up from the catalogues (Liu, 2007, 2014; Didenkulova et al., 2005; Nikolkina and Didenkulova, 2011; Nikolkina and Didenkulova, 2012; Didenkulova (Shurgalina), 2020; Didenkulova et al., 2022; O'Brien et al., 2013; O'Brien et al., 2018; García-Medina et al, 2018) and are supplemented by the missed cases and the latest freak wave accidents. Thus, the considered time period is from 2005 to 2021. In general, these events are not in situ measurements, but are based on the eyewitnesses' reports taken from the mass media sources, different chronicles and collections, and scientific articles. We believe that we cover most of the large accidents, as they were reported worldwide. All of them more or less satisfy the image of a freak wave accident: unpredicted to the eyewitnesses and caused damage and/or human injuries or losses. The majority of descriptions are accompanied by quotes such as "all of a sudden a big wave hit the boat", "when the sudden waves swept away", "a freak wave suddenly came out of nowhere", "three freak waves had materialized from nowhere in rough but not formidable seas", etc. Moreover, some descriptions give the heights of the freak wave(s) and background waves, which help us to validate the definition of freak wave, whose height should be at least twice larger than the significant wave height H_s. In addition to it, the data from the global atmospheric and ocean reanalysis ERA5 (to be discussed in Section 3), are used to put a correspondence between weather conditions in the area, specifically, the significant wave height and the data from the eyewitness reports. Significant wave heights (H_s) are obtained from the data of reanalysis as an average of 1/3 of the highest surface ocean/sea waves, generated by local winds and associated with swell. The event is added to the list if based on both the eyewitness report(s) and ERA5 data, its description and characteristics support the freak wave formation.

The final list of events contains 429 freak wave accidents. Their locations are mapped in Fig. 1. It is clearly seen, that their geography is wide spread. The number of points is larger closer to the coasts and water boarders, because of the more intensive use of these territories compare to the open ocean. The regions with the largest cluster of points are the East and West coasts of the USA, coasts of Ireland and the United Kingdom, Mediterranean Sea, South Africa, the southern and southeastern coasts of Australia, New Zealand. Such distribution is governed by our search engine, as all mentioned territories are the English speaking regions.

The distribution of freak wave accidents by years is presented in Fig. 2. It is not uniform, and deviations are significant. The year with the biggest amount of freak waves from the list is 2006 (60 events). It is difficult to find some reasonable explanation for it. In both 2008 and 2020 there were only 9 events, which is the smallest value in the histogram. The few events in 2020 can be explained by the restrictions during the COVID19 pandemic, including a ban on visiting beaches in many countries.

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Using the GEBCO 2021 bathymetry (https://www.gebco.net/) and Multimaps service (https://multimaps.ru/), the approximate depth of the events is determined. The depth of 50m is chosen to separate deep and shallow freak waves. There is also a class of events called coastal freak waves, which are divided into 'gentle' (unexpected flooding on the gentle beaches) and 'rocks' (unexpected surges on vertical constructions, i.e. rocks or embankments) freak events. Descriptions of several events of each mentioned type are given below. Figure 3 demonstrates freak wave event on the rocks. Young lady was almost swept away by a huge wave while posing for photos on a cliff in Bali (https://www.ibtimes.co.in/watch-bali-tourist-swept-away-by-huge-wave-while-posing-cliff-794272). An example of a freak wave on a flat beach is shown in Fig. 4. On February 13, 2010, a surfing competition took place on Mavericks Beach, near San Francisco in California, USA. Two walls of water 6 feet high took dozens of spectators by surprise, sweeping people off their feet. At least 13 people were seriously injured, including broken legs and arms (https://www.thetimes.co.uk/article/rogue-waves-wipe-out-spectators-at-mavericks-surfing-competition-02n8p27ztfr?region=global). One of the deep water freak wave events is an accident with the cruise ship 'Luis Majesty', when three freak waves smashed into a Mediterranean cruise ship, killing two people as cabins flooded and windows shattered (https://www.youtube.com/watch?v=lvOceI6egg0). Example of a shallow water freak wave is an incident with the whale-watching boat, named 'Spirit of the Gold Coast', which was hit by a freak wave in Queensland (https://www.news.com.au/travel/travel-updates/incidents/monster-wave-smashes-into-gold-coast-whale-watching-boat/news-story/e3303ab316da4f555f89d6d17bb5c149, https://www.youtube.com/watch?v=hWztpRKDmsg).

The distribution of deep, shallow, and coastal freak wave events is shown in Fig. 5. There are 81 (which is 19%) events that happened in deep water, 124 (29%) events in shallow water, and 224 events (52%) that occurred on the coast, including 82 (19%) on the gentle beaches, and 142 (33%) on high cliffs and coastal walls. The number of freak wave observations on high cliffs and sea walls is significantly larger than on gentle beaches, which is in a good correspondence with theoretical findings (Didenkulova and Pelinovsky, 2011).

One more criterion which unites all considerate freak waves is the damage caused. The listed events led to human injuries (575) and death (658), vessel damages (102) and vessel losses (55), including small fishing boats and large ships (Fig. 6).

In spite the larger number of shallow water events compare to those in the deep waters, the number of fatalities happened in deep water is greater. Such a large number of human losses is also connected with two accidents. First is an accident with a fishing boat sunk near Cape Inubosaki on 23.06.2008 when 20 people were drowned, the second on is capsizing of the ferry Rabaul Queen on the east of Lae on 02.02.2012 when 126 people were drowned.

3 Analysis of freak wave characteristics based on atmospheric reanalysis ERA5

Apart from the freak wave parameters taken from the descriptions of the events and analyzed in the previous section, in-depth analysis of the characteristics of sea waves has been performed using the data from the fifth generation of

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ECMWF atmospheric reanalysis of the global climate, ERA5 (Hersbach et al., 2020). The ERA5 reanalysis was developed using model cycle 41r2 of the 4D-Var data assimilation from the Integrated Forecast System (IFS). This reanalysis covers the period from 1979 to present. The characteristics of background waves and freak waves have been determined, including wind speed, gusts, significant wave height, maximal individual wave height, peak wave period, skewness and kurtosis. These parameters were calculated from the 2D wave spectrum, which includes both waves and swell. The maximal individual wave height is an estimate of the height of the expected highest individual wave within a 20 minute time window. The most probable wind and wave conditions for freak wave generation have been discussed.

Freak wave heights (H_{fr}) were determined as maximal individual wave height for the given time interval in the given region. The estimated ratios H_{fr}/H_s mostly belong to the range from 1.8 to 2. Accepting the error in the 10%, we can assert that analyzed events fulfill the amplitude criterion of freak waves (Kharif, 2009).

According to data of reanalysis from ERA5, the significant wave heights from the database ranged from 0.5 to 11.2 m, the peak period ranged from 3.1 to 15.4 s, and the maximum individual wave height (H_{fr}) ranged from 1 to 20.9 m.

The sea state steepness can be analyzed by plotting the significant wave height against the peak period (Christou and Ewans, 2014). Figure 7 demonstrates the dependence of the significant wave heights against wave periods (a) and individual maximal wave heights against wave periods (b) for each freak wave event. The black line corresponds to the maximum steepness of Stokes' wave $kH/2 = 0.44$ (k is a wave number, H is a wave height), after which the irreversible process of wave breaking begins (Toffoli et al., 2010). The cloud of dotes formed by freak wave heights clustered more toward the curve of maximum steepness. However, the large part of the cloud falls within the dotes of H_s from the first plot. Thus, the wave steepness cannot be the single factor of freak wave event (Christou and Ewans, 2014). Freak waves in our dataset are either nonbreaking or have the maximum steepness of Stokes' wave.

One of the most important questions concerning freak waves remains the reason for their appearance. Nowadays it is believed that modulation instability is the main mechanism of freak wave formation in the deep-water regions (Benjamin and Feir, 1967; Onorato et al., 2001; Dyachenko and Zakharov, 2005). Closer to the coast, the role of modulational instability should be diminished (Kharif et al., 2009), and other mechanisms such as dispersive focusing (Fedele et al., 2016), geometrical focusing or wave-current interactions should be prevalent. Using data, obtained from the reanalysis model ERA5, we have checked if chosen freak events satisfy the criterion of modulation instability:

$$kh > 1.363, \quad (1)$$

where h is the water depth and k is the carrier wave number (Osborne, 2010).

The approximate coordinates of the event were determined according to the reports of eyewitnesses. The corresponding depths were obtained using GEBCO bathymetry.

Further, we can use the dispersion relation for gravity waves

$$\omega = \sqrt{gk\tanh(kh)}, \quad (2)$$

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where $\omega = 2\pi/T$ is a wave frequency, T is a period. Wave periods are estimated using reanalysis data. Thus, k can be easily found from Eq. (2).

The dependence of kh versus h is given in Fig. 8a. However, it is more informative to distinguish the region for intermediate water depth (Fig. 8b). Points located to the right from the red line correspond to modulationally unstable waves. Almost all of these events (except one point) occurred on the water depth larger than 20 m. Contrariwise, points located to the left from the red line are stable waves and the depth of these events does not exceed 20 m. Despite the fact that the coordinates and depths of the freak wave events were determined approximately, the depth of 20 m can be chosen as a critical water depth that separates stable and unstable wave regimes. Thus, the criterion of modulation instability is well applied for water depth larger than 20 m according to the considered data of freak wave events. This conclusion coincides with the one, made by (Didenkulova et al., 2013), who used a small amount of data.

The modulational instability criterion can also be rewritten using the measured wave period T and the water depth h:

$$T \leq \sqrt{\frac{4\pi^2 h}{a_0 g}}, \qquad (3)$$

where coefficient $a_0 \approx 1.195$ is taken from the approximation formula for the wave number in (Hunt et al., 1979). Plotting the dependence of the wave periods versus water depths (Fig.9), we obtain the same results as above (only intermediate depths are considered here). The 20-meter water depth separates the modulationally stable and unstable waves quite accurately. The red line in the figure corresponds to the Eq. (3).

Higher statistical moments have been analyzed for deep and shallow events. Skewness takes values between -0.0251 and 0.0913. Kurtosis takes values between 0.0041 and 0.0789. Their distributions versus significant wave height are presented in Fig. 10. This shows the difference from the Gaussian process and larger probability of freak wave appearance.

It was previously noted that wind gusts may increase the local wave and freak wave heights (Touboul et al., 2006; Pleskachevsky et al., 2016). Using the reanalysis data, the winds and gusts for all considered freak wave events were estimated. Dependence of wind speed and gusts versus significant wave heights for coastal freak wave events and their linear approximations are presented in Fig. 11. The coefficients of determination for both wind speed and gusts data for coastal events are around 0.5. In general, higher wind speeds and gusts generate larger wave heights. However, the standard deviation is essential for these distributions, and one can see from the Fig. 11 that the same wind speed (for example 5 m/s) can generate wave heights from 0.5 m to 5 m. Dependence of wind speed and gusts versus significant wave heights for shallow and deep freak wave events and their linear approximations are presented in Fig. 12. The coefficients of determination for both wind speed and gusts data in this case are 0.68, which is larger than for coastal events.

Conclusions

In the present article, the statistics of united database of freak wave events reported in the mass media sources and scientific literature from 2005 to 2021 is analyzed. The database itself can be found at https://www.ipfran.ru/institute/structure/240605316/catalogue-of-rogue-waves. The main source of information here are the eyewitnesses' reports, and not in situ measurements. It is shown that freak wave events are widely spread all over the world, and lead to dramatic consequences on the coastal structures, human lives and navigation. All events were divided into deep-water (water depth more than 50 m), shallow-water (water depth less than 50 m), and a class of coastal waves was also distinguished (sudden flooding of gentle beaches and an anomalously high splashes on rocks and/or vertical structures). The database includes 81 events (19%) that occurred in deep water, 124 (29%) in shallow water, 224 events (52%) on the coast, including 82 (19%) on gentle beaches and 142 (33%) - on high cliffs and vertical structures. Events from the combined catalogue from 2005 to 2021 caused significant damage: 575 people were injured, 658 people were killed, 102 ships were damaged and 55 ships, both small fishing boats and large ships, were sunk.

In addition to the freak wave parameters taken from the event descriptions, an analysis of the characteristics of sea waves was performed using data from the ERA5 fifth-generation ECMWF atmospheric reanalysis of the global climate. According to the coordinates of events taken from the descriptions, the characteristics of background waves and freak waves were determined, including wind speed, gusts, significant wave height, maximum individual wave height, peak wave period, and higher statistical moments: skewness and kurtosis. The significant wave height ranged from 0.5 to 11.2 m, the peak period ranged from 3.1 to 15.4 s, the maximum individual wave height ranged from 1 to 20.9 m. The values of skewness and kurtosis of corresponding sea states also showed the deviation from the Gaussian distribution and larger probability of freak wave occurrence. Also shown, that in general, stronger winds and gusts generate larger wave heights. However, the standard deviation is rather large for these distributions, and the same wind can generate a wide range of wave heights. Using the data obtained from the ERA5 reanalysis model, an analysis of the feasibility of the modulation instability criterion and the involvement of this mechanism in the formation of a specific freak wave was performed. It is shown that according to the considered data of freak wave events, the criterion of modulation instability is well applicable for depths greater than 20 m.

Data availability: All collected catalogue freak wave data from 2005 till 2021 are available at https://www.ipfran.ru/institute/structure/240605316/catalogue-of-rogue-waves

Author contribution: ED and ID collected and analysed the data of freak wave events from the mass media sources. IM provided with climate reanalysis ERA5 data of selected freak waves. ED prepared the original draft of the paper, which was reviewed and edited by ID and IM. All authors have read and agreed to the published version of the manuscript.

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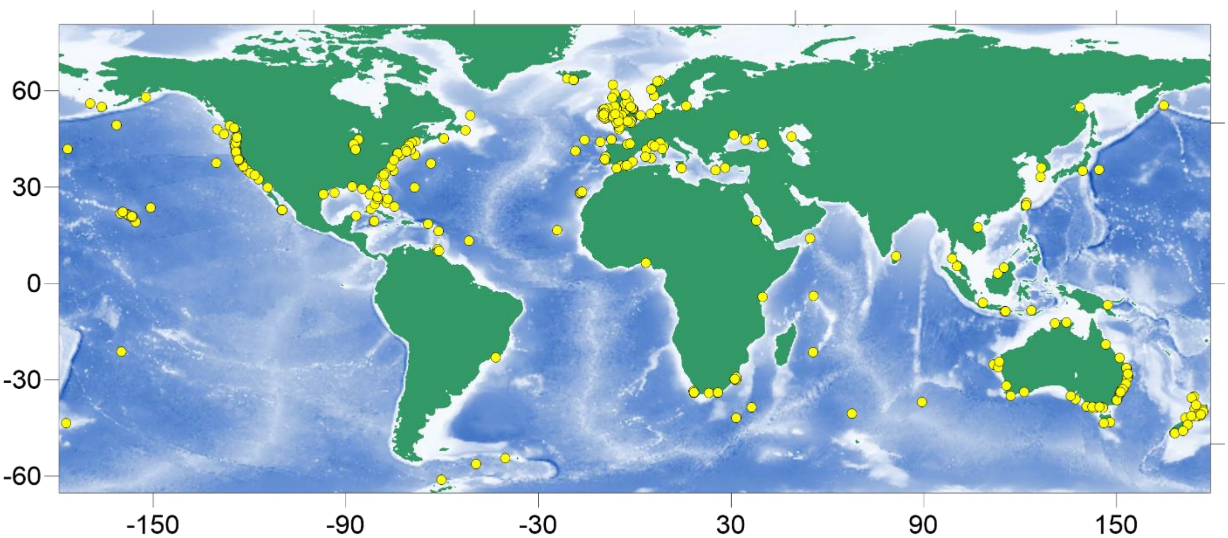

Figure 1: Map of freak wave accidents from 2005 to 2021.

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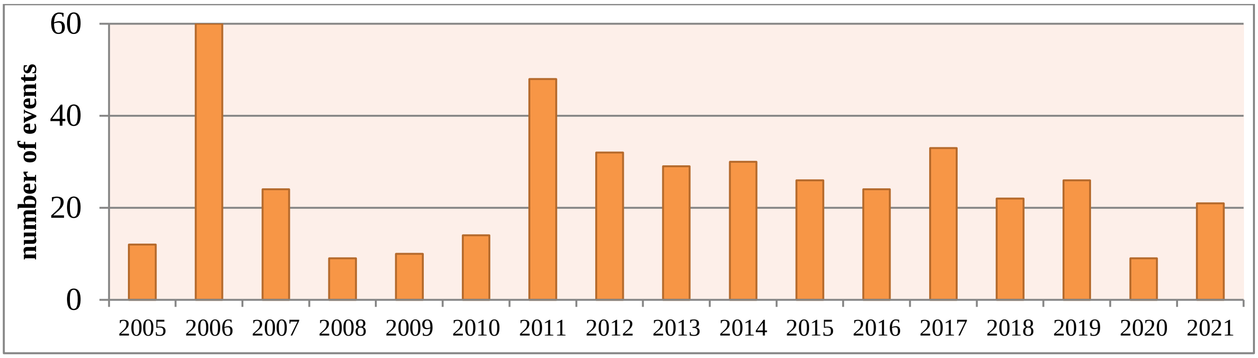

Figure 2: Distribution of freak wave accidents by years.

Figure 3: Young woman was almost swept out to sea from the cliff by a freak wave in Bali, Indonesia, on 17.03.2019 (© Instagram @PDChinese).

Figure 4: Freak wave accident on Mavericks Beach, on 13.02.2010 (© Scott Anderson).

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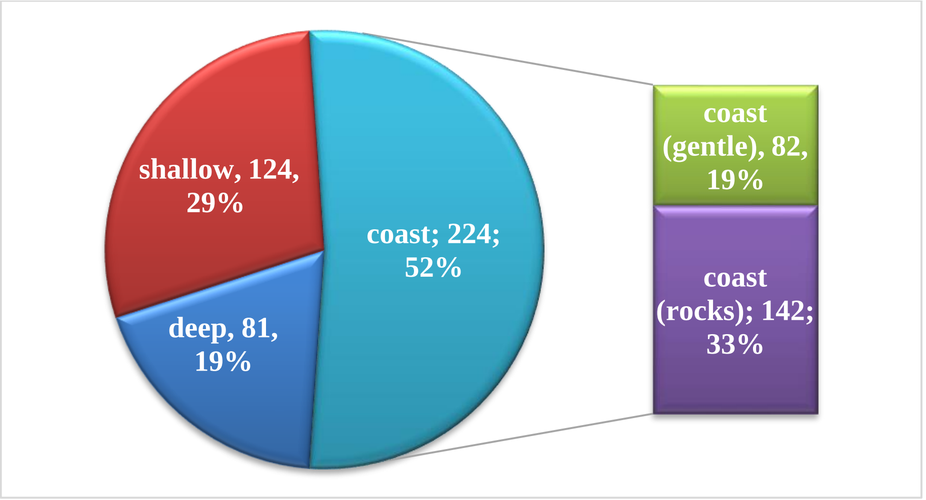

Figure 5: Distribution of deep, shallow, and coastal freak wave events.

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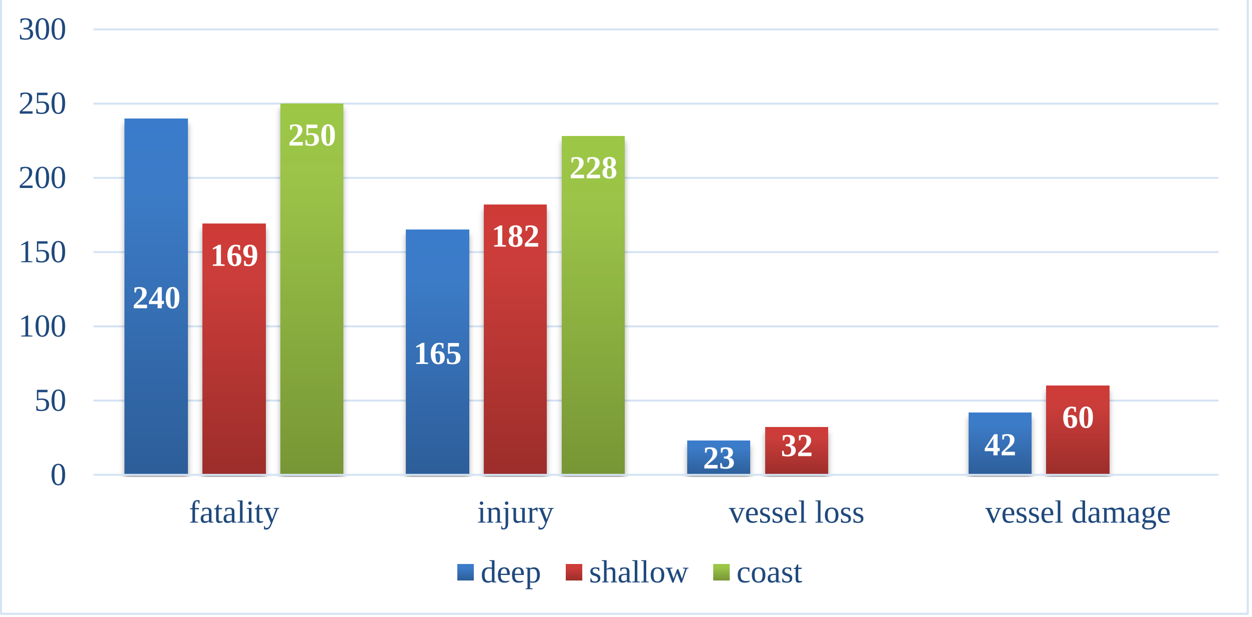

Figure 6: Damage caused by freak waves.

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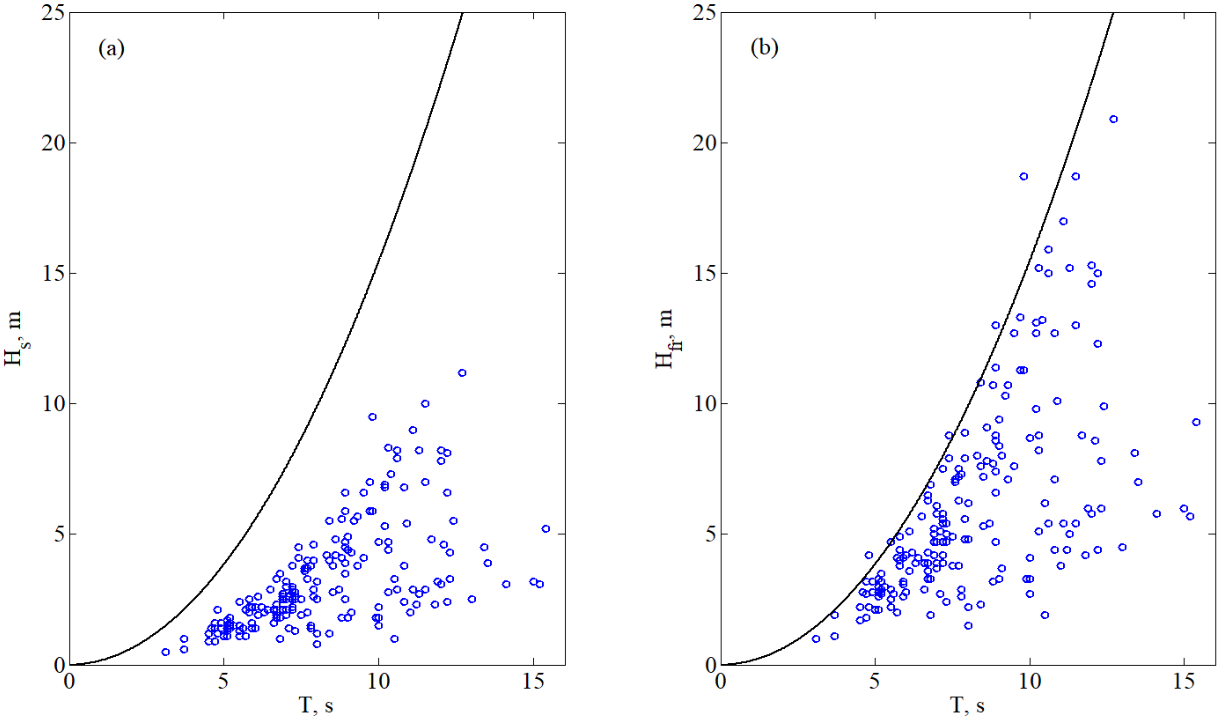
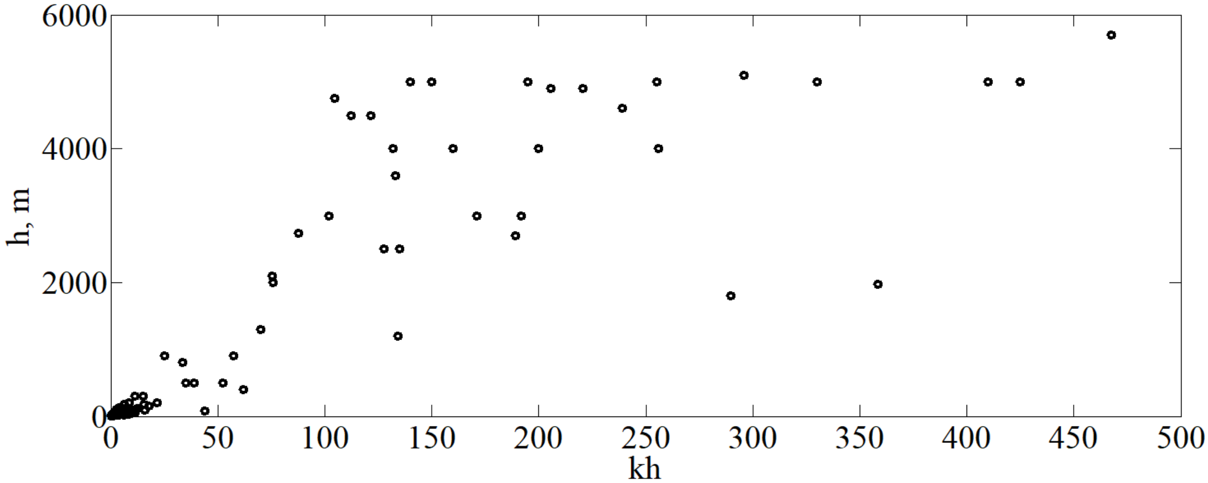


Figure 7: Significant wave height against wave period, (b) Individual maximal wave height against wave period. Black line corresponds to maximum steepness curve.



a)

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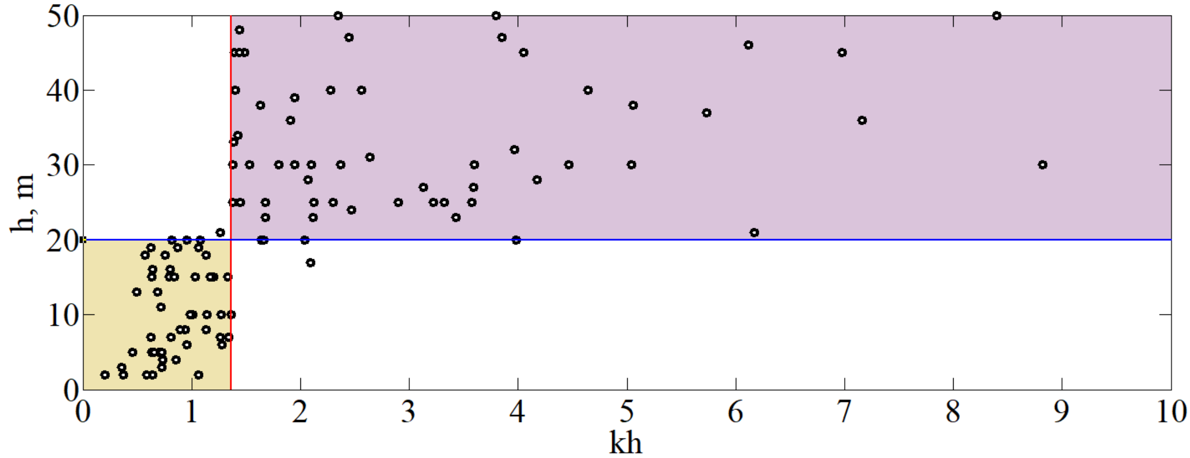

b)

Figure 8: The dependency of the parameter *kh* against the water depth (red line corresponds to the threshold of the criterion of modulational instability): (b) is zoom of (a).

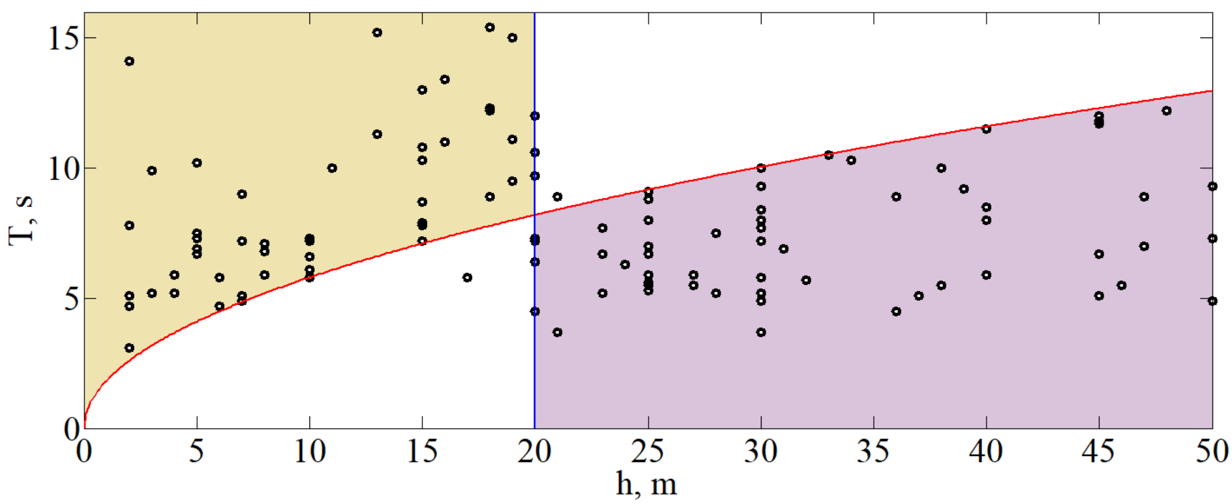

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Figure 9: Period of freak waves plotted against the water depth of their occurrence; the red solid line corresponds to Eq. (3).

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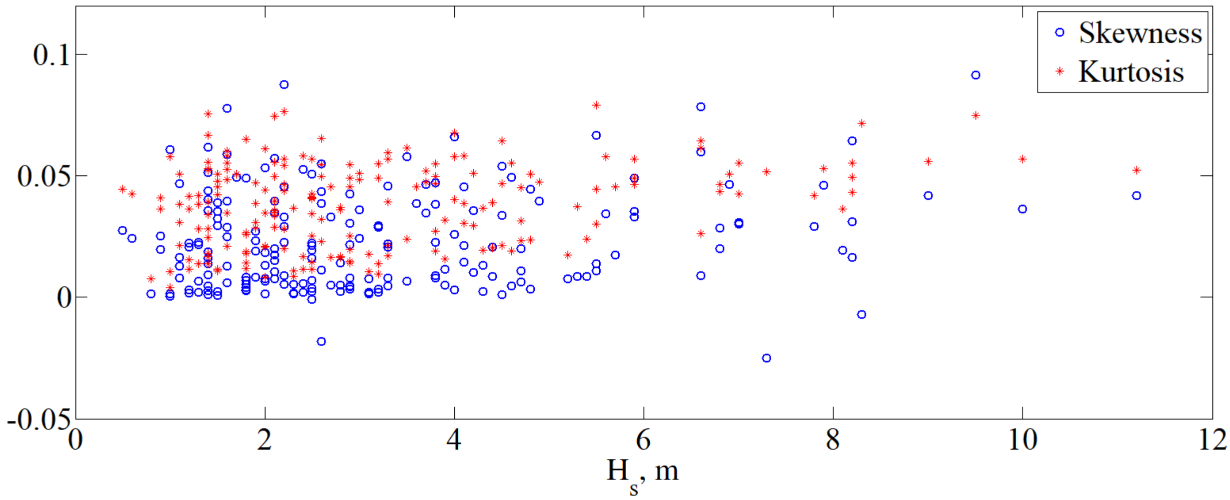
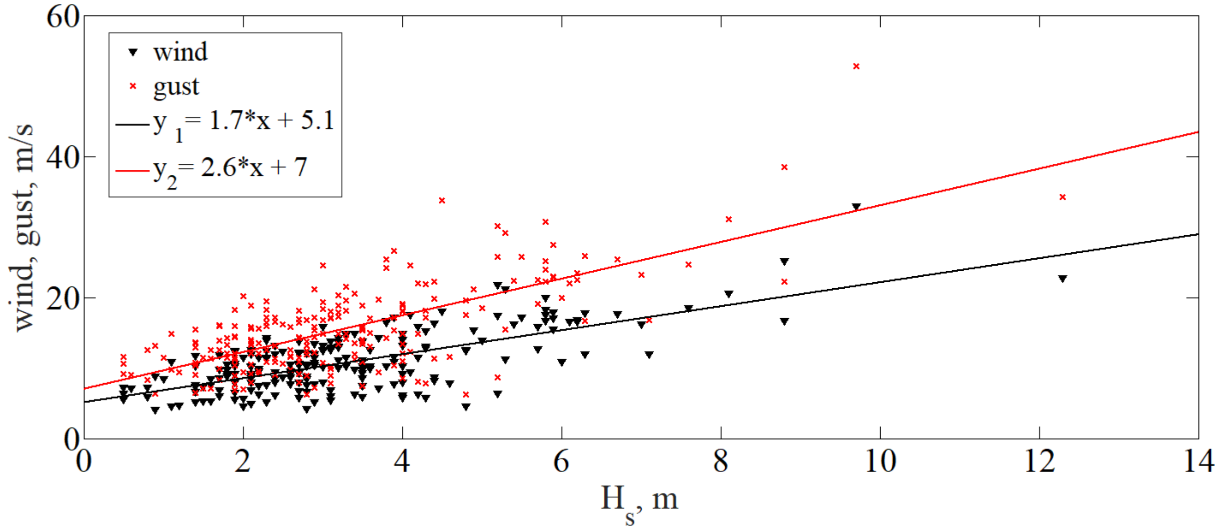


Figure 10: Distributions of skewness and kurtosis versus significant wave height.



355 **Figure 11: Dependence of wind speed and gusts versus significant wave heights for coastal freak wave events.**

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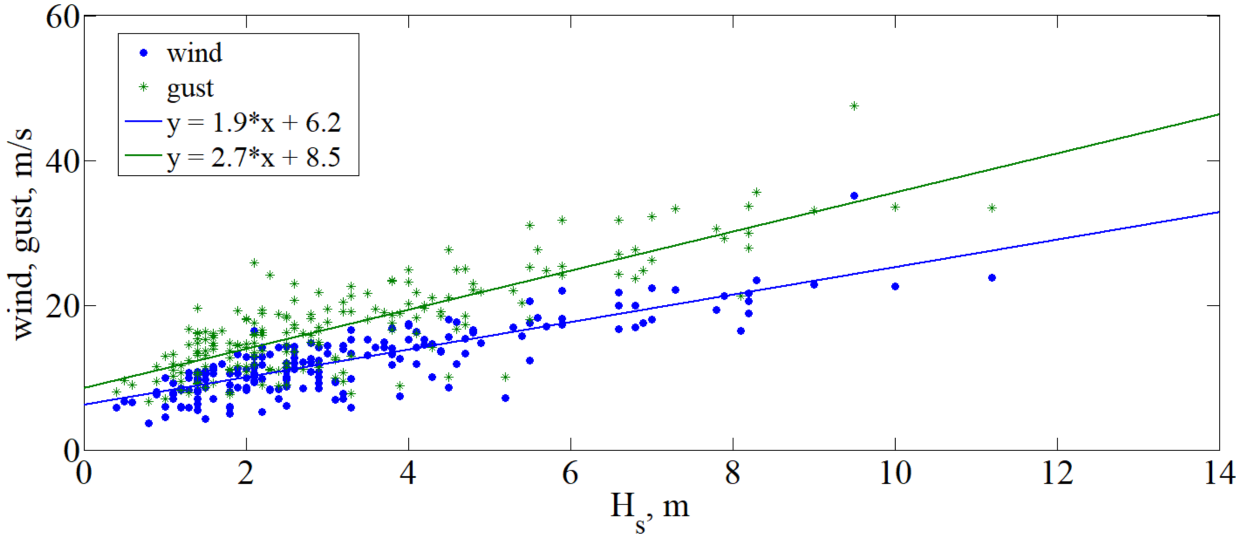

Figure 12: Dependence of wind speed and gusts versus significant wave heights for deep and shallow freak wave events.