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A preliminary investigation of rogue waves off the Jiangsu coast, China

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Abstract. Due to the potential disasters induced by rogue waves, research in this field has increased rapidly in the last 2 decades. However, there are still a lot of open questions left, including some classic ones, such as whether the rogues waves are just rare events or not. One of the key reasons is that not enough of the observed rogue waves have been investigated. China has a wide sea area, but none of the research has addressed the observed rogue waves. In the present study, 1 year of observed wave data from Jiangsu coastal area, China, are analyzed. It is found that rogue waves are present, although the wave heights are not very large; furthermore, the probability of their occurrence is similar to the Rayleigh distribution prediction, due to the local silty coastal topography. The characteristics of rouge waves are investigated and the results indicate that a new type of rogue wave may exist.

1 Introduction

The concept of rogue waves or freak waves was put forward by Draper (1965) for the first time to describe an abrupt surface gravity wave with tremendous wave height, which often causes severe hazardous effects because of its giant energy. The typical and commonly used definition of a rogue wave is one with a wave height exceeding twice the significant wave height. As a distinct kind of disastrous wave, rogue waves have drawn a lot of attentions all over the world in recent years. With the continuous emergence of the achievements associated with the dynamic and kinematic characteristics of rogue wave phenomenon, various academic discussions and debates have also been generated from the advancements on this new and controversial issue.

Nowadays, the study methods on rogue waves mainly focus on theoretical analysis (Onorato et al., 2006a, b), numerical simulation (Tao et al., 2011, 2012a), physical experiment (Toffoli et al., 2010, 2011) and field observations. Some key advances were reviewed by Dysthe et al. (2008) and Kharif et al. (2009). Among all the approaches which can be found in the literature, field measurements are necessary for seeking the nature of rogue waves, since there are still no unifying concepts regarding them. However, since the occurrence of rogue waves is still not fully understood, it is very difficult to develop measurement techniques dedicated specifically to the rogue waves. Most of the related studies based on observed data are only by-products of regular wave analyses.

It is found that the research works aiming to probe the characteristics of rogue waves from observed data or historical wave data documented in the media are mainly in five water areas in the entire world: the Atlantic Ocean, the Indian Ocean, the North Sea, the Sea of Japan and the sea around Taiwan. Pinho et al. (2004) mentioned that the occurrence probability of rogue waves in the Campos Basin in the South Atlantic Ocean is higher than the probability given by the Rayleigh distribution. Liu et al. (2004) mentioned that the occurrence likelihood of rogue waves in the Indian Ocean is also higher than the Rayleigh distribution. Stansell (2005) held the opinion that the Rayleigh distribution considerably underpredicts the occurrence probability of extreme crest heights, but only slightly overpredicts the occurrence probability of extreme trough heights in North

Alwyn, situated in the North Sea. Yasuda and Mori (1997) believed that the occurrence probability of giant rogue waves on the Pacific Ocean side is almost the same as the Rayleigh distribution, while the probability on the side of the Japan Sea is much less. Mori et al. (2002) pointed out that the wave height distribution is in line with the Rayleigh distribution in the sea area 3000 m away from the Yura fishing port in Japan. Tseng et al. (2011) found that the probabilities of dangerous rogue waves in the sea around Taiwan are lower than the Rayleigh distribution.

It could be discerned from the above that the majority of the studies on the rogue waves based on in situ measurements merely concentrates on the open seas rather than nearshore areas, although the rogue waves in shallow water have also attracted attention (Sergeeva et al., 2011; Didenkulova et al., 2006; Didenkulova and Pelinovsky, 2011; Didenkulova, 2011). Chien et al. (2002) once reported about 140 freak wave events in the coastal zone of Taiwan in the past 50 years (1949–1999), which claims the existence of freak waves off the deep water areas. Kharif and Pelinovsky (2003) mentioned that the data of marine observations as well as laboratory experiments both demonstrate that freak waves may appear in deep and shallow waters. Didenkulova et al. (2006) selected 9 cases of true freak wave events from the total number of 27 events reported by mass media or described by eyewitnesses. Of the nine examples, three events correspond to open-sea cases, while the six others occurred near the shore. Soomere (2010) believed that most of the processes resulting in the formation of unexpectedly high surface waves in deep water (such as dispersive and geometrical focusing, interactions with currents and internal waves, reflection from caustic areas, etc.) are also active in shallow areas. Thus, besides rogue waves in the open seas, which are always the subject of investigation, the problem of coastal freak wave events needs to be emphasized as well.

In addition to the five sea areas mentioned earlier in the article, the sea around China is also one of the freak-prone sea areas. From the reports in recent years in China, shipwreck accidents caused by breaking rogue waves were not rare. Tao et al. (2007) found six cases that caused serious damage during 2005 to 2006 in the mainland of China through searching the official news. The latest serious event raised by rogue waves was on 28 November 2012. *Liaodajinyu81073* capsized in the Heidao sea area near the Xingshutun fishing port in Dalian. It was reported that there were level 8 fresh gale and giant waves in the incident area. Except for the case in Dalian, the Wenchang Ship wreck accident happened on 2 November 2010, attracting great attention. The *Qionghaikou03052* sank in the sea area near the Qizhou fishing ground in the city of Wenchang in Hainan, after encountering breaking giant waves.

Therefore, the basic characteristics of observed rogue waves in coastal sea areas around mainland China need to be properly answered. In order to improve the understanding on this issue, wave records in Xiangshui station off the Jiangsu coast, China, in 2011 are applied and analyzed in this paper.

2 Wave data

The wave data used here are from a self-developed wave buoy SBF3-1 (Fig. 1), which was deployed by the Laboratory Center of College of Harbor Coastal and Offshore Engineering of Hohai University in 2010 in the Jiangsu coastal sea area, China (Fig. 2). The buoy SBF3-1 is currently a popular instrument for wave measurement in mainland China, in the coastal ocean or in the deep sea. A strapped-down acceleration meter is installed in a buoy for motion measurement and assumed as the water particle tracker. Surface movement is inversed from a displacement spectrum that is transferred from an acceleration spectrum. The uncertainty of the measurement comes from the response of the buoy to the sea surface. The SBF3-1 buoy telemetry system was designed by Shandong Institute of Instrumentation (SDIOI). According to the two-test comparison with a Waverider MARK II buoy (the Netherlands) and the WAVESCAN buoy (Norway) in 2005 and 2007, the results showed that the measured data of SBF3-1 wave buoy were reliable. The SBF3-1 buoy consists of the buoy system on the sea and the receive and process system on the land. The wave height measuring range was from 0.2 to 25 m, and the limits of measurement of the wave period was from 2 to 30 s. The resolution is 0.1 m and measurement accuracy is $\pm(0.1\,\text{m}+5\,\%\,\text{H})$.

Buoy size, mooring line and sea state are the factors of wave-following capability. Small buoys, like the one used in this study, have better wave-following motion in moderate or calm seas. A mooring line drag in strong currents is also significant. Drag increases with the square of current speed and exposed area of the mooring line. For a small buoy, we used a rubber cord for mooring in order to have better wave-following capability. In addition, we deployed the buoy with 40 m of mooring line 4 times the water depth of the buoy location. The tidal current at the buoy location is between 0.1 to $0.6\,\text{m}\,\text{s}^{-1}$, showing the current drawing effect is relatively small. The sampling rate is increased to 4 Hz compared to typically designed 2 Hz. This is to increase the capability of recording an entire wave profile for a rogue (freak) wave study. Corresponding approaches have been carried out to reduce the uncertainty of buoy measurement on individual wave shape. Baschek and Imai (2011), Cavaleri et al. (2012), Pinho et al. (2004), Divinsky et al. (2004), Doong and Wu (2010), Lee et al. (2011), Liu et al. (2009), Liu and Pinho (2004) all used buoy data for rogue wave studies, although they may not always provide a good approximation of the wave profile.

The latitude and longitude of the buoy position was $34°26.2'$ N and $120°06.0'$ E, respectively. The waves were recorded intermittently for 17.067 min (1024 s) per hour sampled at 4 Hz. The SBF3-1 buoy telemetry system consists

Figure 1. Snapshot of the SBF3-1 buoy set in the Xiangshui station.

of the buoy system on the sea and the receive and process system on the land. The water depth is about 9 m and the tidal range here is about 3 m.

Since the original wave data contained long period components and waves lower than 0.2 m because of the zero drifting of the sensor, they should be pre-processed to guarantee the rationality of the results. In this paper, the finite impulse response (FIR) high-pass filter design was chosen as the primary method to remove the futile signals (cut-off period = 15 s) from the original data sequence.

When dealing with the processed data, the zero-up crossing method was applied to define the wave height and wave period. After dividing the processed wave data into individual waves, the widely accepted criterion $H / H_s \geq 2$ was employed to determine the rogue waves, in which H denotes the maximum trough to crest wave height, and H_s represents the significant wave height; here we use $H_{1/3}$.

3 Occurrence probability

In the Xiangshui station, 40 rogue waves were found among 218 657 waves in January 2011. The occurrence probability of rogue waves in January was approximately 0.0180 %. In the whole year, the occurrence probability of rogue waves mainly fluctuated between 0.0150 % and 0.0261 %. The results are listed in Table 1. The last column of Table 1 is the average significant wave height H_s of all the wave series with the presence of rogue waves.

It could be concluded from the results that the probability of rogue waves was lower than the probability given by the standard Rayleigh distribution (0.0333 %). Different from the conclusions given by scholars like Pinho and Liu, who believe that rogue waves are more frequent than rare, the calculation results of the occurrence probability in the coastal sea region of Jiangsu, China show that the likelihood of rogue waves in this area is comparatively low.

Figure 2. Geographic scheme of buoy position in Xiangshui station (snapshot from Google map).

4 The rogue wave profiles

Theoretically, as described by Kimura and Ohta (1994), a rogue wave stands out among a group of waves for its relatively high crest. Liu et al. (2004) also pointed out that a rogue wave is a particular type of hazardous ocean wave, which displays a singular wave profile and manifests an extraordinarily large crest or trough with very high local steepness. Most of the research works concerned with rogue waves point out their strong nonlinearity. Therefore, whether the wave patterns of the rogue waves in Jiangsu coastal sea areas have a profile similar to the description of Kimura and Liu needs to be verified.

The typical rogue waves discovered in Xiangshui Station are shown in Fig. 3. The three cases appear to be classic rogue wave cases in the Jiangsu coastal sea area. The case of Fig. 3a is a vertically and horizontally symmetrical rogue wave. The second case in Fig. 3b has a high and steep crest in a wave field where the significant wave height is nearly 0.32. Conversely, Fig. 3c is a rogue wave with a large and sharp trough. Most of the rogue wave cases found in Xiangshui station are similar to the first example given by Fig. 3 and do not have an impressive, frightful crest or trough size. The rogue waves mostly show good symmetry both vertically and horizontally (as shown in Fig. 4) when the $H / H_s \geq 2.0$ criterion is used. The main reason is that the wave climate around Jiangsu sea area is not very rough, since there is a broad, mild silt slope.

Table 1. Occurrence probability of rogue waves identified in Xiangshui station.

Month	Rogue waves	Waves	Occurrence probability	H_s
Jan	40	218 657	0.0183 %	0.518
Feb	35	176 477	0.0198 %	0.373
Mar	49	245 944	0.0199 %	0.320
Apr	54	243 388	0.0222 %	0.381
May	58	228 987	0.0253 %	0.359
Jun	38	253 521	0.0150 %	0.396
Jul	45	250 030	0.0180 %	0.347
Aug	59	225 830	0.0261 %	0.371
Sep	31	184 095	0.0168 %	0.519
Oct	42	237 841	0.0177 %	0.359
Nov	19	203 856	0.0093 %	0.494
Dec	33	161 861	0.0204 %	0.538

As is well known, the significance of nonlinearity is related to the wave height, wave length and water depth. In deep water, the intensity of wave nonlinearity is decided by wave steepness. Thus the wave steepness of the single wave before rogue wave ε_f, after rogue wave ε_b and the rogue wave ε are calculated respectively. Here, the wave steepness is defined by the ratio of local wave height and wave length.

It was discovered that in Xiangshui station, the wave steepness increased by 30 to 100 % when rogue waves occurred, and decreased by 20 to 40 % when they disappeared. After the disappearance of rogue waves, wave steepness is restored to the original level. In this case, the change of wave steepness demonstrates that there is great nonlinearity of waves during the appearance of huge waves, while all the values are far from the breaking value of 0.142, which can be seen more clearly in Fig. 5. This happens when the shapes of rouge waves are still symmetric.

5 The relation between BFI and rogue waves

Janssen (2003) used a parameter named the BFI indicator based on the conditions of Benjamin–Feir instability. It is now considered an essential determiner characterizing the occurrence probability of rogue waves. According to the results from the one-dimensional numerical simulation in the laboratory, he pointed out the chance of rogue waves may increase with larger BFI. It is meaningful to investigate the relations between BFI and rogue waves. Here we calculate the BFI as follows: $\mathrm{BFI} = 2\pi\,\varepsilon_{\text{avery}}\,/\,w$, $\varepsilon_{\text{avery}} = k_s H_s\,/\,2$, $w = (m_0 m_2\,/\,m_1^2 - 1)^{1/2}$, where $\varepsilon_{\text{avery}}$ is the average wave steepness and H_s is the significant wave height. k_s is the significant wave number, which is calculated from the significant wave period T_s and local water depth h via dispersion relation. T_s is calculated together with H_s from observed data. w is the wave spectra bandwidth. m_r is the r order moment which can be calculated by $m_r = \int_0^\infty \omega^r S(\omega) d\omega$. However, unfortunately, it could be seen in Fig. 6 that the relationship between the BFI indicator and the ratio of maximum wave height and significant wave height in Xiangshui station was very obscure.

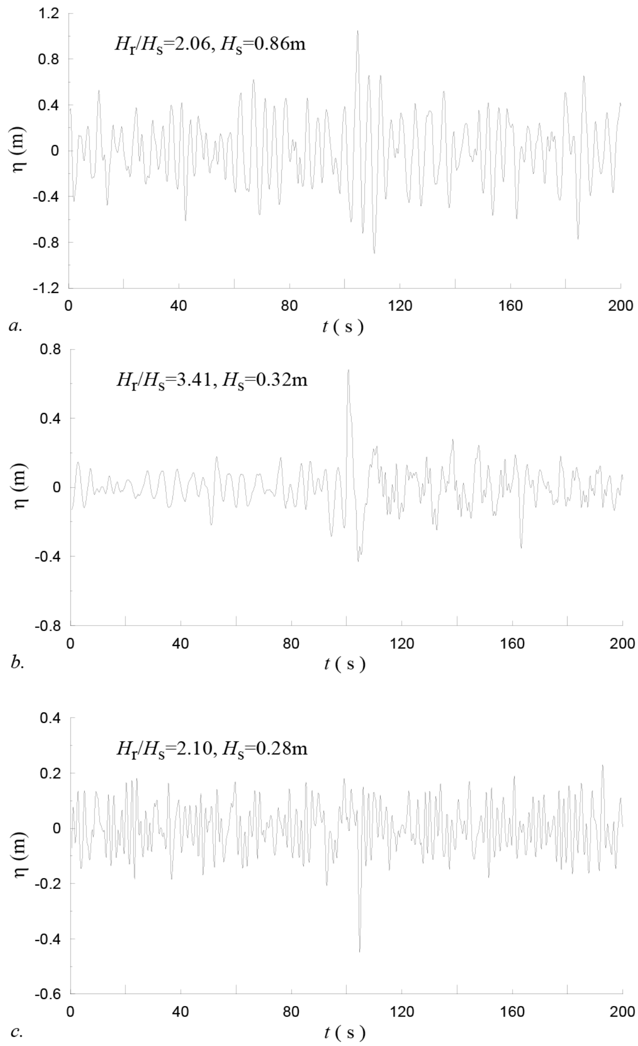

Figure 3. Typical portraits of rogue waves in Xiangshui station.

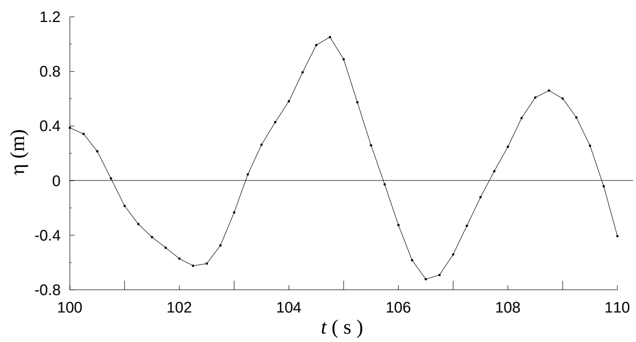

Figure 4. Symmetry of the rogue waves.

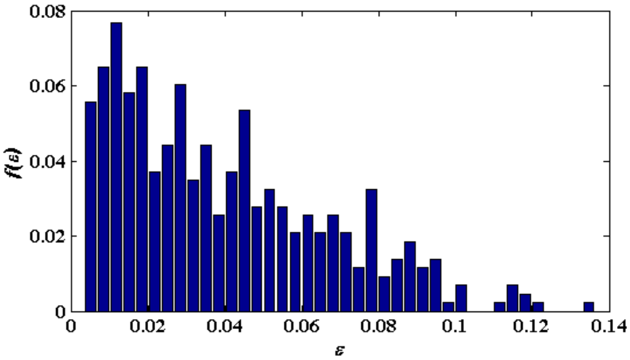

Figure 5. Probability distribution of wave steepness of rogue waves for an entire year.

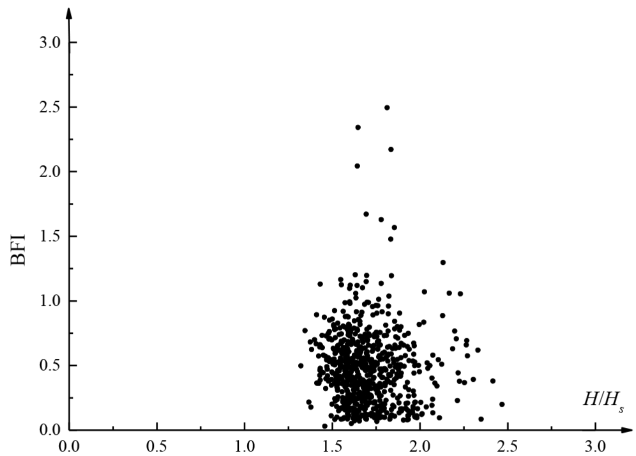

Figure 6. Relationship between BFI indicator and $H\,/\,H_s$.

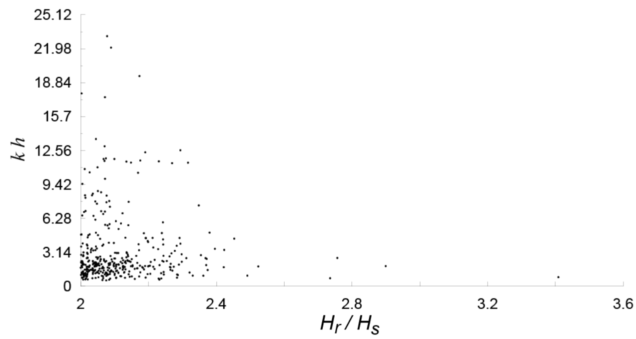

Figure 7. Relationship between kh and $H_r\,/\,H_{\mathrm{S}}$.

Therefore, it cannot be concluded that the rogue waves of Jiangsu are not induced by Benjamin–Feir instability since field data are affected by sampling variability (uncertainty due to the limited number of observations in a wave record) as shown by Olagnon and Magnusson (2004). But from Fig. 7, it can be seen that most of the rogue waves are present in intermediate water depth, where the Benjamin–Feir instability is not as strong as in deep water. In Fig. 7, H_r is the wave height of rogue waves.

Another possible explanation is that the observed rogue waves might be the consequence of linear superposition. Linear focusing is a recognized mechanism generating rogue waves. Thus the observed wave may be a result of linear superposition, because it coincides with the results of the symmetry of rogue wave portraits as discussed above. Furthermore, the waves in this sea area are not severe due to the broad silt bottom slope. The wave heights of rogue waves are also small as shown in Fig. 8. Most of the wave heights are less than 3 m, apart from one case where the wave height is 4.5 m which was recorded during a typhoon. However, the dynamic mechanisms of coastal rogue waves still need reasonable explanation in the future.

6 The relation with kurtosis

As a non-Gaussian and nonlinearity indicator, the kurtosis is commonly used as a typical wave characteristic. It has been verified by many researchers, e.g. Tao et al. (2012b), that the occurrence of rogue waves are always related the high kurtosis μ_4.

By analyzing the measured data in the Jiangsu coastal sea area, it was found that the ratio of $H\,/\,H_{\mathrm{s}}$ was associated to the high value of kurtosis, as shown in Fig. 8. Here, μ_4 is calculated as $\mu_4 = \frac{1}{N}\sum\limits_{n=1}^{N}\frac{(\eta_{\mathrm{n}}-\overline{\eta})^4}{\eta_{\mathrm{rms}}^4}$.

From Fig. 9, it can be seen clearly that the kurtosis increases with the increase of H/H_{s} for all the data with a slope gradient of about 0.6. Interestingly, there appears to be another trend with a large increasing gradient in the green square, where the $H\,/\,H_{\mathrm{s}}$ is larger than 2.4. Liu (2004) created a new classification for rogue waves in the South Indian Ocean based on the analysis of the observations offshore from Mossel Bay, South Africa. He decided to call the cases that satisfy the condition of $2 < H\,/\,H_{\mathrm{s}} < 4$ "typical rogue waves", while rogue waves where $H\,/\,H_{\mathrm{s}} \geq 4$, he named "uncommon rogue waves".

The correlation of the largest wave height and the significant wave height in Xiangshui station was illustrated in Fig. 10. It could be perceived from Fig. 10 that the ratio of the largest wave heights and related significant wave heights of most waves are distributed between 1.5 and 2. When the ratio goes up to 2, the waves are considered as rogue waves. In combination with the above analysis on the relationship between $H\,/\,H_{\mathrm{s}}$ and kurtosis, the rogue waves in Xiangshui station could also be divided into different groups. For the cases where $2 < H\,/\,H_{\mathrm{s}} < 2.4$, which embody most of the available data, the waves are called "common rogue waves", while for the cases where $2.5 < H\,/\,H_{\mathrm{s}} < 3.5$, the waves are regarded as "special rogue waves" in this area since they may be caused by different mechanisms. Because the samples of

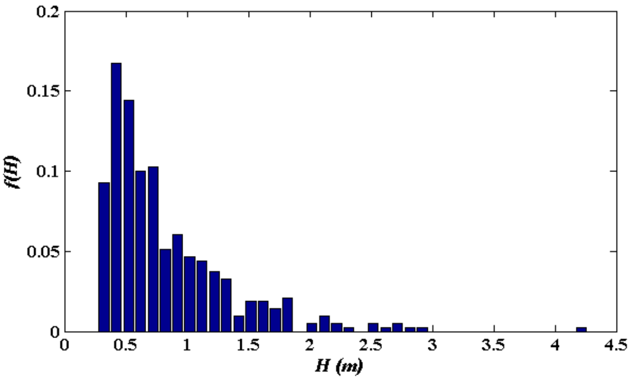

Figure 8. Probability distribution of wave heights of rogue waves of an entire year.

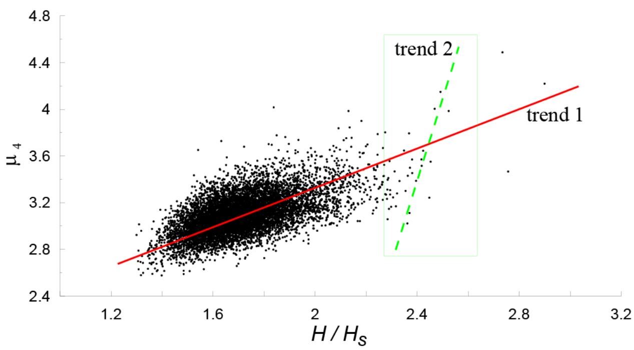

Figure 9. Relationship between H / H_S and kurtosis.

the second type of rogue waves are very limited, more data need to be analyzed to confirm this concept.

7 Concluding remarks

In this study, based on the measured data, some further research has been done to advance the knowledge on rogue waves in the sea area of mainland Jiangsu, China, putting emphasis on the coastal observed rogue waves rather than open-sea cases. The occurrence probability of rogue waves in Jiangsu coastal waters is calculated. It is shown that rogue waves are rare events in this region. The occurrence probability of rogue waves here is lower than the probability given by the Rayleigh distribution.

The horizontal symmetry, vertical symmetry, wave steepness, kurtosis and the BFI indicator are discussed afterwards. The results show that the rogue waves are not so large due to the mild broad silt bottom slope. Most of the rogue waves are present in intermediate water depth, which results in the obscure correlation between BFI and rogue waves, but in the coastal area, it may be other mechanisms that generate rogue waves.

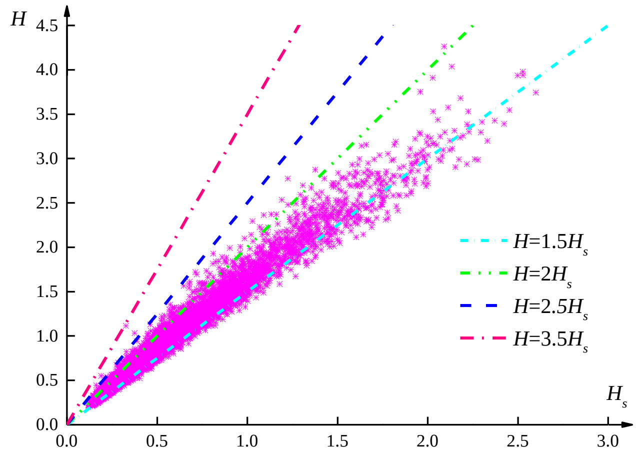

Figure 10. Correlation plot of largest H and H_S.

Finally, according to the calculated kurtosis, a suggestive sorting scheme of rogue waves is presented. It is suggested that there might be two different types of rogue waves. This is supported by investigations of the relationship between the occurrence of rogue waves and the kurtosis. But the results are still preliminary, and further detailed analyses are necessary to reach firm conclusions.

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