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Freak Waves at Campos Basin, Brazil

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Freak waves occur abundantly in Campos Basin, located on the northeast coast of Rio de Janeiro, Brazil in the South Atlantic Ocean. This surprising and unexpected discovery was made from a search of the time-series data of wave measurements recorded in the Campos Basin from 1991 to 1995. In a study on the occurrence of freak waves and their relevant properties, we have also found that freak waves are not of rare occurrence as conventionally presumed, and they occur not only during storm conditions but also during fair weather states as well. While the conventional approach of spectrum analysis provides some weak inference of freak wave effects, the basically stationary random process approach is clearly incapable of contending with the localized non-stationary process of freak wave occurrences.

Keywords: Freak waves, ocean waves, wave data analysis.

1. Introduction

Freak waves, sometimes also known as rogue waves, are a particular kind of ocean waves that display a singular, unexpected wave profile characterized by an extraordinarily large and steep crest or trough as illustrated by the well-known Draupner case (*e.g.* Trulsen and Dysthe, 1997) shown in Figure 1.

The existence of freak waves has been widely proclaimed among seafarers throughout the ages. Its presence clearly poses severe hazardous concerns to navy fleets, merchant marines, offshore structures, and other maritime ventures. While multitudes of seagoing vessels and mariners have encountered freak waves over the years, and many had resulted in disaster, it was only recently, however, that their actual existence was recognized. The emerging interest in freak waves and the quest to grasp an understanding of this phenomenon has inspired numerous theoretical conjectures in the literature in recent years. But the practical void of actual field observations of freak waves renders even the most well-developed theories unsubstantiated.

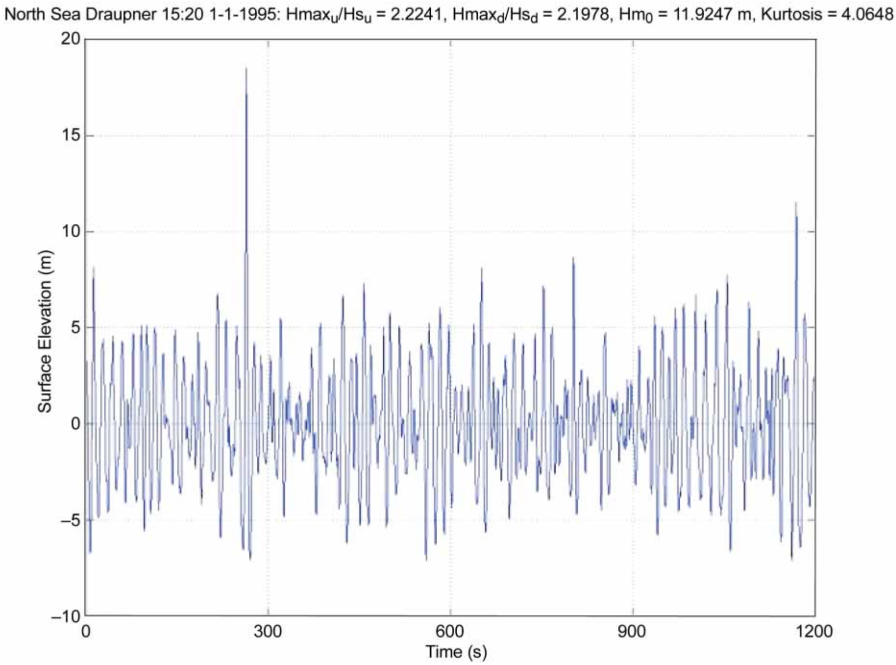

Figure 1. Recognized freak wave case of Draupner platform in North Sea. The subsctripts u and d refer to up-crossing and down-crossing cases respectively.

It may be rather unrealistic to allude to freak wave measurement per se, as freak waves were not being regarded as part of the ocean wave process during most of the second half of the 20th Century, while vigorous growth in ocean wind wave research endeavors were flourishing. All the existing wave measurements, as well as the conventional wave measurement systems, have been based on and primarily designed for ocean waves that are presumed to be from a stationary Gaussian random process that basically negates the existence of freak waves. But that does not necessarily mean freak waves have never been measured. The well-known North Sea freak wave records of Gorm field (Sand et al., 1990) and Draupner platform (Trulsen and Dysthe, 1997) were both discovered from conventional wave measurements. The wave profile of Draupner platform, as shown in Figure 1, has been widely recognized and generally identified as the exemplar depiction for freak waves. Since it is also generally construed that freak waves can happen any time and in any part of the world's oceans, there must be more Gorm/Draupner-like freak waves being recorded but simply need to be discovered. This paper presents the result of an attempt aimed at such a discovery. We readily discovered many freak wave cases recorded from a conventional buoy wave measurement in Campos Basin of Rio de Janeiro, Brazil in

South Atlantic Ocean that spanned over four years between 1991 and 1995. Our studies also point to a need for a new paradigm toward further effective explorations of freak waves.

2. The Data

The wave data analyzed here were recorded from a conventional heave-pitch-roll buoy moored at two nearby deep-water points (points A and B shown in the map of Figure 2) in Campos Basin, located on the northeast coast of Brazil's Rio de Janeiro State in the South Atlantic Ocean. Table 1 lists the latitude, longitude, and local depth in the points »A« and »B«. The buoy was moored from March 1991 to March 1993 at point »A« and then switched to the nearby point »B« from January 1994 to June 1995. There were some gaps in the total time series caused by some buoy damage. The grand total of available data for analysis was 7,457 time series records. The

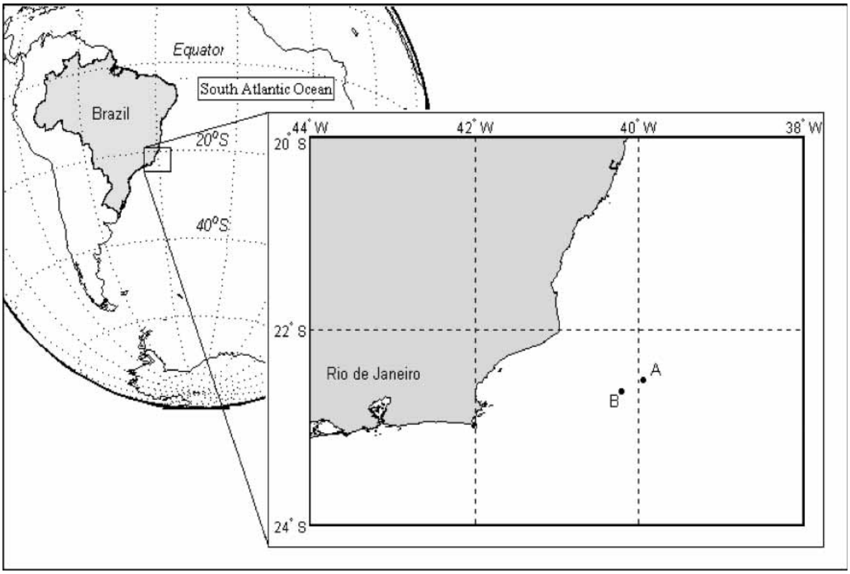

Figure 2. Geographic scheme of buoy position.

Table1. Position and depth of buoy mooring.

Point on the map	Latitude	Longitude	Depth
A	22° 31' S	39° 58' W	1250 m
B	22° 38' S	40° 12' W	1050 m

waves were measured intermittently for 17.067 minutes (1024 s) every 3 hours at 1 Hz sampling frequency. The recorded time series data consists of surface elevations as well as corresponding N–S and E–W slopes for directional spectrum analysis.

3. Relevant Aspects of Freak Waves

As the study of freak waves is still basically at the incipient and formative stage, it is not surprising that neither the cause of occurrence nor a universal definition of freak waves has been firmly established beyond a qualitative description as being an unusually high single wave event. The following features represent a general consensus on freak waves promulgated among available literatures:

– their characteristic freak wave profile resembles the profile of the time series data given from Gorm field or Draupner platform recordings;
– they usually occur during severe storm conditions (Junger, 1997);
– they are events of rare occurrence (Janssen, 2003);
– they can be identified by the ratio of $H_{max}/H_{1/3}$ greater than 2 (Kjelsen, 2000), where H_{max} and $H_{1/3}$ are Maximum and significant wave height of the data respectively.

With the exception of the last item, which is based on the conventional Rayleigh distribution theory (Ochi, 1998), the others all have an inherent vague and uncertain nature that tends to be more intuitive than rational. So it primarily renders the designation of freak waves in a given time series a subjective matter. In some cases there does not seem to be a clear distinction

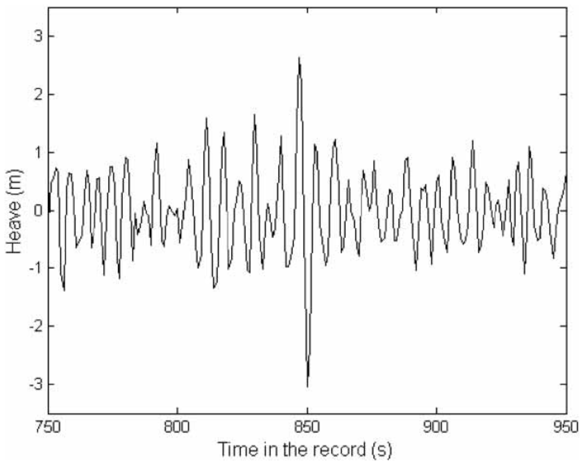

Figure 3. Up-crossing freak wave.

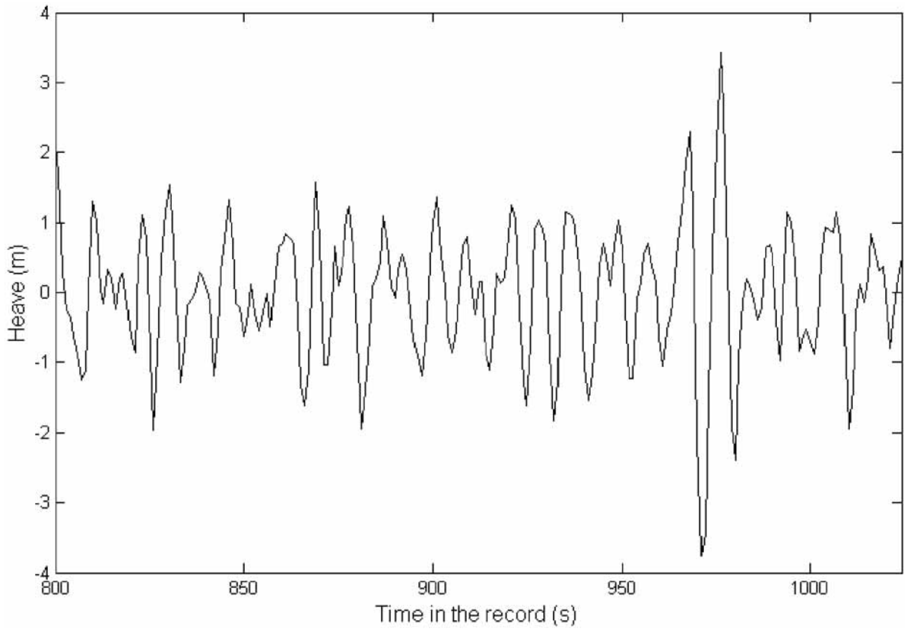

Figure 4. Down-crossing freak wave.

between freak waves and extreme waves in the literature. While freak waves are often perceived as »rare« events, since many theories were developed based on this premise, there is no clear assertion available to readily clarify just how rare is rare.

The widely used notion that freak waves can be identified by the ratio $H_{max}/H_{1/3} \geq 2$ is what we adapted here to implement our study. But the number 2 on the right-hand side is by no means a firmly resolved issue. Some choose to use 2.2 and some suggest the number should be much higher. Clearly statistically predictable extreme waves might be mixed together with freak waves under this criterion as Ochi (1998) has pointed out. Furthermore as H_{max} and $H_{1/3}$ are basically determined from sorting the troughs and crests of waves in the time series through zero crossing procedure, it seems that no one has been mindful of the differences regarding zero down-crossing (height is trough to crest) or zero up-crossing (height is crest to trough) approaches in determining the various wave heights. Since freak waves are singular waves in the record characterized by $H_{max} \geq 2H_{1/3}$, the choice of zero crossing methods can yield different results in the search for freak waves in a record. Because of the asymmetric characteristics of freak waves, the difference, as demonstrated in Figures 3 and 4, can be significant toward defining H_{max} and specifying the $H_{max}/H_{1/3}$ ratios. In this study we have identified 108 occurrences of $H_{max}/H_{1/3} \geq 2$ from the down-crossing approach, and another

197 freak wave events with $H_{max}/H_{1/3} \geq 2$ from the up-crossing approach. Among them there are only 28 cases for which the same H_{max} results from both down-crossing and up-crossing approaches. So, from the 7457 available data sets, we obtained 276 distinctive cases of freak wave occurrences. It may be unprecedented, but we shall incorporate the results of both down-crossing and up-crossing cases of freak waves in our subsequent analyses.

4. Portraits of Freak Waves

As we ventured to implement our study based on the ratio $H_{max}/H_{1/3} \geq 2$ to identify possible freak wave cases, we also visually examined the time series plot of each of the identified cases to ascertain that the identified cases are indeed freak waves. This is necessarily subjective, but we wish to affirm that each identified freak wave should have a similar profile that, to some extent, resembles the widely recognized freak wave profile of Draupner platform as shown in Figure 1. In the figures H_{max} denotes the maximum trough to crest wave height as noted before, H_{mo} and H_s represent significant wave

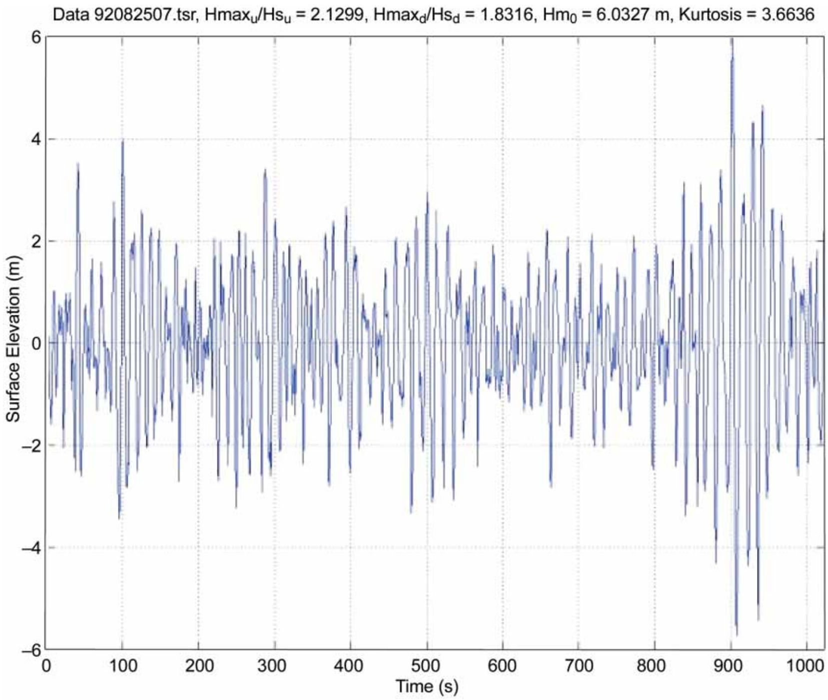

Figure 5. A freak wave case in Campos Basin.. The subsctripts u and d refer to up-crossing and down-crossing cases respectively.

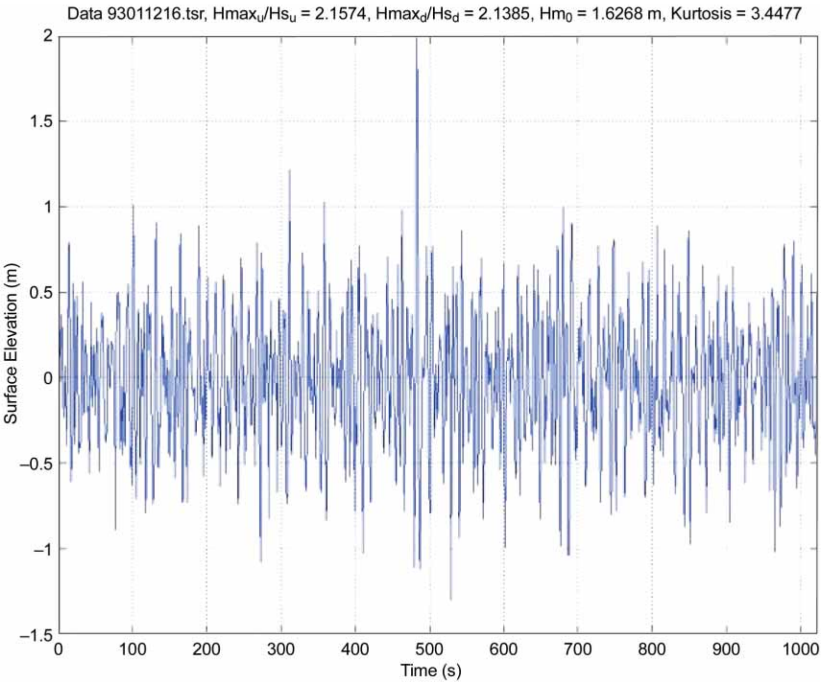

Figure 6. Another freak wave case in Campos Basin. The subscripts u and d refer to up-crossing and down-crossing cases respectively.

heights with respect to 0th moment of the spectrum and trough to crest wave heights respectively, while subscripts u and d denote up-crossing and down-crossing cases respectively.

Here we show two sample cases, given in Figures 5 and 6, which appear to be freak wave cases in the Campos Basin. The case of Figure 5 had a maximum trough-to-crest wave height nearly 12 m in a wave field where the significant wave height is 6 m. The other case, in Figure 6, is a mild case of 1.6 m significant wave height wave field with a maximum trough-to-crest wave height about 3 m. Most of the cases we found, similar to these two, do not have the impressive, frightful size of very large trough-to-crest wave heights, but they all have substantially similar appearance, and the ratio of $H_{max}/H_{1/3}$ as well as other statistical characteristics closely resemble that of the well-known Draupner case of Figure 1. It would be unrealistic to try to ignore these mild cases with H_{max} 3 m or less and define freak waves as only the cases with very large H_{max}'s, because many freak waves are known to have happened in very mild conditions and also have had tragic repercussions. Mariner's logs show that abnormaly large waves occur with little prior warning and appear to »come out of no-where« (*e.g.* Fisheries and Oceans Canada, 2002).

What we have found here suggests that while a Draupner-like wave profile, regardless of the size of its significant wave height, have been generally considered as a rare case of freak waves, it is clearly happening much more frequently than rare. It happens not only in severe storm conditions but also in moderately calm ocean surfaces as well. If this awareness bears out, as it can be done easily from the vastly available wave data in the world, then we may face an immediate need to revisit our long held conventional concept that the wind wave process is a stationary Gaussian random process, which basically invalidates the frequent occurrence of freak waves.

5. The Peril of Conventional Wisdom

The finding of a sizeable number of freak wave cases in Campos Basin is really a surprising development to us. We did not expect to find more than just a handful. Conventional wisdom on wind waves tends to assert two preconceived notions that obviate this kind of outcome. In the first place, as noted before, freak waves are of rare occurrence, and there is no previous studies showing freak wave cases in South Atlantic Ocean. And secondly, buoy wave measurements are theoretically known to be incapable of measuring sharply peaked waves.

The results of what we actually learned, on the other hand, seem to have unwittingly cast off both of the two aforementioned conventional perceptions. We may even surmise the following pertinent consequences from our simple finding:

a). So long as no one knows how rare is rare in the occurrence of freak waves, we may just as well envision that the occurrence of freak waves can be in fact more frequent than rare;

b). Just because there is no known maritime disaster due to freak waves ever reported in the South Atlantic Ocean, it does not mean this area is free from freak waves; and

c). While theoretically one may question the adequacy of a buoy's response in extreme waves, in practice, freak waves have nevertheless been measured from buoy wave measurements.

So in brief, while reliance on a conventional approach can be prudent for seeking general bearings, it is by no means foolproof.

6. Analysis through Conventional Prospects

Along with the lack of specific freak wave measurement, there is also a conspicuous gap in specific means for analyzing freak wave cases. Here we present some results of basic wave data analysis regarding statistical and directional spectral parameters from familiar, conventional perspectives to explore freak wave implications.

6.1 Statistics connection

We start by taking a look at the relationship between the ratio $H_{max}/H_{1/3}$ and the statistical parameter of Kurtosis calculated from the time series data as shown in Figure 7. The cumulation of the plotted points show that they are somewhat correlated. Kurtosis generally measures the peakedness of the data. Janssen (2003) has suggested that Kurtosis is an important parameter for studying freak waves. Note that for a stationary Gaussian random process, which is conventionally presumed to be the process that characterizes ocean waves, Kurtosis will be identically equal to 3. Figure 7 shows clearly that in our collected freak wave cases, with very little exceptions, most of their Kurtosis are not equal to 3. Ostensibly freak waves are unlikely to be in compliance with the precedent of stationary Gaussian random process. So the conventional approach of wave spectrum analysis, which is primarily based on the assumption of stationary Gaussian random process, will not be apposite of yielding a substantive understanding and insight on the non-stationary freak wave processes as one might otherwise expect.

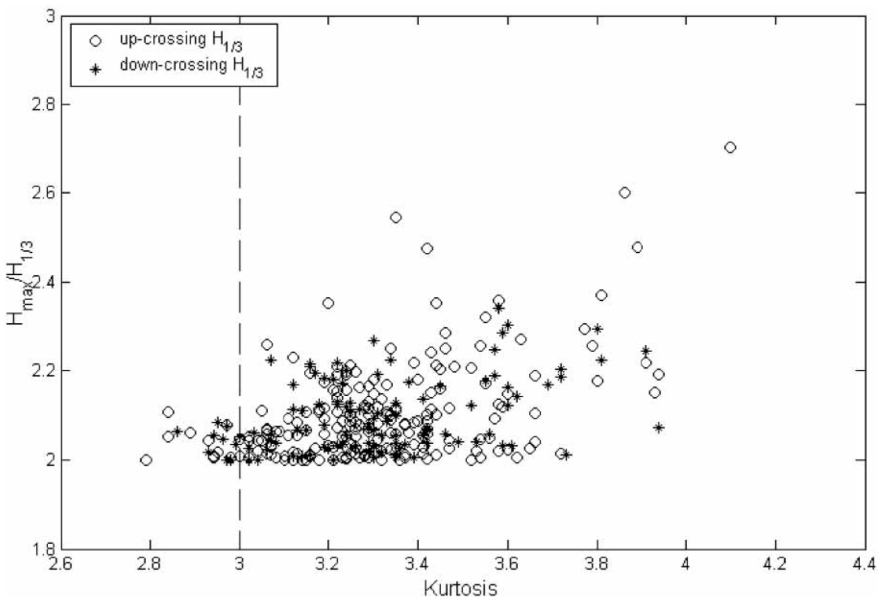

Figure 7. Occurrence of $H_{max}/H_{1/3} \geq 2$ ratio versus kurtosis.

6.2 Directional effects

The heave-pitch-roll buoy wave measurement readily provided us with directional information on the wave field. We choose to examine, in particular, the correlation of $H_{max}/H_{1/3}$ ratios with the directions of the spectral peaks in the data set and also with that of the corresponding directional spread as shown in Figures 8 and 9 respectively.

Local weather perceptions of the South Atlantic Ocean are generally to expect stormy weather over the Campos Basin when a cold front joints with extra-tropical cyclones from the southwest. Thus causing severe sea conditions in the region with SW waves with H_{mo} between 2 m and 3 m and peak period between 10 s and 14 s (Pinho, 2003). The good weather, on the other hand, is produced by the Anticyclone of South Atlantic (ASA) for which moderate northeast winds drive NE waves with H_{mo} usually between 1 m and 2 m and peak period between 5 s and 9 s. Correlation of the occurrence of $H_{max}/H_{1/3} \geq 2$ cases with the direction of spectral peak as plotted in Figure 8 show some indication of cases aggregated around the direction of spectral peak at 225 (SW) and 45 (NE) degrees. Thus we can surmise that freak waves tend to occur both in stormy and good weather conditions.

A further examination of the calculated directional spread for each data set in correlation with $H_{max}/H_{1/3}$ as well as Kurtosis are shown in Figures 9 and 10. While the directional spread was scattered rather evenly between 0 and 80 degrees, the higher congregations of $H_{max}/H_{1/3}$ and Kurtosis appeared to be clustered at the directional spread around 45 degrees. One might boldly interpret these results as the spreading waves actually yielding cross seas leading to the superposition of waves that produces larger wave heights – a

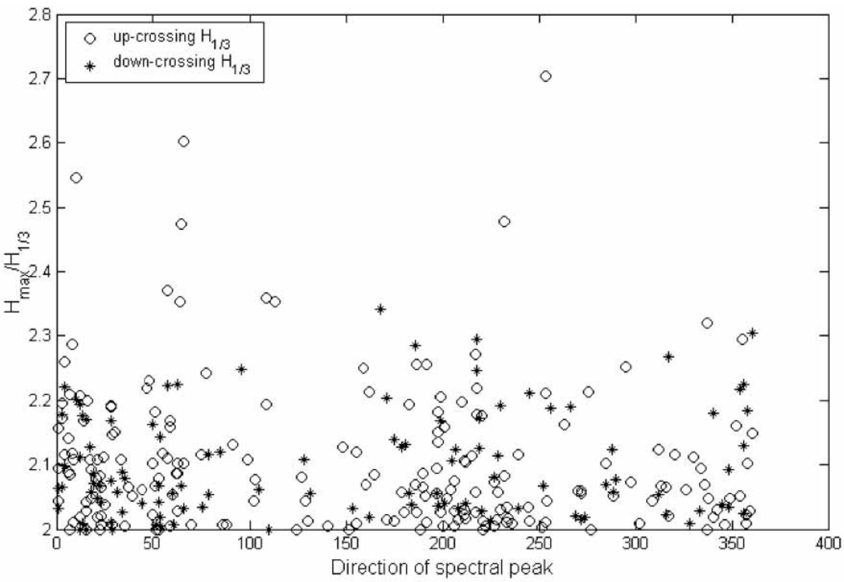

Figure 8. The occurrence of $H_{max}/H_{1/3} \geq 2$ cases versus their corresponding directions of spectral peak in degrees.

favorite scenario for the plausible explanation for how freak waves are generated.

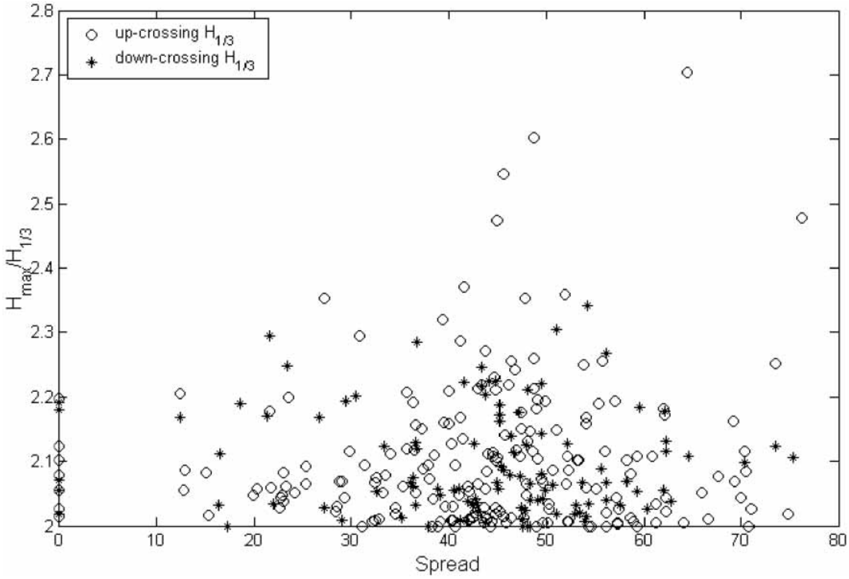

Figure 9. Relationship between $H_{max}/H_{1/3}$ ratio and directional spread in degrees.

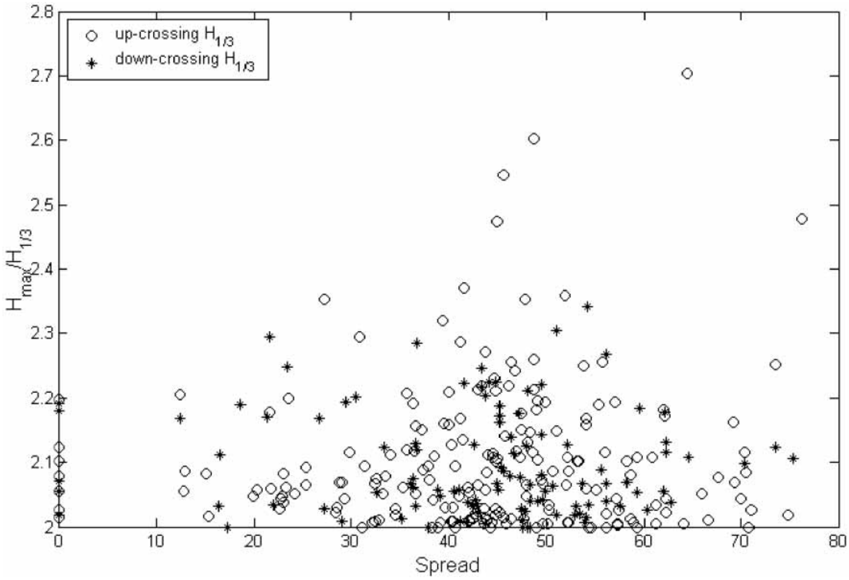

Figure 10. Relationship between kurtosis and directional spread in degrees.

6.3 Correlating with the peak-enhancement factor

One of the interesting speculations regarding conventional wave spectrum and freak waves is the implication of the peak-enhancement factor, γ, in the renowned JONSWAP spectrum formula. While the peak-enhancement refers to the shape of the empirical spectrum shape, it has been hypothesized that an existence of freak waves will increase the magnitude of γ. Now with our data and analysis, we have an opportunity to examine this presumption and show its falsehood.

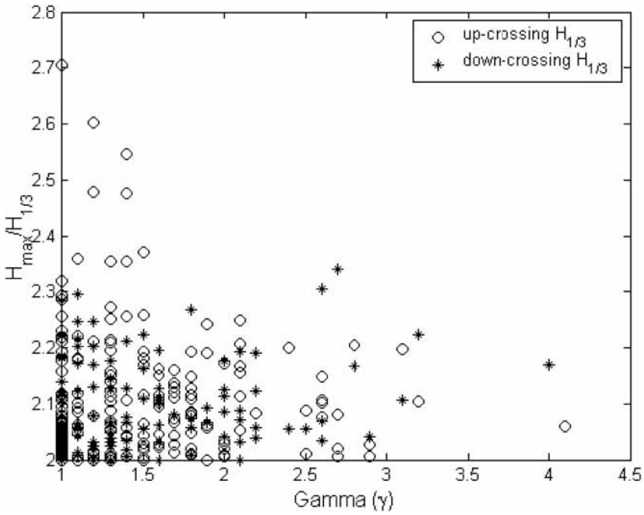

Figure 11. Spectral parameter γ and $H_{max}/H_{1/3}$ ratio.

Figure 11 presents the correlation of the $H_{max}/H_{1/3}$ ratio versus the peak-enhancement factor, γ. The scatters are rather unspecific at the first sight. We can make two inferences. First we see that most of the data points fall below the JONSWAP average of $\gamma = 3.3$, which is understandable since waves in the South Atlantic Ocean are not as fierce or ferocious as the famed North Sea waves. Secondly since all the data points shown here are the ones containing freak waves, their generally lower than average magnitudes dispute the contention that freak waves will enhance the magnitude of peak-enhancement factor, γ. As a matter of fact, some of the cases of high $H_{max}/H_{1/3}$ that imply stronger freak wave appearance, have low γ values closer to 1. On the other hand, a few of the high γ values actually correspond to rather low $H_{max}/H_{1/3}$ ratios. Something contradicts the allusive speculation. Here, again, another attempt to connect conventional wave energy spectrum with freak waves falls short.

6.4 The frequentness of occurrence

We have alluded earlier that the occurrence of freak waves is likely to be more frequent than rare. Recently Mori (2003) also recognized that freak waves appear to occur more frequently than what was expected from the Rayleigh distribution and developed a modified approach based on a weak non-Gaussian process. Mori formulated a rather complicated transcendental representation that can only be solved numerically. He resourcefully expressed his results in an interesting correlation of the normalized $H_{1/3}$ (*i.e.*, $H_{1/3}/\eta_{rms}$) versus Kurtosis as shown in Figure 12. We would like to call attention to the well known relation of $H_{1/3}/\eta_{rms} = 4$, which is effectively the representation of Rayleigh distribution as shown by the thin horizontal dotted line in the figure. Mori's modification is shown by the thicker solid curve showing an increasing $H_{1/3}/\eta_{rms}$ with respect to Kurtosis, which adheres to the Rayleigh distribution only at Kurtosis = 3. To test the theory, he conducted a laboratory experiment in a two-dimensional wave tank with waves generated by the deep water JONSWAP spectrum. The result of Mori's laboratory data is represented by the best fitting dashed line curve below the theoretical curve with a similar trend. We have proceeded to also plot the Campos Basin data on the same figure as the open circles and asterisks, for zero-upcrossing and zero-downcrossing cases respectively. Our data points appeared further below the fitted laboratory curve with the similar approximate trend again. As Mori indicated, his theoretical result represents an enhancement over Ray-

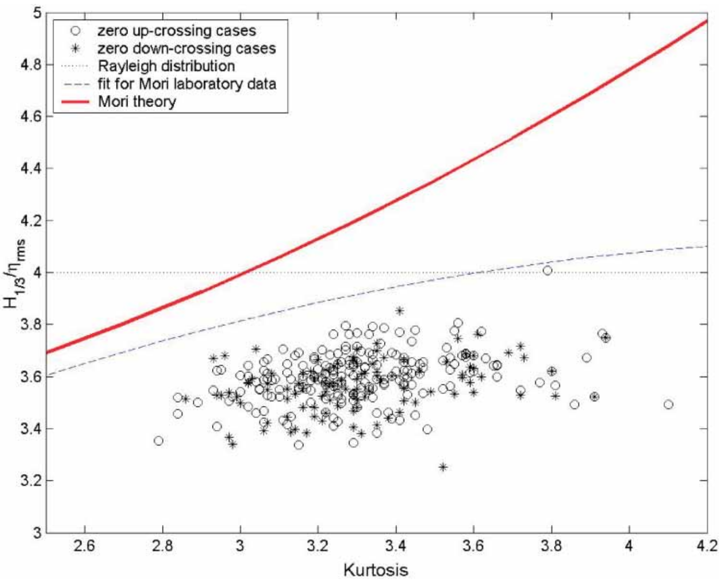

Figure 12. Relationship between kurtosis and normalized $H_{1/3}$ ($H_{1/3}/\eta_{rms}$).

leigh distribution in freak wave occurrence probability, conceivably his laboratory results show still more occurrences. We think a plausible interpretation of the results shown in Figure 12 would be that the natural progression from the Rayleigh distribution through Mori's modification and laboratory experiment to our oceanic results is qualitatively in the logical track of increasing frequency of occurrence of freak waves. Our results represent the reality of actual ocean processes, and certainly substantiate our contention that freak waves occur much more frequently than the rareness one usually concludes from the Rayleigh distribution hypothesis.

Concluding Remarks

We have presented a radical study of freak waves from a measured data set that was not intended for freak wave study per se. The study heralded some surprising and unexpected results that challenge most of the conventional perceptions on freak waves. As freak waves studies are still in the emerging stage, we hope that our results, while signaling divergence from the customary, can serve to stimulate further studies on analyzing available or making new measurements of ocean waves and developing new approaches that recognize freak waves as part of the sweeping ocean wave processes.

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SAŽETAK

Neobični valovi u akvatoriju Campos (Brazil)

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Neobični se valovi često pojavljuju u akvatoriju Campos, sjeveroistočno od Rio de Janeira (Brazil) u južnom Atlantiku. To iznenađujuće i neočekivano otkriće načinjeno je na osnovi vremenskih nizova prikupljenih valomjerima u akvatoriju Campos u razdoblju od 1991. do 1995. godine. Istražujući pojavljivanje neobičnih valova i njihove značajke utvrdili smo da ti valovi nisu tako rijetka pojava kako se obično pretpostavlja te da se javljaju ne samo za olujnih nevremena nego i kad su vremenske prilike stabilne. Premda uobičajena spektralna analiza daje neke informacije o neobičnim valovima, pristup baziran na pretpostavci stacionarnosti slučajnog procesa očito ne može cjelovito dokumentirati jedan takav lokalizirani nestacionarni proces kakav predstavljaju neobični valovi.

Ključne riječi: neobični valovi, oceanski valovi, analiza valomjernih podataka

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