Abnormal waves during Hurricane Camille

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[1] A reanalysis is reported of the wave time series recorded during Hurricane Camille having as objective the identification of individual waves that satisfy current criteria defining abnormal or freak waves. It is shown that during the hurricane development, a very nonstationary situation has occurred during which the second-order sea state parameters changed significantly with time. The parameters of the largest individual waves in sea states which identify abnormal waves did not show any clear trend, and such waves occurred during the development stage and not when the significant wave height was the largest. It is argued that the present criteria of identification of abnormal waves are not satisfactory, as they do not take into account the nature of the sea states in which the waves occur. *INDEX TERMS:* 4560 Oceanography: Physical: Surface waves and tides (1255); 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 4247 Oceanography: General: Marine meteorology; *KEYWORDS:* abnormal waves, freak waves, hurricane

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1. Introduction

[2] Much interest has been raised recently on the identification and understanding of the mechanisms that can generate unusually high waves. The nature of these waves is not completely understood and thus a definition of what should be considered a freak or an abnormal or episodic wave has not gained consensus. The mechanisms that can lead to these waves are not fully identified and understood. *White and Fornberg* [1998] and *Lavrenov* [1998] explained the appearance of the abnormal waves by a wave amplification due to current. *Kharif and Pelinovsky* [2003] modeled the temporal and spatial focusing as a result of the wind wave dispersion and of special distribution of its frequency. *Trulsen and Dysthe* [1996] and *Osborne* [2001] suggested that the Benjamin-Feir instability can cause breaking of a wave train into periodic groups, and further within each group a focusing takes place producing very large and steep wave. *Henderson et al.* [1999] also suggested nonlinear instability as a cause of the large waves.

[3] Independently of the generation mechanisms, the definition accepted by WMO and backed up by many experienced shipmaster's reports [*London Meteorological Office*, 1965] is "a very deep trough ahead a large wave." However, this is just a qualitative description and more quantitative definitions are required.

[4] *Dean* [1990] has considered that freak waves are those that occur within a sequence of waves that have been identified as being higher than can be expected from the Rayleigh distribution of wave heights. He noted that the most probable maximum wave in a record of about 2000 waves is about 2 times the significant wave height according to the Rayleigh distribution. Thus a freak wave in such a long record would need to have a height larger than that limit.

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[5] *Haver and Andersen* [2000] favor second-order wave theory as being more appropriate to describe several moderately nonlinear sea states and thus they define freak wave as one that goes outside the bounds predicted by second-order theory. *Hagen* [2002] calculated the probability of occurrence of a measured freak wave from the North Sea based on a Gaussian and even with a nonlinear model. He concluded that the probability would be extremely small. *Bitner-Gregersen* [2003] studied the same sea state and concluded that only assuming that it had lasted for 16 days would this lead to a reasonable probability of occurrence as predicted by a second-order wave model.

[6] *Guedes Soares et al.* [2003] have analyzed several records of storm waves measured in the North Sea and concluded that several observed abnormal waves have occurred in sea states that showed higher nonlinearities than the ones that could be explained by second-order theory. They concluded that a theory higher than second-order was necessary to explain the characteristics of these waves.

[7] In this state of knowledge the evidence that can be extracted from full-scale measurements is very useful to help identifying the characteristics of these waves and of the sea states in which they occur. Several papers have been published with this type of results showing waves that are identified when the ratio between maximum wave and significant wave (denoted here as the abnormality index (AI)) is above two. This value should be related to the duration of the record as noted by *Dean* [1990], but this aspect has not been generally retained.

[8] Other definitions are based on the ratio between the crest of the maximum wave and significant wave and different authors chose different level of this ratio. *Tomita and Kawamura* [2000] have chosen a combination of the two ratios while others [*Wolfram et al.*, 2000; *Clauss*, 2002] opt for combinations between the abnormality index and some other global wave parameters.

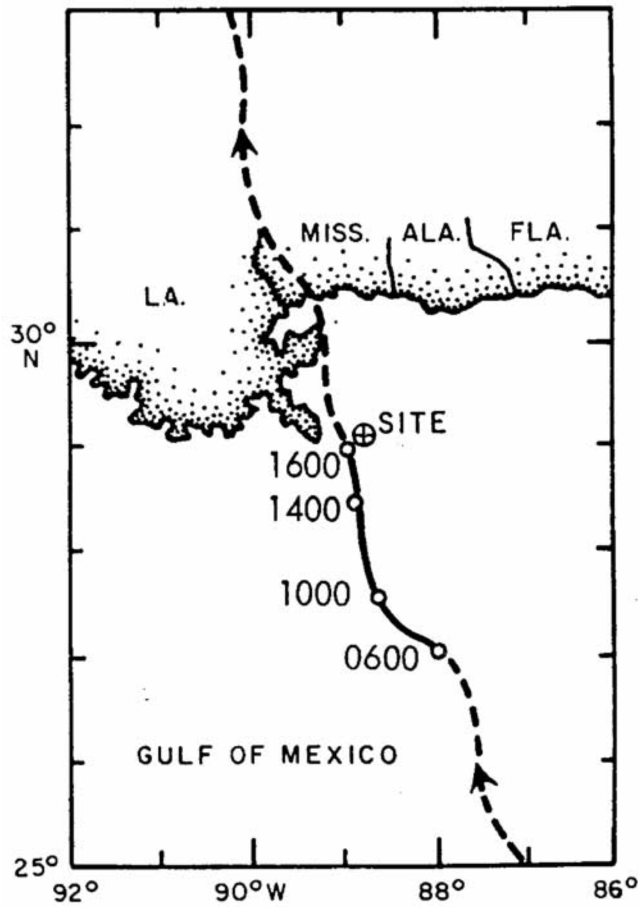

Figure 1. Measurement site and Hurricane Camille track [from *Earle*, 1975].

[9] The common approach is to accept that sea waves are described by a wave model either linear or nonlinear and then to look at different parameters whose values are predicted by those theories. The term freak or abnormal wave is given to the one that is larger than the ones that would normally be expected to occur under those conditions. It becomes clear that as one uses higher-order theories the boundary between what is considered "normal" or "abnormal" is changing.

[10] This paper reanalyzes the wave data from Hurricane Camille during which some exceptionally high waves have occurred. The main goal of this work is to identify the waves that occurred in this hurricane with very large values of some relevant parameters and to correlate them with the characteristics of the sea state in which they occurred. It is shown that the abnormal waves identified in this data set have occurred in sea states with high-order statistical moments larger than the ones predicted by second-order theory and closer to what would be expected in a third-order wave theory.

2. Time Evolution of the Hurricane

[11] Hurricane Camille, which occurred on 17 August 1969, was one of the most destructive hurricanes that crossed the coastline of the USA. It approached the Gulf coast along a relatively straight track and passed within 23 km from platform where a wave staff was measuring the waves, as shown in Figure 1 [*Earle*, 1975]. Several publications have been dedicated to Hurricane Camille [*Thom and Marshall*, 1971; *Murray*, 1970; *Forristall*, 1974; *Earle*, 1975; *Earle et al.*, 1974] describing different features of the phenomenon.

[12] The wind waves were measured by an inductance wave staff and later were digitalized at a 0.5 s rate. The data available was a continuous one until the moment that the wave staff was broken by the wave loading.

[13] As the parameters that identify the abnormal waves are given by the ratio of the wave height or the crest height by a significant wave height, it might happen that in the very nonstationary situation associated with this hurricane the ratio might become large just because the wave was occurring at one of the extremes of a time interval with otherwise lower waves. Therefore instead of splitting the time period in a series of nonoverlapping sea states, a moving average was considered to calculate the significant wave height.

[14] Data analysis was made assuming that process is stationary during each 17 min subinterval record. The possible linear trend in each time series is taken off. Every one of these subrecords has length of N = 2048 samples and is shifted in n = 128 samples to the right from the previous one. So the largest maximum waves are translated gradually from the end of the first to the beginning of the last file from the group of at least Q = 16 subrecords.

[15] The waves were defined using the down-crossing definition and crests and troughs of the waves were also determined. Significant wave height is estimated as the average of the highest one third of the zero down-crossing H_{sd}, or upcrossing H_{su} waves, respectively. Here the subscript d indicates estimation using down-crossing definition and the subscript u means upcrossing definition. The significant wave height from spectrum is calculated as $H_{ss} = 4\sqrt{m_0}$, where m_0 is the variance of the spectrum. As *Forristal* [1978] mentions, the $H_{1/3}$

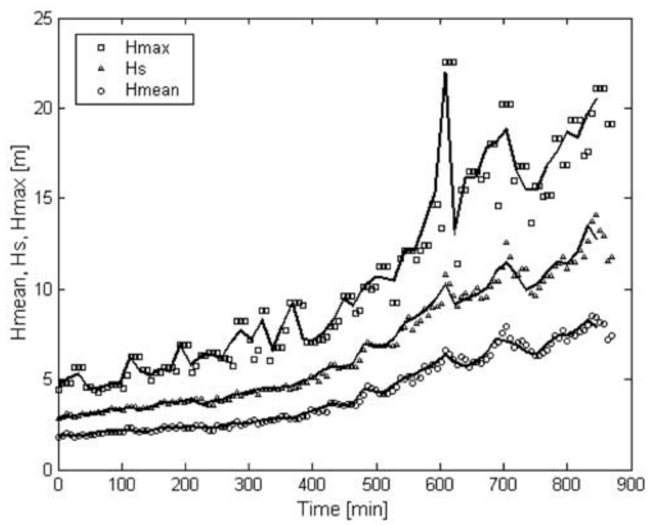

Figure 2. Time development of wave height characteristics during Hurricane Camille and moving average trend.

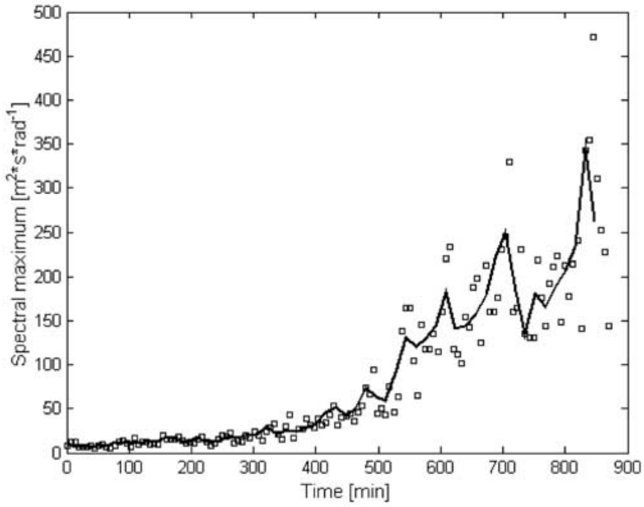

Figure 3. Time development of the spectral maximum, showing individual estimates and moving average trend.

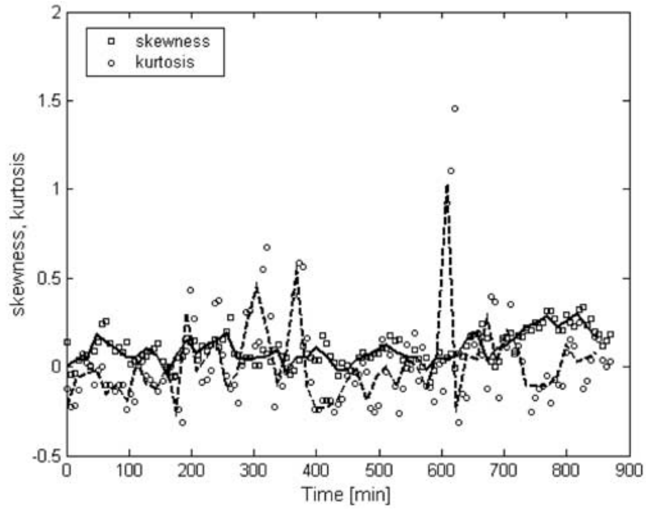

Figure 5. Time development of the coefficients of skewness and kurtosis, showing individual estimates and moving average trend.

definition of significant wave height gives usually about 5% lower values than the definition from the spectrum. The results of *Guedes Soares et al.* [2003] corroborate this conclusion.

[16] The wave records showed the development of the storm and thus a strong nonstationarity of the wind wave process was apparent during the hurricane. Some of the main wave characteristics and their development in time are presented in Figure 2. It can be seen in that figure that after 400 min all wave height characteristics change very quickly. Significant wave height for example grows about one meter every hour.

[17] The spectral peak, shown in Figure 3, grows rapidly too, although showing increased variability. The development of the waves is accompanied with changing of the peak frequency to the low frequencies as shown in Figure 4.

[18] The time development of the coefficients of skewness and kurtosis, which are related to the third and forth cumulants of the sea states, are presented in Figure 5. Because they are higher cumulants, their estimates exhibit larger variability than the other parameters. The coefficient of skewness, which should be zero in a Gaussian sea state, grows with time but in a steeper way during the second half of the period of investigation, as can be seen more clearly in the regression coefficients in Tables 1 and 2.

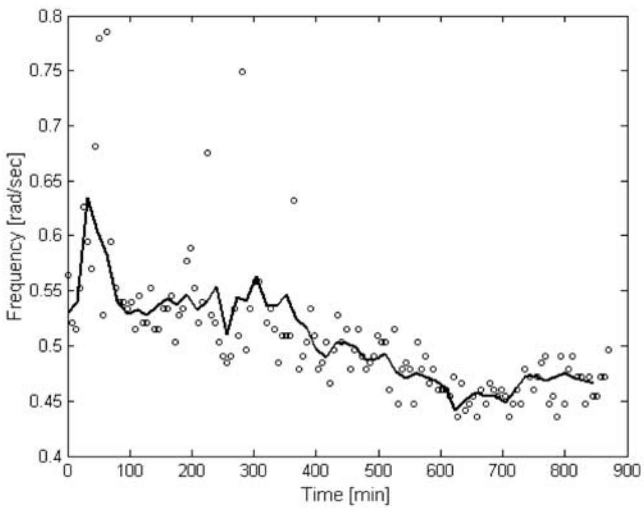

Figure 4. Time development of the spectral peak frequency showing individual estimates and moving average trend.

[19] The coefficient of kurtosis also shows some increase during the whole period. The coefficient of kurtosis should be zero (corresponding to a kurtosis of 3) in a Gaussian sea state, but, although it oscillates around zero, some peaks occur at some occasions and later in the paper these will be related with the largest waves that occurred in those sea states.

[20] The existence of the very large waves affects the statistics and the large values of coefficient of kurtosis are influenced by these occurrences. To assess how sensitive the higher-order statistics would be to the individual occurrences, the same analysis was repeated by calculating the sea state statistics during periods of 34 min instead of 17 min used in the reported results. The results show that the variability of the estimates is much reduced

Table 1. Statistics of the Parameters and Coefficients of the Regression on Time for the 900 min of the Time Series

				$y = a \times t + b$	
y	Mean	Standard Deviation	Coefficient of Variation, %	a	b
Signal height	6.690	3.21	48.1	0.01	1.35
Spectral maximum	85.98	89.60	104.2	0.31	−46.83
Peak frequency	0.51	0.06	11.0	−1.44	0.57
Coefficient of skewness (17 min)	0.10	0.09	87.8	1.55	0.03
Coefficient of kurtosis (17 min)	0.014	0.25	1781.5	1.44	−0.05
Coefficient of skewness (34 min)	0.10	0.08	76.2	1.57	0.03
Coefficient of kurtosis (34 min)	0.04	0.18	509.8	1.85	−0.04

Table 2. Statistics of the Parameters and Coefficients of the Regression on Time for the Last 500 min of the Time Series

y	Mean	Standard Deviation	Coefficient of Variation, %	$y = a \times t + b$ a	b
Signal height	9.41	2.18	23.1	0.02	−0.99
Spectral maximum	152.39	81.47	53.5	0.49	−165.34
Peak frequency	0.47	0.02	4.8	−6.97	0.52
Coefficient of skewness (17 min)	0.12	0.10	81.7	5.95	−0.26
Coefficient of kurtosis (17 min)	0.03	0.27	1031.8	3.00	−0.17
Coefficient of skewness (34 min)	0.13	0.09	72.5	6.22	−0.27
Coefficient of kurtosis (34 min)	0.07	0.20	307.9	2.71	−0.11

in particular in the case of coefficient of kurtosis, but the trends are unchanged.

3. Characteristics of Individual Waves

[21] The characteristics of individual waves are described using different definitions of steepness. The common definition is:

$$s = \frac{H}{1.56T^2},$$

where H and T are respectively the height and the period of the wave. This definition is not able to describe any asymmetry that may exist in the wave.

[22] As often these waves are asymmetric, it is useful to define also the coefficient of front steepness [*Guedes Soares et al.*, 2004]:

$$s_f = \frac{H_d}{9T_{fr}^2},$$

where T_{fr} is the time interval between the lowest and the highest point of the down-crossing wave and H_d is the height of the wave defined between the down-crossing points.

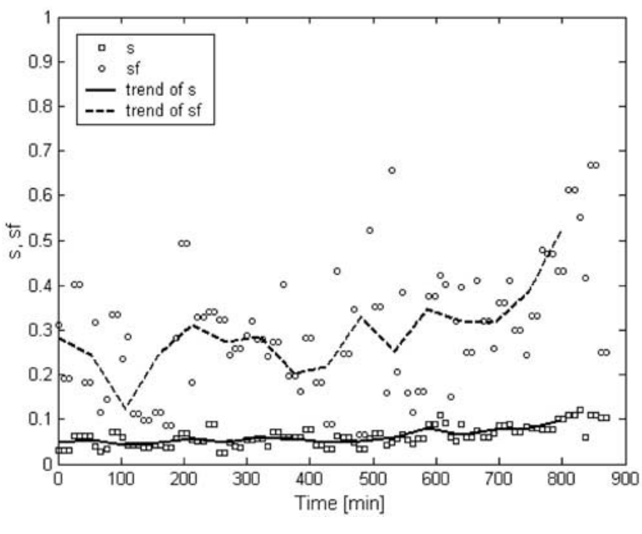

Figure 6. Time development of steepness s and coefficient of front steepness during Hurricane Camille.

Table 3. Statistics of the Parameters and Coefficients of the Regression on Time for the 900 min of the Time Series

y	Mean	Standard Deviation	Coefficient of Variation, %	$y = a \times t + b$ a	b
Steepness	0.01	0.0035	35.3	0.09′10-4	0.01
Front steepness	0.05	0.0224	47.9	0.38′10-4	0.03
Back steepness	0.04	0.0196	48.0	0.17′10-4	0.03

[23] The coefficient of crest back steepness is given by

$$s_b = \frac{H_u}{9T_{bc}^2},$$

where T_{bc} is the time interval between the highest and the lowest point of the upcrossing wave and H_u the height of the wave between upcrossing points [*Guedes Soares et al.*, 2004].

[24] Figure 6 shows how these individual characteristics of the maximum waves occurring in each 17 min period develop in time. It can be seen that s and s_f have a tendency to grow with time during the hurricane. The trend of s_b was similar to s_f and is not shown not to overcrowd the figure.

[25] Tables 3 and 4 show statistics from the parameters plotted in Figure 6, where it is easy to see that in general the regressions show a steeper increase of significant wave height, spectral maximum and front steepness of the waves, while the peak frequency decreases.

[26] It is interesting to note that the rate of change of coefficient of kurtosis and wave steepness do not change much in the two periods of reference and the wave back steepness even has a smaller tendency to increase in the second period of interest, when the storm intensity was increasing very quickly. It is also worth mentioning that the coefficients of variation of the coefficients of skewness and kurtosis are significantly higher that the other quantities as one would expect from being related with the third and forth statistical moment of the data. However, in most cases the coefficient of variation decreases because the increase of the mean is larger than the increase in standard deviation.

[27] For the identification of abnormal waves the interest is focused on waves that have abnormality index (AI) bigger than two, where AI is defined as the ratio between the maximum wave height and the significant wave height in the record. Usually a wave with AI > 2 when it exists, is only one in the subrecord and it is the maximum wave. However, most of the maximum waves, denoted with the subscript mw will not reach that value of the parameter.

Table 4. Statistics of the Parameters and Coefficients of the Regression on Time for the Last 500 min of the Time Series

y	Mean	Standard Deviation	Coefficient of Variation, %	$y = a \times t + b$ a	b
Steepness	0.01	0.0035	30.6	1.92	−0.0011
Front steepness	0.05	0.0245	45.2	8.81	−0.0031
Back steepness	0.04	0.0163	37.1	2.30	0.0290

Table 5. Time Series With Abnormal Wave Using Down-Crossing Definition (First Three) and Upcrossing Definition (Last Four)

Items	$\frac{H_{mwd}}{H_{sd}}$	$\frac{H_{mwd}}{H_{ss}}$	$\frac{H_{mwu}}{H_{su}}$	$\frac{H_{mwu}}{H_{ss}}$	γ_3	γ_4
File 20, 1982						
Mean	1.98	1.83	1.81	1.66	0.0556	0.4604
95% Confidence Intervals	2.01	1.86	1.83	1.69	0.0658	0.5857
	1.95	1.80	1.79	1.64	0.0453	0.3352
File 23, 1732						
Mean	2.04	1.86	1.73	1.60	0.0396	0.5718
95% Confidence Intervals	2.06	1.88	1.75	1.62	0.0690	0.6085
	2.02	1.84	1.71	1.58	0.0102	0.5351
File 37, 1911						
Mean	2.18	2.10	2.28	2.17	0.0421	1.1071
95% Confidence Intervals	2.22	2.13	2.32	2.20	0.0541	1.2032
	2.14	2.07	2.24	2.14	0.0302	1.0110
File 13, 1337						
Mean	1.85	1.72	2.02	1.90	0.1500	0.2810
95% Confidence Intervals	1.83	1.71	2.00	1.88	0.1594	0.3358
	1.86	1.73	2.03	1.91	0.1406	0.2261
File 16, 614						
Mean	1.76	1.62	2.18	2.01	0.1376	0.2633
95% Confidence Intervals	1.80	1.65	2.23	2.05	0.1513	0.3264
	1.72	1.58	2.14	1.96	0.1239	0.2002
File 41, 1938d, 1913u						
Mean	1.76	1.67	2.07	2.00	0.0185	0.3365
95% Confidence Intervals	1.79	1.68	2.10	2.01	0.0384	0.3694
	1.74	1.66	2.04	1.98	0.0072	0.3035

[28] There exist different definitions of waves as well as of significant wave height, depending on whether one uses the down-crossing or the upcrossing definition for waves. Four combinations between them are possible to calculate the abnormality index.

[29] In the whole data set 6 waves were identified as having large values of one or more of the abnormality index definitions and they are presented in Table 5. All characteristics in the table are normalized by their mean values over Q overlapping intervals and by their 95% confidence intervals respectively. The numbers of the files given in the first special row coincide with the consecutive numbers of the files without overlapping. Additionally the time of the largest crest is given in the same row too. The coefficients of skewness γ_3 and kurtosis γ_4 of the time series are presented in the last two columns.

[30] In the first three rows are shown waves with AI > 2, using the down-crossing definition. In the last four rows are files having AI > 2 using the upcrossing definition. The high wave in record 41 is due to very deep trough between two high waves. In this case they are the maximum waves defined both by the upcrossing and down-crossing definitions.

[31] Only record 37 has abnormality index bigger than two according all definitions. It should be noted that the coefficient of kurtosis of this time series is the largest one. The high waves registered in files 16 and 41 coincide with high waves mentioned by *Earle* [1975]. The high wave in file 13 belongs to the subinterval outside of the time period investigated by *Earle* [1975]. The waves of these six time series are presented in Figure 7.

[32] *Tomita and Kawamura* [2000] use one additional condition to define what they call a "genuine freak wave."

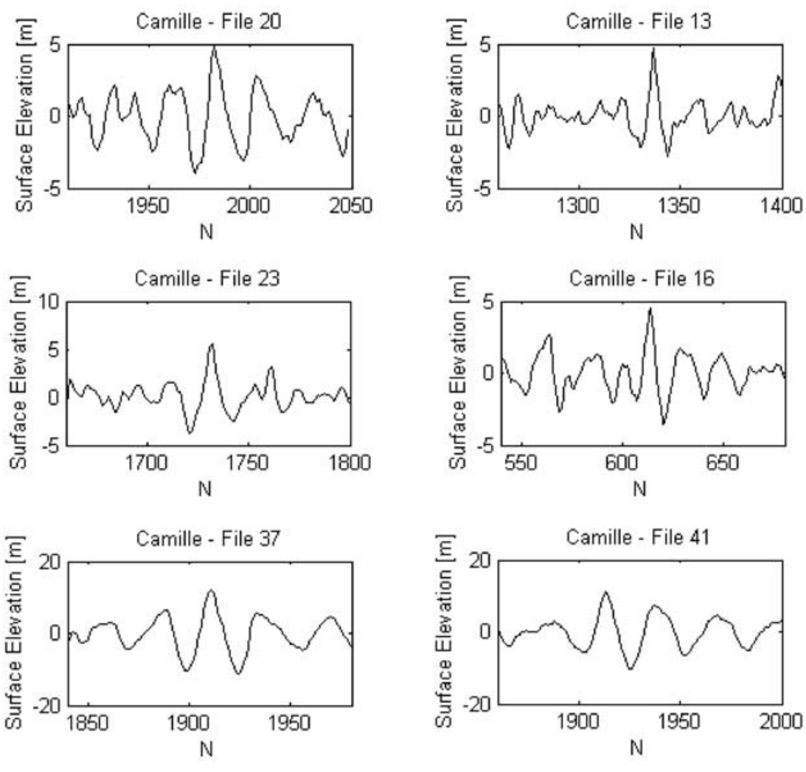

Figure 7. Maximum waves with AI > 2 using different definitions.

Table 6. Parameters of Largest Individual Waves

Items	$\frac{Cr_{mwd}}{H_{md}}$	$\frac{Cr_{mwd}}{H_{sd}}$	$\frac{Cr_{mwd}}{H_{ss}}$	$\frac{Cr_{mwu}}{H_{mu}}$	$\frac{Cr_{mwu}}{H_{su}}$
File 20					
Mean	0.551	1.009	1.090	0.607	1.101
95% confidence intervals		1.024	1.105		1.114
		0.994	1.074		1.087
File 23					
Mean	0.595	1.106	1.213	0.690	1.196
95% confidence intervals		1.118	1.226		1.210
		1.094	1.200		1.181
File 37					
Mean	0.544	1.142	1.184	0.526	1.200
95% confidence intervals		1.159	1.208		1.223
		1.124	1.161		1.177
File 13					
Mean	0.691	1.191	1.277	0.628	1.267
95% confidence intervals		1.198	1.287		1.277
		1.183	1.268		1.258
File 16					
Mean	0.698	1.131	1.231	0.563	1.229
95% confidence intervals		1.157	1.256		1.256
		1.105	1.204		1.203
File 41					
Mean	0.418	0.736	0.697	0.533	0.723
95% confidence intervals		0.694	0.677		0.681
		0.778	0.716		0.766

According to their definition, the ratio between the crest and the significant height of the candidate for freak wave has to be larger than 1.3, in addition to the condition AI > 2. This means that the maximum wave must have a large vertical asymmetry due to a large crest.

[33] This definition excludes the maximum waves that have very deep trough between them like the waves in file of 41. The first maximum wave with an upcrossing definition has a height of 21.58 m. The next wave, with a down crossing definition, is 18 m high. The trough between crests is 10.50 m deep. This is an example of an abnormal wave using the definition adopted by WMO as mentioned by *Haver and Andersen* [2000]. Even if this case is not an abnormal wave, it is surely dangerous for any platform or ship at sea.

[34] The ratios between crests of the maximum waves and significant wave heights were determined too and are shown in Table 6. No one of the chosen waves obeys the definition of *Tomita and Kawamura* [2000] for genuine freak wave. On the other hand *Clauss* [2002] defines an abnormal wave by: $H_{\max} = 2H_s$ and $Cr = 0.6H_{\max}$. Using this definition, all waves except that from file 37 are abnormal.

4. Criteria to Identify Abnormal Waves

[35] While it is possible to identify the waves that satisfy quantitative criteria like the ones mentioned, it continues being unclear which waves to define as "normal" and "abnormal." The parameters generally used were determined having as reference the values expected by a sea state that follows the Rayleigh distribution and has a given duration. However, waves that do not satisfy that criterion may be considered "normal" if the wave theory considered is of second order. However, the analysis of the Camille data indicated that while many sea states may conform to the second-order theory, there are three cases for which probably only a third-order theory would be appropriate.

[36] *Guedes Soares et al.* [2004] have discussed this topic and stressed that the coefficients of skewness and kurtosis of sea states could be used to characterize their degree of nonlinearity. For processes of any type which are nonlinear of second and third order at the same time it is impossible to choose the coefficients of skewness and kurtosis independently from each other and there is a range of possible values.

[37] While in a Gaussian sea state both coefficients should be zero, in a second-order theory the coefficient of kurtosis is zero while in a third-order theory skewness may be zero. Figure 8 plots the sea states in which the largest wave was larger than 8 m and steepness was larger than 0.04. It can be observed that most sea states have coefficient of kurtosis varying between −0.2 and 0.2, which could be interpreted as the statistical variability of the estimation process of sea states that could follow second-order theory, i.e., with zero coefficient of kurtosis and with coefficient of skewness different from zero.

[38] In fact, the statistics of Table 1 and 2 show that for the whole period the average coefficient of skewness is 0.10, while the average coefficient of kurtosis is 0.014, although in the last period of the storm these values increase to 0.12 and 0.026 respectively. There are, however, three sea states in Figure 8 that have coefficients of skewness close to zero and coefficient of kurtosis around 0.8, which would indicate that they could follow third-order theory. It happens that these are the sea states that contain the three largest waves in the Camille time series analyzed here.

[39] Therefore if these waves occur in third-order sea states and if they would be considered normal in light of this theory then a new definition of abnormal waves would be required. It should also be noticed that these waves have occurred at time equal to 340, 390 and 630 min which correspond to peaks of kurtosis in Figure 5. Inspecting Figure 2, it is apparent that these waves occurred during the developing phase of the hurricane and not at the end of the record, when there was the largest Hs. This reinforces

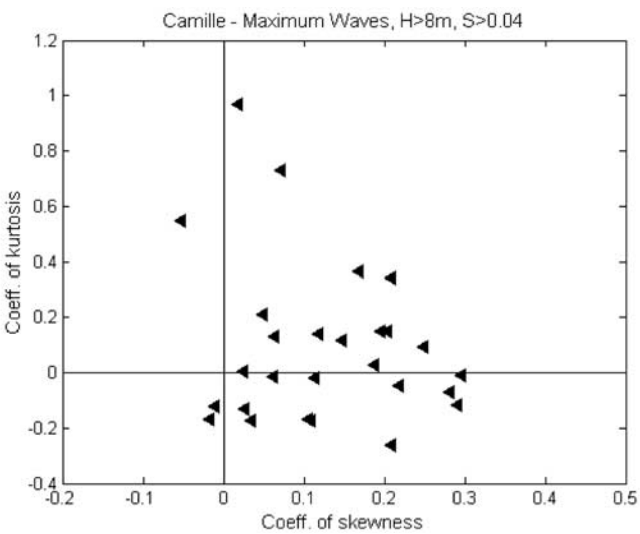

Figure 8. Relation between the coefficients of skewness and kurtosis for sea states during Hurricane Camille.

the belief that these waves do not occur necessarily at the sea states with the highest Hs in a storm.

5. Conclusions

[40] Individual waves that occurred during Hurricane Camille were analyzed and several waves with AI > 2 were found. Depending on whether upcrossing or down-crossing definition of waves is adopted the waves that satisfy the above inequality of the abnormality index are different ones. The time series containing these high waves have the largest kurtosis.

[41] A strong wave nonstationarity occurred during the hurricane development, which can be clearly seen for the significant wave height, the maximum of the spectral peak and its frequency, and the steepness of the maximum wave in each time series. However, the coefficients of skewness and kurtosis of the sea states did not show any clear trend with time although the coefficient kurtosis exhibited a large variability.

[42] It was shown that while it is possible to identify waves that have high values of some parameters like the ratios between maximum wave heights or its crest height and significant wave height, these ratios are not enough to define an abnormal wave. In fact these parameters alone do not reflect the nonlinear and nonstationary characteristics of the sea states in which the individual abnormal waves occur.

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