INTENSITY AND DURATION OF SEA STORMS OFF THE CALIFORNIAN COAST

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Abstract: Based on the equivalent triangular storm (ETS) model, Boccotti (2000) obtained the analytical solutions for the return period of a sea storm in which the maximum significant wave height exceeds a fixed threshold, and for the mean persistence of the significant wave height above a fixed threshold.
In this paper these analytical solutions have been particularized assuming the three parameters Weibull distribution for the significant wave height and the exponential regression base-height of the ETS; the latter distributions have been estimated by using the data of some NOAA buoys moored off the Californian coast.
In particular the directional distribution of the significant wave height has been obtained in order to predict the intensity of severest sea storms for fixed wave directions.
Finally, the prediction based on the ETS model has been compared to the prediction obtained by applying the total sample method.

INTRODUCTION

A bi-parametric analysis of sea storms is undertaken by applying the *equivalent triangular storm* (ETS) model (Boccotti, 2000). According to the ETS model, a triangle is associated to each actual sea storm: the triangle height and base represent respectively the intensity and the duration of the sea storm. In particular the intensity of the ETS is fixed equal to the maximum significant wave height during the actual storm. The duration of the ETS is such that the maximum expected wave height during the actual

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storm (Borgman, 1970, 1973) is equal to the maximum expected wave height during the ETS.

The analytical solutions for the return period of a sea storm in which the maximum individual wave exceeds a fixed threshold, have been derived by applying ETS model: in particular Boccotti (1986, 2000) obtained the return period $R(H)$ of a sea storm in which the maximum wave height exceeds the fixed threshold *H*.
Recently Arena (2001) derived the non-linear return period $R(C)$ of a sea storm in which the maximum crest height exceeds the fixed threshold *C* (the non-linear $R(C)$ is calculated assuming the second-order crest height distribution). These solutions solve the problem of the prediction of extreme individual waves.
Moreover, Boccotti (2000) obtained the analytical solution for the return period $R(H_s > h)$ of a sea storm in which the maximum significant wave height (H_s) exceeds the fixed threshold h, and for the mean persistence $D(h)$ of H_s above the threshold *h* (in the storms where this threshold is exceeded).

Both the $R(H_s > h)$ and the $D(h)$ depend upon two functions: the distribution of the significant wave height, and the function $\bar{b}(a)$; the latter defines the average value of the bases of the triangles (ETS) having height equal to *a*.

In this paper we have analyzed the data of some NOAA buoys moored off the California. In order to evaluate the values of $R(H_s > h)$ and of $D(h)$, the lower-bounded three parameters Weibull model has been assumed for the significant wave height distribution; $\bar{b}(a)$ is estimated by an exponential regression, according to Boccotti (2000).

Furthermore a directional analysis for the prediction of the extreme storms has been done, for the directional NOAA buoy 46042 off the California. For this purpose the directional probability of exceedance of the significant wave height $P(H_s > h; \theta_1 < \theta < \theta_2)$ is obtained; the latter is the probability that the significant wave height is larger than *h* when the dominant wave direction is within the range (θ_1, θ_2) (sectors with 20° amplitude have been considered). Therefore the directional return period $R(H_s > h; \theta_1 < \theta < \theta_2)$ is obtained: this is the return period of a sea storm in which the maximum significant wave height H_s exceeds the fixed threshold *h* when the dominant wave direction is within the range (θ_1, θ_2).

Finally we have compared the $R(H_s > h)$ to the return period obtained by applying the total sample method. It is found that the total sample method overestimates the significant wave height for a fixed return period, according to the result of Van Vleddler et al. (1993): they obtained that the total sample method over-predicts the significant wave height obtained by applying the peaks-over-thresholds method (see also Goda, 1999). The total sample method is conservative because it assumes that the significant wave height has persistence of the H_s above the fixed threshold *h*, equal to the sampling rate Δt_{samp} (that is 1 hour for the NOAA buoys). In reality H_s remains above a fixed threshold *h* for many hours and its mean persistence decreases as *h* increases (Graham, 1982; Sobey and Orloff, 1999; Boccotti, 2000).

THE PROBABILITY OF EXCEEDANCE $P(H_s > h)$ OF THE SIGNIFICANT WAVE HEIGHT

The probability of exceedance $P(H_s > h)$ of the significant wave height at a fixed location is usually obtained from data of buoys, satellites, or hindcast. In particular from buoy or hindcast data, the $P(H_s > h)$ is obtained respectively at the fixed buoy location or at the grid node.

From satellite data we can derive the $P(H_s > h)$ for a fixed area; the area has to be small enough in order to be homogenous and in the same time large enough to contain a sufficient cross of the satellite (see Young, 1999; Arena and Barbaro, 1999; Boccotti, 2000).

The theoretical $P(H_s > h)$ distributions used to fit the samples in extreme data analysis have been investigated by many authors (some complete reviews were proposed by Isaacson and Mackenzie, 1981; Muir and El Shaarawi, 1986; Guedes Soares, 1989).

The Weibull model for the estimation of the extreme significant wave height has been widely applied (see Battjes, 1970; Burrows and Salih, 1986; Mathiesen and Bitner-Gregersen, 1990; Ochi, 1998; Boccotti, 2000; Arena and Barbaro, 1999).

In this paper the lower-bounded three-parameters Weibull distribution has been used: it fits well the extreme significant wave height off the Californian coast. The analytical expression of probability of exceedance is therefore given by:

$$P(H_s > h) = \exp\left[-\left(\frac{h-h_l}{w}\right)^u\right] \tag{1}$$

which is defined for $h \geq h_l$. The location parameter h_l and the scale parameter w have the same units as H_s; the shape parameter u is non-dimensional.

In order to estimate the parameters, an iterative procedure is considered (see Goda, 1999): for fixed values of the shape parameter u, the values of h_l and w can be evaluated by applying the least square method. We choose the value of u - and consequently the values of h_l and w - which maximizes the correlation coefficient between the sample data and the estimate distribution (the closer is the correlation coefficient to the unit the better is the fitting).

The NOAA buoys data

We have considered the data of the buoys 46059 and 46006 moored far from the coast and the data of the buoys 46022, 46014, 46042, 46023, 46054 moored close to the coast as well (see Figure 1). Figure 2 shows the $P(H_s > h)$ of two buoys plotted on a Weibull paper.

The parameters (u, w, h_l) of the $P(H_s > h)$ have been estimated for each buoy and are showed in Table 1.

THE SEA STORMS: THE EQUIVALENT TRIANGULAR STORM MODEL

A sea storm is a non-stationary process, with the wave spectrum and the significant wave height variable in time. In particular Boccotti (2000) defined sea storm '*a sequence of sea states in which the significant wave height exceeds the fixed threshold* $1.5\overline{H_s}$ *and does not fall below this threshold for a continuous time interval greater than 12 hours*', where $\overline{H_s}$ is the mean annual significant wave height on the examined site.

The statistical properties of waves in a sea storm have been investigated by Borgman (1973). He obtained the expression of the probability of exceedance $P(H_{\max} > H)$ of the maximum wave height in a sea storm, which is given by:

$$P(H_{\max} > H) = 1 - \exp\left\{ \int_0^D \frac{1}{\overline{T}[h(t)]} \ln[1 - P(H; H_s = h(t))] \mathrm{d}t \right\}, \qquad (2)$$

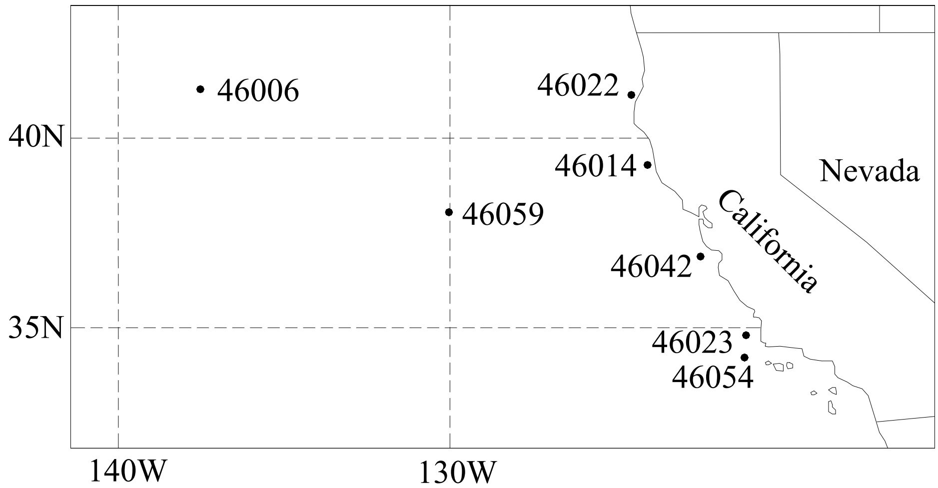

Figure 1. NOAA buoys off the California that have been analyzed.

Table 1. The Weibull distribution parameters (see equation 1), and the parameters of the equivalent triangular storms for the NOAA buoys showed in Figure 1.

NOAA Buoy	u	w [m]	h_l [m]	$\overline{H_s}$ [m]	K_1	K_2	a_{10} [m]	b_{10} [hour]
46006	1.31	2.12	0.8	2.8	1.335	-.440	9.1	59.5
46059	1.28	1.76	1.1	2.7	1.161	-.236	7.6	63.6
46022	1.25	1.47	1.0	2.4	1.398	-.474	6.5	54.7
46014	1.30	1.45	1.0	2.4	1.379	-.462	5.5	58.9
46042	1.33	1.28	1.0	2.2	1.409	-.459	5.6	60.6
46023	1.34	1.30	1.0	2.2	1.021	-.145	5.6	63.3
46054	1.35	1.21	1.0	2.1	1.681	-.695	5.2	61.8

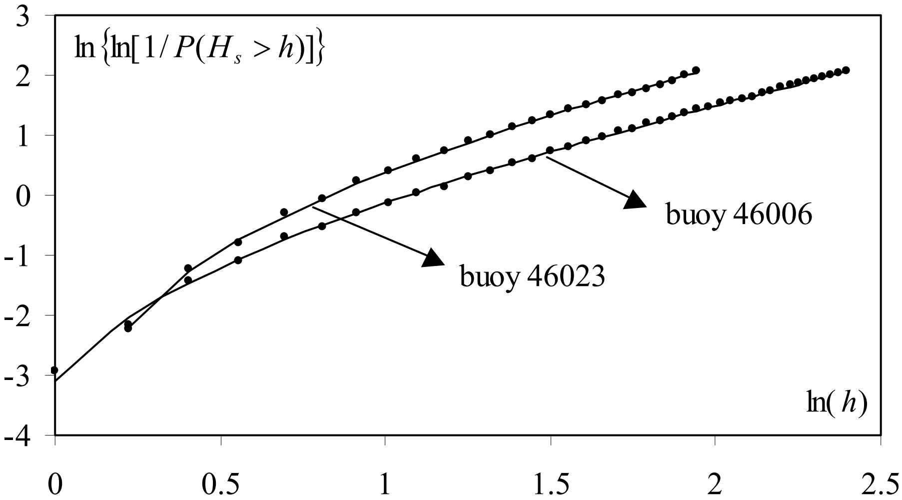

Figure 2. The probability of exceedance $P(H_s > h)$ of the NOAA buoys 46006 and 46023 plotted on the Weibull paper. Continuous lines: Weibull distributions (1) with parameters of Table 1.

where D is the storm duration, $h(t)$ is the significant wave height at the time t, $\overline{T}(h)$ is the mean period (Rice, 1944, 1945) and $P(H;H_s = h)$ is the probability of exceedance of the individual wave height in a sea state having significant wave height $H_s = h$.
The $P(H;H_s = h)$ is given by the Rayleigh law for an infinitely narrow spectrum (according to Longuet-Higgins, 1952) and it tends to the Weibull distribution for finite bandwidth (according to Boccotti, 1981, 1997, 2000).
Figure 3 shows some severe storms, recorded by the NOAA buoys moored off the Californian coast. For each storm the $P(H_{\max} > H)$ is obtained from equation (2).

The "equivalent triangular storm" model

Following the "equivalent triangular storm" (ETS) model by Boccotti (1986, 2000), we represent each actual sea storm with an equivalent triangular storm. The height *a* (that is the storm intensity) of the ETS is equal to the maximum significant wave height during the actual storm. The base *b* (that is the storm duration) is defined such that the maximum expected wave height of the actual storm is equal to the maximum expected wave height of the ETS. The maximum expected wave height during a sea storm is obtained by integrating the probability of exceedance $P(H_{\max} > H)$ [equation (2)] between the limits (0, ∞).
Figure 3 shows the ETS associated to each actual storm. Furthermore the $P(H_{\max} > H)$ for the actual storm and for the corresponding ETS are compared. According to Boccotti (2000) and Arena and Barbaro (1999) these two probabilities are very close to each other, and therefore we have a full equivalence between each actual storm and the associated ETS.
It is interesting to observe that the base of the equivalent triangular storm depends on the peak of the actual storm.

Smaller bases are order of few dozens of hours. Figure 3*a-b* shows two sea storms having a small base; let us observe that the smaller ETS duration are usually associated to an actual storm having the strongest peak very steep. (For steep peak we mean that the absolute value of the gradient of the function $H_s(t)$, before and after the strongest sea state, is very high.)

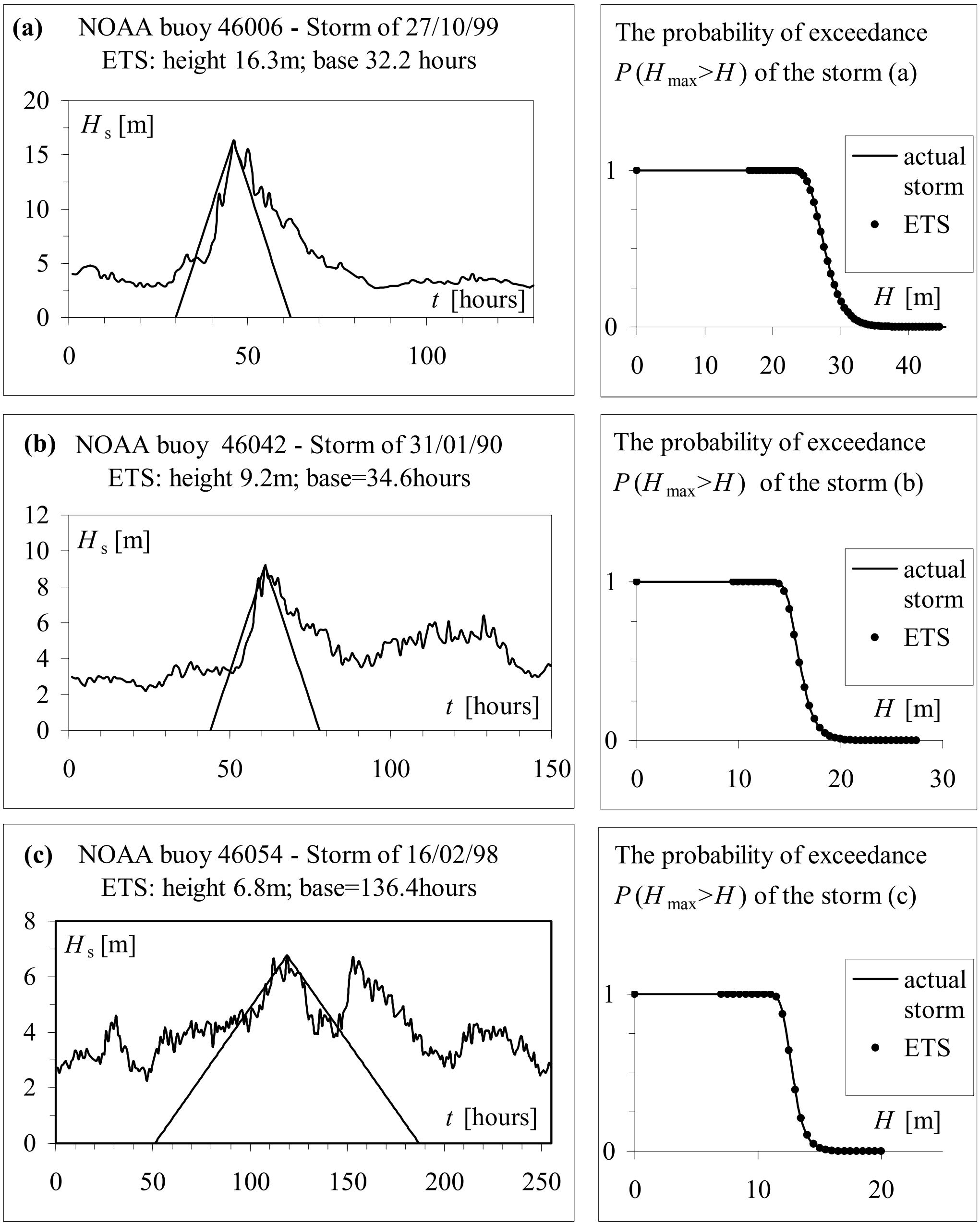

Figure 3. Some severe storms recorded off the Californian coast with the associated equivalent triangular storms (ETS). On the right panels are compared the probability of exceedance (2) of each actual storm and the $P(H_{max} > H)$ of the associated ETS.

Larger bases are order of 100-200 hours: they occur generally for a sea storm having the strongest peak with small steepness, or for a sea storm having many peaks with intensities very close to each other (see Figure 3*c*).

Extreme storms recorded off the Californian coast

The analysis of the sea storm recorded off the Californian coast has been performed. In particular, for each actual storm the height and the base of the equivalent triangular storm have been calculated. Some examples of ETS are showed in Figure 3. The severest storm is showed in Figure 3*a*: it was recorded by buoy 46006 and it had intensity of 16.3m and duration of 32.2hours.

Finally, the mean height a_{10} and the mean base b_{10} of the *N'* strongest ETS at the examined location are obtained for each buoy (*N'* is equal to 10 times the number of observation years). The values of a_{10} and b_{10} are showed in Table 1. As we can see, we find the highest values of a_{10} (and therefore the strongest storm) for the buoys 46006 and 46059 far from the coast (see Figure 1).

For the buoys close to the coast, a_{10} is generally smaller, as we can see from Table 1. From Table 1 we can see also that b_{10} (that is the mean duration of the strongest storm) is more uniform than a_{10}.

Storm duration

The storm duration can be estimated by using the exponential base-height regression proposed by Boccotti (2000) (see also Arena and Barbaro, 1999):

$$\overline{b}(a) = K_1 b_{10} \exp\left(K_2 \frac{a}{a_{10}} \right) \tag{3}$$

where K_1 and K_2 are characteristic parameters of the location (these parameters were estimated in the Central Mediterranean Sea, in the Northwest Atlantic Ocean and in the Northeast and Central Pacific Ocean – see Boccotti, 2000 and Arena and Barbaro, 1999).

Figure 4 shows the relation between the storm duration and the storm intensity for the NOAA buoy 46006. Each point in the figure represents an actual storm having intensity *a* and duration *b*.

The parameters K_1, K_2, a_{10} and b_{10} of $\overline{b}(a)$ for the examined locations off the Californian coast are showed in Table 1.

Effects of seasonality for the occurrence of severe storms.

In order to capture seasonal effects in the occurrence of severe storms, the data from buoys 46006 and 46059 have been analyzed. In particular by classifying the data by month and by season of occurrence, we have calculated the mean height $(a_1)_m$ and the mean base $(b_1)_m$ of the *N* strongest ETS recorded at the examined location during the month *m* (or the season *m*), being *N* the years number of observation.

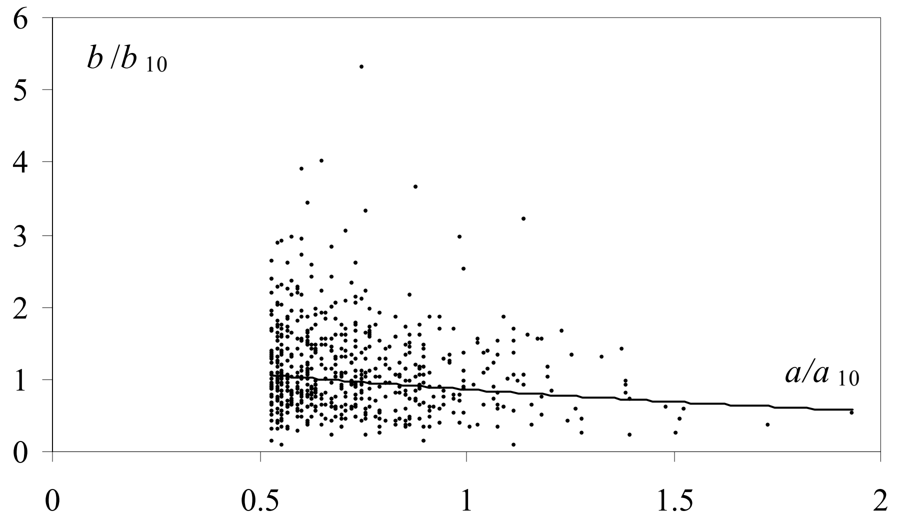

Figure 4. NOAA buoy 46006: the storm duration vs. the storm intensity, and the exponential regression (3).

Figure 5 shows the parameters $(a_1)_m$ and $(b_1)_m$ for the four seasons. Table 2 shows also the seasonal average number (per year) of storms having the maximum significant wave height greater than 4.5m. As we can see the strongest and more frequent storms occur during the winter and the autumn seasons. During the spring season both the intensity and the average number (per year) of storms are smaller. We have the smallest (a_1) value and the smallest mean number of storm (per year) during the summer (let us note that $(a_1)_m$ and $(b_1)_m$ for the summer season have been calculated for a number of storm that is smaller than the number N of years of record – compare to Table 2).
The seasonal effects are generally reduced for the storm duration as we can see by comparing the values of $(b_1)_m$ for the different seasons.
Finally Figure 6 shows the parameters $(a_1)_m$ and $(b_1)_m$ for the different months.

EXTREME SIGNIFICANT WAVE HEIGHT ANALYSIS: THE 'EQUIVALENT SEA' MODEL

The equivalent sea is obtained by substituting an equivalent triangular storm to each actual storm (Boccotti, 2000). In particular Boccotti obtained the analytical solutions for the return period $R(H_s > h)$ of a sea storm in which the maximum significant wave height exceeds a fixed threshold h and for the mean persistence $\overline{D}(h)$.

The return period $R(H_s > h)$

The general analytical expression of the $R(H_s > h)$ is (Boccotti, 2000)

$$R(H_s > h) = \frac{\overline{b}(h)}{h\, p(H_s = h) + P(H_s > h)}. \tag{4}$$

where $p(H_s = h)$ is the probability density function of the significant wave height.

Assuming the three-parameters Weibull distribution (1) for the significant wave height and the exponential regression for the $\bar{b}(h)$ [equation (3)], the equation (4) may be rewritten as

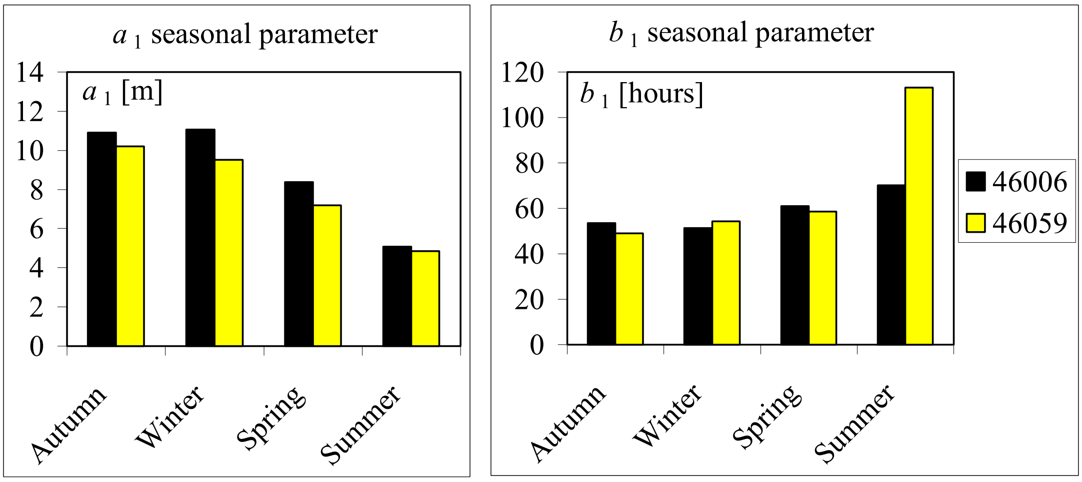

Figure 5. The seasonal parameters $(a_1)_m$ and $(b_1)_m$ for the buoys 46006 and 46059.

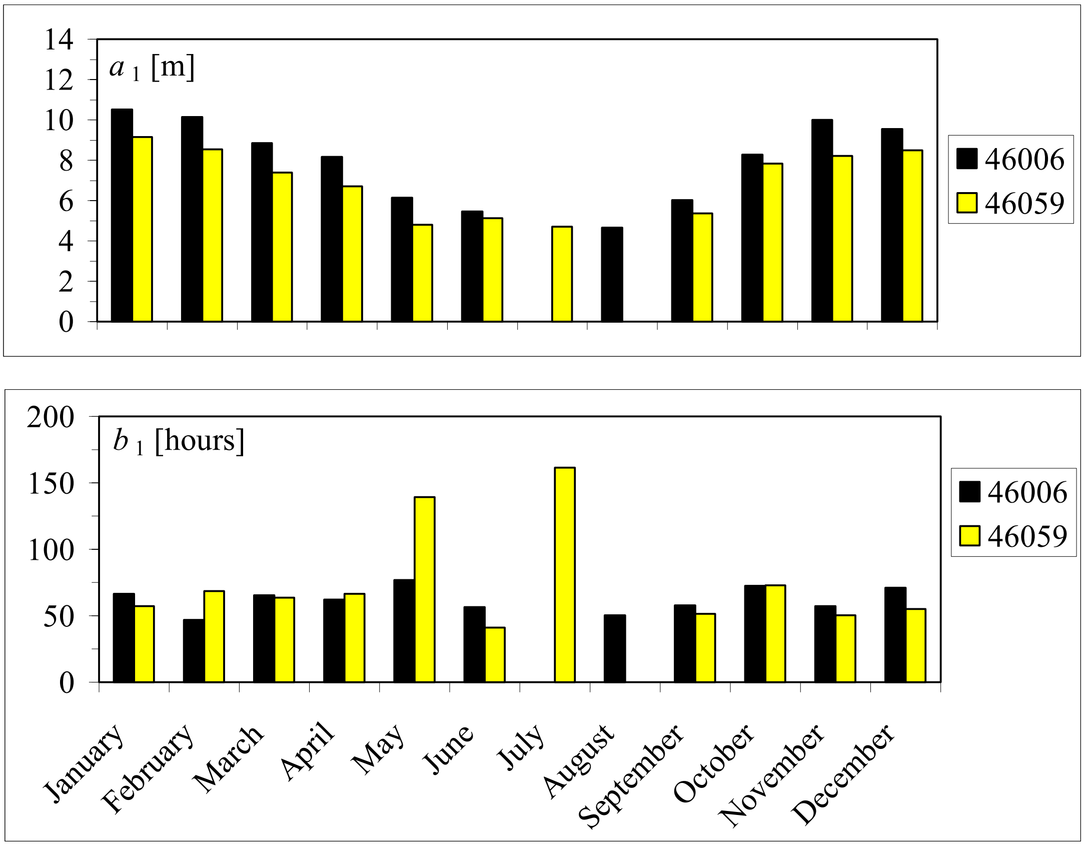

Figure 6. The monthly parameters $(a_1)_m$ and $(b_1)_m$ for the buoys 46006 and 46059.

Table 2. The seasonal average number per year of storms having the maximum significant wave height greater than 4.5m for the NOAA buoys 46006 and 46059.

	Autumn	Winter	Spring	Summer
46006	13.4	16.6	6.5	0.6
46059	12.0	13.1	6.1	0.7

$$R(H_s > h) = \frac{K_1 b_{10} \exp\left(K_2 \dfrac{h}{a_{10}}\right)}{1 + \dfrac{uh(h-h_l)^{u-1}}{w^u}} \exp\left(\frac{h-h_l}{w}\right)^u . \tag{5}$$

The return periods $R(H_s > h)$ for some locations off the Californian coast are showed in Figure 7. Table 3 shows also the significant wave heights for fixed values of the return period $R(H_s > h)$, calculated for the buoys of Figure 1.

The mean persistence $\overline{D}(h)$

The mean persistence of the significant wave height H_s above the threshold h in the storms where this threshold is exceeded, is given by the general expression (Boccotti, 2000):

$$\overline{D}(h) = R(H_s > h) P(H_s > h) . \tag{6}$$

Assuming the Weibull model for the $P(H_s > h)$ (equation 1) and the expression (5) for the $R(H_s > h)$, the mean persistence may be rewritten as

$$\overline{D}(h) = \frac{K_1 b_{10} \exp\left(K_2 \dfrac{h}{a_{10}}\right)}{1 + \dfrac{uh(h-h_l)^{u-1}}{w^u}} . \tag{7}$$

Some examples of the mean persistence $\overline{D}(h)$ off the Californian coast are showed in Figure 8.

PREDICTION OF THE EXTREME SIGNIFICANT WAVE HEIGHT: THE TOTAL SAMPLE METHOD

The prediction of the extreme significant wave height may be obtained by applying the total sample method. By analyzing the whole sample of significant wave height we obtain an analytic form of the cumulative distribution function (or equivalently of the probability of exceedance) that well fits the data. Therefore extrapolating the cumulative distribution function, or the $P(H_s > h)$, we may estimate the significant wave height for any fixed return period.

In particular, fixing a large time interval T, the term $\mathrm{T}P(H_s > h)/\Delta t_{\mathrm{samp}}$ defines the number of records during T in which the significant wave height is greater than *h*. Finally the return period $R_{ts}(H_s > h)$ of a sea state in which the significant wave height exceeds the threshold *h* is given by

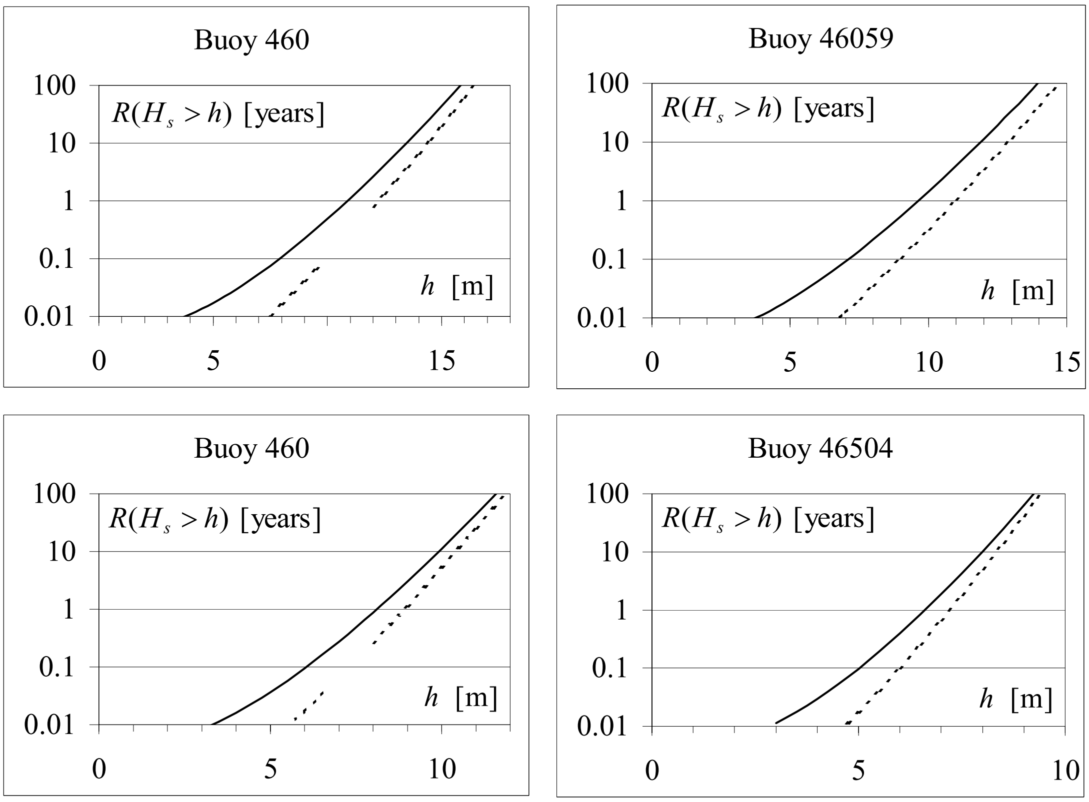

Figure 7. The return periods $R(H_s > h)$ for some buoys moored off the Californian coast. Continuous lines: 'equivalent triangular storm' model predictions (equation 5). Dashed lines: 'total sample' method predictions (equation 8).

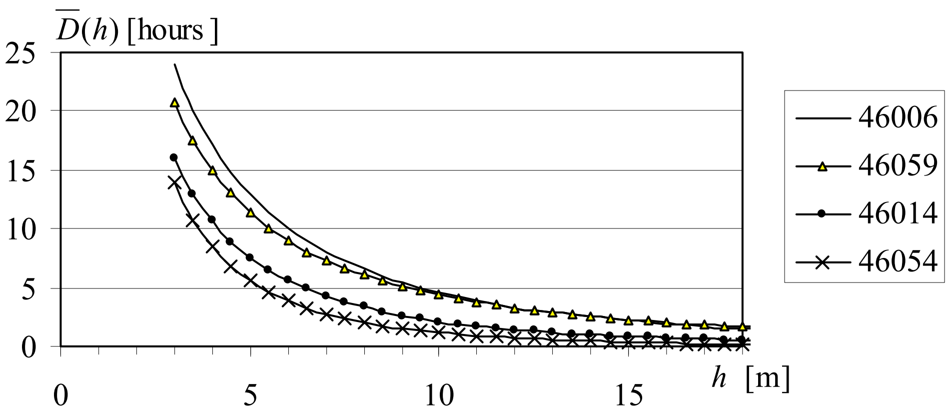

Figure 8. The mean persistence $\overline{D}(h)$ (equation 7) for some buoys moored off the Californian coast.

Table 3. The significant wave height for fixed values of the return period (the NOAA buoys of Figure 1 are considered). The predictions are obtained by applying either the Equivalent Triangular Storm (ETS) model (equation 5) and the total sample method (equation 8).

	R=10 years		R=100 years	
NOAA Buoy	ETS model	Total sample method	ETS model	Total sample method
46006	13.4 m	14.4 m	15.8 m	16.4 m
46059	11.9 m	12.8 m	13.9 m	14.7 m
46022	10.7 m	11.3 m	12.6 m	12.9 m
46014	9.9 m	10.4 m	11.6 m	11.8 m
46042	8.5 m	9.0 m	9.8 m	10.1 m
46023	8.3 m	9.0 m	9.7 m	10.1 m
46054	8.0 m	8.3 m	9.2 m	9.4 m

$$R_{ts}(H_s > h) = \frac{\Delta t_{\text{samp}}}{P(H_s > h)}, \tag{8}$$

where Δt_{samp} is the sampling rate of the H_s ($\Delta t_{\text{samp}} = 1\,\text{hour}$ for the NOAA buoys). The return periods $R_{ts}(H_s > h)$ are showed in Figure 7. In Table 3 the significant wave heights for fixed values of the return period $R_{ts}(H_s > h)$, obtained from equation (8), are compared with the predictions based on the ETS model.

A CRITICAL COMPARISON BETWEEN THE TOTAL SAMPLE METHOD AND THE EQUIVALENT TRIANGULAR STORM MODEL

The return period $R_{ts}(H_s > h)$ (equation 8) is obtained assuming that the mean persistence of the H_s above the fixed threshold h (in the sea storms in which this threshold h is exceeded) is equal to Δt_{samp}. In reality, the mean persistence is equal to dozens of hours for significant wave height close to the storm threshold $1.5\overline{H_s}$, and it decreases as h increases, as was pointed out by Graham (1982), Sobey and Orloff (1999) and Boccotti (2000).

As a consequence the total sample method tends to overestimate the extreme significant wave height during severe storms, as we can see from Figure 7 and from Table 3, where the predictions based on the ETS model have been compared to the total sample method predictions (let us note also that for the NOAA buoys, being Δt_{samp} =1 hour, the H_s data are not stochastically independent – see Goda, 1999).

For this purpose, besides the ETS model proposed in this paper, other models have been proposed to predict extreme waves: for example the annual maxima method, that analyzes the largest significant wave height in each year (an application was recently proposed by Winterstein et al, 2001) and the peak-over-threshold method (see Van Vledder et al. , 1993 and Goda, 1999).

EFFECTS OF DIRECTIONALITY FOR THE PREDICTION ON EXTREME SIGNIFICANT WAVE HEIGHT

The effects of the wave direction can be investigated by analyzing directional data. Firstly we need to estimate the probability of exceedance $P(H_s > h; \theta_1 < \theta < \theta_2)$ of the significant wave height for a given direction of the wave propagation [direction within the range (θ_1, θ_2)]. In order to estimate the probability $P(H_s > h; \theta_1 < \theta < \theta_2)$, Boccotti (2000 - see note) proposed the difference between two Weibull distributions as

$$P(H_s > h; \theta_1 < \theta < \theta_2) = \exp\left[-\left(\frac{h-h_l}{w_\alpha}\right)^u\right] - \exp\left[-\left(\frac{h-h_l}{w_\beta}\right)^u\right] \tag{9}$$

where the parameters w_α and w_β depend upon the sector selected, while u and h_l are the same parameters of the omni-directional $P(H_s > h)$. Let us note that, according to Boccotti (2000), equation (9) usually well fits the extreme directional significant wave height.

The parameters w_α and w_β have to be positive, with $w_\beta < w_\alpha \le w$ in order to verify the condition

$$P(H_s > h; \theta_1 < \theta < \theta_2) \le P(H_s > h) \quad \text{for any } h > h_l. \tag{10}$$

We have analyzed the data of the directional buoy 46042; the sample of data analyzed covers the last ten years, that is June 1991-May 2001.

Furthermore we have considered sectors with amplitude of 20°, and for each sector we have estimated the parameters w_α and w_β.

The analysis done reveals that the strongest sea states have dominant direction in a well-defined range. In particular the 95% of the sea states having $H_s > 1.5\,\text{m}$ has dominant wave direction between 235° and 335°, and the 96% of the sea states having $H_s > 6.0\,\text{m}$ has dominant wave direction between 265° and 305°.

Figure 9 shows the parameters w_α and w_β for some directional sectors. Let us note that the φ angle in abscissa is associated to the sector ($\varphi - 10°; \varphi + 10°$).

As we can see the strongest sea states have dominant direction between 295° and 315° ($\varphi = 305°$): it is the sector with the highest value of w_α.

Note: Boccotti (2000) proposed as fitting distribution for the $P(H_s > h; \theta_1 < \theta < \theta_2)$ the difference between two Weibull with two parameters. It is easy to verify that his procedure to obtain the parameters w_α and w_β may be applied also if $P(H_s > h; \theta_1 < \theta < \theta_2)$ assumes the more general form (9).

The directional return period $R(H_s > h; \theta_1 < \theta < \theta_2)$

The return period $R(H_s > h; \theta_1 < \theta < \theta_2)$ of a sea storm in which the maximum significant wave height exceeds the threshold h, with direction of the wave propagation within the range (θ_1, θ_2) is defined as

$$R(H_s > h; \theta_1 < \theta < \theta_2) = \frac{\bar{b}(h)}{h\, p(H_s = h; \theta_1 < \theta < \theta_2) + P(H_s > h; \theta_1 < \theta < \theta_2)}. \tag{11}$$

By assuming for $P(H_s > h; \theta_1 < \theta < \theta_2)$ the expression (9) , this yields

$$R(H_s > h; \theta_1 < \theta < \theta_2) =$$

$$= \frac{K_1 b_{10} \exp\left(K_2 \dfrac{h}{a_{10}} \right)}{\left[1 + \dfrac{uh(h-h_l)^{u-1}}{w_\alpha^u}\right] \exp\left[-\left(\dfrac{h-h_l}{w_\alpha} \right)^u \right] - \left[1 + \dfrac{uh(h-h_l)^{u-1}}{w_\beta^u}\right] \exp\left[-\left(\dfrac{h-h_l}{w_\beta} \right)^u \right]}. \tag{12}$$

The return period $R(H_s > h; \theta_1 < \theta < \theta_2)$ of the NOAA buoy 46042 is shown in Figure 10. As we can see the strongest sea storms have direction within the sector (295°, 315°) (sector having φ=305°), according to the data of Figure 9. Furthermore, for fixed values of the return period, we obtain different values of H_s associated to the different sectors. For example for a fixed return period R=100years we obtain H_s =9.8m by the omni-directional analysis. By the directional analysis we obtain the maximum value of H_s equal to 9.0m for the sector centred on 305°; for the sectors centred on the angles 265°, 285° and 325° we obtain significant wave heights equal to 8.2m, 8.2m and 7.3m respectively.

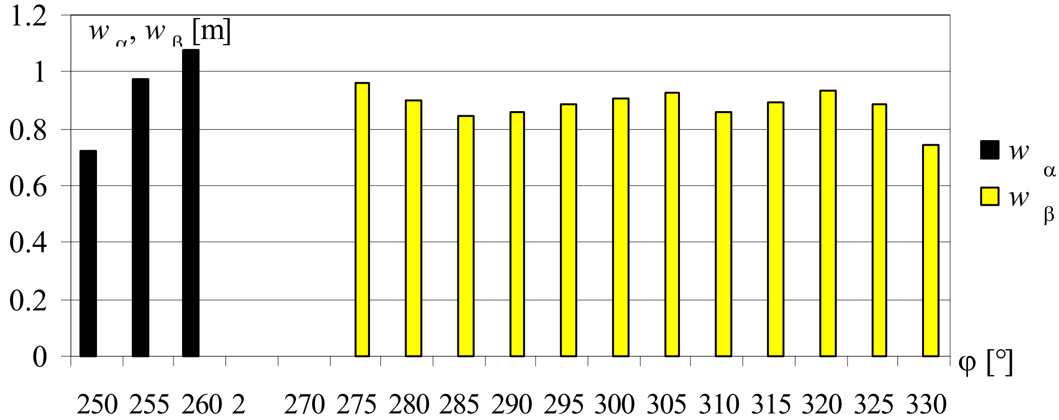

Figure 9. The parameters w_α and w_β of the directional $P(H_s > h; \theta_1 < \theta < \theta_2)$ (equation 9) for the NOAA buoy 46042. To each angle φ in abscissa is associated the sector ($\varphi - 10°; \varphi + 10°$).

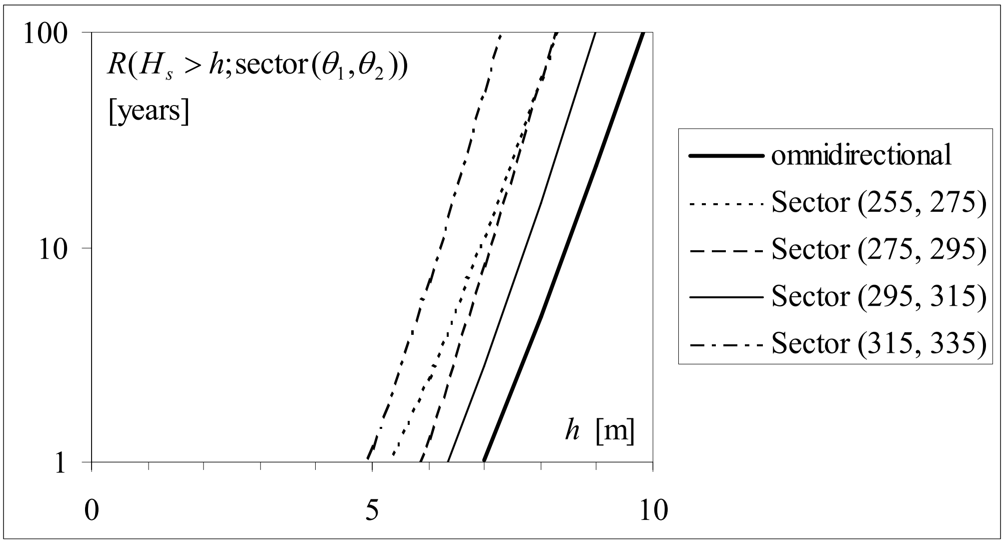

Figure 10. Directional NOAA buoy 46042. The return periods $R(H_s > h)$ and $R(H_s > h; \theta_1 < \theta < \theta_2)$ for some 20° sectors.

CONCLUSIONS

In this paper a bi-parametric analysis of sea storms by using the data of some NOAA buoys moored off the California is done. The *equivalent triangular storm* (ETS) model (Boccotti, 2000) have been applied. We have estimated the return period $R(H_s > h)$ of a sea storm in which the maximum wave height exceeds the fixed threshold *h* (Boccotti, 2000), assuming the lower-bounded three parameters Weibull distribution for the significant wave height.

Therefore we have compared the ETS model prediction to the total sample method predictions finding that the latter tends to overestimate the significant wave height for fixed return period.

Finally in order to predict the direction of the strongest sea storms, a directional analysis is done, using the data from the directional NOAA buoy 46042.

REFERENCES

Arena, F., 2001. Non-linear statistics for the return period of high wave crest, *Proc. 3rd EGS Plinius Conference 'Mediterranean Storms'*. 1-6.

Arena, F. and Barbaro, G., 1999. Risk analysis in the Italian seas (in Italian), *Publ. CNR-GNDCI num. 1965, BIOS*, 1-136.

Battjes J. A., 1970. Long term wave height distribution at seven stations around the British isles. *Report A44 National Oceanographic Institute*, Worley U.K.

Boccotti, P., 1981. On the highest waves in a stationary Gaussian process. *Atti Acc. Ligure di Scienze e Lettere*, 38, 271-302.

Boccotti, P., 1986. On coastal and offshore structure risk analysis. *Excerpta of the Italian Contribution to the Field of Hydraulic Engng.*, 1, 19-36.

Boccotti, P., 1997. A general theory of three-dimensional wave groups. *Ocean Engng.*,

24, 265-300.
Boccotti, P., 2000. *Wave mechanics for ocean engineering*. Elsevier Science, 1-496.
Borgman L. E., 1970. Maximum wave height probabilities for a random number of random intensity storms. *Proc. 12th Conf. Coastal Engng*. 53-64.
Borgman, L., 1973. Probabilities for the highest wave in a hurricane, *J. Port Coastal and Ocean Engng*.
Burrows, R. and Salih, B.A., 1986. Statistical modelling of long-term wave climates. *Proc. 20th Int. Conf. Coastal Engng.*, 1, 42-56.
Goda, Y., 1999. *Random seas and Design in Maritime Structures*, World Scientific.
Graham C., 1982. The parameterisation and prediction of wave and wind speed persistence statistics for oil industry operational planning purposes. *Coastal Engng*., 6, 303-329.
Guedes Soares, C. 1989. Bayesian prediction of design wave height. *Reliability and Optimization of Structural System '88*. Springer-Verlag, 311-323.
Isaacson M. and Mackenzie N.G., 1981. Long-term distributions of ocean waves: a review. *J. Waterway, Port, Coastal Ocean Div*., 107, 93-109.
Longuet-Higgins, M. S., 1952. On the statistical distribution of the heights of sea waves. *J. Mar. Res*., 1952, 11, 245-266.
Mathiesen, J. and Bitner-Gregersen, E., 1990. Joint distribution for significant wave height and zero-crossing period. *Appl. Ocean Res.*, 12, 93-103.
Muir, L. R., and El Shaarawi, A. H., 1986. On the calculation of extreme wave heights: a review. *Ocean Engng.*, 1, 13, 93-118.
Ochi, M. K., 1998. *Ocean waves*. Cambridge University Press, Cambridge, 1-319.
Rice, S. O., 1944. Mathematical analysis of random noise. *Bell Syst. Tech. J.*, 23, 282-332.
Rice, S. O., 1945. Mathematical analysis of random noise. *Bell Syst. Tech. J.*, 24, 46-156.
Sobey R.J. and Orloff L.S., 1999. Intensity-duration-frequency summaries for wave climate. *Coastal Engng*., 36, 37-58.
Van Vledder, G., Goda, Y., Hawkes, P., Mansard, E. Martin, M.H. Mathieses, M., Peltier, E. and Thompson, E., 1993. Case studies of extreme wave analysis: a comparative analysis, *Proc. 2nd Int. Symp. Ocean Wave Measurement and Analysis*, ASCE, 978-992.
Winterstein, S. R., Kleiven, G. and Hagen, O. 2001. Comparing extreme wave estimates from hourly and annual data, *Proc. 11th Int. Offshore and Polar Engineering Conf. (ISOPE 2001),*III, 700-707.
Young L. R., 1999. An intercomparison of GEOSAT, TOPEX and ERS1 measurements of wind speed and wave height. *Ocean Engng*., 26, 67-81.