CHAPTER 6

Wind Variability and Extremes Statistics

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Abstract

Continuous records of wind speed and direction show a high variability both in the high and low frequency ranges. This variability is usually not considered in the numerical hindcast of a storm. We discuss the related implications for the maximum wave heights and for the values from the statistics of extremes.

1. Introduction

Extremes statistics at a given location are based on the availability of extended time series of the parameter of interest. Notwithstanding the recent increase in their number, measured wave data are still scarce and not sufficiently representative closer to coast where the wave conditions exhibit a strong variability. If proper data are not available at the location of interest, the usual solution is the hindcast, with suitable mathematical models, of all the relevant storms of the last 10 or 20 years, using their output as a basis for the extremes statistics. In this paper we analyze one aspect of this reconstruction relevant for the final results.

Meteorological models provide a smooth description of the atmosphere, their filtering characteristics depending on the grid step size and on the time integration step. In a model, the representation of the passage of a storm at a given location is characterized by a smooth growth of the wind speed and a similarly smooth decay. This is not what is experienced in the field. Cavaleri and Burgers (1992, henceforth referred to as CB) point out that levels of turbulence with rms percentage variability $\sigma = 0.10$, up to values $\sigma = 0.30$, are common in nature. This turbulence leads to a substantial increase of the maximum significant wave height Hs in a storm.

In this paper, first we briefly describe (in section 2) the physics of the process and the effects on the evolution of a storm. Then (section 3) we focus on the statistics of the extremes, showing how the related results are affected by data derived from "turbulent" storms. The overall findings are summarized in section 4.

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2. Turbulent Wave Growth

Figure 1 shows four records of wind speed U with different degrees of turbulence taken from an oceanographic platform located in the Northern Adriatic Sea (Cavaleri, 1979). The turbulence ranges from periods of seconds, where it interacts with the basic wave generation process, till one hour and beyond, shifting gradually into the synoptic variability. Here we focus our attention on the part from one minute upwards. In practice we do not deal with the frequency range connected to the pure generation.

Within its range of variability, the wind speed happens to be for part of the time lower than the phase speed of part of the spectral frequencies. CB show that, through a rectification of the Miles generation process (1957), the relatively fast turbulence (i.e., with period approximately between one and twenty minutes) leads to an enhancement of the actual significant wave height Hs, the enhancement increasing with the level σ of the turbulence. A second order effect, but acting also on the low speed waves, i.e., on the high frequency range of the wave spectrum, is associated with the non linear relationship between friction velocity and wind speed.



Figure 1. Records of wind speed with different degrees of turbulence. Wind speed in knots. Time in hours (after Komen et al., 1994).

Figure 2 shows the classical case of time limited wave growth, with different turbulence σ ranging from 0.0 (uniform wind) till 0.30 (very strong turbulence). We see that the latter value leads to an increase of the final Hs of more than 30%.

A further increase of the maximum wave height in a storm derives from the relatively long period of turbulence of the wind field (periods from twenty minutes till several hours). These oscillations are clearly recognizable by direct inspection of a record lasting one day or more. Obviously the wave field reacts to this variability with a related Hs variability throughout the field. To simulate such a variability we need first to simulate the turbulent wind. CB show that this can be done with a Markov chain, where, for a given σ , the time scale of the turbulence is dictated by the correlation α between the sequential U values. Actual turbulent records seem to be well reproduced by this approach, provided the correct σ and α are used. The α =0.90 seems to be a good value for data taken at one minute intervals. CB have introduced a Markov chain turbulence with these characteristics in a uniform wind field, then repeating the test of figure 2. The results are shown in figure 3, where the test has been extended also to the cases of α =0.95 and 0.99. The σ was equal to 0.25. The effect of air turbulence is clear. The "turbulent" growth curve follows the smooth one (already enhanced by fast turbulence, compare with figure 2), waving around it. Note that in figure 3 each couple of lines has been shifted up by 2 meters for the sake of clarity.

By direct inspection of the diagram in figure 3 (but similar results are often found in recorded Hs time series, even if obscured by the usual 3-hour intervals), we recognized immediately the further increase of the maximum Hs value, the increase being directly dependent on σ and α .

We can summarize the present situation as follows. Standard numerical wave hindcasts are based on wind fields obtained from meteorological models. Turbulence is usually not considered, and the field evolves smoothly in time. The introduction of wind turbulence affects the wave field in two ways. On one hand, it increases the actual Hs values. On the other, it forces the wave field to oscillate around the otherwise smooth growth curve, reaching in the process still higher wave heights. Note that, while the first effect is fully determined by σ , and it can therefore be correctly evaluated, for the latter we come across statistics. The highest Hs in a turbulent storm is crudely a matter of chance. The consequence of this on the statistics of the extreme wave heights is the subject of the next section.

3. The Uncertainty in the Extremes Statistics - The Probability of a Probability

The classical procedure of extremes statistics starts from a long term time series of the parameter of interest, typically available as a regular sequence of single values at 3-hour intervals. Then, a subset of values is selected, according to one of two principles: pick up (a) all the values above a certain threshold, (b) the highest value for each pre-established time interval (for wave height a month, a semester, or, one year are a regular choice). If an extended time series is not available, the wave hindcast of a large number of storms is performed, retaining as input information for the extremes statistics the highest Hs in each storm. The selected data are then bestfitted by some extremal distribution, Weibull, Gumbel or FT-1, exponential being among the common ones. Given the distribution and the number of data in the subset, we can then estimate the probability to overcome a given value at the next event or



Figure 2. Time growth of the significant wave height under a 20 m/s wind with different degree of turbulence (after Komen et al., 1994).



Figure 3. Oscillations of the significant wave height in the time growth curve as a function of the degree of correlation in the sequential wind values (after Komen et al., 1994).

during the next time interval, depending on how the data have been selected. Given the period covered by the input time series, the statistics can be usefully referred to time. In practice, we can reply to the following question. What is the probability P^+ to overcome a certain value H within T years? More generally, given two of the quantities P^+ , H, T, we can immediately deduce the third one.

The analytical expression relating the three quantities is

$$P^{+} = 1 - [p^{-}(H)]^{nT}$$
(1)

where p^- is the no-exceeding probability at the next event deduced from the extremal distribution, and n is the average number of storms per year. A full discussion of the subject is found in Gumbel (1958) and practical applications illustrated in Cavaleri et al. (1986).

The graphical representation of the results is particularly enlightening. Figure 4 shows the exceedance probability for a certain area of the Tyrrhenian Sea (see Cavaleri et al. 1986). The enhancement of the wave height H due to the somehow more efficient generation described in the previous section means that we are dealing with higher wave heights. This crudely shifts all the lines in figure 4 to the right, the shift depending on the σ of turbulence typical of the area and on the kind of storms we are considering.



Figure 4. Exceedance probability (given by the number close to each continuous curve) with respect to wave height and elapsed period. The broken lines represent the corresponding confidence limits due to a) choice of the storms and b) wind turbulence.

Three points must be stressed. First, Resio (1978) warns that an extremal statistic produces meaningful results only if applied to a consistent data set, i.e., including only data of the same kind. We cannot mix data associated with substantially different kinds of storms, e.g., southern swell and extra-tropical storms in the North Atlantic Ocean. Clearly the presence of turbulence stresses further this point.

Second, the confidence we have in our input data must depend on the actual source. If derived from a hindcast, we must be aware that they are likely to be underestimated (if turbulence is likely to be present and it has not been considered). But also recorded data have problems. Our usual 20 minute sample chosen for the record is just a random choice in a waving time series as the ones in figure 3. As such, the confidence limits on the actual average representative value (the smooth growth curves in figure 3) are much larger than those associated only to the sampling variability connected with the randomness of the surface, typically 15% instead of 6-8%.

Third, after estimating, by means of diagrams as the one in figure 4 or the related expression (1), the extremal conditions, i.e., a certain H_e , we must warn the user of our results that the maximum H he will be likely to come across in such conditions is going to be higher than H_e . Our numerical results suggest an increase between 5 and 10%. Starting from the extremes in figure 4, we have evaluated the associated confidence limits by a combined used of the Jack-knife and Montecarlo techniques.

A full description of the Jack-knife technique can be found in Cavaleri et al. (1986) who also describe practical applications. Basically, given a subset of N data and the extremal distribution fitted to them, the technique estimates the reliability of the results by checking how much they depend on the single datum. This is done by excluding in turn each datum and getting a new extremal fit on the remaining N-1 data. This produces N new estimates of the extremes that are statistically analyzed to provide an estimate of the confidence limits of the overall extremal evaluation. Acting on the extremes shown in figure 4, we have so obtained the limits given by the two (a) curves lying close to the original ones.

This procedure does not account for the uncertainty on the single data due to sampling variability and/or turbulence effects. This can be obtained by Montecarlo technique. Each datum has been left oscillating randomly around its original value, following a Gaussian distribution with $\sigma=10\%$, and the fitting procedure repeated for each realization. Similarly to the Jack-knife technique, the results have been statistically analyzed providing a new estimate of the confidence limits. These are given in figure 4 by the wider (b) limits associated with each extremal curve. It is obvious that the turbulence introduces into the estimate of the extremes an uncertainty much larger than derived from the sampling of the input data.

4. Conclusions

We summarize here the relevant points for extremes statistics when dealing with measured or hindcast data.

Measured data.

- enhancement of wave height: naturally present in the data, hence automatically considered.
- confidence limits for choice of input data: to be evaluated by Jack-knife technique (or similar one).
- enhancement of estimated extreme values, because of oscillations in the growth curve, estimated to be 5-10%.

Hindcast data.

- enhancement of wave height: its consideration requires introduction of turbulence into the input wind data.
- confidence limits for choice of input data to be evaluated by the Jack-knife technique (or similar one).
- confidence limits for turbulent records: not required.
- enhancement of estimated extreme values, because of oscillations in the growth curve, estimated to be 5-10%.

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