CHAPTER 20

THE MAXIMUM SIGNIFICANT WAVE HEIGHT IN THE SOUTHERN NORTH SEA

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Abstract

The maximum possible wave conditions in the southern North Sea are estimated with synthetic storms and a third-generation wave model. The storms and the physics in the wave model have been chosen within the uncertainty of the state-of-the-art to have maximum effect. The wave conditions appear to be limited by the presence of the bottom and to some extent by the assumed maximum wind speed of 50 m/s. The maximum significant wave height thus determined for the southern North Sea is about 0.4 times the local water depth.

Introduction

Extrapolations of observations usually provide fair estimates of extreme conditions as long as the physical regime of the waves does not change dramatically. Such a change may occur because the wind speed is limited and in shallow seas the water depth is limited. An extrapolation of the significant wave height should take this into account, possibly as an upper limit of the significant wave height. In the present study, the existence of such an upper limit in the southern North Sea is investigated.

Although the maximum wind speed in the North Sea is not well known, consultation with meteorologists suggested the 50 m/s wind speed as an upper limit. We investigate the sensitivity of the our results for this assumption. The physical phenomena of waves in these conditions are not well known either but we use a state-of-the-art wave model. For deep water this type of model has shown to be reliable in hurricane conditions.

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The wave model

We use the numerical wave model WAVEWATCH II (Tolman, 1991, 1992). It is based on the discrete spectral action balance equation with a number of optional formulations for wave generation and dissipation. First we use it with initial choices for these formulations and then we investigate the alternatives.

The wave model

The action balance equation is a generalization of the energy balance equation in the presence of currents (e.g., Phillips, 1977). In the model this balance is formulated for propagation over a sphere with coordinates longitude λ and latitude ϕ:

$$\frac{\partial N(\omega,\theta)}{\partial t} + (\cos\phi)^{-1}\frac{\partial C_\phi \cos\phi N(\omega,\theta)}{\partial \phi} + \frac{\partial C_\lambda N(\omega,\theta)}{\partial \lambda} + \frac{\partial C_\omega N(\omega,\theta)}{\partial \omega} + \frac{\partial C_\theta N(\omega,\theta)}{\partial \theta} = S(\omega,\theta)$$

in which $N(\omega,\theta)$ is the action density of the waves, defined as the energy density $E(\omega,\theta)$ divided by the relative frequency σ, as function of absolute frequency ω and direction θ. The left-hand-side represents the local rate of change of the action density, propagation along great circles, shifting of the absolute frequency due to time variations in depth and currents, and refraction. The expressions are taken from linear wave theory (e.g. Mei, 1983). We will not consider currents in the present study. The right-hand-side of the above balance (the net production of wave action) represents all effects of generation and dissipation of the waves. The processes which are included in the model are: wave generation by wind, nonlinear quadruplet wave-wave interactions and dissipation (white-capping and bottom friction). The WAVEWATCH II model incorporates more than one formulation for each of these processes except for depth-induced wave breaking, which we added. For this we used the formulation of Battjes and Janssen (1978) and Battjes et al. (1993). As an alternative for Battjes and Janssen (1978) we added the formulation of Roelvink (1993).

In discretizing the spectrum we used a logarithmic frequency distribution from .022 Hz (a rather low frequency, chosen to cover extreme conditions) to .75 Hz with a 10% resolution. The directional resolution is 15°. From the numerical options in WAVEWATCH II (see Tolman, 1992) we choose to use the up-wind propagation scheme with either the static integration of the source terms (constant-wind cases) or dynamic integration (all other cases). The spatial resolution of the bottom grid is about 8 km except near the Dutch coast where it is 3 km. The bathymetry is indicated in Fig. 1. In view of the type of storms that we will consider, we imposed a uniform increase of 5 m in water depth to simulate the corresponding storm surge. We verified with sensitivity computations that the wave conditions at the northern boundary of the model (at 62° N) are not relevant for the southern North Sea in the extreme conditions considered here.

Maximum wave physics

We initially use formulations that are identical to those of the published WAM model (WAMDI group, 1988; to investigate the sensitivity of the results for the assumed maximum wind speed). However, we replaced the bottom friction

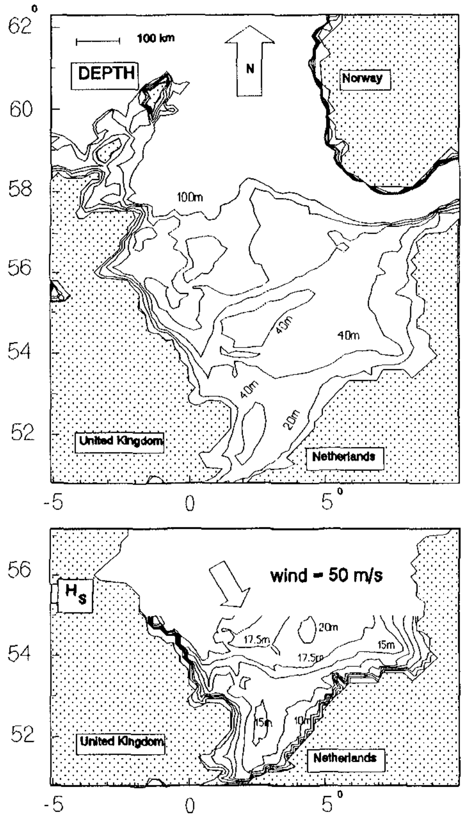

Fig. 1 The bathymetry of the North Sea (8 km resolution; upper panel) and the maximum significant wave height in the southern North Sea computed with 16 km resolution in a uniform wind field (50 m/s from 330°; lower panel). Physics selected for maximum effect.

formulation of Hasselmann et al. (1973) with the formulation of Madsen et al. (1988) and we added the depth-induced breaking of Battjes and Janssen (1978) and Battjes et al. (1993). This setting of the physics is summarized in Table 1 under the heading "initial".

The maximum significant wave height in given wind conditions is achieved by minimizing the effect of dissipation and maximizing the effects of generation (within the uncertainty of the state-of-the-art). We therefore varied the formulations of the physics in the model to each of the available options in WAVEWATCH II (Table 1).

WAVEWATCH II		
physics	initial	options
wind input	Snyder et al. (1981) + Komen et al. (1984)	Janssen (1991)
wave-wave interactions	Hasselmann and Hasselmann (1985)	-
white-capping	Komen et al. (1984)	Komen et al. (1984) + Janssen (1991)
bottom friction	Madsen et al. (1988)	Hasselmann et al. (1973)
depth-induced breaking	Battjes and Janssen (1978) + Battjes et al. (1993)	Roelvink (1993) + Battjes et al. (1993)

Table 1. *The formulations of the physics of wave generation and dissipation in WAVEWATCH II (Tolman, 1991, 1992). The formulations that generate the maximum significant wave height are indicated with shading.*

We hindcasted for each variation independently the significant wave height at all stations indicated in Fig. 4 for wind speed 50 m/s from direction 330°. After all variations were considered and selected (as indicated in Table 1), we hindcasted the significant wave height in the southern North Sea with the selected formulations of the physics combined. The results are shown in Fig. 1. The significant wave height thus obtained is typically 1 m higher than obtained with the initial model setting.

Verification

We verified results of the model with the selected formulations for generation and dissipation (Table 1) with WAVEC buoy observations in a severe storm (December 12, 1990). The time series of the significant wave height for the station with best agreement between observed and computed maximum significant wave height and the station with the worst agreement are given in Fig. 2. The maximum significant wave height at these and other stations is given in Table 2. The agreement between observation and computation is generally reasonable except at station SON which is planned to be investigated further (the buoy seems to be located between two ship wrecks).

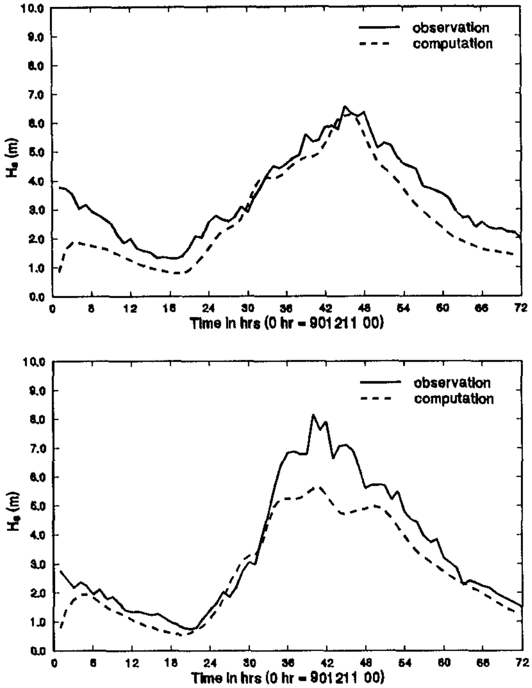

Fig. 2. The observed and measured time series of the significant wave height in the storm of December 12, 1990 at stations EUR (top panel) and SON (bottom panel).

station	observations	computations	difference
AUK	12.20 m	12.47 m	-0.27 m (2%)
SON	7.70 m	5.60 m	+2.10 m (26%)
ELD	7.70 m	7.25 m	+0.45 m (6%)
K13	7.70 m	7.60 m	+0.10 m (1%)
YM6	6.70 m	6.40 m	+0.30 m (4%)
EUR	6.25 m	6.30 m	-0.05 m (1%)
LEG	6.00 m	5.42 m	+0.58 m (10%)

Table 2. Observed and computed maximum significant wave height at various locations in the storm of December 12, 1990.

The wave model for the parametric storms

To find the storm that would generate the maximum significant wave height in the southern North Sea, we used a search procedure with a large number of synthetic storms (see below). For economic reasons these hindcasts were carried out with the second-generation wave model DOLPHIN-B described by Holthuijsen and de Boer (1988). This wave model has been adapted for shallow water and tuned to resemble the behaviour of the WAVEWATCH II model (initial setting) at station K13 in the storm of Feb. 1953. Dedicated computations showed that the storms that generated the largest significant wave heights at station K13 also generated the largest values at the other locations along the Dutch coast. The computations for the selected synthetic storm were repeated with the WAVEWATCH II model.

The wind field

In search for the existence of a physical upper-limit of the significant wave height we assume, in consultation with meteorologists of the Royal Netherlands Meteorological Institute, a wind speed of 50 m/s to be the maximum realizable sustained wind speed over the North Sea (at 10 m elevation). This is only a crude estimate and we will therefore determine the sensitivity of the maximum significant wave height for this assumption.

Uniform wind

The waves are hindcasted in a uniform wind field over the entire North Sea until a stationary situation is achieved for various wind speeds and directions. For these hindcasts a 16 km spatial resolution was used (sensitivity tests showed practically no effect of refining the resolution to 8 km). Fig. 3 shows that between northerly and westerly wind directions the significant wave height is weakly dependent of the direction with most (but not very pronounced) maxima at wind direction 330°. To find the sensitivity for the wind speed, we repeated these hindcasts for wind speeds in this direction increasing from 20 m/s to 60 m/s. As shown in Fig. 3 the sensitivity is rather weak (practically absent at the shallower stations) around the assumed maximum wind speed of 50 m/s.

Results

To obtain high resolutions results along the Dutch coast, we refined the computations in the southern North Sea with nested computations (from a 16 km via an 8 km to a 3 km grid resolution). The results are shown in Fig. 4.

Synthetic storm

To investigate whether the maximum wave conditions found in the above constant wind field are physically realizable, we hindcasted the waves in an extreme storm that we synthesized from historic storms. We selected this storm with search procedures involving wave hindcasts in a large number of synthetic storms.

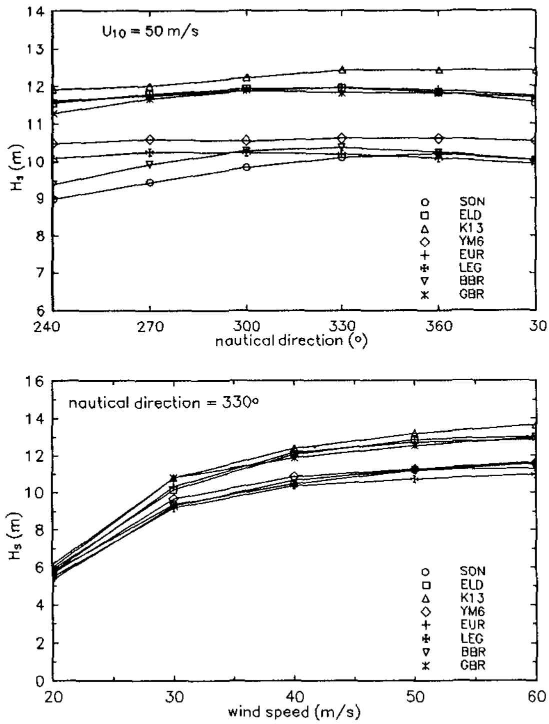

Fig. 3 The significant wave height as a function of wind direction (50 m/s) at various stations (top panel). The significant wave height as a function of wind speed from 330° at various stations (bottom panel).

Storm parameterization

To represent the atmospheric pressure in the synthetic storms we used a spatial Gaussian distribution with the radius to maximum wind different along the four major (orthogonal) axes of the storm. This created an elliptical asymmetric pressure field. From this pressure field we computed the geostrophic wind which we reduced to 65% and turned counter-clockwise by 15° to estimate the surface wind at 10 m elevation. Storms with surface wind speeds exceeding 50 m/s were removed from the search (due to the incremental nature of the search, small overshoots of about 2 m/s were permitted). The parameters of these synthetic storms were all assumed to vary linearly in time, characterized by one value at the moment when the centre of the storm is located at 10° W and one value 72 hours later.

We varied these time histories in the following search procedure within limits obtained from historic storms. To that end we analyzed five storms that are considered by meteorologists to be the severest storms in the southern North Sea over the last decennia.

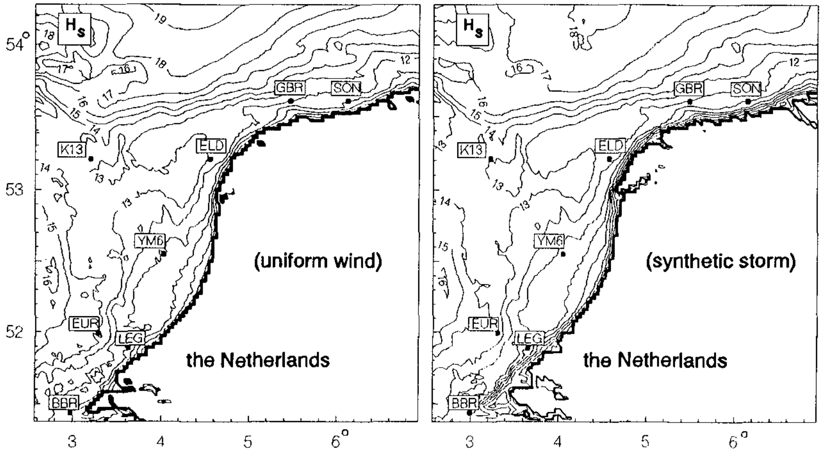

Fig. 4 The maximum significant wave height along the Dutch coast computed with 3 km resolution in a uniform wind field (wind speed = 50 m/s from 330°) and in a synthetic storm (maximum wind speed = 51.8 m/s).

These are all storms from westerly or north-westerly directions: 1st Feb '53, 21st Dec '54, 3rd Jan '76, 19th-25th Nov '81 and 26th Feb - 2nd March '90. (We verified with extra hindcasts that storms with tracks from more northerly directions were irrelevant.) We followed these storms on standard weather maps after they passed 10° W longitude and we visually estimated as a function of time: the forward speed, the central pressure, the orientation of the major axes and the radii along these axes. We thus obtained for each of these parameters five time histories. By roughly approximating the upper and lower envelope of these time histories with straight lines. From this we estimated the limits of the parameter values at the start of the storm and 72 hours later. For the start and end positions of the storms we used the results of an earlier and more extensive analysis of historic storms by Zwart (1993).

The search procedure

To determine which synthetic storm would lead to the largest significant wave height in the southern North Sea, we have used a sequential binary search with the storm parameters varying within the limits obtained from the above analysis of historic storms. First a reference hindcast is carried out with the value of all storm parameters (start and end values considered separately) set at their mid-range value. In sequence each storm parameter is then investigated: it is set at two values, one at the centre of the upper half-range and one at the centre of the lower half-range. All other parameters retain their reference value. Two hindcasts then decide which of these two values produces the largest significant wave height. The reference value of this parameter is then replaced by this selected value (it retains this value during the continuation of the search). Then the next storm parameter is modified similarly. After all storm parameters are thus investigated and selected the procedure is repeated twice, each time cutting the range of the storm parameter in half and centering it at the last selected reference value (three iterations in all). To increase the probability that the proper storm has been selected, we also carried out a synoptic binary search (replacing the reference values only after each of the three iterations has been completed) and a random search (shifting the mean to the selected value and reducing the widths of the assumed distributions by 50% after each of three iterations). A total of about 800 hindcasts was thus carried out. As the searches are carried out with three iterations, the resolution of the result is 1/8 of the original parameter range.

Results

The storm with the maximum significant wave height was selected by the sequential binary search. It is a fairly small but intense storm (300 to 400 km radius) tracking across the southern North Sea from a westerly direction. An inspection of the results suggests that to achieve the extreme wave heights, the wave field in the southern North Sea requires a locally high wind speed to compensate for local, bottom- induced dissipation (particularly breaking). Within the permitted range of atmospheric pressure, this locally high wind speed can be achieved only with a fairly small radius of the storm. The results of the other searches (synoptic binary and random) were storms that were similar in pattern to the one found with the sequential binary search but with somewhat lower significant wave heights.

To obtain the results with third-generation formulations, we carried out the hindcast for the selected synthetic storm with the WAVEWATCH II model with the formulations selected for maximum effect of the physics. This hindcast was nested to 3 km along the Dutch coast. The resulting maximum significant wave height (at each location) is given in Fig. 4.

Discussion

Comparing the two wave fields in Fig. 4, it is obvious that the maximum significant wave height obtained with a uniform wind field is practically equal to that obtained with the extreme synthetic storm. Apparently the wave field in these conditions (maximum wind speed of about 50 m/s) is dominated by the local water depth. This is supported by the similarity between the pattern of the maximum significant wave height and the water depth (Figs. 1 and 4). In fact, in the region considered with depth between 10 and 55 m, the ratio between maximum significant wave height and depth varies only between 0.35 and 0.45. This suggests a local equilibrium between generation on the one hand (for 50 m/s wind speed) and dissipation on the other. An uncertainty analysis based on sensitivity computations and on the uncertainty range of the coefficients in the selected formulations of the physics of wave generation and dissipation (not presented here) indicates that (a) the mechanism of bottom-induced breaking dominates the estimate of the maximum significant wave height and (b) the uncertainty of the estimated maximum significant wave height is about 5% upward and 25% downward.

Conclusions

The significant wave height in the southern North Sea seems to be limited by the local water depth and to some extent by an upper limit of the wind speed. The physics of wave generation and dissipation in these extreme conditions are not well known but with the available formulations selected for maximum effect, an estimate of the physical maximum of the significant wave height has been made. This has been done for selected wind fields using the third-generation model WAVEWATCH II (Tolman, 1991, 1992). The wind speed was limited to 50 m/s.

The results in a uniform wind field over the entire North Sea and in a selected extreme synthetic storm (based on historic information) are almost equal, indicating a local balance between wind generation and bottom induced dissipation. The local ratio between maximum significant wave height and water depth is nearly constant in the southern North Sea and equal to about 0.4.

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