CHAPTER 43

WAVES IN TURNING WIND FIELDS

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Abstract

A numerical model to compute to a high degree of accuracy nonlinear wave-wave interactions of wind generated waves supplemented with formulations of wind generation and white-capping, has been used to estimate qualitatively and quantitatively the effect of these physical processes on the directional response of waves in a turning wind field. After a sudden shift in wind direction the wave spectrum develops a secondary peak in the new wind direction. The initial peak of the spectrum either merges fairly quickly with this new peak or it slowly disappears, depending on the magnitude of the directional wind shift. The turning of the mean wave direction towards the new wind direction is caused by wind generation. The processes of nonlinear wave-wave interactions and white-capping tend to slow down the turning rate induced by the wind generation. The net turning rate of the mean wave direction in the model is twice as slow as in observations acquired in the central and southern North Sea.

Introduction

The directional characteristics of waves at sea are still poorly understood due to the scarcity of observations and the operational problems with wave models that properly represent the physics of waves in a wind field. In both aspects significant developments have taken place in the last few years. Instrumentation to observe wave directions is available on an acceptable operational basis and computers and numerical techniques are now available that permit a limited degree of experiments with the indicated type of wave models.

In the present study the EXACT–NL model of Hasselmann and Hasselmann (1985) is used to quantitatively determine the contributions of generation, dissipation and

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nonlinear wave-wave interactions to the variation of the mean wave direction in a turning wind field. The results are compared with observations in the North Sea which have been treated to separate the effects just mentioned from the effects of wave propagation.

Numerical computations

The EXACT–NL model is a discrete spectral wave model which has been developed by Hasselmann and Hasselmann (1985) to determine numerically to a high degree of accuracy the rather complicated nonlinear wave-wave interactions formulated by Hasselmann (1968). These computations have been supplemented with formulations from the literature for wind generation and white-capping. For a description of the model reference is made to Hasselmann and Hasselmann (1985) and Van Vledder and Weber (1988). In the EXACT–NL model the evolution of a homogeneous wave field is described by the energy balance equation:

$$\frac{\partial E}{\partial t} = S = S_{in} + S_{ds} + S_{nl} \tag{1}$$

in which E is the two-dimensional variance density spectrum $E(f,\theta)$ and S_{in}, S_{ds} and S_{nl} are the source terms representing the effect of wind input, dissipation by white-capping and nonlinear wave-wave interactions. The model is applied in six situations where a constant, spatially homogeneous wind suddenly turns to a 'new' directions after which the wind direction is constant again. The wind shifts considered are: 30°, 60° and 90° in combination with a constant wind speed U of 10 and 20 m/s. All computations start with a relatively young sea and the waves grow until the peak frequency has dropped to twice the Pierson-Moskowitz frequency at which time the wind direction shifts to the 'new' wind direction.

The mean wave direction θ_0 is defined as in the routine analysis of pitch-and-roll buoys (e.g Kuik et al., 1988):

$$\theta_0 = \arctan\left(\frac{b}{a}\right) \tag{2}$$

in which

$$a = \int_0^{2\pi}\int_0^{\infty} \cos(\theta)E(f,\theta)dfd\theta \tag{3}$$

and

$$b = \int_0^{2\pi}\int_0^{\infty} \sin(\theta)E(f,\theta)dfd\theta \tag{4}$$

The response of the mean wave direction in turning towards the new wind direction is found to occur in a manner somewhat similar to that of a relaxation process.

Therefore, the rate of change of the mean wave direction is quantified by means of a time scale τ of a relaxation model:

$$\frac{\partial\theta_0}{\partial t} = \frac{1}{\tau} \sin(\theta_w - \theta_0) \tag{5}$$

in which θ_w is the wind direction.

It can be shown by applying the definition operator of mean direction (see equation 2) to the energy balance equation (1), that:

$$\tau = \frac{\cos(\theta_s) \int_0^{2\pi}\int_0^{\infty} \cos(\theta)E(f,\theta)dfd\theta}{\cos(\theta_0) \int_0^{2\pi}\int_0^{\infty} \cos(\theta)S(f,\theta)dfd\theta} \frac{\sin(\theta_w - \theta_0)}{\sin(\theta_s - \theta_0)} \tag{6}$$

in which θ_s is the mean direction of the total source function $S(f,\theta)$.

The contributions of the above mentioned physical processes to this response are available in the model results as a function of time in the form of spectral source functions. Visual inspection of these provide a qualitative insight in the effect of the various processes. To quantitatively determine the effect of each source term a time scale per source term is introduced in a way similar to that of the time scale of the relaxation model (5), i.e. replace in equation (6) $S(f,\theta)$ by the source term considered. The rationale of this is that upon applying the definition operator of mean direction to the energy balance equation (1), the time scale τ of the relaxation model (5) is related to the time scales per source term as:

$$\frac{1}{\tau} = \frac{1}{\tau_{in}} + \frac{1}{\tau_{ds}} + \frac{1}{\tau_{nl}} \tag{7}$$

The time scales of the response of the mean wave direction (τ) and of the source terms (τ_{in}, τ_{ds} and τ_{nl}) are determined with their definition based on equation (6) from the computed spectra and source functions.

Observations

Observations have been carried out in the central and southern North Sea with a WAVEC pitch-and-roll buoy at two locations near the offshore platforms AUK and K13 (geographic locations 56.39 N, 2.05 E and 53.22 N, 3.22 E respectively). The directional behaviour of the waves in these observations are obviously affected by the inhomogeneity of the wave field. These effects are estimated with the results of an operational hindcast model (the WINCH model, Eide et al., 1986) and the observations are corrected accordingly. The time scales of the response of the mean wave direction are subsequently determined with a finite difference treatment of the time series of the observed mean wave direction.

To account for effects of measurement errors and to correct for propagation effects, the wave, wind and model data have been selected rather carefully to retain high quality data (e.g. good correspondence between observations and hindcast results). Consequently only five of the fifteen hundred observations were accepted for further analysis.

Results

An example of the response of the two-dimensional spectrum is given in Fig. 1. An example of the various acting and counter-acting energy fluxes (source terms) is given in Fig. 2. The spectrum and the source functions are given for the situation in which the wind shifts suddenly over 90° (constant wind speed of 20 m/s). The illustrated situation is taken half-way through the turning of the wave spectrum towards the new wind direction. The mean wave direction at this moment is 50.3° and the spectrum has developed a secondary peak in the new wind direction (panel a). The wind input source function is this case is located around the new wind direction and turns the spectrum towards this direction (panel b). The dissipation source function is located at the high frequencies while skewed towards the new wind direction thus counteracting (the contribution is negative) the effect of the wind input somewhat (panel c). The nonlinear wave-wave interaction transfers energy from the newly generated high-frequency energy towards the old low-frequency energy in the old direction (panels d and e, for the positive and negative parts of this source function respectively) thus also counteracting the effect of the wind input.

A review of all model results (not shown here) indicates that after a shift in wind direction the wave spectrum always develops a new peak at high frequencies in the new wind direction, resulting in a bi-modal spectrum. However, the spectrum assumes a uni-modal shape rapidly when the wind shift is small or moderate. In a situation with a large wind shift (more than 60 degrees, say) the spectral shape remains bi-modal for a long period of time. In both cases the wind generates energy in the high frequencies in the new wind direction. In the case with a small or moderate wind shift the nonlinear wave-wave interactions siphon part of this new, high-frequency energy away towards lower frequencies in the 'old' wind direction. This, together with the rapid fusion of the two peaks due to their proximity, prevents the continued growth of a distinctly separate high-frequency peak. In the situation with a large wind shift the nonlinear interactions between the high-frequency energy in the new wind direction and the low-frequency energy in the old wind direction is almost nonexistent which provides the high-frequency peak with the opportunity to develop more or less independently from the peak in the old wind direction.

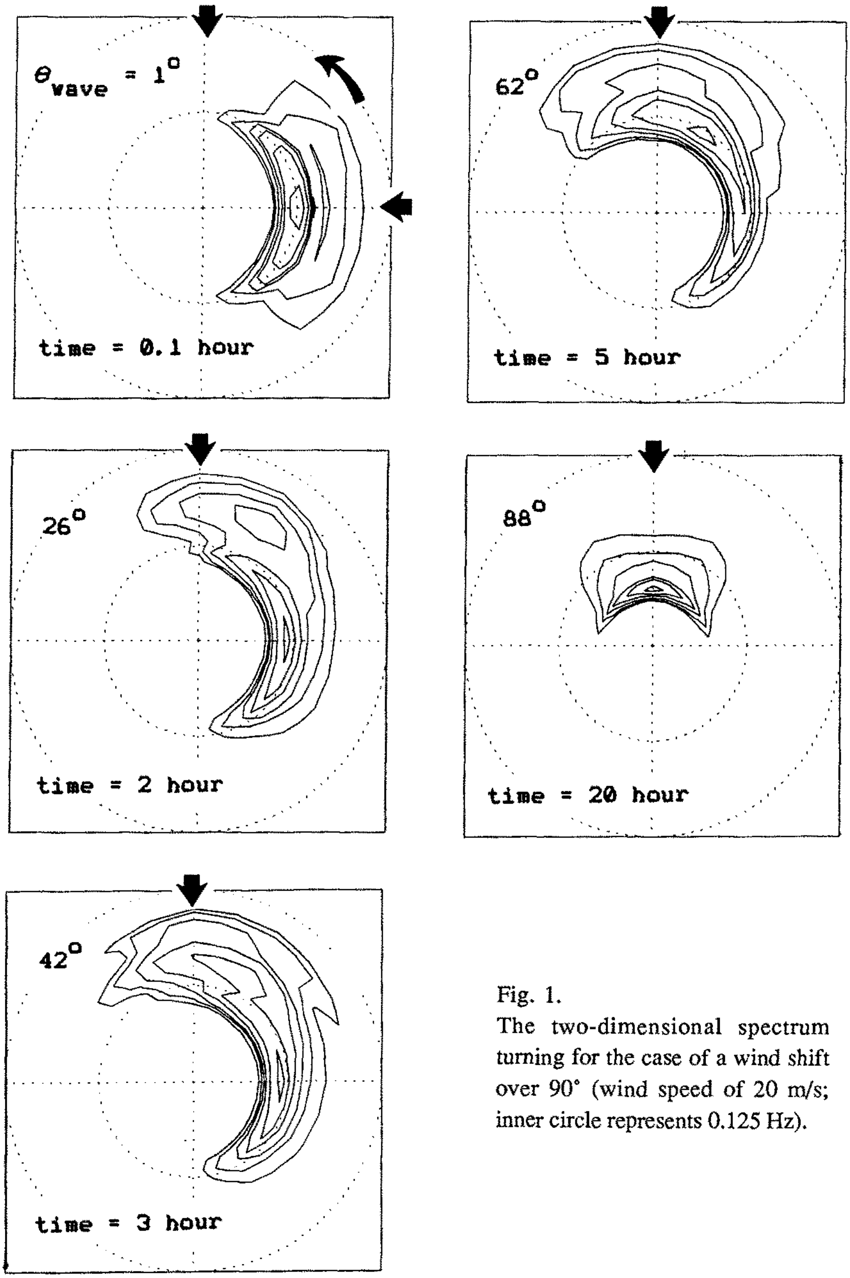


Fig. 1.
The two-dimensional spectrum turning for the case of a wind shift over 90° (wind speed of 20 m/s; inner circle represents 0.125 Hz).

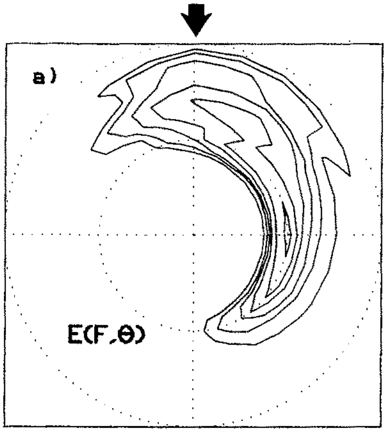
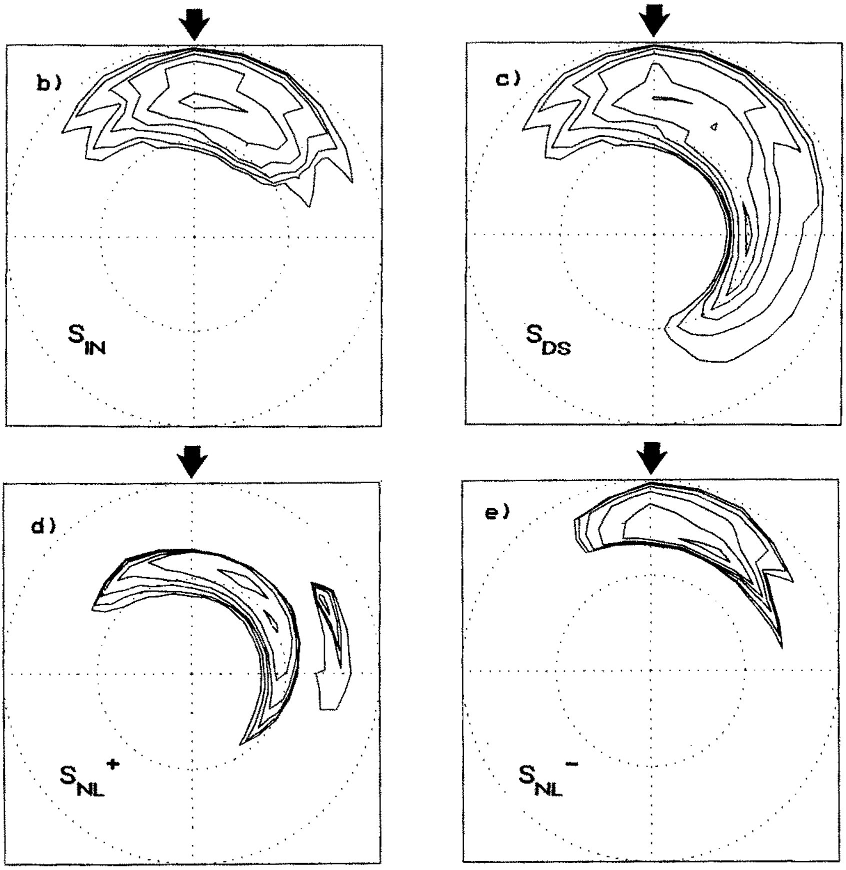


Fig. 2.
The two-dimensional spectrum (panel a) and the source functions (panels b through e) in a situations roughly half-way through the directional response of the spectrum after a 90° shift in wind direction. The frequency axis has been normalized with the peak frequency (wind speed 20 m/s; inner circle represents unity).



To generalize the computational results and to compare these results with information from the literature, the time scale estimates are normalized using the friction velocity U_* and the gravitational acceleration g. They are given as a function of growth stage, represented by the nondimensional peak frequency υ_*:

$$\tau_* = \tau \, g/U_* \tag{8}$$

and

$$\upsilon_* = f_p \, U_*/g \tag{9}$$

in which f_p is the peak frequency of the spectrum. Where necessary in the following U_* is determined from the wind speed at 10 m elevation (U_{10}) with the drag coefficient from Wu (1982).

The results of the time scale estimates obtained from the numerical computations and the observations are given in Fig. 3. It appears that the time scale increases with the stage of development of the waves (the response becomes slower as υ_* decreases). A similar increase in time scale is found in the observations. However, the time scales obtained from the observations are about a factor 2 lower than those obtained from the computations. One possible reason for this discrepancy is the severity of the selection of the wave measurements, which perhaps eliminates large time scales.

Comparison with literature

The time scale estimates are compared in Fig. 4 with the results of computations by Young et al. (1987), the results of observations (Hasselmann et al., 1980 and Allender et al., 1983) and with results of Günther et al. (1981) and Holthuijsen et al. (1987) who both parameterized the energy balance equation to estimate the time scales.

The dimensionless time scale τ_* obtained by all these investigators (except Holthuijsen et al., 1987) are only weakly dependent on υ_*, in contrast to the time scales obtained in this study (both the numerical and observational results). The difference between the results of Young et al. (1987) and of the present study (both based on the EXACT–NL model) can be explained by the fact that Young et al. (1987) assumed a constant time scale during the directional response in each case, whereas in the present study the time scale was allowed to vary. The results of Holthuijsen et al. (1987) are generally somewhat closer to those of Young et al. (1987). Holthuijsen et al. (1987) predict the rapid increase in time scale for waves approaching the fully developed stage ($\upsilon_* = \upsilon_{*,PM}$).

Relatively large differences occur between the computational results of the present study and the observational results of Hasselmann et al. (1980) and Allender et al. (1983) (as interpreted by Holthuijsen et al., 1987). For the most part ($\upsilon_* > 0.075$, say), these observed time scales are about a factor 2 to 5 higher than those of the

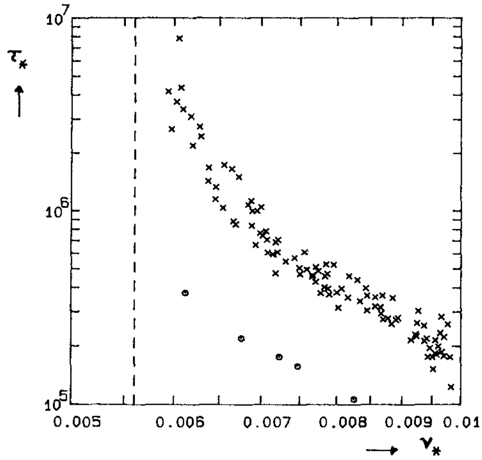


Fig. 3. Nondimensional time scale estimates τ_* as a function of growth stage υ_* The results of the computations and observations are indicated with the symbols (x) and (o) respectively. Computations refer to the cases of a sudden wind shift of 30°, 60° and 90° and to the wind speeds U = 10 and 20 m/s. The dashed vertical line at $\upsilon_* = \upsilon_{*,PM}$ indicates the non-dimensional Pierson-Moskowitz frequency (fully developed waves).

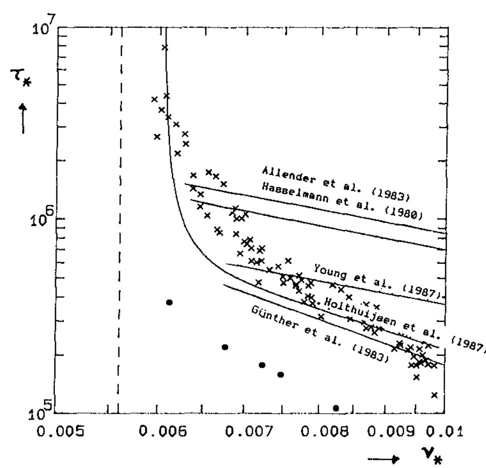


Fig. 4. Time scale estimates obtained from the model computations (x) and from the observations of the present study (o) and time scale estimates in the literature (————).

computations. This difference is possibly due to the nature of the selection procedure followed for these observations. A reanalysis of part of these observations (based on illustrations 7 and 8 in Hasselmann et al., 1980) shows that, when the same selection criteria are used as in the present study (except those related to the hindcast data and not corrected for propagation effects), the remaining observed time scales of Hasselmann et al. (1980) are on the average about a factor 3 lower than the original ones.

Conclusions

Numerical calculations with an advanced wave model (Hasselmann and Hasselmann, 1985) show that the response of the mean direction of waves in a turning wave field is primarily due to the effect of wind generation. This effect is counteracted to some degree by white-capping and nonlinear wave-wave interactions. For comparison with these model results, time scales of directional wave response have been estimated from observations in the southern and central North Sea. Both the model results and the observations indicate that the time scales increase with increasing growth state. However, the observed time scales are a factor of two smaller than the model time scales.

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