CHAPTER 91

NORTH SEA WIND WAVES ON TIDES AND STORM SURGES

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ABSTRACT

The influence of tide- and surge-induced currents and surface level variations on wind wave generation and propagation in the North Sea is investigated. The main interest is focussed on the shift of the absolute frequency due to time varying currents. For several North Sea storms calculations have been performed with a third-generation wave model, which includes all relevant effects of wave-current interactions and wave generation. Results of several hindcasts have been compared with data. The study shows that tides and surges result in relatively small but distinct modulations of mean wave parameters (5 - 10%), and large variations of spectral energy densities (50%). The tide-induced modulations of in particular wave periods are strongly influenced by the unsteadiness of depth and current. Observed modulations of mean wave parameters with periods comparable to that of the tide appear to be wind-induced for a significant part.

1 Introduction

In the present study effects of tides and storm surges on North Sea wind waves are assessed. Such effects have been recognized by people living of the sea for centuries; charts of shelf seas like the North Sea indicate that tidal races (e.g. severe current induced breaking) occur near many headlands and offshore shoals. Theoretically the interactions between (wind) waves and currents have also been recognized. The subject is treated in many textbooks and review papers (e.g., Whitham 1974; Peregrine 1976; Phillips 1977; Mei 1983; Peregrine and Jonsson 1983; Jonsson 1990).

The separate modeling of waves (and currents) is well developed; all relevant kinematic and dynamic aspects of waves (including sources and sinks of wave energy) can be accounted for explicitly (e.g. WAMDI group 1988). In models for waves on currents, however, only a limited part of this knowledge is used. Source terms for input and

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dissipation are usually not considered at all (e.g., Dobson and Irvine 1983; Gutshabash et al. 1986; Liu et al. 1989), or highly parameterized (e.g., Holthuijsen et al. 1989). Furthermore all these models assume quasi-stationary current fields.

In the present study two aspects are added to the scope of previous studies on wave-current interactions. First, the present study deals with unsteady currents, accounting for the corresponding shift of absolute frequency. As is indicated in previous papers (Tolman 1988, 1990b), this effect of unsteadiness should not be neglected if waves on tides are considered. Secondly both wave-current interactions *and* wave growth and decay are fully accounted for. For the scale of shelf seas such an approach seems necessary, since scales of wave-current interactions and of growth and dissipation of wave energy are approximately equal (i.e. of the order of 1000 km and 1 day). To obtain both qualitative and quantitative results, the present study deals with some practical storm cases in the (southern) North Sea.

This paper presents a selection of the results of the authors PhD study (1990a). Formulations and models are described briefly. For an extensive review of the governing equations, numerical models and results, reference is made to Tolman (1989, 1990a).

2 Wave-current interactions

Wind waves are usually described with a variance (or energy) density spectrum F as a function of wave phase parameters such as the wavenumber k, the intrinsic or relative frequency σ (as observed in a frame or reference moving with the mean current $\mathbf{U}$), the absolute frequency ω (as observed in a fixed frame) and the direction θ (normal to the wave crest of the component). In the linear theory for (quasi-) uniform surface gravity waves on slowly varying depths and currents (e.g., LeBlond and Mysak 1978; Phillips 1977; Whitham 1974), the wavenumber k is related to the frequencies σ and ω in the dispersion relation (surface tension neglected, d is the water depth averaged over the wave field):

$$\sigma = \sqrt{gk \tanh kd} = \omega - \mathbf{k} \cdot \mathbf{U} \tag{1}$$

Wind wave propagation in an unsteady and inhomogeneous medium is (within the linear wave theory) most conveniently described with the spectral action balance equation (e.g., Whitham 1965; Bretherthon and Garrett 1968; Hasselmann et el. 1973; Willebrand 1975). In the present study, the following version of the action balance equation is used:

$$\frac{\partial N}{\partial t} + \nabla_x \cdot [(\mathbf{c}_g + \mathbf{U})N] + \frac{\partial}{\partial \omega}[c_\omega N] + \frac{\partial}{\partial \theta}[c_\theta N] = \frac{S}{\sigma} \tag{2}$$

$$N = \frac{F(\omega, \theta, \mathbf{x}, t)}{\sigma}$$

$$c_g = \frac{\sigma}{k}\left[\frac{1}{2} + \frac{kd}{\sinh 2kd}\right] \tag{3}$$

$$c_\omega = \frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial t} + \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial t} \tag{4}$$

$$c_\theta = -\frac{1}{k}\left[\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} + \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial m}\right] \tag{5}$$

where N is the action density spectrum, the quantities c represent propagation velocities in several spaces (see below) and S represents the net source term for wave variance. The energy propagation velocity $\mathbf{c}_g$ has the direction θ and m is a coordinate perpendicular to θ.

The left hand side of (2) represents conservative action propagation. The first term of Eq. (2) is the local rate of change of the action density. The second term of Eq. (2) represents convection in the physical space due to the wave energy propagation velocity $\mathbf{c}_g$ and the mean current velocity $\mathbf{U}$. This term includes straining of the wave field due to spatial variation of $\mathbf{c}_g + \mathbf{U}$ (which is usually called shoaling if depth variations are considered). The third term of Eq. (2) represents the change of absolute frequency due to the unsteadiness of depth and current (e.g., Barber 1948; Mei 1983 page 96). The fourth term of Eq. (2) represents refraction.

The right hand side of Eq. (2) describes non-conservative processes. A distinction is made here between four separate source terms: (i) wind input; (ii) nonlinear resonant wave-wave interactions; (iii) dissipation due to deep-water wave breaking (whitecapping) and (iv) dissipation due to bottom friction. Formulations for the first three terms are taken directly from the WAM model (WAMDI group 1988). The formulation for the fourth term is taken from Madsen et al. (1988). For slowly varying currents, these formulation are valid in a frame of reference moving with the mean current velocity. Expressions for a fixed frame of reference are obtained using a straightforward Jacobian transformation and some minor adaptations to the original expressions (see Tolman 1990a).

3 Method of investigation

Wind wave hindcasts for this study have been performed with the third-generation wave model WAVEWATCH (Tolman 1989, 1990a), which has been developed specially for this study. The model includes all relevant wave-current interactions and explicit formulations for all source terms for wave growth and dissipation as described in the previous section. The model utilizes second order accurate propagation schemes in all discrete spaces ($\mathbf{x}$, ω, θ). The numerical treatment of source terms is taken from the WAM model (WAMDI group 1988). In the hindcasts the spectrum is described with 24 discrete directions ($\Delta\theta = 15°$) and with 26 frequencies (0.041 Hz - 0.453 Hz, $f_{i+1}/f_i = 1.1$, $f = \omega/2\pi$). The spatial resolution Δx = 24 km and the time step Δt = 15 min. The bathymetry of the North Sea is shown in figure 1.

Wind fields for the hindcasts consist of UK6 wind fields of the British Meteorological Office (BMO). Input current and water level fields for WAVEWATCH have been calculated with the model DUCHESS (e.g. Wang 1989), which solves the depth integrated shallow water equations on a fixed grid. The current fields have been calculated using both tidal constituents and wind forcing, so that the current and water level fields consist of both tides and surges. Wave boundary conditions at the open northern model boundary have been calculated with the deep-water no-current ocean wave model DOLPHIN (Holthuijsen and De Boer 1988).

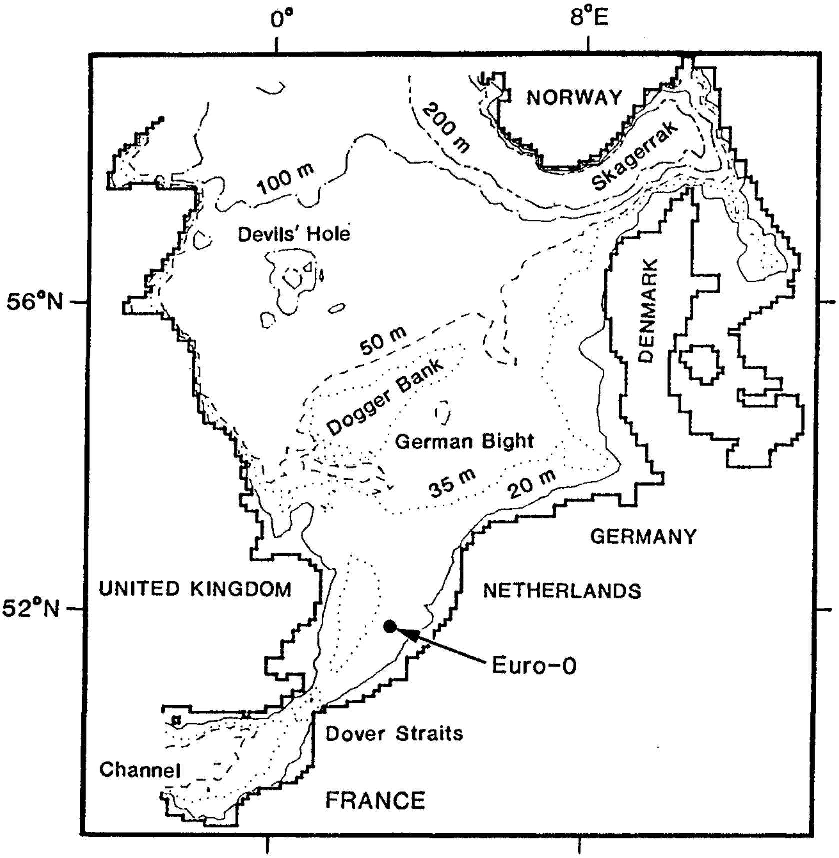

Fig. 1: The North Sea bathymetry.

Three storm cases on the North Sea are considered. Cases I (Jan. 1-4 1988) and II (Sept. 26-28 1987) consist of tide-dominated conditions with moderate SW and NW winds, respectively. For these cases wave observations were available. Case III consists of a surge-dominated case (Feb. 28-29 1988), for which no sufficient observations were available. The effects of the surge in this case are illustrated in Fig. 2 with water levels and the northerly current component U_N at location Euro-0 (see Fig. 1).

The tide- and surge-dominated cases are discussed separately below. In the discussion of the results for the tide-dominated cases the attention will be focussed on tide induced modulations of mean wave parameters and of parts of the spectrum, the specific effects of the unsteadiness of the tidal currents, the spatial distribution of tide-induced modulations of mean wave parameters and on a comparison of observed modulations of mean wave parameters with data. The results for the surge-dominated case will be

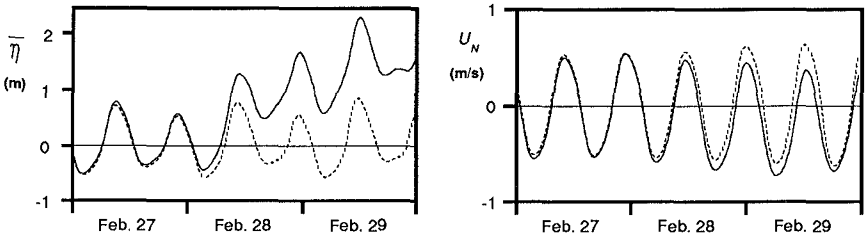

Fig. 2: Water levels $\bar{\eta}$ and northerly current components U_N for case III at location Euro-0. —— *: with wind forcing;* ····· *: without wind forcing.*

discussed only for as far as they differ from the results of the tide-dominated cases. The mean wave parameters assessed here are the significant wave height H_s, the absolute period T_a and the mean wave direction $\bar{\theta}$:

$$H_s = 4\sqrt{\int\int F(\omega,\theta) d\omega d\theta} \quad (6)$$

$$T_a = \overline{2\pi/\omega} \quad (7)$$

$$\bar{\theta} = \arctan\frac{b}{a} \quad (8)$$

The overbar notation at the right hand side of these equations denotes a straightforward average over the spectrum $F(\omega,\theta)$; a and b are the first two Fourier coefficients of the directional distribution (e.g., Kuik et al., 1988).

4 Results for tide-dominated cases

In the tide-dominated cases I and II, mean wave parameters show a small but distinct tide-induced modulation, as is illustrated in Fig. 3 with the significant wave height and the mean absolute period at Euro-0 for case I. In this figure, tide-induced modulations are observed as the difference between results of calculations in which tides are accounted for (solid lines) and where tides are neglected (dotted lines). As expected, the tide-induced modulations reflect the tidal period. The mean wave direction $\bar{\theta}$ is not presented in the figure, since it did not show significant tidal influences (tide-induced modulations less than 2°). The negligible tide-induced modulation of the mean wave direction suggest that current refraction has negligible influences on mean wave parameters. This is confirmed by practically identical results of repeated calculations, in which refraction is neglected altogether. Note that depth refraction is not relevant here, since waves are relative short (due to the moderate wind speeds) and are therefore not influenced by the bathymetry (e.g., deep water waves).

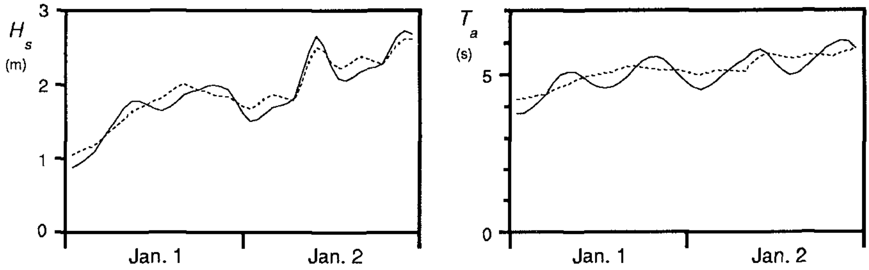

Fig. 3: Mean wave parameters at Euro-0 in case I (1988). ——— *: with tides and surges;* ····· *: without tides and surges.*

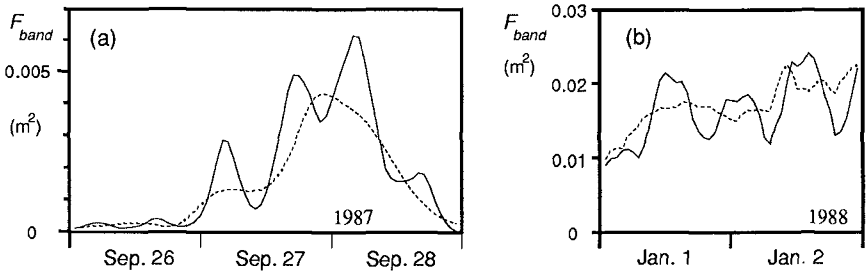

Fig. 4: Energy in fixed spectral bands (F_{band}) at Euro-0. (a) Case II, 0.1 - 0.2 Hz *(b); case I,* 0.3 - 0.5 Hz. ——— *: with tides and surges;* ····· *: without tides and surges.*

Modulations within the spectrum can be much larger than modulations of mean wave parameters, as is illustrated in Fig. 4 with the total energy in selected frequency bands at location Euro-0. Modulations of the order of 50% have been found in all frequency bands in the cases considered here. Since such large modulations have not been found in the significant wave height, modulations of different parts of the spectrum obviously have opposite signs and therefore largely cancel out in spectral averages.

The unsteadiness of tidal currents mainly manifests in modulations of the absolute period, since the unsteadiness explicitly causes a modulation of the absolute frequency (Eqs. (2) and (4), see also Tolman 1988, 1990b). The tide-dominated cases indeed show a significant modulation of the absolute period, as is illustrated in Fig. 3. The unsteadiness proved to have only a mild effect on the wave height modulation, as follows from results of repeated calculations in which the effects of unsteadiness are neglected (figures not presented here). The effects of unsteadiness are furthermore illustrated in Fig. 5 with the tide-induced modulations of the absolute period (ΔT_a, the difference between results of calculations with an without tides) for Euro-0 in case II, plotted as a function of the current velocity in the mean propagation direction of the waves, U_p (θ_U is the current direction).

$$U_p = |\mathbf{U}| \cos(\theta_U - \overline{\theta}). \qquad (9)$$

Plotted are both the results as obtained with a fully unsteady approach (solid line) and results as obtained with a quasi-stationary approach (dashed line) where $c_\omega \equiv 0$. In this case, the modulation of the absolute period completely disappears if depth and current unsteadiness are neglected. Apparently the entire modulation of the absolute period in this case is caused by the unsteadiness of depth and current. Figure 5 furthermore indicates, that the modulations of the wave parameters do not have a one-on-one relation with the local current velocity. Since the relation between modulations of wave parameters and the local current was found to vary with location and storm case, effects of wave-current interactions cannot be estimated from local parameters of tides only. This contrasts with the results of a analysis of effects of quasi-stationary currents, where many interaction effects can be estimated directly from the local current velocity.

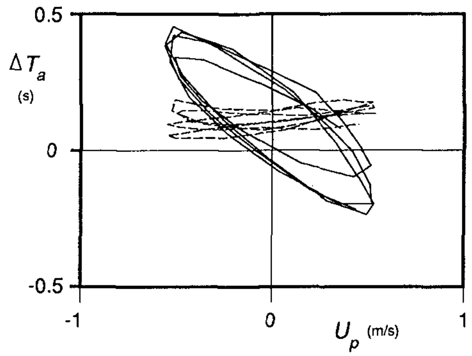

Fig. 5: Modulations of the absolute period ΔT_a as a function of the current velocity in the propagation direction of the waves U_p at Euro-0 for case II.
——— *: unsteady* [c_ω *given by* (4)] *;* – – – *quasi-stationary* ($c_\omega \equiv 0$).

The spatial distribution of effects of tides (and surges) on wind waves is assessed by considering the normalized rms modulation of wave parameters (i.e., the coefficient of variation CV). For example, the coefficient of variation of the wave height $CV(H_s)$ is defined as:

$$CV(H_s) = \frac{\sqrt{T^{-1}\int \Delta H_s^2 dt}}{T^{-1}\int H_s dt} \qquad (10)$$

where T is the duration of the averaging period (typically several tidal periods). The largest effects of the tides occur in the southern North Sea, as was expected, since the largest current velocities also occur in this region. In fact, the spatial distribution of the coefficients of variation of the wave heights, periods and lengths is similar to that of the

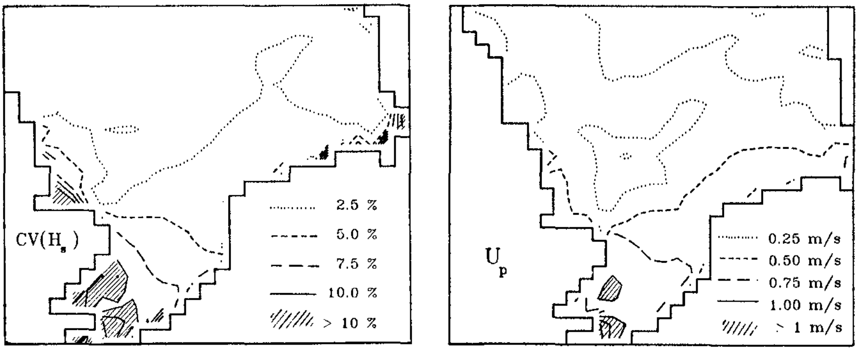

Fig. 6: Spatial distribution of the coefficient of variation of the significant wave height ($CV(H_s)$, total effect of wave-current interactions) and the distribution of the maximum current velocities in the mean wave direction (U_p) for case I (Jan. 1-2 1988).

maximum current velocities in the mean wave direction U_p, as is illustrated in Fig. 6. This figure shows values of $CV(H_s)$ of up to 15 % in the southernmost North Sea. The absolute period, relative period and the wave length show coefficients of variation of up to 10 %, 5% and 10% respectively. In case II coefficients of variation and current velocities U_p are somewhat smaller, with maxima concentrated near the British coast (figures not shown here).

Observed data were available for both tide-dominated cases. To compare the relatively small observed modulations as found in the calculations with observations, the modulations have been isolated. In the calculations modulations are the difference between results of repeated calculations in which tides and surges are either incorporated or ignored; the modulations in the observations have been defined as modulations with periods between approximately 9 h and 15 h (obtained by filtering the observed data). Calculated tide-induced modulations of the significant wave height (ΔH_s) and of the mean absolute period (ΔT_a) show some agreement with observed modulations, but also significant differences. This is illustrated in Fig. 7 with observed and calculated modulations for Euro-0 in case I. However, the residual modulations of the significant wave height and the mean absolute period, defined as the difference between observed and calculated modulations, proved to be highly correlated with observed wind speed variations with periods between approximately 9 h and 15 h. This is illustrated in Fig. 8. The high correlation suggests that the differences between observed and calculated modulations of wave parameters in Fig. 7 are caused by wind speed variations, and are not due to model errors.

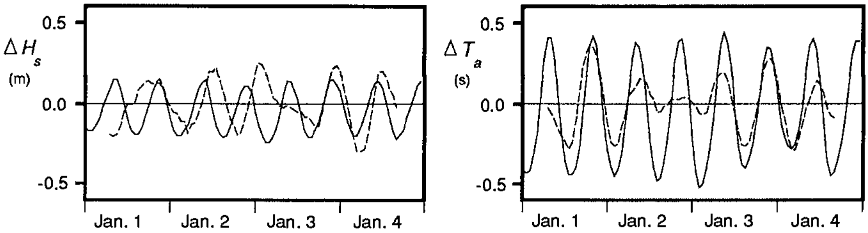

Fig. 7: Observed and calculated modulations (dashed and solid lines respectively) of the significant wave height and the mean absolute period at Euro-0 in case I (1988).

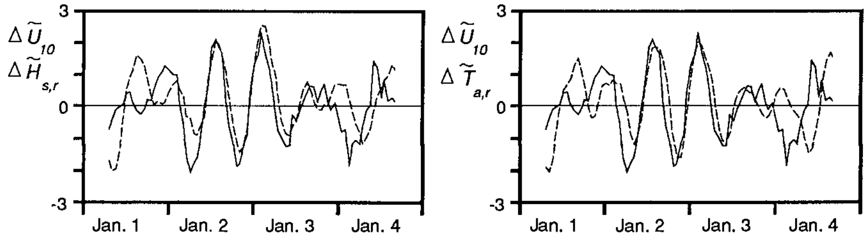

Fig. 8: Residual modulations of the significant wave height and the mean absolute period ($\Delta H_{s,r}$, dashed line and $\Delta T_{a,r}$, dotted line, respectively) and observed wind speed modulations (solid line) at Euro-0 in case I (1988).

5 Results for surge-dominated case

Results for the surge-dominated case III are presented, for as far as the results differ systematically from those of the tide-dominated cases (as mentioned above).

In the surge-dominated case, waves are essentially in shallow water, so that interactions can be caused by both surface level variations and currents. The numerical calculations indeed show effects of surface level variations and of currents on mean wave parameters; results of calculations with and without tides and surges, with surface level variations only and with currents only all show significant differences. This is illustrated in Fig. 9 with the corresponding wave heights at Euro-0. Since the time scale of computed interactions as presented in Fig. 9 is clearly larger than that of the tide, the interactions appear to be surge-dominated. For the effects of surface level variations this was expected, since surface level variation are surge dominated (see Fig. 2). For the effects of the currents this is somewhat surprising, since local currents are still tide dominated (see Fig. 2). It seems that the systematic nature of small wind driven currents results in more lasting (i.e. accumulated) effects than the larger, but oscillating tidal currents.

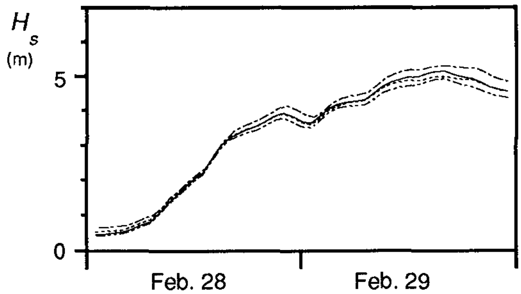

Fig. 9: Significant wave heights at Euro-0 in case III. —— *: with tides and surges;* ····· *: without tides and surges;* –·–· *: surface level variations only;* –··– *: currents only*

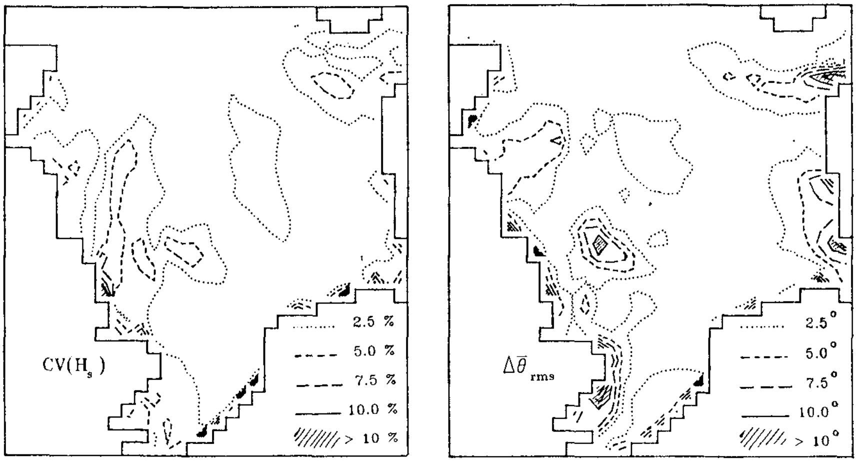

Fig. 10: Spatial distribution of the coefficient of variation of the significant wave height and rms differences of the mean wave direction due to refraction (case III, Feb. 28-29 1988).

The higher surface level and corresponding larger depth due to the surge result in higher waves (dash-dot lines versus dotted lines in Fig. 9), probably due to a reduced bottom-induced energy dissipation due to the increased water depths. On the other, hand currents reduce wave heights and periods (dash-dot-dot lines versus dotted lines in Fig. 9). This might be explained from the wind-induced currents, which in the southern North sea are systematically in the propagation direction of the waves, reducing the effective fetch and wind speed. The separate contributions of surface level variations and currents to the interactions are opposite and largely cancel out, resulting in a practically negligible total effect of all interactions.

Furthermore the surge-dominated case differs from the tide-dominated cases since depth refraction plays a distinct role in case III. This is illustrated in Fig. 10 with coefficients of variation for the significant wave height and rms differences of mean wave directions, obtained by comparing model results in which refraction was either incorporated or ignored. Effects of refraction are observed in areas with large gradients in the bottom level (compare Fig. 1), but do not spread over larger areas.

6 Discussion

The results of the North Sea hindcasts presented here show that the unsteadiness of tidal currents has a significant influence on wave-tide interactions. The relative importance of unsteadiness and inhomogeneity varies in space and time, so that effects of wave-tide interactions cannot be estimated from local depth and current parameters only, nor with a quasi-stationary or quasi-homogeneous approximation. Nevertheless effects of tides and surges seem to be restricted to areas with significant tide- and surge-induced currents and surface level variations.

The tidal currents results in modulations of mean wave parameters with an oscillating character (see e.g. Fig. 3), whereas currents and surface level variations of surges result in more monotonic variations (see e.g. Fig. 9). Wave-tide interactions seem to accumulate much less than wave-surge interactions, since case III shows that current-induced interactions appear to be surge dominated, although the local currents are clearly tide-dominated (as discussed in section 5). In the storm surge case considered here, effects of currents and surface level variations largely cancel out and resulting relative modulations of mean wave parameters are much smaller than in the moderate cases. It might therefore be concluded that the relative importance of wave-tide and wave-surge interactions decreases with increasing storm severity. However, the cancelling out of effects of currents and surface level variations cannot be expected to occur in any complex storm case. The potential magnitude of wave-surge interactions therefore is given by the potential magnitudes of effects of water level variations and currents separately, which are roughly of the same order of magnitude as the effects of tides in the tide-dominated conditions considered here. Consequently, it can not be concluded from the present results that the relative importance of interactions decreases with increasing storm severity.

This paper focuses on modulations of mean wave parameters. However, modulations of spectral densities or of energy in fixed frequency bands in general are much more pronounced than those of the mean wave parameters (modulations of 50% or more in all parts of the spectrum, e.g., Fig. 4). In particular the effects of the tides and surges on the low frequency variance (or energy) is striking, since wave-current interactions for monochromatic waves suggest a decreasing effect of currents with decreasing frequency due to decreasing Doppler shifts kU_p and relative current velocities U/c_g. This large impact is explained from the steep gradients in the low frequency flank of frequency spectra, where small shifts of the spectral peak frequency (or mean frequency) can cause large modulations of the total variance in fixed frequency bands. Like the frequency shifts, these modulations of spectral densities are strongly influenced by the unsteadiness of depth and current and cannot be estimated from local depth and current parameters only, or with conventional quasi-stationary approaches (as discussed above).

Considering the relatively small magnitude of effects of wave-tide and wave-surge interactions on the significant wave heights H_s and the mean wave period T_a (typically 5 to 10%), the implications for North Sea wave forecasting seem to be small. Such a conclusion is supported by the fact that observed modulations appear to be mainly wind-induced. However, the calculated modulations might be significant when assessing design wave heights for e.g. offshore platforms. Furthermore the large modulations of spectral densities due to tides has implications for e.g. the dynamic analysis of structures, as is illustrated by a study of the wave-induced movements and accelerations of the Euro-0 platform (tide-induced modulations of the order of 50%, Peters and Boonstra 1988).

7 Conclusions

This study on effects of tides and storm surges on wind waves in the North Sea has given rise to the following conclusions. Tides and storm surges in the North Sea should be treated as an unsteady medium for wind wave propagation. Both the unsteadiness and the inhomogeneity of depth and current play a significant role in the interactions so that neither a quasi-stationary nor a quasi- homogeneous approximation to wave-current interactions can be used. In moderate wind and wave conditions interactions are predominantly caused by (tidal) currents, whereas in severe conditions both currents and (mean) surface level variations contribute to the interactions. Due to accumulation of effects, relatively small currents of surges might have larger impacts on mean wave parameters than larger (but oscillating) tidal currents. Tide- and surge-induced modulations of mean wave parameters such as the significant wave height and the mean wave periods are relatively small (typically 5 to 10%). Tide-induced variations of spectral densities can be of the same order of magnitude as the average spectral density over a tidal period. Observed modulations of mean wave parameters (in particular the wave height) appear to be wind-dominated rather than tide-dominated.

Acknowledgements. The author acknowledges with pleasure that the Dutch Ministry of Public Works and Transportation (Rijkswaterstaat) has supplied the bottom schematization of the North Sea, the tidal boundary conditions and observed wind and wave data. The the Royal Netherlands Meteorological Institute (KNMI) has supplied the wind fields for this study. In this, the help of in particular J. de Ronde, R. van Dijk, A.J. van der Kerk, H. Ligtvoet (Rijkswaterstaat), H.W. Riepma and E. Bouws (KNMI) was greatly appreciated. Permission to use the numerical wave model DOLPHIN of Digital Hydraulics Holland B.V. is highly valued. Furthermore, the support, suggestions and comments of colleagues at the Delft University of Technology, KNMI, Delft Hydraulics and Rijkswaterstaat, and of members of the WAM group, in particular L.H. Holthuijsen, J.A. Battjes and N. Booij was of great help. This study has been performed while the author was working at the Delft University of Technology. This paper has been written while the author held a National Research Council - NASA Research Associateship.

REFERENCES

Barber, N.F., 1949: Behaviour of waves on tidal streams. *Proc. Roy. Soc. London,* **A 198**, 81-93.

Bretherthon, F.P., and C.J.R. Garrett, 1968: Wave trains in inhomogeneous moving media. *Proc. Roy. Soc. London,* **A 302**, 529-554.

Dobson, E.B., and D.E. Irvine, 1983: Investigation of Gulf Stream ring detection with spaceborne altimeter using mean sea height, wave height and radar cross section. The Johns Hopkins University, Applied Physics Laboratory, Space Department, Rep. JHU/APL S1R3U-005, 51 pp.

Gutshabash Ye. Sh., and I.V. Lavrenov, 1986: Swell transformation in the Cape Agulhas Current. *Izvestiya, Atmospheric and Ocean Physics*, **22** No. 6, 494-497.

Hasselmann, K., T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright K. Enke, J.A. Ewing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D.J. Olbers, K. Richter, W. Sell and H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Ergänzungsheft zur Deutschen Hydrographischen Zeitschrift*, Reihe A (8°) Nr. 12, 95 pp.

Holthuijsen, L.H., and S. de Boer, 1988: Wave forecasting for moving and stationary targets. In : *Computer modelling in ocean engineering*, Eds. B.Y. Schrefler and O.C. Zienkiewicz, Balkema, Rotterdam, 231-234.

Holthuijsen, L.H., N. Booij and T.H.C Herbers, 1989: A prediction model for stationary, short crested waves in shallow water with ambient currents. *Coastal Engineering*, **13**, 23-54.

Jonsson, I.G., 1990: Wave-current interactions. In: *The Sea volume 9: Ocean engineering science*. Le Mehaute Ed., Wiley, 65-120

Kuik, A.J., G.Ph. van Vledder and L.H. Holthuijsen, 1988: A method for the routine analysis of pitch-and-roll buoy wave data. *J. Phys. Oceanogr.*, **18**, 1020-1034.

LeBlond, P.H. and L.A. Mysak, 1978: *Waves in the Ocean*. Elsevier, Amsterdam, 602 pp.

Liu, A.K., F.C. Jackson, E.J. Walsh and C.Y. Peng, 1989: A case study of wave-current interaction near an oceanic front. *J. Geophys. Res.*, **94**(C11), 16189-16200.

Madsen, O.S., Y.-K. Poon and H.C. Graber, 1988: Spectral wave attenuation by bottom friction: theory. *Proc. 21st Int. Conf. Coastal Eng.*, Malaga, 492-504.

Mei, C.C., 1983: *The applied dynamics of ocean surface waves*. Wiley, New York, 740 pp.

Peregrine, D.H., 1976: Interaction of water waves and currents. *Adv. Appl. Mech.*, **16**, 9-117.

Peregrine, D.H., and I.G. Jonsson, 1983: Interaction of waves and currents. Miscellaneous Report No. 83-6, CERC, U.S. Army Corps of Engineers.

Peters, H.C. and H. Boonstra, 1988: Fatigue loading on a single pile platform due to combined action of waves and currents. *Proc. 5th Int. Conf. on the Behaviour of Offshore Structures*, 1015-1034.

Phillips, O.M., 1977: *The dynamics of the upper ocean*. 2nd edition. Cambridge University Press, 336 pp.

Tolman, H.L., 1988: Propagation of wind waves on tides. *Proc. 21st Int. Conf. Coastal Eng.*, Malaga, 512-523.
Tolman, H.L., 1989: The numerical model WAVEWATCH: a third generation model for the hindcasting of wind waves on tides in shelf seas. *Communications on Hydraulic and Geotechnical Engineering*, Delft Univ. of Techn., ISSN 0169-6548, Rep. No. 89-2, 72 pp.
Tolman, H.L., 1990a: Wind wave propagation in tidal seas. Doctoral thesis Delft Univ. of Techn., also *Communications on Hydraulic and Geotechnical Engineering*, Delft Univ. of Techn., ISSN 0169-6548, Rep. no. 90-1, 135 pp.
Tolman, H.L., 1990b: The influence of unsteady depths and currents of tides on wind wave propagation in shelf seas. *J. Phys. Oceanogr.*, **20**, 1166-1174.
Wang, Z.B., 1989: Mathematical modelling of morphological processes in estuaries. Doctoral thesis Delft Univ. of Techn., also *Communications on Hydraulic and Geotechnical Engineering*, Delft Univ. of Techn., ISSN 0169-6548, Rep. no. 89-1.
WAMDI group, 1988: The WAM model - a third generation ocean wave prediction model. *J. Phys. Oceanogr.*, **18**, 1775-1810.
Whitham, G.B., 1965: A general approach to linear and non-linear dispersive waves using a Lagrangian. *J. Fluid Mech.*, **22**, 273-283.
Whitham, G.B., 1974: *Linear and nonlinear waves*, Wiley, New York, 636 pp.
Willebrand, J., 1975: Energy transport in a nonlinear and inhomogeneous random gravity wave field. *J. Fluid Mech.*, **70**, 113-126.