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EVALUATION OF THE SWAN WAVE MODEL IN SLANTING FETCH CONDITIONS

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Abstract: In this paper, the role of non-linear four-wave interactions in conditions with slanting fetch (with wind blowing obliquely off a coast) is investigated. This is done by running the SWAN wave model with three different quadruplet formulations and by comparing the results with 7 years worth of routine wave measurements in Lake IJssel in the Netherlands. For short fetches (< 5 km), and near and below the spectral peak, the SWAN results clearly showed a steering of the wave direction by the fetch geometry. Exact quadruplet methods (Xnl) yielded relatively strong wave steering but relatively weak four-wave interactions. Remarkably, using Xnl did not lead to better overall agreement with measurements – improvements for the mean wave period T_{m01} were offset by some deterioration for the wave height H_{m0}.

INTRODUCTION

One aspect of wave growth that still seems to be poorly understood is wave growth in slanting fetch conditions. This lack of understanding is illustrated by some conflicting findings in scientific literature. For example, Holthuijsen (1983) suggested that slanting fetch wave growth is mainly a directionally decoupled phenomenon. By contrast, Pettersson (2004) suggested that a directionally decoupled model was unable to predict the steering of the wave direction in such situations and that non-linear four-wave interactions play a significant role.

Wave growth in slanting fetch conditions is not only of scientific interest but also of practical interest. For example, ship traffic may be affected as the sheltered conditions

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near a coast disappear rapidly if the wind blows obliquely off the coast, rather than perpendicularly. For dike design, it is important to notice that some dikes around bays or estuaries may experience the most critical conditions when the local winds are blowing offshore. Actually, many dike breaches during the 1953 flooding disaster in the Rhine-Scheldt-Meuse estuary occurred on south(east)wards facing dike sections which experienced offshore local winds. Hence, it is also worth investigating wave conditions near relatively sheltered dikes.

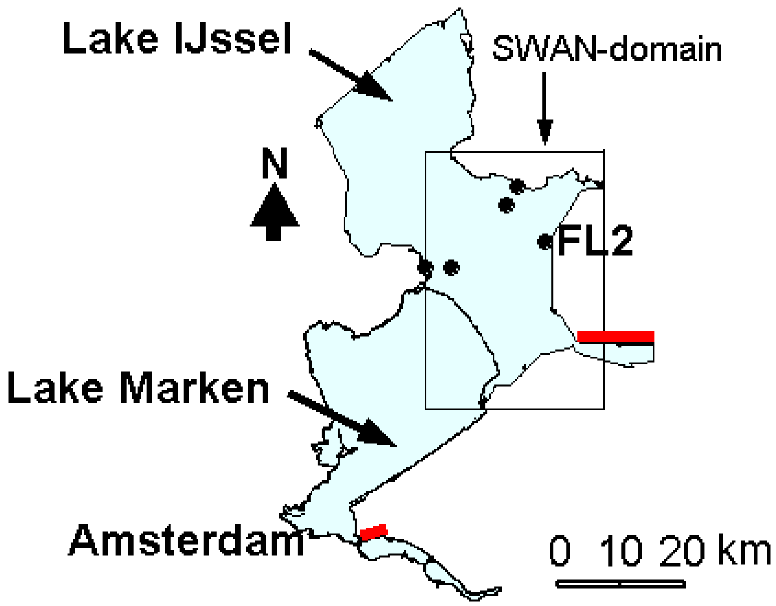

Fig. 1: Lake IJssel, measurement location FL2 and SWAN model domain.

The present area of interest is Lake IJssel (Figure 1), which is about 60 kilometres Northeast of Amsterdam. Up till 1932, Lake IJssel used to be an estuary connected to the Wadden Sea; at present it is a large lake with a mean depth of about 4-5 metres. The geometry of Lake IJssel seems to be highly suitable for slanting fetch investigations as much of the lake is surrounded by shores and dikes that run straight for up to 10 kilometres. Also, slanting fetch phenomena may be of practical relevance for a number of areas in the Southeastern part of Lake IJssel and Lake Marken. Some of those are indicated with thick red lines in Figure 1. The lines indicate areas where the most critical conditions (due to wind set-up of the mean water level) coincide with wave growth during slanting fetch conditions.

Unfortunately, no dedicated slanting fetch measuring campaign has been carried out so far. Still, 7 years of routine wave measurements (including 1D-spectra) are available for 5 locations (Figure 1). Together with wave model predictions, these data can increase our understanding on slanting fetch wave growth. In the present paper, we will consider the role of the non-linear four-wave interactions in slanting fetch conditions by running the SWAN wave model with some different formulations for these interactions. In addition, we will compare the SWAN results with experimental data.

FIELD DATA

Wave conditions in Lake IJssel are measured year-round by Rijkswaterstaat IJsselmeergebied (henceforth RIJG), using five measurement locations in the southeastern half of the lake (Bottema et al., 2003). Considering the coastline and the position of the present measurement locations, the location FL2 is best suited for the present analysis. FL2 (Figure 1) is about 1.15 kilometres from the eastern shore of Lake IJssel, which can be divided in two sections: a North-South-section of 11.5 kilometres length to the Southeast of FL2, and a SSW-NNE-section to the Northeast of FL2.

Since 2000, capacitance wires are used for the wave measurements. In earlier years however, a step gauge with a resolution of 5 centimetres was used. The wind is measured at 10 metres above the mean water level, using cup anemometers and wind vanes. The sample frequency is 4 Hz for the wave data and 1 Hz for the wind data. The wind data are stored as vectorial means of wind speed and wind direction, but in order to reduce scatter, hourly averages are used for the present analysis.

For the present study, seven years of data (1997-2004) are available. As a precaution, all summer data (may-september) were excluded because of the risk of marine growth, which is difficult to detect from individual measurements but may cause large errors. Careful screening of the data made us also exclude a limited amount of winter data with insufficient quality. Finally, we focussed on winds with an offshore (easterly) component and a wind speed range of 10-11 m/s. At higher wind speeds too little data were left for a meaningful comparison with the SWAN wave model. At lower wind speeds, the scatter in the data tended to be too great.

NUMERICAL WAVE MODELLING

All model simulations were carried out with the SWAN wave model (Booij et al., 1999) and a wind speed of 10.5 m/s. However, simulation of slanting fetch situations is far from trivial because one needs a large computational domain *and* a fine spatial resolution. The large domain is needed because some wave components in slanting fetch conditions are actually propagating in an *onshore* direction. The fine resolution is needed because slanting fetch wave fields also contain short fetch components. Recent studies of fetch-limited wave growth showed that SWAN needs as much as 15, 30 and 100 upwind grid points to make certain that discretisation errors at a given location are less than 10%, 5% and 2% respectively. The latter two options were far from feasible so we chose a domain size of 29 x 40 kilometres and a spatial resolution of 80 metres. In spectral space, we used 31 frequencies between 0.08 and 1.9 Hz and a directional resolution $\Delta\theta$ of 10^o (as $\Delta\theta=5^o$ led to less than 1% and 0.5^o change in wave height and directional parameters). For the iteration process, we prescribed a strict convergence criterion of 50 iterations to make sure SWAN was well converged in all cases.

Except for the four-wave interaction process, all physical model settings were in agreement with the default settings for SWAN, version 40.31. As for the four-wave interactions, not only the default Discrete Interaction Approximation (**DIA**) was used, but also a multiple-DIA technique (**mDIA**; Hashimoto and Kawaguchi, 2001) and an exact technique (**Xnl**, Resio et al., 2001; Van Vledder and Bottema, 2003). The latter technique requires lots of CPU-time (other things being equal, over 300 times as much as DIA). In addition some numerical settings were modified to assure convergence; Van Vledder (2005) recommends to use a maximum frequency of at least 6 times the peak frequency. Hence, the present frequency domain was extended from 1.9 to 8 Hz (using 49 instead of 31 frequencies) whilst the number of iterations was increased to 70.

SENSITIVITY STUDY

Because of the prohibitive CPU-times of the exact (Xnl) approach, only a one-dimensional (1-D) comparison of quadruplet formulations in SWAN was feasible. The 1-D simulations were carried out with a constant water depth of 4.2 metres and a domain of 24 kilometres length; the latter to make sure there were no end-of-domain effects; the other numerical settings were equal to the two-dimensional simulations.

First, it was verified whether DIA, mDIA and Xnl yield similar SWAN-results for perpendicular fetches, so that a benchmark would be available for slanting fetch tests. For SWAN with default (DIA-)settings, the wave height H_{m0} in the perpendicular fetch range of 0.3 to 4 kilometres was within 2% of Kahma and Calkoen (1992); the SWAN peak period T_p typically was 3-7% lower. For larger fetches, the default SWAN wave heights and periods tended to be lower than Kahma and Calkoen (1992) because of shallow-water effects. With the alternative quadruplet-formulations (mDIA and Xnl), the SWAN-values of H_{m0} and T_{m01} generally exceeded the default values by 2-4% and 1-3% respectively. However, for fetches shorter than the ones considered in this study (fetches < 1 km), the H_{m0}-difference between DIA and Xnl was considerably larger.

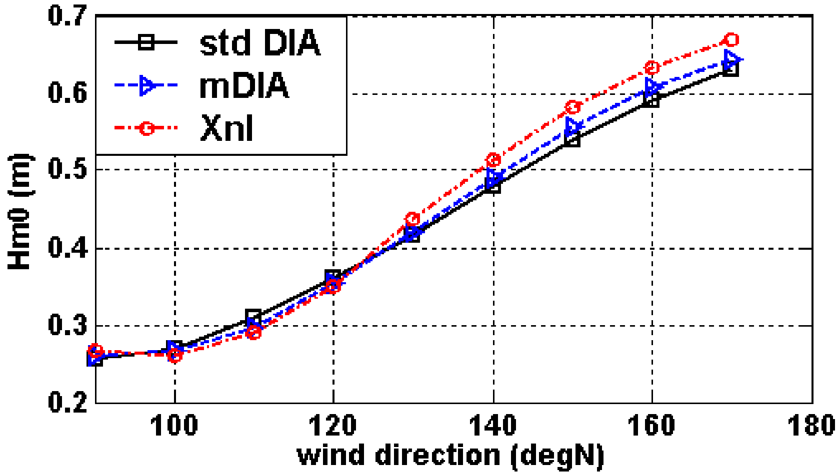

Fig. 2: Wave height H_{m0} as function of wind direction (orthog. fetch x : 1120 m)

Next, the slanting fetch tests themselves were carried out. Figure 2 shows the wave height as a function of wind direction, for a distance to the coastline (orthogonal fetch) x that is typical of the FL2-location. Wind directions of 90^o and 180^o correspond to perpendicular and parallel fetch respectively, and to easterly and southerly winds in reality. Figure 2 shows that, in comparison to DIA, mDIA yields up to 3% H_{m0}-reduction for slightly slanting fetch and up to 3% H_{m0}-increase for nearly parallel fetch. Similar trends were observed for various wave period measures (not shown). The Xnl-simulations show trends similar to mDIA, but the differences with DIA are up to 6%. Remarkably, the lowest H_{m0} in the Xnl-simulations did not occur for perpendicular fetch but for 100^{o} wind. This seems to be due to some spurious low-frequency energy at short fetches for the case of 90^{o} winds.

a)

b)

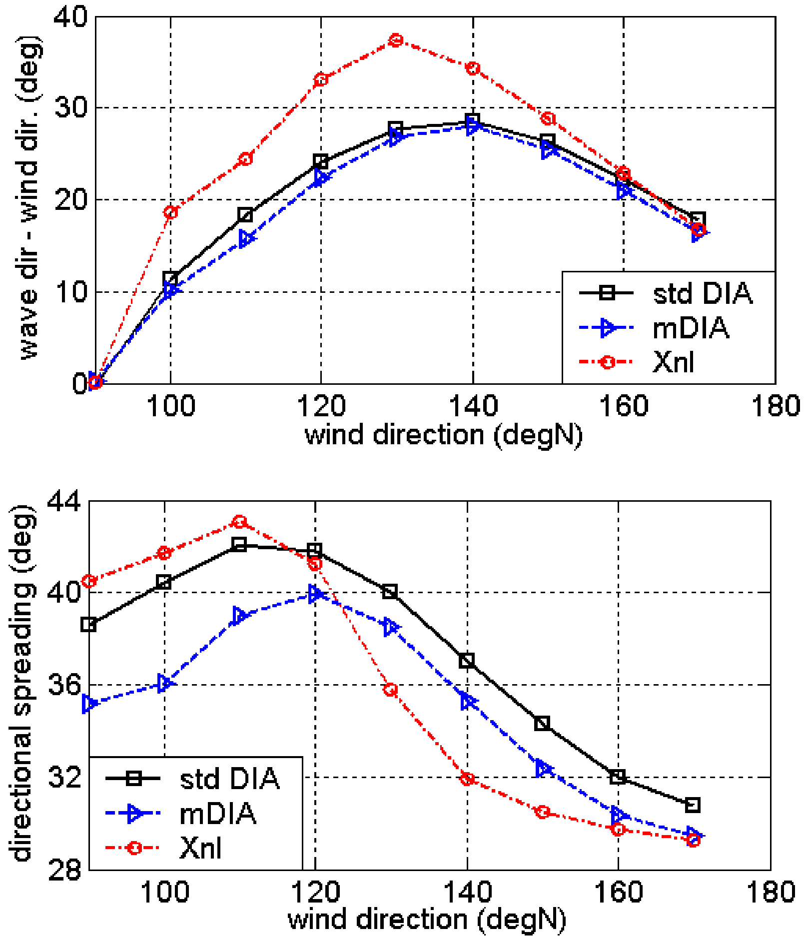

Fig. 3: Difference between wind and wave direction (a) and directional spreading (b) as function of wind direction (orthogonal fetch x = 1120 m)

In slanting and parallel fetch conditions, the mean wave direction θ may deviate considerably from the wind direction. We found no dependence on wind speed but a clear relation with fetch, the largest deviations occurring for short fetches (up to roughly 5 kilometres). At a fetch of 1.12 kilometres (Figure 3a; top panel), the SWAN-results with DIA (default) and mDIA both suggest a maximum deviation of 28^{o} when the angle between the wind and the coast line is about 45^{o}. The SWAN-results with the exact quadruplet formulation (Xnl) differ markedly from the other SWAN-versions, even when the wind is almost (but not fully) perpendicular to the coast. Unfortunately, no directional measurements are available. Hence, it is not yet possible to determine whether Xnl or DIA predicts the wave directions correctly.

Compared to perpendicular fetch, the directional spreading σ_θ initially tends to increase for slanting fetch, and to decrease for parallel fetch (Figure 3b; lower panel). These trends appear to be strongest for fetches of the order of 1 kilometre. As for the differences between the quadruplet formulations, mDIA yields systematically a somewhat (2^o) lower σ_θ than DIA. Xnl yields largely the same σ_θ as DIA for nearly perpendicular fetch, but its σ_θ is as much as 5^o lower for slanting fetch. Unfortunately, these detailed trends are hard to explain as they do not correlate well with the trends of the wave height (Figure 2) and the deviation of the mean wave direction (Figure 3a).

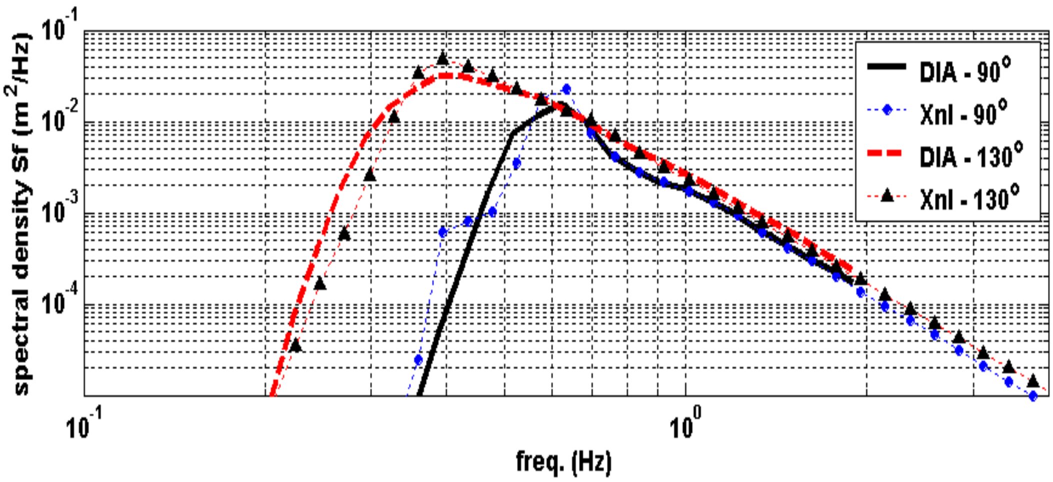

Fig. 4: Variance spectra (log-log scale); orthogonal fetch *x* = 1120 m

Figure 4 shows some variance spectra for perpendicular and slanting fetch (90^o and 130^o). Only the results with DIA- and Xnl-quadruplets are shown as the difference between the DIA- and mDIA-results is relatively small. Overall, the DIA and Xnl-spectra look quite similar. However, the Xnl-spectrum for perpendicular fetch (90^o) shows a small but spurious hump at about 0.4 Hz. The hump occurs for all fetches of about 1 kilometre and less, and in absolute terms, it remains almost constant. In relative terms, its relevance is largest for very short fetches (the first grid points off the coast). For slanting fetch conditions (130^o), the DIA spectral peak seems to be relatively flat compared to the Xnl result. A remarkable result of both the DIA- and Xnl-simulations is the fact that slanting fetch conditions can be recognised by the shape of the *one-dimensional* wave spectrum. Especially the normalised height of the spectral peak (max(S_f) *($H_{m0}^2 T_p$)) in SWAN is a good indicator. For perpendicular fetch it tends to be about 0.1-0.2, for slanting fetch it is typically about 0.07.

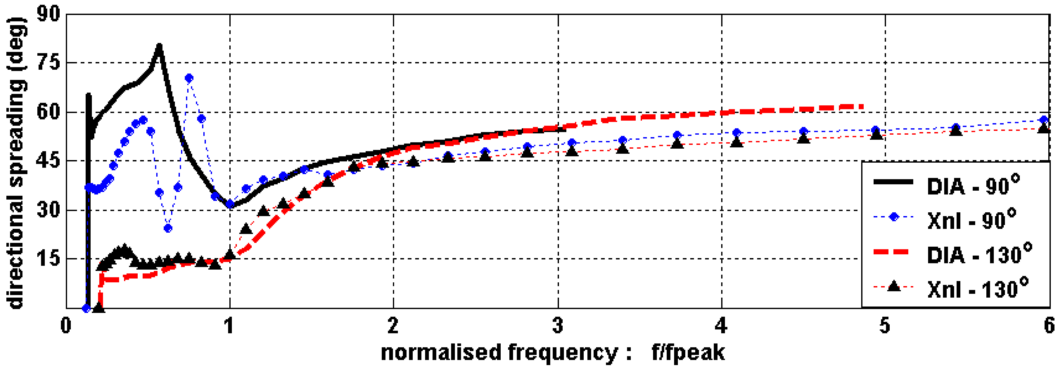

Fig. 5: Directional spreading as a function of f/f_p (x = 1120 m)

Figure 5 shows the spectral directional spreading $s_\theta(f)$ as a function of f/f_p where f is the frequency and f_p the peak frequency. The differences between perpendicular and slanting fetch mainly occur near and below the peak frequency, where the directional spreading for slanting fetch is about 15^o only. This is 2-5 times lower than for perpendicular fetch. In the high frequency tail, locally generated waves dominate, and the fetch conditions have little or no effect. For all frequencies, there are clear differences between the DIA- and Xnl-approach. Compared with DIA, Xnl yields slightly larger $s_\theta(f)$ –values around the spectral peak, but much (5^o-10^o) lower values in the spectral tail. The irregular low-frequency behaviour of Xnl at perpendicular fetch is probably due to the spurious spectral hump mentioned above.

For the mean wave directions (not shown), a marked frequency dependency was found. For low frequencies ($f < (1.5\text{-}2)*f_p$), the wave direction strongly depends on the fetch geometry and tends to be parallel to the coast or even shorewards. For higher frequencies, the waves are roughly parallel to the wind. The main differences between DIA and Xnl appear to occur for $0.7 < f/f_p < 2$, where the DIA mean wave directions tend to be much (10^o-25^o) closer to the wind direction than the Xnl-results.

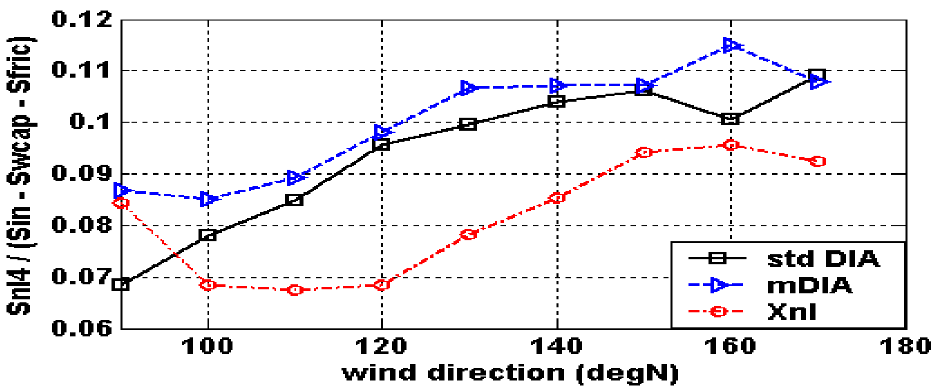

Fig. 6: Ratio of quadruplet and net wave growth source terms as a function of wind direction (orthogonal fetch x: 1120 m)

Figure 6 shows the ratio of the net absolute value of the quadruplet source term S_{nl4} in SWAN and the net wave growth source term S_{in}-S_{wcap}-S_{fric} ; S_{in} is the wind input, S_{wcap} the whitecapping and S_{fric} the bottom friction. The normalised S_{nl4} of mDIA is slightly larger than the DIA result whereas the Xnl-value is clearly lower, especially for slanting fetches. The net effect of the weaker Xnl-quadruplets on the H_{m0}- and σ_θ-trends seems to be small as the trends in Figure 2 and 3b are quite dissimilar from the trends in Figure 6. The similarity in the trends of Figure 3a and 6 is much greater, suggesting that the mean wave direction is relatively sensitive to the quadruplet formulation.

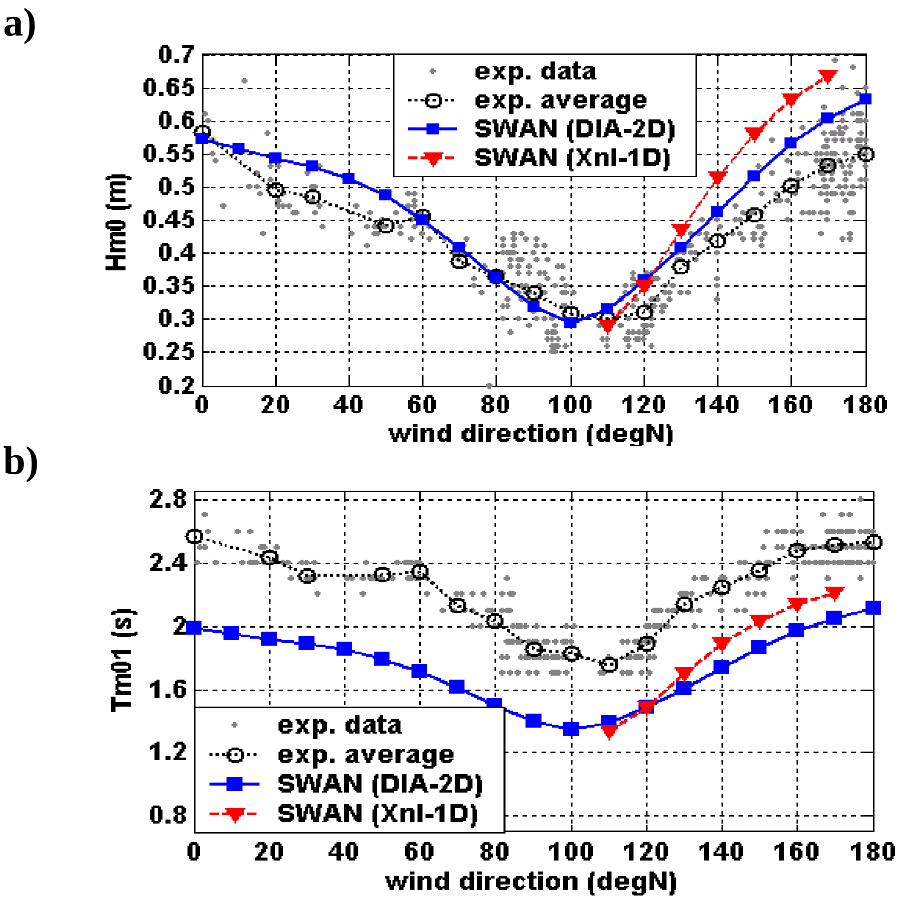

Fig. 7: Wave height H_{m0} (upper panel) and mean wave period T_{m01} (lower panel) as a function of wind direction (at FL2 for 10-11 m/s wind speeds).

COMPARISON WITH MEASUREMENTS

In Figure 7a, the measured wave heights H_{m0} at FL2 are compared with SWAN. Two types of SWAN simulations are considered, the first being two-dimensional with DIA-quadruplets, the second being one-dimensional with Xnl-quadruplets. For the latter, only the wind direction range of 110°-170° was considered as this was the range with negligible differences between 1-D and 2-D simulations with SWAN-DIA (< 3% in H_{m0} and T_{m01}; < 1° in σ_θ and the mean wave direction θ). Remarkably, SWAN with DIA-quadruplets fits better with the measurements than SWAN with Xnl, especially for slanting and nearly parallel fetch. This is surprising as the wave growth rate of DIA and Xnl is comparable (for perpendicular fetch, both are close to Kahma and Calkoen, 1992) and because one would expect that in more complex situations, Xnl would be superior to the relatively crude DIA. The results for the wave period T_{m01} are shown in Figure 7b. With DIA-quadruplets, SWAN underestimates the measured T_{m01} by 20-25% for all wind directions. With Xnl, SWAN does a slightly better job, especially for nearly parallel fetch where the T_{m01} -underestimation is reduced to about 12%.

For a number of stationary and representative data, wave spectra were analysed. In the spectral tail, SWAN overestimated wave energy while the slope of the tail was slightly underestimated. This applied both to the DIA and Xnl-approach. Near and below the spectral peak, the variability in the experimental results was quite large, causing rather ambiguous results. In some cases, SWAN-Xnl clearly did a better job (Figure 8); in other cases SWAN-DIA appeared to be better. Due to the experimental variability and the non-ideal fetch geometry (the kink in the coastline near FL2), only the SWAN wave spectra allowed us to recognise slanting fetch conditions from the spectral shape, not the measured spectra.

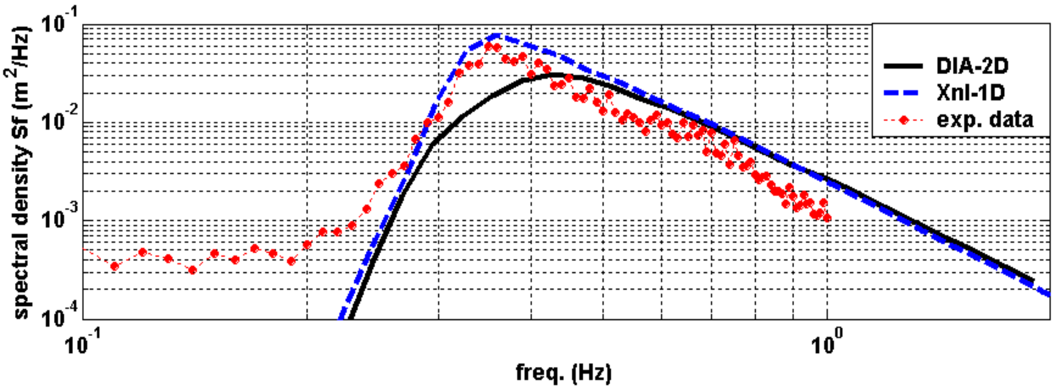

Fig. 8: SWAN-wave spectra for SE-wind (10.5 m/s ; 130°) and experimental data at the FL2-location (10/10/2000, 3-4h MET)

DISCUSSION, CONCLUSIONS, FUTURE RESEARCH

The aim of this paper was to investigate the role of non-linear four-wave (quadruplet) interactions in slanting fetch conditions. To this end, we used the SWAN wave model and 7 years of surface elevation data. Three quadruplet formulations were considered: the default Discrete Interaction Approximation (**DIA**), multiple-DIA (**mDIA**) and an exact method (**Xnl**). Our conclusions and recommendations for future research are:

- For slanting fetch, and compared with DIA and mDIA, Xnl has a much weaker quadruplet source term and a much larger steering of the wave directions by the fetch conditions. This suggests that for slanting fetch, non-linear interactions play a significant role, in accordance with (Pettersson, 2004).
- Slanting fetch situations can be identified from *one-dimensional* SWAN-spectra, but not always from measured spectra in which variability is too large.

- The spectral tail ($f > 2f_p$) seems unaffected by slanting fetch. DIA and Xnl both overestimate wave energy in the spectral tail, where they are almost identical.
- Generally, the SWAN-Xnl wave spectra are more peaked than the DIA-spectra.
- At present, Xnl requires over 300 times as much CPU time as the default DIA approach. Hence, only 1D studies with Xnl are feasible. Further optimisation of Xnl, which is strongly desirable, is underway (Van Vledder, 2005).
- It is not yet recommended to use SWAN with Xnl for very short fetches (< 1 km) as these results can be affected by some spurious low-frequency energy.
- A retuning of the deep water source-term balance in SWAN is recommended.
- It is recommended to increase bottom friction since this may improve the fit between SWAN results and measured data, especially for H_{m0} (see Figure 7a).
- It is worthwhile to extend this study to narrow fetch situations as in such situations, unlike the present case, wave steering is not limited to the first few kilometres off the coast but occurs at much longer fetches (Pettersson, 2004).
- It recommended to measure 2-D wave spectra near one of the westerly dikes of Lake IJssel, where slanting fetch conditions occur more often than at FL2.

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