HINDCASTING OF WAVES AND WAVE LOADS ON DUTCH WADDEN SEA DEFENSES

Ap van Dongeren[1], Jacco Groeneweg[1], Gerbrant van Vledder[2,3], André van der Westhuysen[1], Sofia Caires[1] and Jeroen Adema[2]

[1]WL|Delft Hydraulics, PO Box 177, 2600 MH Delft, The Netherlands.
Corresponding email: Ap.vanDongeren@wldelft.nl, Tel: +31-15-2858951.
[2]Alkyon Hydraulic Consultancy & Research, P.O. Box 248, 8300AE Emmeloord, The Netherlands
[3] Delft University of Technology, P.O. Box 5048, 266 GA Delft, The Netherlands.

INTRODUCTION

About half the area of the Netherlands lies below mean sea level and is protected from flooding by a network of dikes. In compliance with the Flood Defenses Act ("Wet op de Waterkering, 1996"), these primary coastal structures must be checked every five years (2001, 2006, 2011, etc.) for the required level of protection on the basis of Hydraulic Boundary Conditions (HBC) in terms of wave height, period, direction and water level. These HBC must be derived anew every five years and established by the Minister of Transport, Public Works and Water Management.

Currently, there is a degree of uncertainty concerning the quality of the HBC in the Wadden Sea, which is a shallow tidal inlet sea in the North of the Netherlands (Figure 1) and which stretches further northeastward to Germany and Denmark. The uncertainty stems from the fact that the HBC in this area are derived on the basis of an inconsistent set of measurements and design values while for the rest of the Dutch coast (the closed Holland Coast and the Zeeland Delta) the HBC are determined by a probabilistic approach in which the wave model SWAN (Booij et al., 1999) is applied for the transformation of offshore wave conditions to the nearshore. The model was not used in the Wadden Sea because there was insufficient confidence in the SWAN wave model to produce reliable boundary conditions there. This was due to an apparent lack of swell penetration in the model for the case of the Norderney Inlet in the German Wadden Sea (Kaiser and Niemeyer, 2001) and and due to absence of sufficient data to verify the model in the Dutch Wadden Sea itself.

Therefore, the Dutch Department of Transport, Public Works and Water Management has commissioned a project "Wadden Sea" within the framework of SBW (*Sterkte en Belasting Waterkeringen;* Strengths and Loads on Water Defenses) to investigate and improve the performance of SWAN in the Wadden Sea, so that reliable Hydraulic Boundary Conditions can be computed for the Wadden Sea in 2011. The overall aim of the SBW project is to improve the quality of the models and methods used to derive the HBC to enable the managers and experts to have sufficient confidence to use these tools for the five-yearly tests.

One of the aims of the Wadden Sea project is to perform hindcasts of storm events in the Wadden Sea or comparable tidal inlets and investigate the sensitivity to physical formulations and model inputs, the key results of which are summarized in this paper. A companion paper by Van Vledder et al. (2007) discusses some numerical aspects.

Figure 1: Map of the Dutch and German Wadden Sea, with the Ameland and Norderney Inlet indicated by the red circles (source: Google Earth).

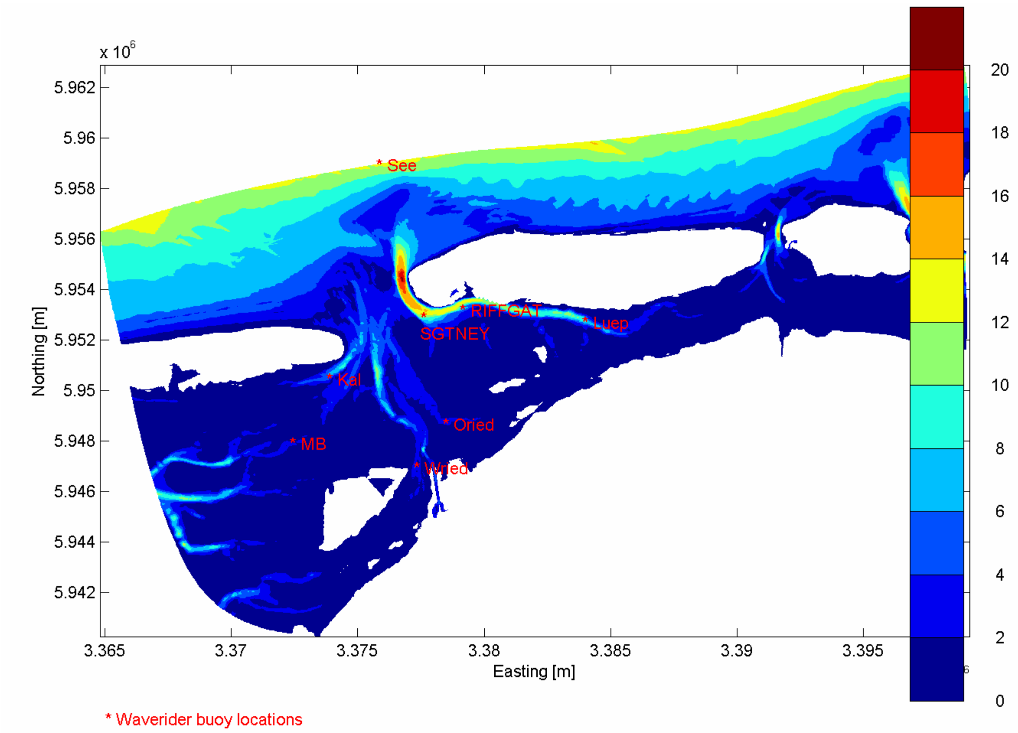

Figure 2: Bathymetry (in meters relative to German datum) and measurement stations in the Norderney Inlet.

HINDCASTS

Extensive hindcasts of wave conditions in the Ameland Inlet (in the Dutch part of the Wadden Sea) and Norderney Inlet (in the German part) for a variety of storms were performed and compared to field data (WL|Delft Hydraulics and Alkyon, 2007), which were acquired with a unique and large array of directional wave buoys in the last few years. These inlets (see Figure 1) are situated on the German and Dutch Northern Coasts, and are subject to waves from the North Sea from northern to south-western directions.

Norderney Inlet

The Norderney Inlet is shown in detail in Figure 2. For a more thorough description of the measurement program in this inlet we refer to Kaiser and Niemeyer (2001). The focus of our study was on the penetration of swell in this inlet and the (perceived) lack of modelled low frequencies in the measurement station "Riffgat", which is located just south of the island. The hindcasted storms are summarized in Table 1.

Table 1: Boundary conditions and inputs of 2 storm events in Norderney Inlet

date	time	WL [m MSL]	θ_w [°N]	U_{10} [m/s]	H_{m0} [m]	T_p [s]	θ_{peak} [°N]
5/02/99	03h40	3.4	290	19.0	6.0	14.3	330
3/12/99	18h30	3.2	290	25.7	5.9	13.3	300

In Kaiser and Niemeyer (2001) and in an initial hindcast in the current project using the latest version (40.51 with the new wind growth and whitecapping formulations of Van Der Westhuysen et al., 2006) of SWAN, the modelled variance spectrum agreed with the spectrum obtained from measurements for the storm of 3/12/1999 but not for 5/2/1999, which showed a distinctly more fully-grown shape (lower peak frequency and a larger wave height) in the measurements, see Figure 3 (bottom left). Figure 3 (top left and top right) shows the significant wave height and the peak period for the December 3rd storm respectively, where the wave height decay over the ebb tidal delta can be clearly seen, with some energy penetrating into the inlet. Since the inlet is rather "short", North Sea waves reach the mainland coast. This can also be seen in the top right panel which shows the penetration of waves with large peak periods into the inlet. The important realization is that the longer period waves do not penetrate through the channel (contrast with the bathymetry in Figure 2) but rather refract over the tidal flats, where they ultimately dissipate due to breaking and bottom friction. The measured low frequencies in Riffgat during some storms are therefore not due to propagation of North Sea waves but are rather due to local effects.

The main local effect turns out to be the currents. Since the spectra were measured at astronomical slack tide, previous investigations did not take the currents into account. However, in these storm conditions a significant wind-driven current is existant. To study its effect, Kaiser (Forschungsstelle Küste, Norderney) provided a current field obtained from PCA/NN modelling (for details we refer to Herman et al., 2006), see Figure 4 (left). This 2DH-Delft3D model is driven by the interpolated 1-hourly water level time series from the HIPOCAS dataset (Weiße et al., 2003) applied as open boundary conditions and by wind fields obtained from a wind atlas produced by the German Weather Service (DWD). Wave effects are not included in the flow modelling.

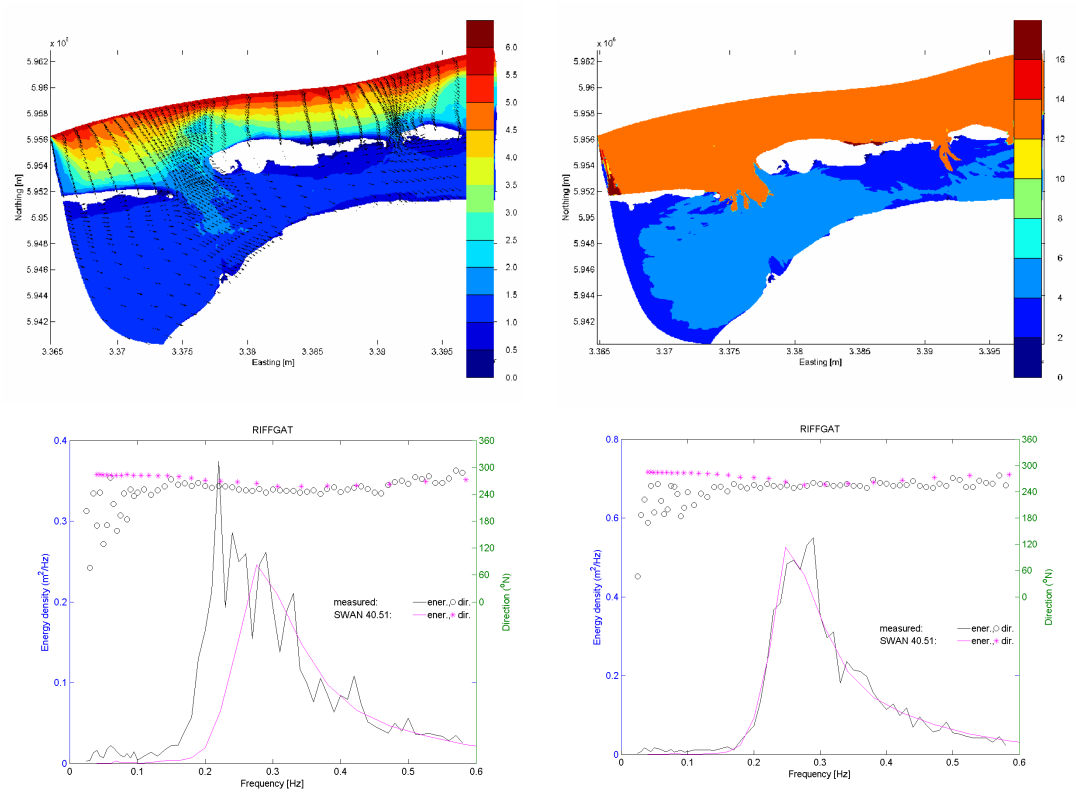

Figure 3: Significant wave height (top left) and peak period (top right) for the December 3rd storm. Measured and modelled spectra at RIFFGAT for the 5/2/1999 storm (bottom left) and 3/12/1999 storm (bottom right).

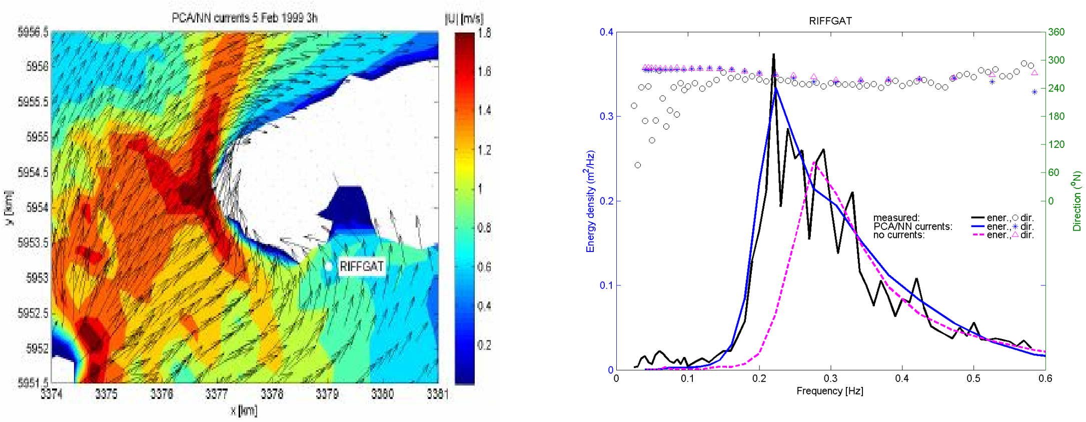

Figure 4: Left: current field (magnitude and directions); right: measured (black), modelled with current (blue) and modelled without current (magenta) spectra at RIFFGAT

The currents run across the inlet from Southwest to Northeast and turn just south and west of Norderney island in a counterclockwise fashion, where they have a more northerly and westerly direction and "jet" out of the inlet. This current field has been applied in the SWAN computations and the result is shown in Figure 4. Because the local waves (driven by winds from the Northwest) experience a mostly opposing current before they reach RIFFGAT, their effective wave age $\left(\vec{U}_{cur}+c_{rel}\right)/\vec{u}_*$ (where $\vec{U}_{cur}$ is the current velocity, $c_{rel}=\sigma/\vec{k}$ is the relative wave celerity (ratio of the relative frequency and the wavenumber) and $\vec{u}_*$ is the wind friction velocity) is smaller (relative to the situation without current) and the waves experience more wind-induced growth (until they reach equilibrium) in both wave height and period. This results in the blue modelled spectrum which almost perfectly agrees with the measured spectrum for this storm. The effect on the energy period change is opposite to what one would expect from a Doppler-shift in an opposing current, without wind.

Ameland Inlet

The Ameland inlet (Figure 1 and Figure 5) has been instrumented with directional and non-directional buoys since the Fall of 2003. While the layout of the instrument array has been changed up until the present, we will focus on storms of 2004 and 2005 at which time the buoy configuration was as in Figure 5. The storm boundary conditions are summarized in Table 2.

Table 2: Boundary conditions and inputs of the storms at Ameland Inlet. Wave data are taken at AZB11.

date	time (MET)	tidal stage	Wind speed (m/s)	Wind dir. (°N)	Water level (m + NAP)	H_{m0} (m)	$T_{m-1,0}$ (s)	Wave dir (°N)
08-02-2004	22h30	slack	16.6	325	2.60	5.3	9.5	319
09-02-2004	01h30	ebb	16.3	328	1.75	4.8	9.7	338
02-01-2005	10h00	flood	20.0	277	1.04	5.1	9.0	310

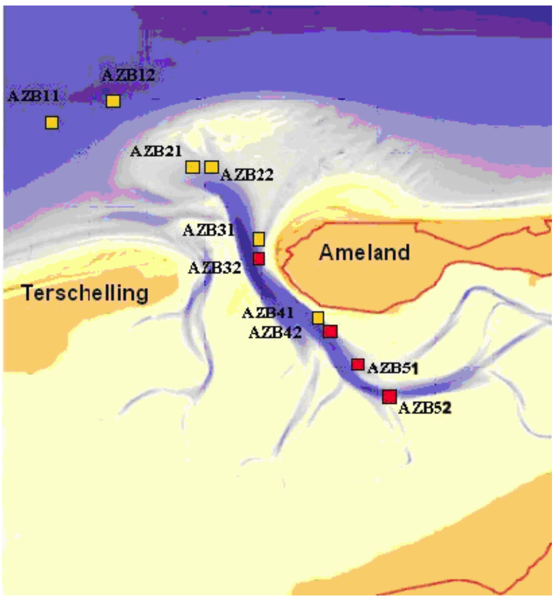

Figure 5: Map of Ameland Inlet with wave buoy configuration of 2004 and 2005. The red and yellow boxes indicate non-directional and directional buoys, respectively.

Besides investigating the performance of SWAN the aim of the investigation was to assess the importance of inputs of water level, current and wind field on the hindcast results. Several simulations were run with either spatially uniform or spatially varying input fields. For all cases the bathymetry was taken from a composite of local surveys taken over the last few years. For the uniform case, the water level was taken from the NES measurement station (at the south side of Ameland Island) and for the non-uniform case from WAQUA hydrodynamic simulations which also provided currents. The wind was taken from a measurement station at Vlieland Island (two islands west of Ameland) for the uniform case and from HIRLAM fields for the non-uniform case.

In this paper we will contrast the results of the cases with a uniform water level, no currents and a uniform wind field (called "ccu") on the one hand, and a spatially-varying water level with currents but still a uniform wind field (called "flu") on the other hand. The comparison of measured and computed integral wave parameters (H_{m0} and $T_{m-1,0}$) shows that in the latter case (Figure 6 bottom row) the integral parameter prediction improves although scatter for the "inner" buoys remains large and in the inlet gorge the wave periods are underestimated. However, the overall agreement is good.

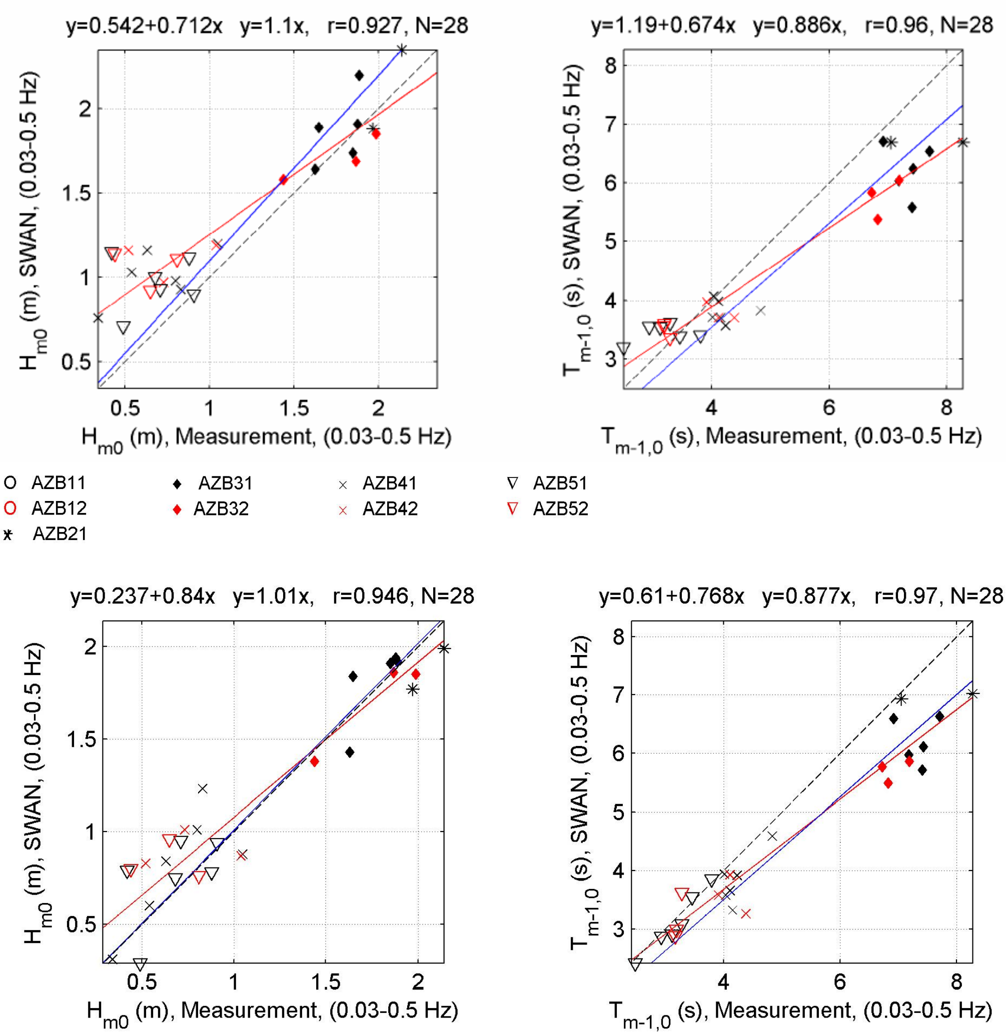

Figure 6: Significant wave height (left) and energy period (right) for the case of uniform input ("ccu") fields (top) and non-uniform ("flu") fields (bottom).

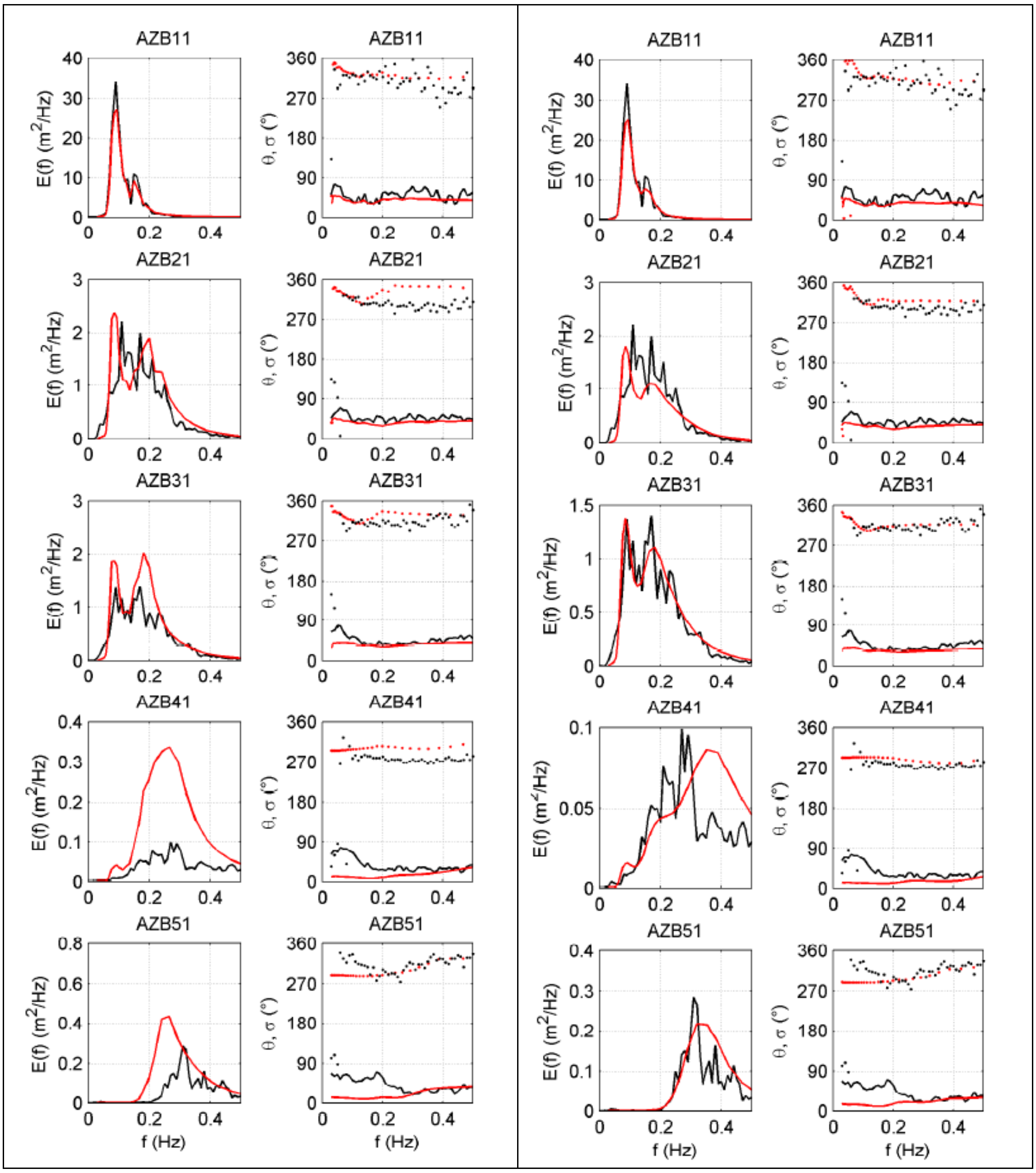

Figure 7: Measured (black) vs. modelled (red) variance spectra (1st and 3rd columns), mean wave direction and directional spreading (2nd and 4th columns) for two cases "ccu" (essentially no currents) on the left hand side and "flu" (with currents) on the right hand side for the conditions of the storm on 8/2/04 at "slack" water.

The improvement for the case "flu" over "ccu" of the modelled spectra is shown in Figure 7. The spectra show that offshore (at AZB11, which is the boundary condition) the modelled variance, mean wave direction and wave directional spreading are in agreement with the measured data, and that the agreement remains good through AZB31 for case "ccu". The agreement in the "ccu" case is poor further down the inlet where the wave height and wave period are severely overpredicted because of the application of a uniform water level and no current, which causes differences in the predicted wave direction. For the case including spatially-varying water levels and currents ("flu") the wave directions are much better predicted throughout the inlet, and the agreement of the wave variance density is thus much better at the inner buoys (note the difference in vertical scale between the cases). The main reason for this difference is a slight following current (i.e., in the same direction as the waves) which increases the wave age and retards the growth of the wave height and period.

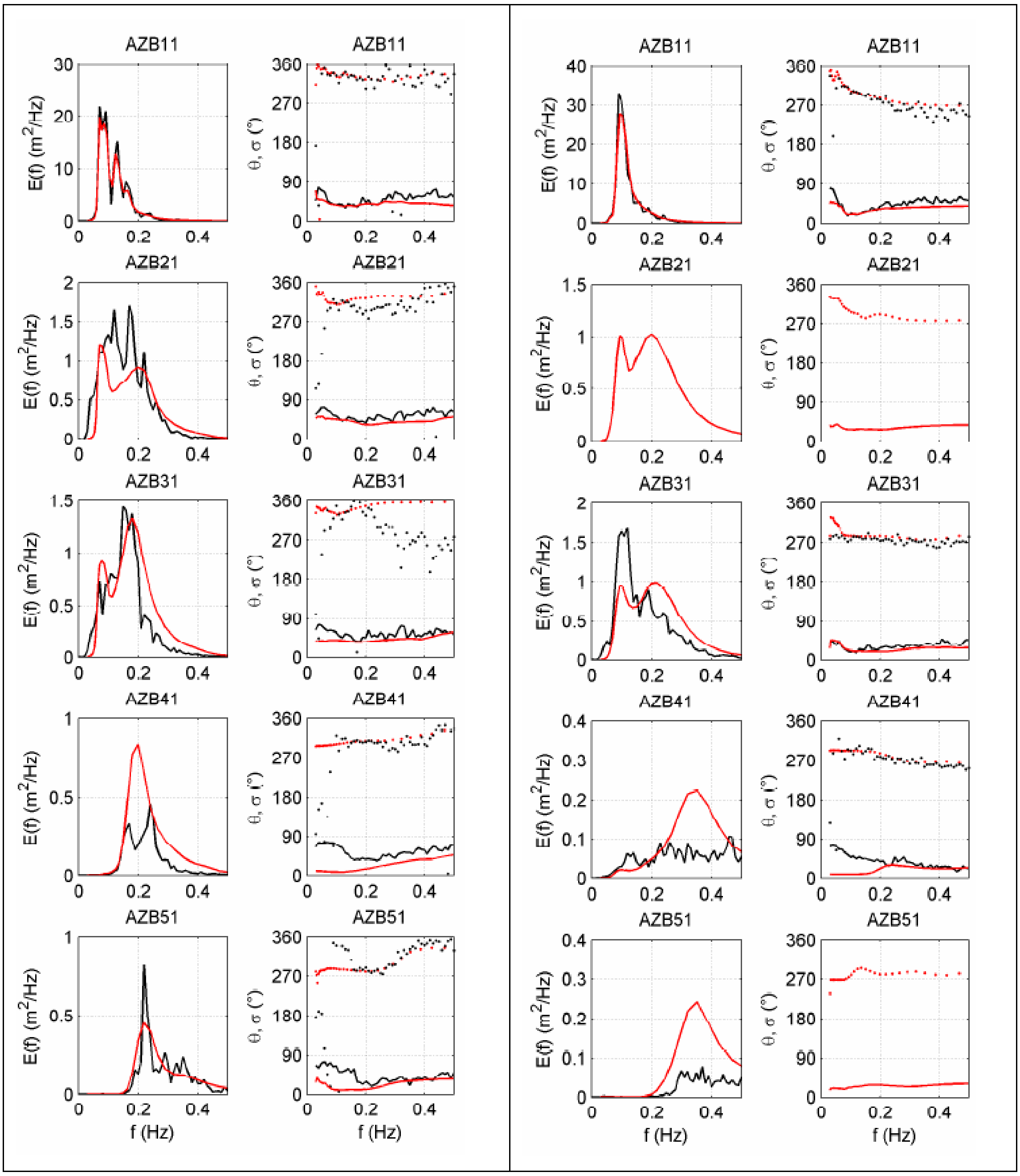

Figure 8: Measured (black) vs. modelled (red) variance spectra (1st and 3rd columns), mean wave direction and directional spreading (2nd and 4th columns) for case "flu" (with currents for the conditions of the storm on 9/2/04 at "ebb" on the left hand side and for the conditions of the storm on 2/1/05 at "flood" on the right hand side.

At ebb tide, (Figure 8 left hand side) the spectra are also in good agreement, except at buoy AZB41, where the wave height is overpredicted. This is due to the severe underprediction in directional spreading, which indicates a too-strong focussing into the ebb current (wave tunneling), a subsequent shoaling of the wave height without sufficient whitecapping in an opposing current. This results in a relatively smaller wave age, and therefore more growth of the wave height and period. Finally, on the right hand side, the spectra at 2/1/2005 at flood stage show a distinct growth of the second harmonic at AZB31, which is due to the overestimation of the transfer of energy to the second harmonic in the LTA (Lumped Triad Approximation; Eldeberky, 1996) formulation. Note that the measured spectra at the inner buoys are essentially noise spectra, and are not reproduced by the model.

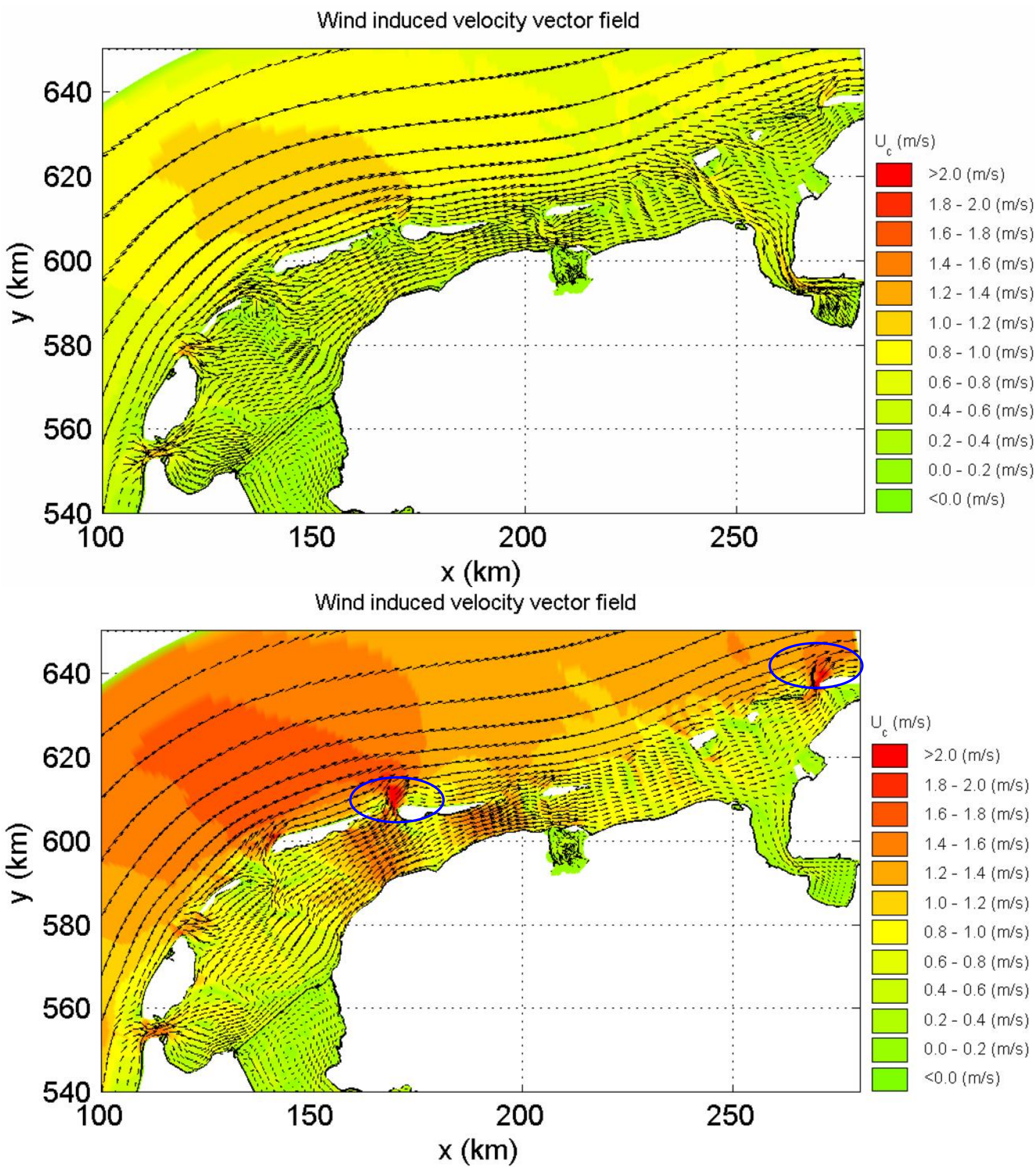

Figure 9: Current pattern (magnitude and directions) for the 18th January, 2007 storm at 20:00 hrs. Top: measured conditions; bottom: scaled conditions to probability of 1/4000 years. Outflow events are marked with blue ovals.

EXTREME EVENTS

The hindcast results above show that the inclusion of currents improves the agreement with data dramatically, which means that they are therefore important to take into account in the computation of HBC's. However, the hindcasts were done for severe, but measured (in our lifetime) conditions, and the question is what the effect of currents will be in the case of a truly severe event such as the normative storm with a return period of 4000 years.

To this end, the flow patterns for the case of a measured storm (of January 18th, 2007) and for and for a hypothetical extreme event with "scaled-up" wind generating a 1/4000 per year probability water level at station Nes on the island of Ameland (but from the same wind direction as the 18 January storm) were simulated (Alkyon, 2007).

Figure 9 (top) shows the current pattern for the measured conditions around the peak of the storms at January 18th, 2007 at 20:00 hrs. Since the wind is from west-southwest, the water is driven to the east and into Eems-Dollard Estuary (on the right in the figure). The flow is across the tidal flats and separate tidal basins served by individual inlet systems are not noticeable anymore. The same is true for the scaled-up event (Figure 9 bottom), only in more extreme form. Since the flow in the Wadden Sea is forced to contract through an ever more narrow sea, a jet, acting much like a valve, is noticeable at some inlets, including the Ameland and Norderney Inlets (see blue ovals in Figure 9 bottom).

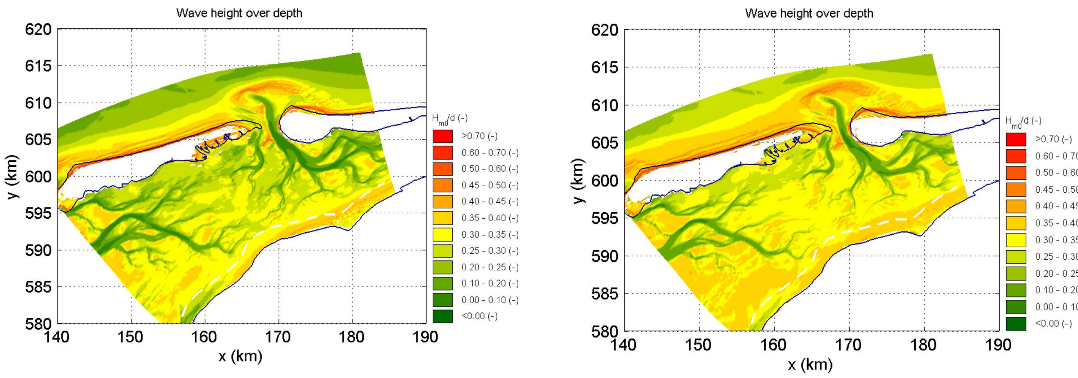

Figure 10: Ratio of wave height over water depth for the storm case (left) and the extreme case (right).

The effect of the extreme flows on the waves is twofold. The increase in water level in the extreme event allows for a larger amount of penetration of larger wave heights into the inlet (not shown). Also, with increased wind and water level the waves will grow more quickly. However, near the main land dikes the ratio of wave height over water depth reached the same limit in both cases, see Figure 10 (left: storm case and right: extreme case). This means that inside this inlet the total water depth is the limiting factor, and the wind wave growth is depth-limited.

The effect of the flow in the extreme case is not large for the wave height (relative to the case of "no current") and is not shown. The effect on the wave period is rather large. Since the wave direction and the flow direction are more or less aligned, the following current over large distances causes an increase in the wave age, less growth and therefore a smaller period (relative to the case of "no current"). The percentage difference is shown in Figure 11, which can reach up to 30% reduction in wave period. Although this result is only valid for this one storm, in general the wave, flow and wind directions will be more or less aligned so that the waves will experience a following current most of the way. This would imply a reduction in wave period and hence (since the difference is shown to extend all the way to the main land dikes) a reduction in wave loads on the coastal defenses. This result points to a necessity to include currents in the HBC computations, something that has not been previously done.

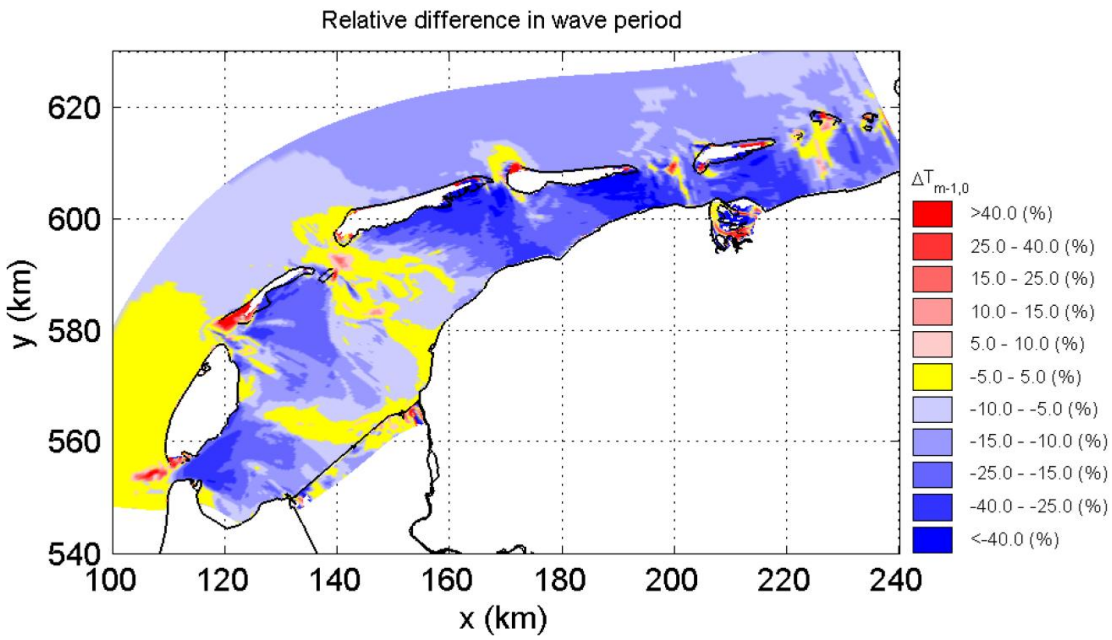

Figure 11: Percentage difference in wave period for the case of current vs. no current.

CONCLUSIONS

The SWAN model has been the subject of a number of hindcast studies. In general, the model performs well, but with degrading performance further into the tidal basin of the Ameland Inlet. The model-data agreement is improved when taking non-uniform water levels and (especially) currents into account. Rather than causing a Doppler-shift alone, the currents also change the effective wave age, and therefore change the wave height and period growth. This change in spectral shape explains the measured results at Norderney whereas hitherto in the hindcasts currents (at “slack” tide) were not taken into account.

The results and measurements of the Ameland Inlet show that the ebb tidal delta (due to depth-limited breaking) is a phenomenal wave energy dissipator, and the small amount of energy that does penetrate is negligible relative to energy generated by the processes inside the inlet sea, where local wave growth, wave-current interactions and depth-limited breaking are dominant. The wider and shorter Norderney Inlet shows more North Sea wave penetration.

SWAN shows important shortcomings compared to buoy measurements due to the wave model inputs of (especially) ebb currents which cause too much focussing of wave energy with insufficient dissipation in an opposing current, and to the wave model physics of triad interactions which causes an overprediction of the first higher harmonic and an underprediction of the spectral wave period.

Finally, the application to a hypothetical extreme event shows that wave heights along the coast are still depth-limited (due to a large wind speed and despite a larger water depth) and that currents are driven in the same direction as the waves. This causes an increase in wave age and hence less growth in spectral period. This shows that the presence of currents (at “slack” but also in extreme events) is an important aspect in the calculation of Hydraulic Boundary Conditions.

ACKNOWLEDGEMENTS

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