INTERCOMPARING THIRD-GENERATION WAVE MODEL NESTING

R. Padilla[1], P. Osuna[1], J. Monbaliu[1] and L. Holthuijsen[2]

[1]Hydraulics Laboratory, K.U.Leuven, de Croylaan 2, B-3001 Heverlee, Belgium
[2] Civil Engineering, T.U. Delft, Stevinweg 1, 2628 CN Delft, the Netherlands

1 INTRODUCTION

To forecast or hindcast coastal wave conditions with numerical models, nesting of computational grids is often necessary. In the present study, wave conditions in the southern North Sea have been generated on a coarse grid (50 x 50 km^2) using the WAM Cycle 4 model. As a first step towards a high resolution (1 x 1 km^2) coastal wave prediction model for the Belgian coastal area, a nested grid with an intermediate spatial resolution (10 x 10 km^2) was implemented. For the nested runs both the WAM cycle 4 and SWAN cycle 2 model have been used.

For coastal engineering studies wave information is required in shallow water areas where wind growth, bottom dissipation and wave-current interactions may play an important role. An accurate and efficient wave model is essential. In the present paper, the WAM-model in its standard version, as well as the SWAN-model are used for the nested runs. The WAM-model is considered state-of-the-art up to intermediate water depth but has a number of limitations and shortcomings in shallow water. Note that extensions and modifications to the WAM model have been made or are being developed. They include amongst others, the incorporation of five different bottom friction dissipation formulations, the addition of depth-induced wave breaking according to the Battjes-Janssen formulation (Luo and Monbaliu, 1994; Luo, 1995) and the introduction of a more efficient numerical scheme. This last item reduces the computational effort for shallow water applications considerably (Luo et al., 1997). These and some other features are currently being put together and tested in the EC- Marine Science and Technology program PROMISE (Pre-Operation Modelling In the Seas of Europe). However these modifications were not yet used for this study.

A nearshore third-generation wave model SWAN has been developed at Delft University (Ris *et al.,* 1997) and it has been released recently into public domain. This model is also a third-generation, fully spectral model. Like the WAM model, it solves the wave action density transport equation without *a priori* spectral constraints. It takes into account depth-induced wave breaking and triad interactions. Triad interactions are not included in the WAM model but are considered important for wave evolution in nearshore areas. Attractive aspects of the SWAN model are its computational efficiency since the model uses an implicit scheme allowing the use of a large time step (greater than the CFL limit), and the ability to easily chose between different computational options. Note that SWAN can also be run in a first and in a second-generation mode.

The objective of this paper is to investigate and compare in more detail the nesting of WAM in WAM and SWAN in WAM and to point out a number of findings. Note that the non-stationary version of the SWAN-model is still under development and what is described below can therefore be seen as a contribution to this development. The SWAN model was used in its version 30.20.

In the following, the WAM and SWAN models are briefly described in section 2. In section 3, a wave hindcast study was carried out for the southern North Sea and model results are compared to buoy measurements. In section 4 the results are analysed and discussed in more detail by turning on and off different options in the SWAN model and by looking at the spectra at different locations. Finally, the paper ends with conclusions in section 5.

2 MODEL DESCRIPTION

2.1 The WAM model

The WAM (Cycle 4) model is a third-generation wave model, which solves the wave transport equation explicitly without any *ad hoc* assumption on the shape of the wave energy spectrum. The basic equation in Cartesian co-ordinates is

$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial x}(c_x F)+\frac{\partial}{\partial y}(c_y F)+\sigma\frac{\partial}{\partial \sigma}(c_\sigma \frac{F}{\sigma})+\frac{\partial}{\partial \theta}(c_\theta F)=S_{tot} \quad (1)$$

where $F(\sigma, \theta)$ is the wave energy spectrum, t is the time. σ is the intrinsic angular frequency, θ is the wave direction measured clockwise from true north, c_x, c_y, are the propagation velocities in geographical space, c_σ and c_θ are the propagation velocities in spectral space (frequency and directional space). The left-hand side of the above equation represents the local rate of change of wave energy density, propagation, shifting of frequency due to time variation in depth, and refraction. The right hand side represents all effects of generation and dissipation of the waves, including wind input S_{in} , whitecapping dissipation S_{ds}, non-linear quadruplet wave-wave interactions S_{nl} and bottom friction dissipation S_{bf}. A detailed description of the WAM model can be found in Günther *et al.* (1992) and Komen *et al.* (1994).

The WAM (Cycle 4) can run for deep and shallow water conditions, can include depth and current refraction (steady depth and current field only), and can be set up for any local or global grid with a prescribed topographic dataset. The model solves the wave propagation equation using a first-order, upwind, explicit scheme. Therefore, the propagation time step is limited by the CFL condition. The propagation can be computed on a spherical or a Cartesian grid. The source term integration is solved by a semi-implicit scheme. Nesting of grids is possible for WAM. The boundaries of a nested fine grid have to be pre-defined in the set-up of a coarse grid run. The corner points of the nested fine grid have to coincide with nodes of the coarse grid. The coarse and fine grid model runs are separate. At the interface boundary, the wave spectra are output at the boundary points of the fine grid from the coarse grid run, and then interpolated in space and time to the boundary points of the fine grid. They are consequently used as boundary condition for the nested fine grid run (one-way nesting).

2.2 The SWAN Model

The SWAN (Simulation of WAves in Nearshore areas) model is based on the action balance equation since the wave energy density is not conserved in presence of currents, whereas action density is conserved. The equation solved by the SWAN model is

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}(c_x N)+\frac{\partial}{\partial y}(c_y N)+\frac{\partial}{\partial \sigma}(c_\sigma \frac{N}{\sigma})+\frac{\partial}{\partial \theta}(c_\theta N)=\frac{S_{tot}}{\sigma} \quad (2)$$

where $N(\sigma,\theta)$ is the wave action density ($=F(\sigma,\theta)/\sigma$). The other symbols are identical to the ones used for the WAM-model description (see section 2.1). The source terms in SWAN include the wave energy growth by wind input, wave energy transfer due to wave-wave non-linear interactions (both quadruplets and triads), the decay of wave energy due to whitecapping, bottom friction and depth-induced wave breaking. For the wind energy input into the spectrum, two different formulations can be used, i.e. the Komen et al. (1984) and the Janssen (1989, 1991) formulation. The first formulation refers to the wind input term expression of Snyder et al. (1981) but it has been rescaled in function of the air friction velocity. The second formulation refers to the wind input term expression of Janssen (1989, 1991) which takes the interaction between the waves and the wind explicitly into account. For each of these wind input term formulations, a corresponding whitecapping dissipation term is used. A detailed description of the SWAN (Cycle 2) model can be found in Ris (1997) and Ris *et al.* (1997).

The basic spectrum considered in SWAN (Cycle 2) is the action density spectrum. The model propagates the wave action density of all components of the spectrum across the computational area using an implicit scheme. It has the great advantage that the propagation time step is not limited by a numerical stability condition since the implicit scheme is unconditionally stable in geographic and spectral space. Therefore, for high-resolution applications in shallow water, the computational effort required is expected to be reduced compared to WAM since a longer time step can be used in SWAN. In geographical space the scheme is a first-order upwind and it is applied to each of the four directional quadrants of wave propagation in sequence (i.e., divided into four sweeps). In the spectral space the scheme is a user-controlled combination of an upwind scheme and a central scheme. The propagation is done in a Cartesian co-ordinate system. The numerical scheme used for the source term integration is user defined. The users can chose between a fully implicit, a semi-implicit or an explicit scheme. SWAN can be run in several modes: first-, second- or third-generation mode, according to the chosen level of parameterisation. Nesting of grids is possible in SWAN. The idea of nesting in SWAN is similar to that in WAM. However, the corner points of the nested fine grid in SWAN do not have to coincide with nodes of the coarse grid. A description on the nesting of a finer SWAN run into a WAM coarse run can be found in Luo and Flather (1997).

3 NESTED RUNS

3.1 Application to the southern North Sea

A hindcast study for the period of February 1993, using nesting techniques was carried out in the southern North Sea. A severe storm occurred on the 21st of February. To account for swell generated in the Norwegian Sea and propagating into the southern North Sea, a WAM coarse grid covers the whole North Sea from 48° N to 70° N latitude and from 7° W to 12° E longitude on a grid of 25 x 48 points. The spatial resolution is about 50 km. Note that a stereographic projection was used to run the model on a Cartesian grid.
The model was implemented with a nested grid. Close to the Dutch and Flemish coasts, a finer grid with a spatial resolution of about 10 km was set up, nested into the coarse grid. The WAM coarse grid model was run for the whole month of February 1993. The nested fine grid was run for the period February 14 to 25 using both the WAM and the SWAN model.

To analyse the results from both models in more detail, buoy measurements from two locations were used for comparisons. The Dutch Europlatform (EUR) buoy is close to the fine grid model input boundary and in relatively deep water (model water depth of 26 m), while the Belgian A2B buoy is close to the coast in relatively shallow water (model water depth of 7 m). Figure 1 shows the nested fine grid model bathymetry and the exact locations of the two buoy stations.

The wind fields used come from the United Kingdom Meteorological Office (UKMO) atmospheric model. Analysed fields or forecasts are used depending on their availability. They were interpolated to the WAM coarse and fine grid.

4 ANALYSIS OF THE RESULTS

4.1 Time series WAM and SWAN

To intercompare the WAM and SWAN results, SWAN was run with option Janssen (excluding triads and depth-induced wave breaking), i.e. the WAM-Cycle4 physics, but also with the option Komen, i.e. the WAM-Cycle3 physics. The difference between these two SWAN options is in the source term formulation for wind input and whitecapping dissipation.

Comparisons between the computed results from WAM and SWAN, and buoy data were carried out. The time series of significant wave height during extreme conditions from February 17 to 23 are shown in Figures 2 and 3. In Figure 2 one can see that significant wave height at the EUR location is underestimated by both WAM and SWAN, and this mainly at the peak of the storm. Luo (1995) pointed out that UKMO predicted winds tend to be underestimated but the main reason for this underestimation is of course the underestimation of the energy from the coarse grid WAM computation. This underestimation will be propagated into the computational domain by the WAM and SWAN nested runs. In location A2B WAM reproduces quite well the measured values, which is somewhat surprising considering the underestimation at the boundary. SWAN is more

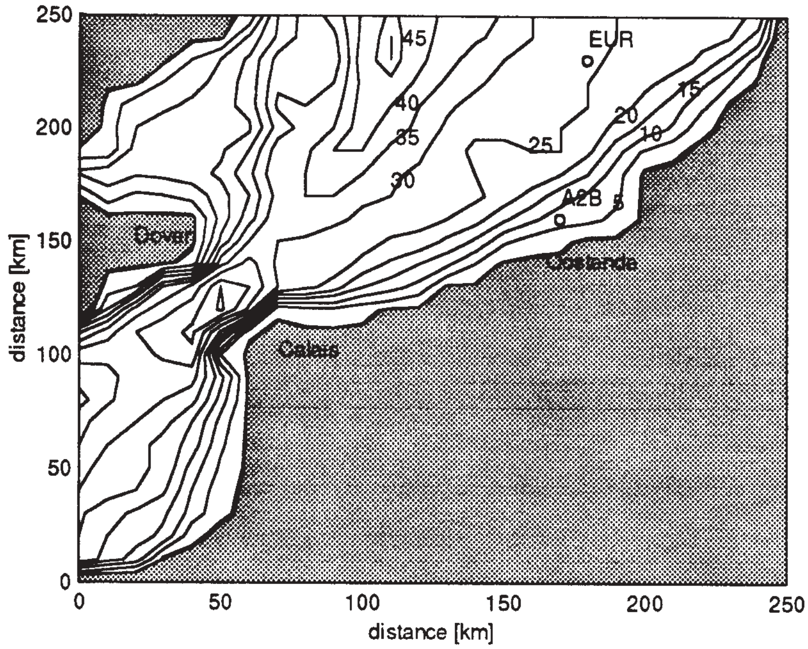

Figure 1. Bathymetry of the nested area with indication of buoy location

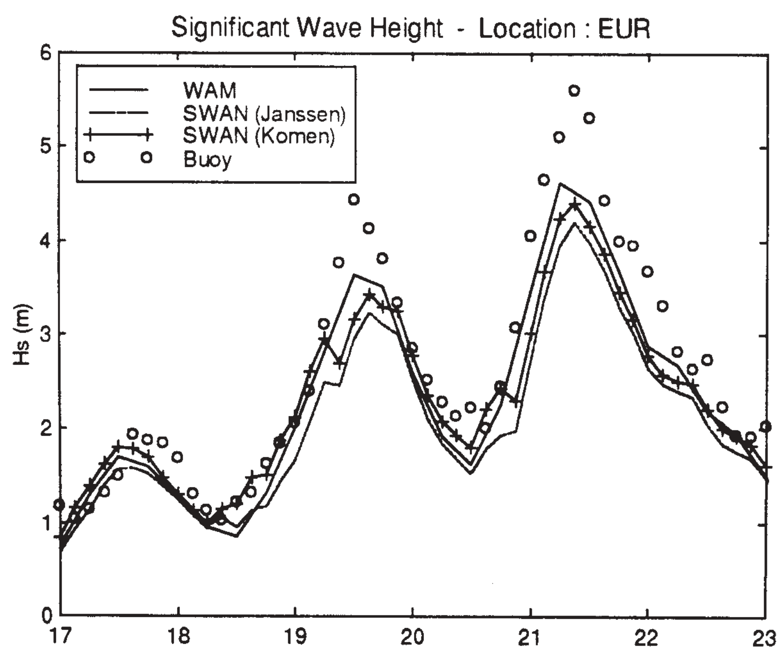

Figure 2. Time series of significant wave height at the EUR location.

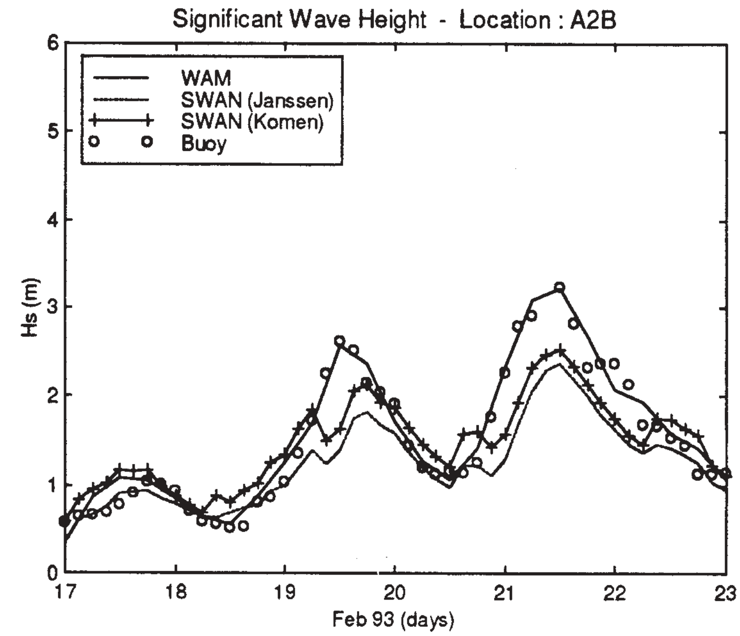

Figure 3. Time series of significant wave height at the A2B location.

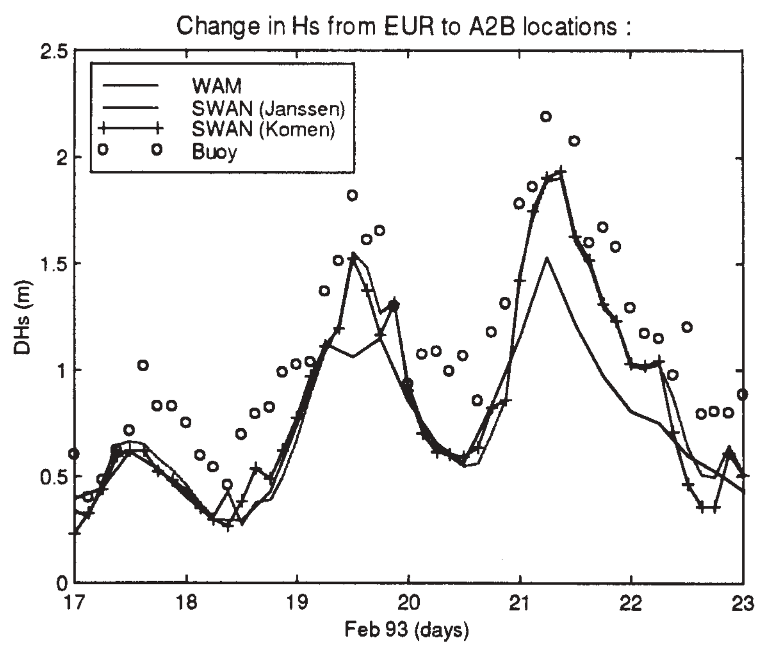

Figure 4. Computed change (ΔHs) in wave height (Hs in EUR minus Hs in A2B).

consistent with the boundary conditions coming from the WAM coarse grid run (see Figure 2). In model intercomparison the computed change in wave height (ΔHs) is probably a more relevant parameter to consider. The absolute wave height is affected too much by the wrong boundary conditions (in comparison with the observations). The computed ΔHs is therefore compared with the ΔHs from the observations, see Figure 4. It can be seen that the results from WAM in location A2B compensate for the low energy levels entering from the north boundary (from the coarse WAM run).

At the A2B location the water depth is about 7 m and bottom friction might play an important role in the wave dynamics, see also section 4.2 and 4.3. Another possible cause of discrepancy may be the directional resolution. For these runs a resolution of 30 degrees was used, which is according to Luo and Flather (1997) not the most appropriate resolution. It could be too poor for shallow water regions, especially when there are significant spatial gradients. Although not attempted in this study, it might be worthwhile to tune source term coefficients, in particular the bottom friction. However, it seems premature at this stage to put a lot of effort into this. It is more important to gain more experience with the model set-up by understanding better the sensitivity of the models to the different source terms. Therefore, in the next sections, propagation only and SWAN without bottom friction have been investigated.

4.2 Pure propagation

The purpose of this test is to point out how the propagation scheme in WAM and SWAN works in the nested runs. All the source terms were turned off. Figures 5 and 6 show the resulting time series for the wave height at the EUR and A2B locations. At the first location the output from both models match perfectly. This is due to the fact that the station EUR is very close to the boundary where the wave conditions obtained from the coarse WAM run, are imposed at the boundary every ten minutes and the waves have only propagated over a very short distance from the boundary (20 km). This however shows that the boundary conditions are read and incorporated into the numerics of SWAN properly without any changes in the total energy. However, in location A2B the energy level is lower in SWAN than the level of energy in the WAM run without source terms. This is an indication that the implicit scheme used in SWAN for the wave propagation is more diffusive than the explicit scheme used in WAM. The case considered here is for the SWAN model, in concept developed for relatively small coastal areas, beyond the intended limit in terms of spatial extent. It is intuitively clear that the behaviour of the source terms in the WAM and the SWAN model will be influenced by the diffusivity of the propagation. The source terms are related to and influenced by the shape or energy content of the spectrum.

4.3 Role of bottom friction

4.3.1 SWAN without bottom friction

To investigate the importance of the bottom friction in SWAN, the SWAN model was run with bottom friction turned off. The results can be seen in Figures 7 and 8. The wave heights from SWAN at location EUR are only slightly modified compared to the run with bottom friction on (see Figure 2). At the A2B location hindcasted wave heights seem to have 'improved', especially the predicted peak wave heights. However after the peak of the storm, wave heights are overestimated. Wave growth seems to be given at the "right time", but the decay of the energy is too slow. Bottom friction seems to be a dominating source term and plays an important role for the prediction of wave heights at the coastal location A2B. Luo *et al.* (1996) has shown that the bottom dissipation has quite significant effect on the energy balance using different bottom friction formulations, reporting difference as big as 80% of the total energy along the Belgian coast.

4.4 Role of triads and depth in induced breaking

This has not been looked at, but it is anticipated that these source terms will not play a significant role in this particular set-up, where due to still a relatively coarse grid resolution, local bathymetric effects such as sandbars have been smoothed out. These source terms might however play an important role when the grid resolution will be further reduced. Then it will be possible to resolve the different sandbanks and it will become important to take these effects into account.

4.5 The wind input term

It can be seen in Figures 2 and 3 that there are several occasions where the wave energy predicted by SWAN is larger than the results from WAM. This happens precisely at times when the wind speed increases and changes its direction (Figure 9a and 9b). SWAN responds faster than WAM, building up new components in the spectrum. The main reason can be traced back to the fact that the wind-input term in SWAN is the sum of two expressions, a linear input term and an exponential input term. The linear terms puts energy from the wind into the wave field at the early stages of wave development. Afterwards the exponential term becomes much more important. This is also illustrated in more detail in the Figures 10 and 11. Note that the spectra have been plot when there is an increase of energy and that the spectra have been normalised with the peak value (E_{max}) of the WAM spectrum. From the spectral distributions, one can see that SWAN responds faster than WAM when waves are building up in a direction considerably different from the wave direction of the energy peak of the spectrum.

5 CONCLUSIONS

Nesting WAM and SWAN in a coarse WAM run has been successfully applied to simulate the waves in the southern North Sea. The intercomparison reveals that the incorporation of the spectral distribution from WAM to SWAN is done properly despite the differences in numerics in both models. The largest differences between the output of both numerical models can be found in the shallowest locations. Although WAM at first sight seems to give better results at the shallow A2B location, SWAN is more consistent with the imposed boundary conditions. SWAN reproduces better the differences in wave height between the location EUR at the boundary of the nested grid and the location A2B close to the coast.

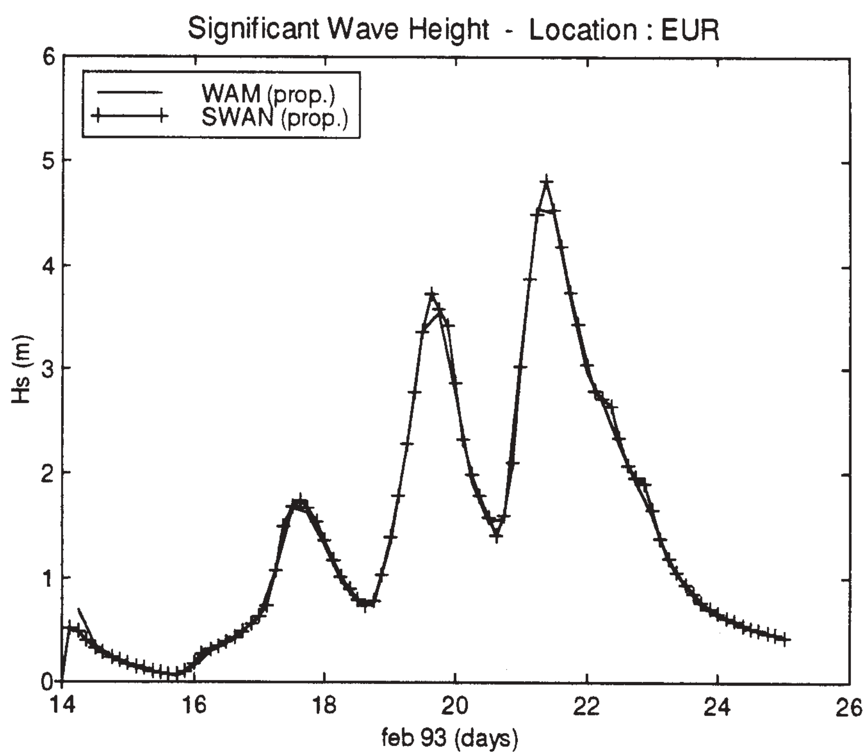

Figure 5. Time series of wave height at the EUR location, pure propagation case.

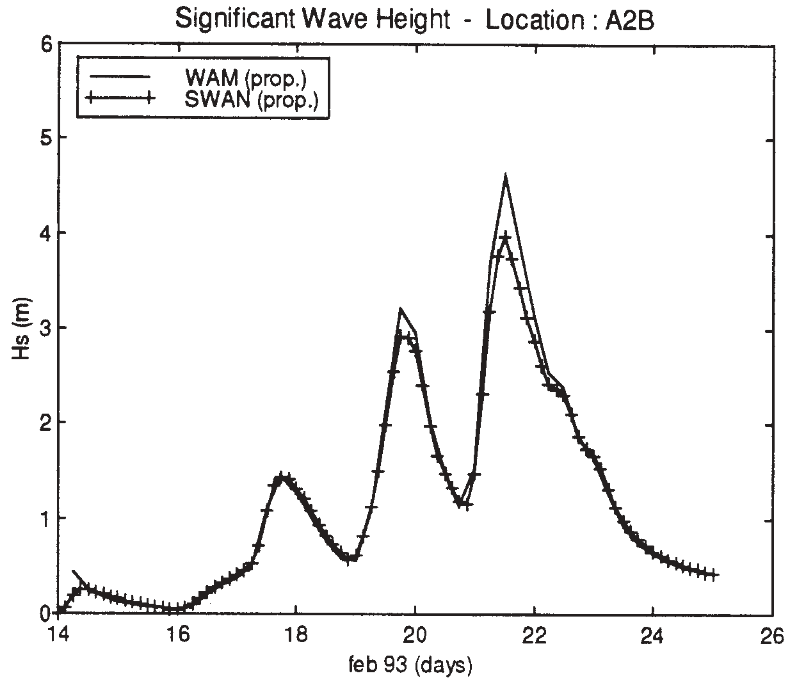

Figure 6. Time series of wave height at the A2B location, pure propagation case.

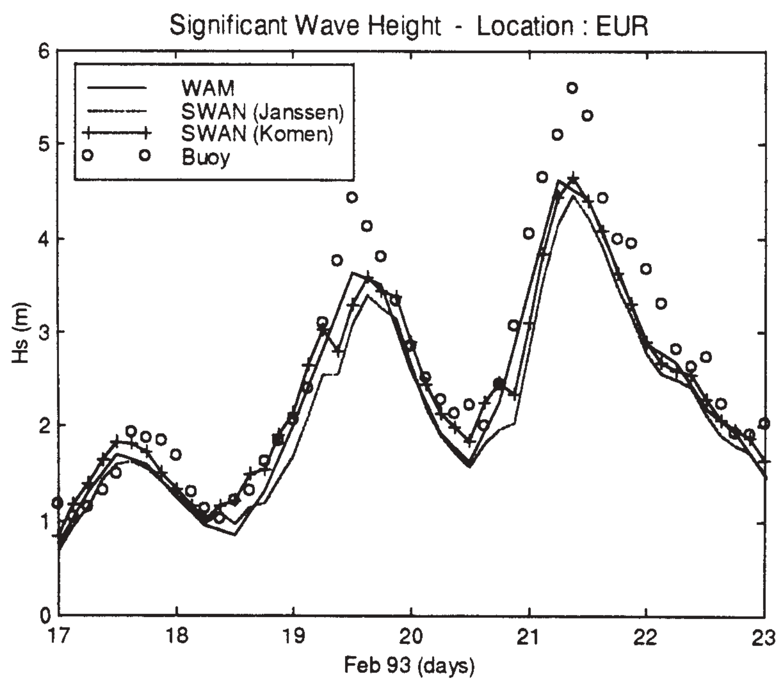

Figure 7. Time series of wave height at the EUR location, friction off case.

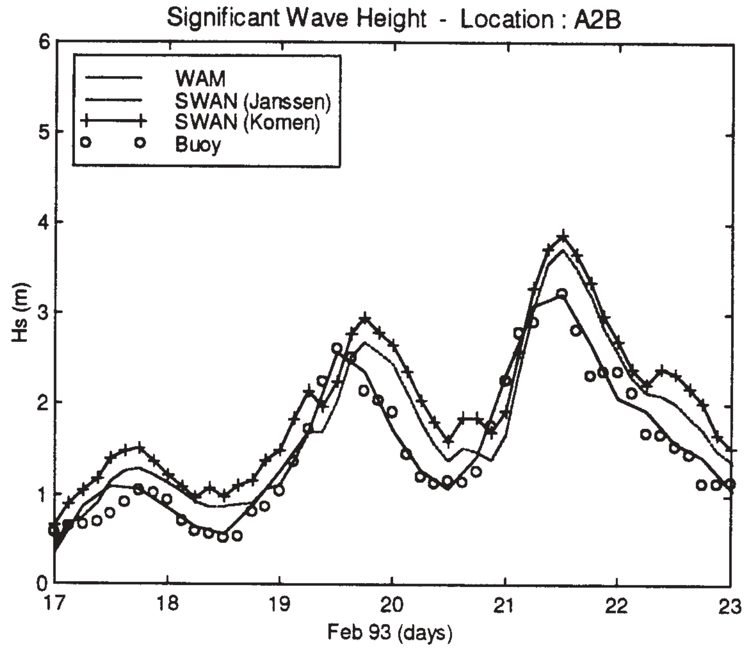

Figure 8. Time series of wave height at the A2B location, friction off case.

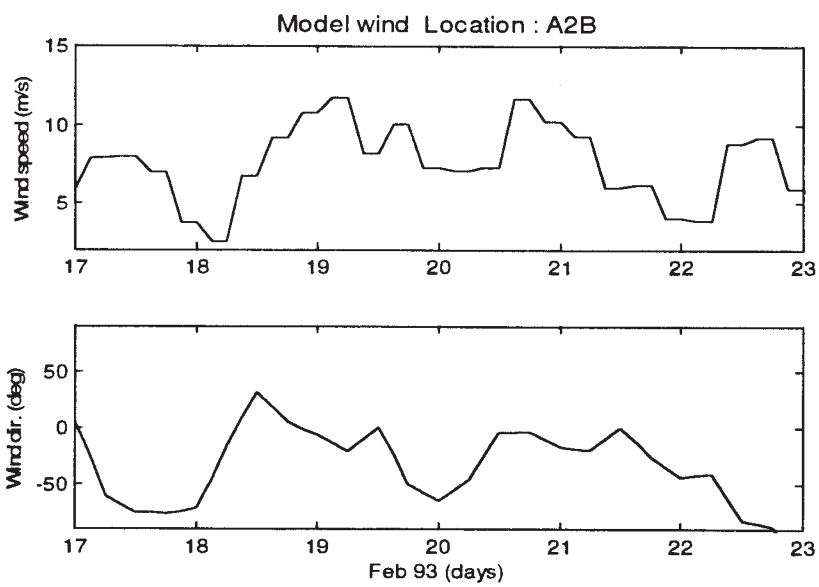

Figure 9. Model wind speed (on top) and wind direction (on bottom) at the A2B location.

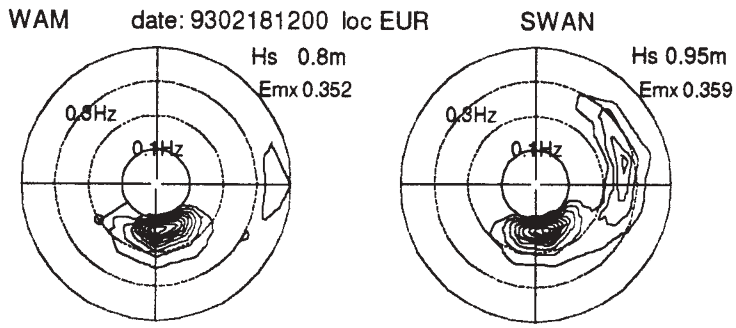

Figure 10. Spectral energy distribution at the EUR location. The line indicates wind direction (going to).

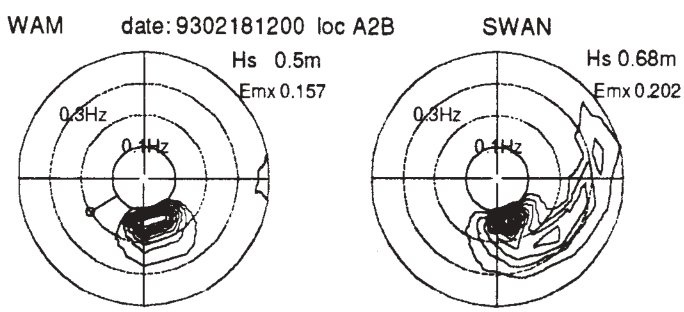

Figure 11. Idem Figure 10 but at the A2B location.

SWAN is in concept a shallow water wave model applicable to small areas. If it is applied to large areas, numerical diffusion due to the implicit propagation scheme used, is apparent. The exercise described in this paper is probably close to the SWAN limit of applicability in terms of spatial extent.

SWAN responds quickly to changes in the wind field. The linear term in the wind input source term formulation adds energy in the high frequency spectral bins.

Bottom friction plays an important role in this shallow water region. Tuning of the bottom friction parameter could improve the model results. However depth-induced wave breaking and triads were not taken into account for this study. Further tests with a finer grid in order to resolve the complex bathymetry of this region have to be made in order to estimate the importance of the different processes involved.

Acknowledgements

This study was partially carried out with financial support from the EC-MAST III PROGRAME, contract MAS3 CT 9500025.
We thank RIKZ (the Netherlands) and AWK (Belgium) for supplying the buoy data at the EUR and A2B location respectively.

6 REFERENCES

Günther, H., S. Hasselmann, & P.A.E.M Janssen, 1992: The WAM model Cycle 4, Report No. 4, Hamburg.

Janssen, P.A.E.M., 1989: Wave-induced stress and the drag of air flow over sea waves, *J. Phys. Oceanogr.*, **19**, 745-754.

Janssen, P.A.E.M., 1991: Quasi-linear theory of wind-wave generation applied to wave forecasting, *J. Phys. Oceanogr.*, **21**, 1631-1642.

Komen, G., S. Hasselmann, and K. Hasselmann, 1984: On the existence of a fully developed wind-sea spectrum, *J. Phys. Oceanogr.*, **14**, 1271-1285.

Komen, G.J., L. Cavaleri, M. Donelan, K. Hasselmann, S. Hasselmann & P.A.E.M. Janssen, 1994: Dynamics and Modelling of Ocean Waves, Cambridge University Press, Cambridge, 532p.

Luo W. and J. Monbaliu, 1994: Effects of bottom friction dissipation formulation on the energy balance for gravity waves in shallow water, *J. Geophys. Res.*, **99** (C9), 18,501-18,511.

Luo, W., 1995: Wind wave modelling in shallow water with application to the southern North Sea, Ph.D. thesis, K.U.Leuven, Belgium, ISBN 90-5682-003-6.

Luo W. and J. Monbaliu and J. Berlamont, 1996: Bottom friction dissipation in the Belgian coast regions, Proc. of the 25th International Conference on Coastal Engineering, 836-849.

Luo, W. and R. Flather, 1997: Nesting a nearshore wave model (SWAN) into an ocean wave model (WAM) with application to the southern North Sea", in Computer Modelling of Seas and Coastal Regions III, edited by J. R. Acinas and C.A. Brebbia, Computational Mechanics Publications, 253-264.

Luo, W., R. Flather and J. Monbaliu, 1997: An efficient computational scheme for the use of the third generation WAM model in coastal regions, submitted for publication in *J. of Waterway, Port, Coastal, and Ocean Engineering.*

Ris, R.C., 1997: Spectral modelling of wind waves in coastal areas. Ph.D. thesis, Delft University of Technology, the Netherlands.

Ris R.C., N. Booij, L.H. Holthuijsen and R. Padilla-Hernandez, 1997: SWAN Cycle 2 User Manual - Simulation of WAves in the Nearshore Zone, Delft University of Technology, the Netherlands.

Snyder, R.L., F.W. Dobson, J.A. Elliot and R.B. Long, 1981: Array measurements of atmospheric pressure fluctuations above surface gravity waves, *J. Fluid Mech.*, **102**, 1-59.