



### 3 Wave model - WAM

WAM (WAVE Model) is a third-generation wave model designed for ocean wave modelling (Komen et al., 1994; WAMDI, 1988). WAM is based on the spectral energy balance equation, which equates the evolution of the wave spectrum to the sum of the local wind input, wave dissipation, nonlinear wave-wave interaction and the propagation of waves from non-local sources. The model solves the wave transport equation explicitly without restrictions on the shape of the wave spectrum. The equation is written as

$$\frac{\partial}{\partial t}F(f, \theta) + \nabla \cdot (c_g F(f, \theta)) = S \quad (1)$$

where  $F(f, \theta)$  is the two-dimensional wave variance spectrum,  $f$  is frequency,  $\theta$  is the direction in which the waves propagate and  $c_g$  is the group velocity of the waves. The source term  $S$  is given by

$$S = S_{in} + S_{ds} + S_{bot} + S_{nl} \quad (2)$$

where  $S_{in}$  represents the physics of wind input,  $S_{nl}$  nonlinear wave-wave interactions,  $S_{bot}$  bottom friction and  $S_{ds}$  dissipation due to whitecapping.

The spectral resolution and the spatial resolution in WAM are flexible and the model can be run globally or regionally with open or closed boundaries. To be able to run the WAM model, wind forcing from an atmospheric model is required. The WAM model runs for deep or shallow water and can include depth refraction and current refraction if current fields are available. For assimilation of the wave field, WAM can use significant wave height from buoy or altimeter measurements.

### 4 Coupled atmosphere-wave model

The coupled atmosphere-wave model is based on the ECAWOM model (European Coupled Atmosphere-Wave-Ocean Model). ECAWOM was developed and set up by a European group of scientists and modellers during the MAST 2 project ECAWOM (1994-1996), which FIMR participated. The model consists of the atmospheric circulation model HIRLAM (the version of the Max-Planck-Institut für Meteorologie), the third-generation wave model WAM and the 3D baroclinic ocean circulation model HAMSON in version of Programa de Clima Marítimo (Weisse and Alvarez, 1997).

The coupling in the new coupled model is done on the basis of the ECAWOM model. In the coupled model the lowest level wind field is transferred from HIRLAM to WAM and the roughness length and the sea state dependent Charnock parameter are transferred from WAM to HIRLAM for surface flux calculations. Some modifications were made to the wave-atmosphere transfer. The roughness length calculated by WAM is transferred directly to HIRLAM and no recalculation of the roughness length is made in the coupling routines as was done in the ECAWOM model. The atmospheric model was changed to the HIRLAM 4.6.2 version used operationally at FMI and a new parallel version of the WAM model was received from the Norwegian Meteorological Institute (DNMI) to be able to run the coupled model operationally on parallel computers.

The wind speed  $U$  at level  $z$  computed by HIRLAM is transformed to surface roughness accordingly.

$$U(z) = \sqrt{\frac{\tau}{C_D}} \quad (3)$$

where  $\tau$  is the total stress and  $C_D$  the drag coefficient

$$C_D = \frac{\kappa^2}{\ln^2(z/z_0)} \quad (4)$$

Table 1: Affected HIRLAM routines and scripts.

<b>grdy</b>	
<b>HLPROG</b>	parallel system for WAM initialized
<b>GEMINI</b>	calls wave model initialization, collects lowest level wind field for WAM, calls wave model main routine, distributes $z_0$ and $\alpha$ calculated by WAM
<b>NAMEIN</b>	reads namelist for coupling
<b>EULER</b>	transfers $z_0$ and $\alpha$ calculated by WAM to physic routines
<b>PUTDAT</b>	significant wave height, mean wave direction and mean wave period to <b>POSTP</b>
<b>POSTP</b>	significant wave height, mean wave direction and mean wave period to <b>POSTPP</b>
<b>phys</b>	
<b>PHCALL</b>	transfers $z_0$ and $\alpha$ calculated by WAM to <b>PHTASK</b>
<b>PHTASK</b>	transfers $z_0$ and $\alpha$ calculated by WAM to <b>PHYS</b>
<b>PHYS</b>	transfers $z_0$ and $\alpha$ calculated by WAM to <b>SLFLUX0</b>
<b>SLFLUX0</b>	$z_0$ and $\alpha$ calculated by WAM used for surface flux calculations over sea
<b>prpo</b>	
<b>POSTPP</b>	significant wave height, mean wave direction and mean wave period written into post-processed file
<b>PUTGRB</b>	significant wave height, mean wave direction and mean wave period written into history file
<b>scripts</b>	
<b>Preparelibs</b>	<b>wave</b> and <b>coup</b> libraries are constructed
<b>Makefile_x</b>	<b>wave</b> and <b>coup</b> libraries to <b>hlprog.x</b>
<b>Prog</b>	input files needed by WAM copied to working directory
<b>Forecast</b>	coupling namelist added, input controlling WAM created

where  $\kappa$  is the von Karman constant ( $\kappa = 0.41$  in WAM) and surface roughness  $z_0$  is calculated from

$$z_0 = \frac{\alpha \tau}{g} \quad (5)$$

where the dimensionless Charnock parameter  $\alpha$  is not constant, but depends on sea state

$$\alpha = \frac{\hat{\alpha}}{\sqrt{1 - \tau_w/\tau}} \quad (6)$$

The constant  $\hat{\alpha} = 0.01$  is chosen in such a way that for old wind sea the Charnock parameter  $\alpha$  has the value 0.0185 and  $\tau_w$  is the wave-induced stress. The wave-induced stress is defined as the integral over all directions and spectral components of the atmospheric momentum flux to the wind-generated wave field. An iterative technique is used to calculate  $\tau_w$  based on the lowest level wind speed, drag coefficient and the total stress.

Coupling of WAM together with HIRLAM affects some HIRLAM routines and scripts. Modified HIRLAM routines and scripts related to coupling are listed in Table 1. Furthermore, two new libraries

have been added: one for the wave model containing the wave model code (`wave`) and the other for coupling containing the routines transferring data between HIRLAM and WAM (`coup`). A new namelist, `NAMCTRL`, has been added to control the coupled model run. It contains the atmospheric time step in respect to the wave time step and two logical switches (`hirwam` and `fullcoup`) controlling the mode in which the coupled model is run. The coupled model can be run in three different modes:

1. Pure HIRLAM: Only HIRLAM is run. Roughness over sea is calculated via Charnock's formula with  $\alpha = 0.014$  for pure sea points. (`hirwam=.false.` and `fullcoup=.false.`).
2. One-way coupling: Both HIRLAM and WAM are run. Lowest level wind field is transferred from HIRLAM to WAM. Roughness over sea is calculated via Charnock's formula with  $\alpha = 0.014$  for pure sea points. (`hirwam=.true.` and `fullcoup=.false.`).
3. Two-way coupling: Both HIRLAM and WAM are run. Lowest level wind field is transferred from HIRLAM to WAM and sea surface roughness and sea state dependent Charnock parameter are transferred from WAM to HIRLAM (`hirwam=.true.` and `fullcoup=.true.`).

The wave model (WAM) has been coupled with the  $0.2^\circ$  version of HIRLAM and the same horizontal grid is used in both models. The integration area of the coupled model is seen in Fig. 5. The land-sea distribution in HIRLAM and WAM is different because successful modelling of waves in the Baltic Sea demands a specially tuned grid, where areas impassable for waves, e.g. the archipelago in the northern part of the Baltic Proper, are coded as land. HIRLAM computes the roughness over sea from Charnock's formula to those grid points where it is not computed by WAM. The wave model receives information about ice cover from HIRLAM ice cover analysis, and the wave model is run only in grid points where fraction of ice is less than 0.25. The atmospheric model is integrated with a time step of 2 minutes and the wave model with a 4 minute time step. The coupling time step is 4 minutes. The wave model time step has to be the same or longer than the atmospheric one because the wave model needs the wind field to be specified in every time step.

Three horizontal fields from WAM, significant wave height, mean wave direction and peak wave period (frequency), are written into the history (and optionally into post-processed) file in GRIB format. Furthermore, the wave model writes into its own output files the following parameters: significant wave height, mean wave direction, mean and peak frequencies, swell height, mean swell direction and mean and peak swell frequencies, wave induced stress and drag coefficient at each grid point at chosen output times. The 2-dimensional wave spectrum at chosen grid points and output times can also be written into output files.

The coupled model is run operationally on parallel computers: on the Cray T3E as default by using SHMEM libraries for parallelization, and on the SGI Origin 2000 as back-up with the MPI parallelization.

## 5 Results

The operational implementation was preceded by comprehensive parallel testing that took place in 2001. Two lengthy periods from mid-March to the beginning of June, and from the end of July until the operational implementation on 13 September 2001 were used for careful checking and evaluation. Furthermore, before these parallel test periods, a couple of two-week test periods were used for parallel tests. Additional tests were carried out for November 2001, when the coupled model was already operational. The aim of all these tests was to see the impact of the coupled model on the meteorological part of the model as well as to evaluate the performance of the wave model.

The two different test experiments, referred to later in the text, are defined as follows:

- ENO : reference HIRLAM system, roughness over sea from Charnock's formula
- ECA : coupled HIRLAM-WAM system, roughness over sea calculated by the wave model

## 5.1 WAM results

The wave model WAM receives horizontal wind components from the lowest HIRLAM model level for each wave model grid point at 4 minute intervals. The resolution of the wind field is the same as the resolution of the wave model and wind input time step is the same as the wave model time step.

The significant wave height and wave direction computed by the coupled model are compared to measurements made by wave buoys operated by FIMR in the middle of the Northern Baltic Proper (NBP) and in the Gulf of Finland outside of Helsinki. The locations of these wave buoys are shown in Fig. 1.

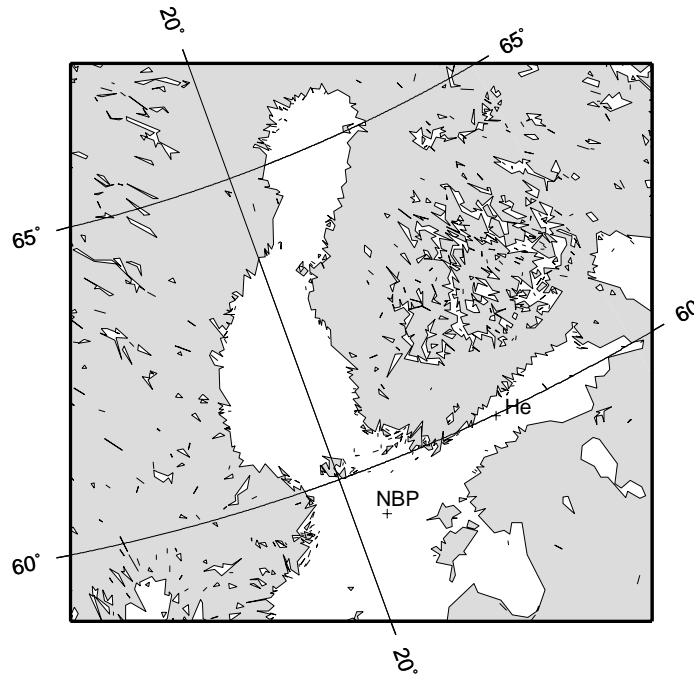


Figure 1: Location of the Northern Baltic Proper wave buoy (NBP) and Helsinki wave buoy (He).

In the pre-operational tests (spring and summer 2001) the wind speeds were moderate resulting in significant wave heights below 3 m in the Northern Baltic Proper. The modelled significant wave heights during this period were quite accurate compared to wave buoy measurements.

The wave model results presented in this section are from November, when the coupled model was already operational. In November there were several storms in the Baltic Sea area. In two storms the measured significant wave height was over 5 m in the Northern Baltic Proper (on 1 and 15 November) and in the Gulf of Finland near Helsinki a significant wave height of 5.2 m was measured on 15 November. This was the highest significant wave height ever measured in this area. Figure 2 presents the predicted significant wave height and direction during the storm on 15 November over the Baltic Sea. This figure also demonstrates the changes in the wave direction during the storm.

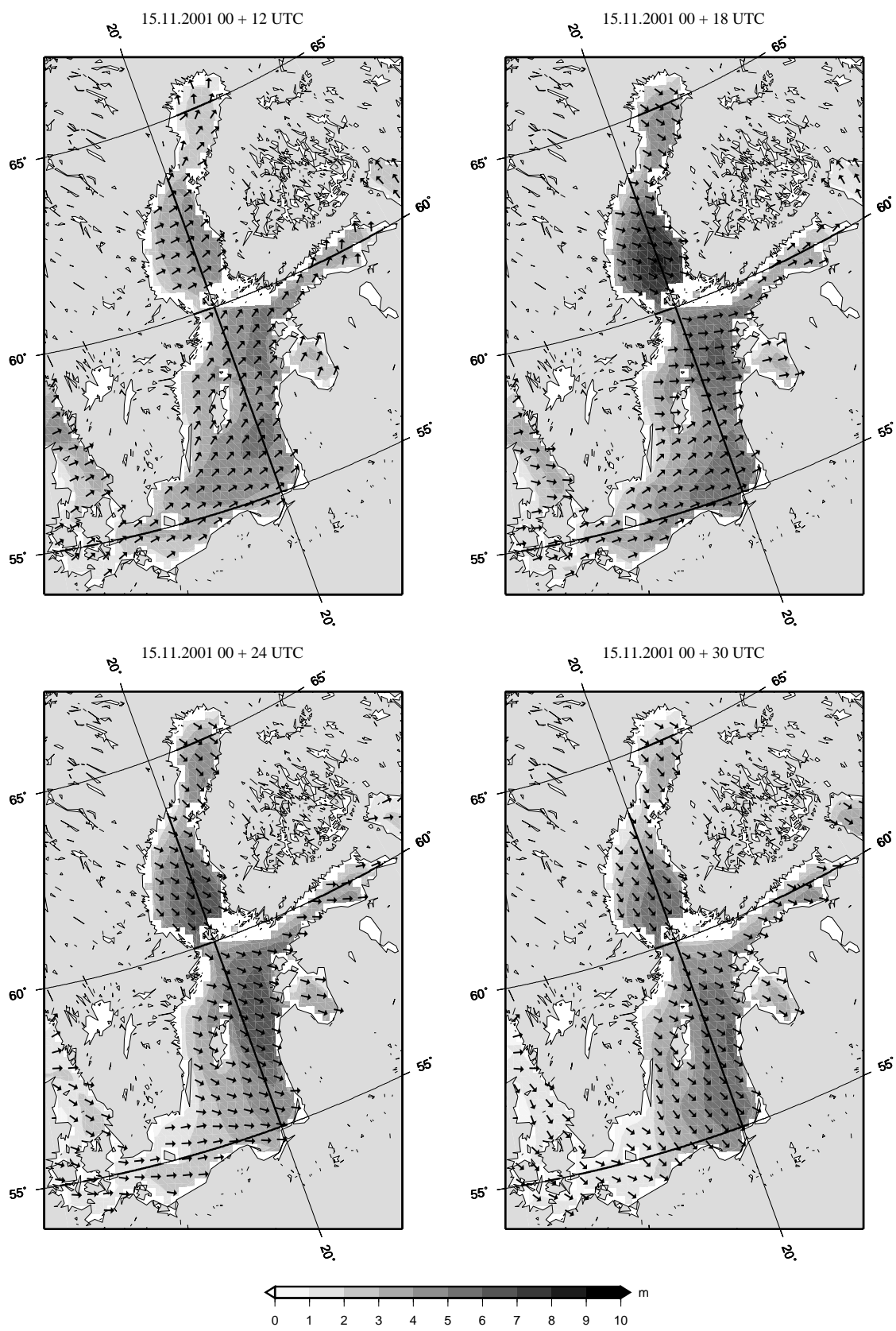


Figure 2: Significant wave height (in shades of gray) and wave direction (arrows) in the Baltic Sea during the storm on 15 November.

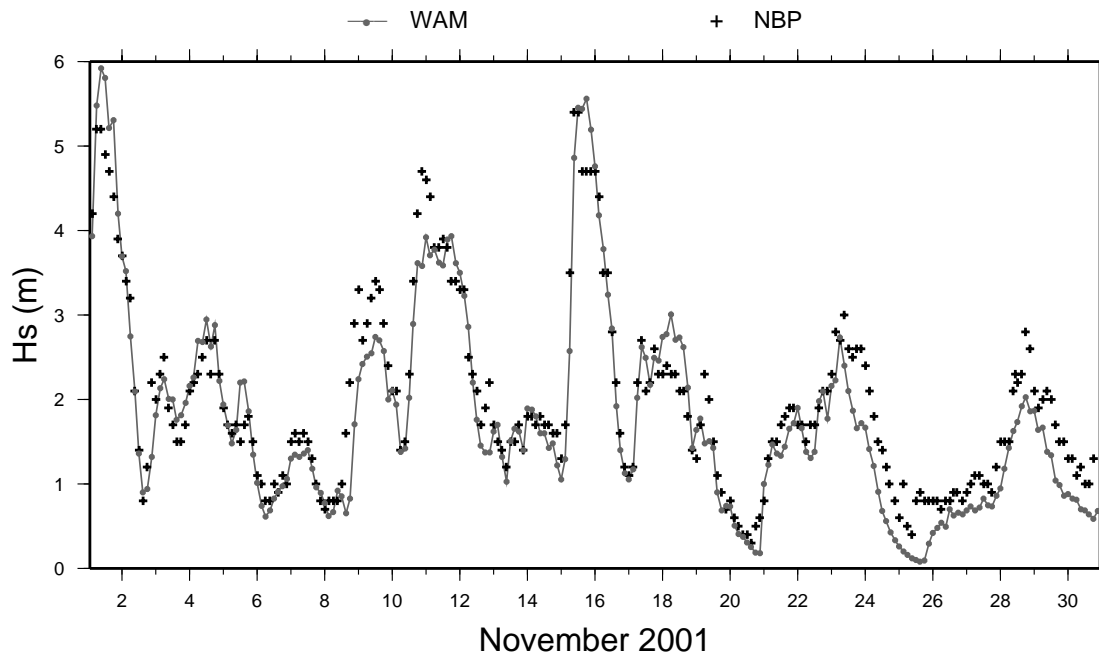


Figure 3: Modelled significant wave height (WAM, line with dots) compared to significant wave height measured by the Northern Baltic Proper wave buoy (NBP, crosses).

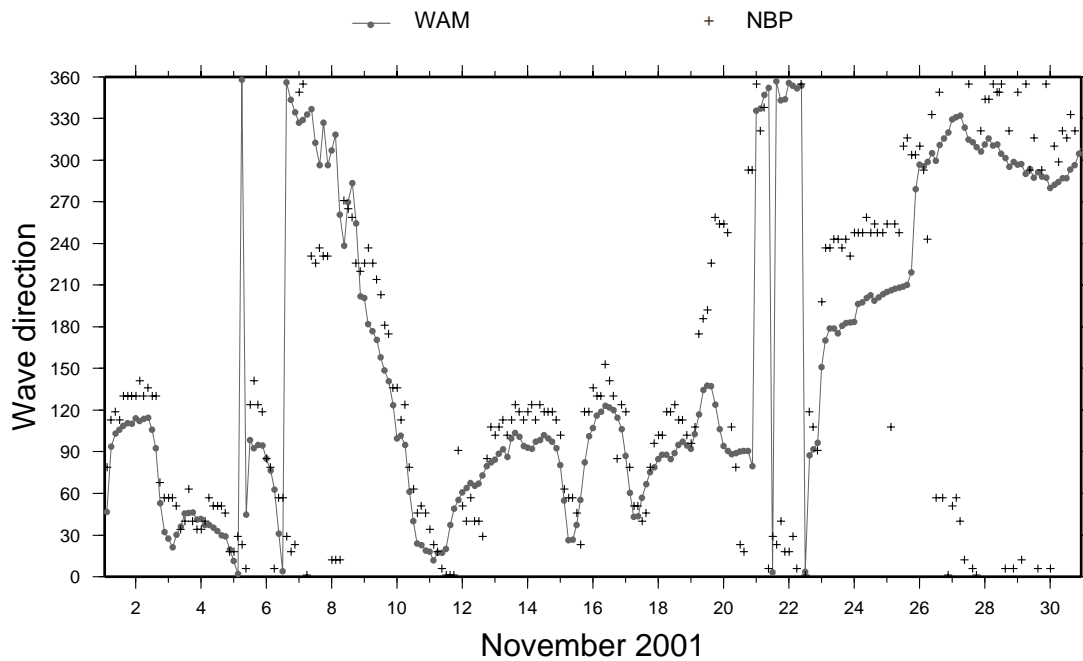


Figure 4: Modelled wave direction (WAM) compared to wave direction measured by the Northern Baltic Proper wave buoy (NBP).

The modelled significant wave height (3 and 6 h forecasts) together with the Northern Baltic Proper wave buoy measurements is shown in Fig. 3. The modelled significant wave height follows the measured wave height quite well. Both storms (1 and 15 November) are well predicted. Slight underestimation of the significant wave height can be seen in the middle and in the end of the month. The modelled wave direction together with the measured one in NBP is shown in Fig. 4. The figure clearly shows the bias between the modelled and measured wave direction throughout the whole period. The reason for this is not yet understood. The same bias occurred also for other periods during the pre-operational and operational runs.

Table 2: WAM statistics from the Northern Baltic Proper.

forecast length	BIAS Hs(m)	RMS Hs(m)	BIAS dir(deg)	RMS dir(deg)
06	-0.14	0.37	-25	42
12	-0.15	0.42	-20	50
18	-0.14	0.57	-18	58
24	-0.12	0.67	-21	54
30	-0.08	0.69	-15	39
36	-0.02	0.57	-26	49
42	0.00	0.66	-25	58
48	-0.05	0.53	-27	52

Table 3: WAM statistics from Helsinki.

forecast length	BIAS Hs(m)	RMS Hs(m)	BIAS dir(deg)	RMS dir(deg)
06	-0.33	0.56	-20	45
12	-0.30	0.49	-30	47
18	-0.23	0.41	-25	48
24	-0.29	0.49	-26	44
30	-0.40	0.70	-17	48
36	-0.23	0.43	-29	39
42	-0.25	0.43	-34	53
48	-0.30	0.54	-32	51

The bias and rms between the modelled and measured significant wave height and wave direction in 48 h forecasts (only forecasts starting from 00 UTC) in the Northern Baltic Proper and in Helsinki are shown in Tables 2 and 3, respectively. The bias in significant wave height (Hs) in the Northern Baltic Proper is rather small, but the bias in wave direction, already seen in 3 and 6 h forecasts (Fig. 4), can be seen throughout the whole forecast. For the Gulf of Finland the bias in the significant wave height is higher than for the Northern Baltic Proper. The narrowest part of the Gulf of Finland is only about 50 km wide and the 22 km resolution of the wave model is still too coarse for predicting the significant wave heights accurately in this area. The shape of the Gulf of Finland is also demanding for the correct modelling of the wave direction.

## 5.2 HIRLAM results

The atmospheric model (HIRLAM) receives the roughness length for the water points from the wave model and uses this value in calculation of surface fluxes. This value differs from the one calculated via the Charnock's formula. As the roughness length affects the momentum flux, the impact can be seen in the lowest model level winds as well as in 10-metre winds ( $V_{10m}$ ).

The wind speeds were rather moderate in the pre-operational test months (spring and summer), so that the impact of the different roughness on  $V_{10m}$  was rather small. This is demonstrated in Fig. 5, which shows the systematic difference in  $V_{10m}$  between ECA and ENO (ECA - ENO) 48 h forecasts, starting from 00 UTC, in August 2001. The coupled model (ECA) gives slightly smaller wind speeds (0.2 - 0.8 m/s) over the Atlantic, but a small reduction (0.2 m/s) is seen also in some areas over the Baltic Sea. The mean wind speed over the Atlantic was 6-8 m/s and about 6 m/s over the Baltic Sea. The systematic differences in other parameters were negligible, for instance  $\pm 0.2$  hPa at most in the mean-sea-level pressure ( $p_{msl}$ ).

In November 2001 the coupled model was already operational. However, due to the active flow pattern with several storms in Scandinavia, it was decided to carry out a 'pure HIRLAM' experiment also for November and compare the results with those of the coupled model. The mean wind speed in November was much higher than in spring and summer months, being more than 14 m/s over the Atlantic west of Norway and above 10 m/s over the Baltic Sea (Fig. 6). Figure 7 shows the systematic difference in  $V_{10m}$  between ECA and ENO 48 h forecasts, starting from 00 UTC, in November 2001. The differences vary between 0.2 - 1 m/s over the Atlantic, with ECA giving smaller values. The differences over the Baltic Sea are also of the same magnitude, with a value of 1 m/s close to the NBP buoy (Fig. 1).

There were a few storms in Finland and over the Baltic Sea in November 2001. One of the storms occurred on 15-16 November. During 15 November, a deep low moved from the west across central Finland. Strong to stormy winds, first from SW and later behind the low from NW and N, were blowing over southern Finland and surrounding sea areas. The highest 10-minute mean wind speed measured was about 25 m/s, with the gust wind speed exceeding 30 m/s at coastal stations west of southern Finland, e.g. at Kylmäpihlaja (61°09' N, 21°18' E). Figure 8 demonstrates the predicted 10-metre winds (+18 h) from the ENO experiment (pure HIRLAM) for the evening of 15 November, the storm case for which the significant wave height and wave direction are shown in Fig. 2. Wind speeds of over 20 m/s were predicted for the northern part of the Baltic Sea and over the Gulf of Bothnia, with the highest values of 28 m/s predicted for the Bothnian Sea. The impact of the coupled model on the wind speed is seen in Fig. 9, which shows the difference in  $V_{10m}$  between ECA and ENO 18 h forecasts for this case. The difference in  $V_{10m}$  is generally 1 m/s over the Baltic Sea, the Gulf of Bothnia and the Gulf of Finland, i.e. in the area of the storm. The difference is above 3 m/s at most over the Bothnian Sea. The reason for the difference in  $V_{10m}$  is the different roughness length over sea (friction) in the different experiments. Figures 10 and 11 demonstrate  $z_0$  for ENO as computed with the aid of Charnock's formula and for ECA as computed by the wave model, respectively. The roughness in the ENO experiment is of the order of a few millimetres, with a maximum value of just over 5 mm on the eastern coast of the Bothnian Sea. The roughness in the ECA experiment is much larger, with values of over 5 mm common all over the area of the storm and the maximum value as much as over 15 mm in the Bothnian Sea. The larger roughness in the ECA experiment, in case of strong winds (20 m/s or more), leads to significant reduction in the wind speed. The reduction is much smaller for moderate winds, as was pointed out earlier in connection of Figs. 6 and 7. The different roughness length in ECA and ENO experiments results in different surface fluxes over the sea. The differences in the fluxes are small. For example, in case of latent heat flux over the sea, ENO gives generally 2-5 W/m<sup>2</sup> (and 10 W/m<sup>2</sup> at most) larger flux than ECA, on average in November 2001.

The impact of the coupled model on other meteorological variables is rather small. A tiny effect can be seen, for example in  $p_{msl}$ . The observation verification scores, as computed against EWGLAM stations, are very similar. Hardly any differences can be seen even in wind verification scores, due to the fact there are no or only a few stations in sea areas, where some impact from the coupled model on the

scores could be expected.

## 6 Concluding remarks

The 22 km resolution is sufficient for wave modelling in open sea areas such as the Northern Baltic Proper, but in narrow bays such as the Gulf of Finland the resolution is too coarse.

It is important for wave modelling in the Baltic Sea that the resolutions of the wave model and atmospheric model are the same and that the wind input time step is equal to the wave model time step. From our experiments during the development phase of the coupled model it was found that best results with the wave model are achieved when no interpolation of the wind field, in space or in time, has to be done. With a small wind input time step (4 min) the wave model can also react to rapidly changing wind speed and direction.

The impact of the coupled model on the meteorological part of the model can mainly be seen in predicted surface winds. The roughness length provided by the wave model is larger than the one computed via Charnock's formula, especially in case of strong winds. Therefore the coupled model gives slightly smaller wind speeds over sea areas. The reduction is less than 1 m/s for wind speeds of the order of 10 m/s. For wind speeds of around 25 m/s the reduction can be as much 3 m/s. The impact of the coupled model on other meteorological variables is small, and hardly any differences in the verification scores can be seen.

## Acknowledgement

Thanks to Øyvind Sætra from DNMI for providing us with the parallel version of the WAM model.

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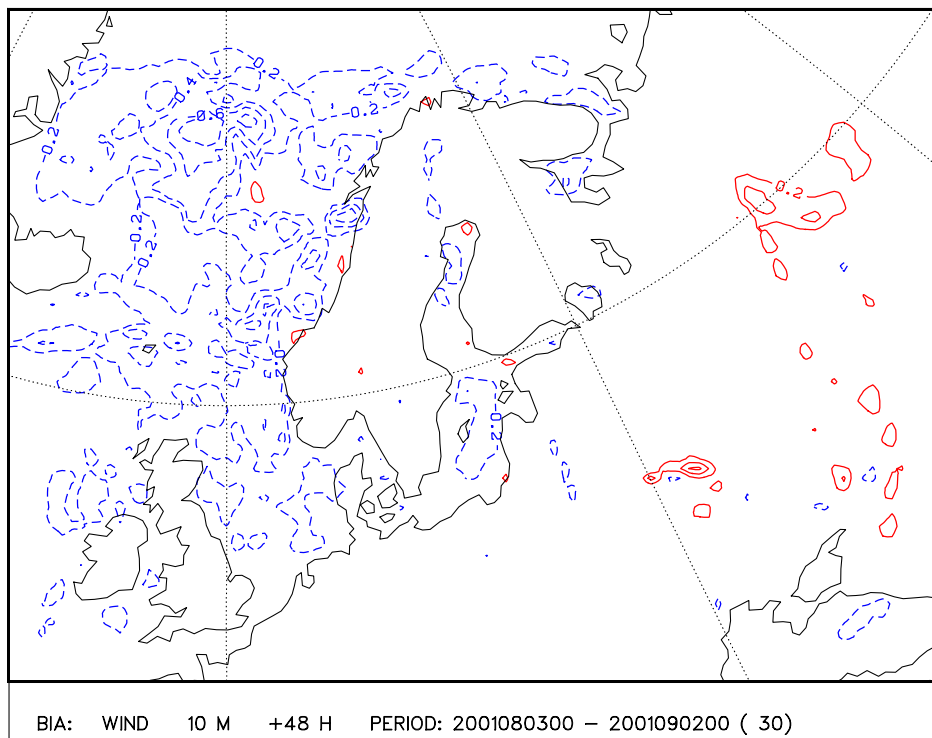


Figure 5: Systematic difference in  $V_{10m}$  for 48 h forecasts between ECA and ENO (ECA-ENO) experiments in August 2001. Contour interval: 0.2 m/s. The zero isoline not plotted, negative values indicated with dashed lines.

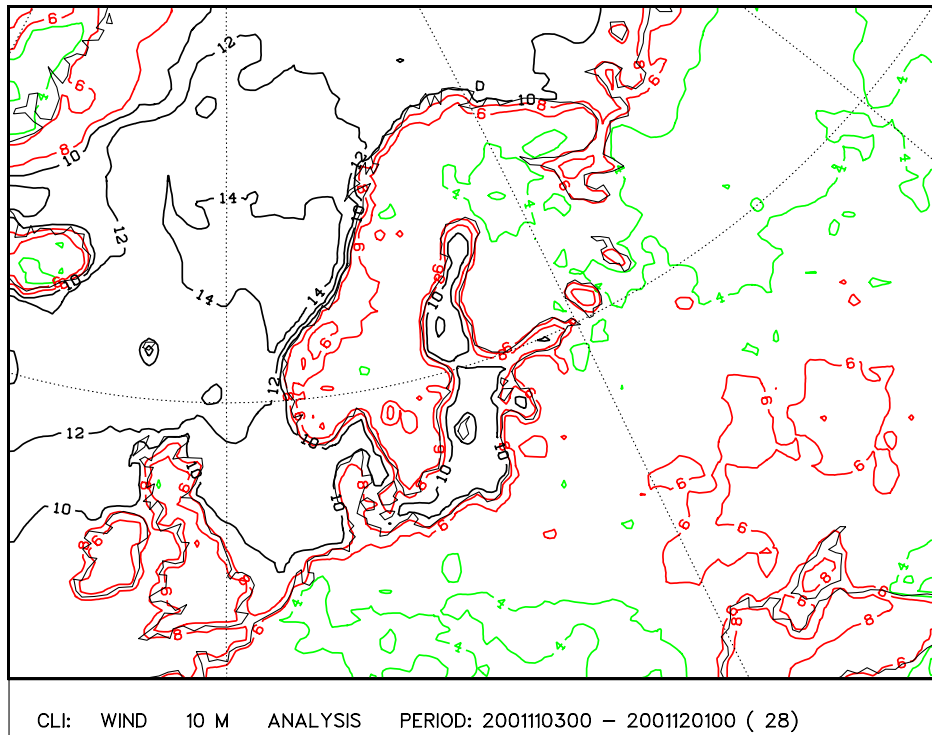


Figure 6: Average 10-metre wind speed in November 2001, as from 48 h ENO forecasts. Contour interval: 2 m/s.

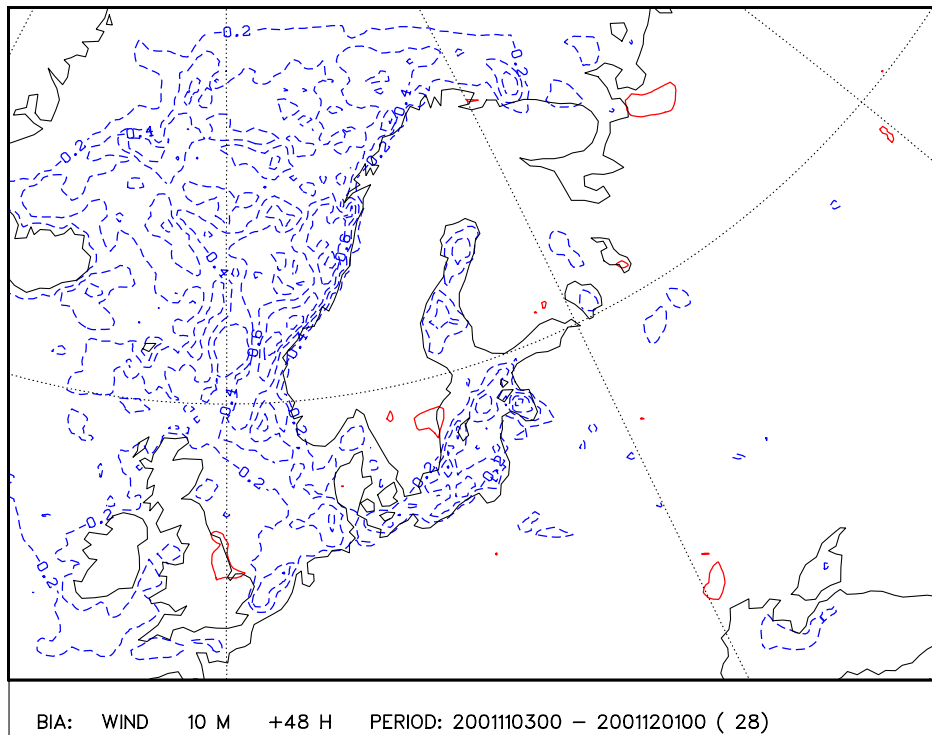


Figure 7: Systematic difference in  $V_{10m}$  for 48 h forecasts between ECA and ENO (ECA-ENO) experiments in November 2001. Contour interval: 0.2 m/s. The zero isoline not plotted, negative values indicated with dashed lines.

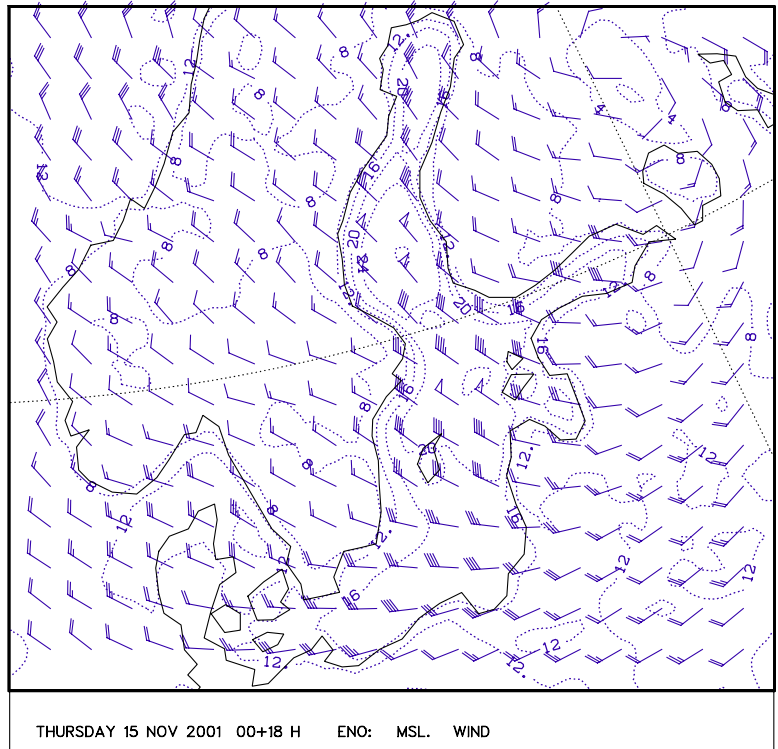


Figure 8: Predicted (+18 h)  $V_{10m}$  for 18 UTC 15 November 2001 from the ENO experiment. Winds are shown in barbs, but also isotachs are plotted in dotted lines. Contour interval for isotachs: 4 m/s.

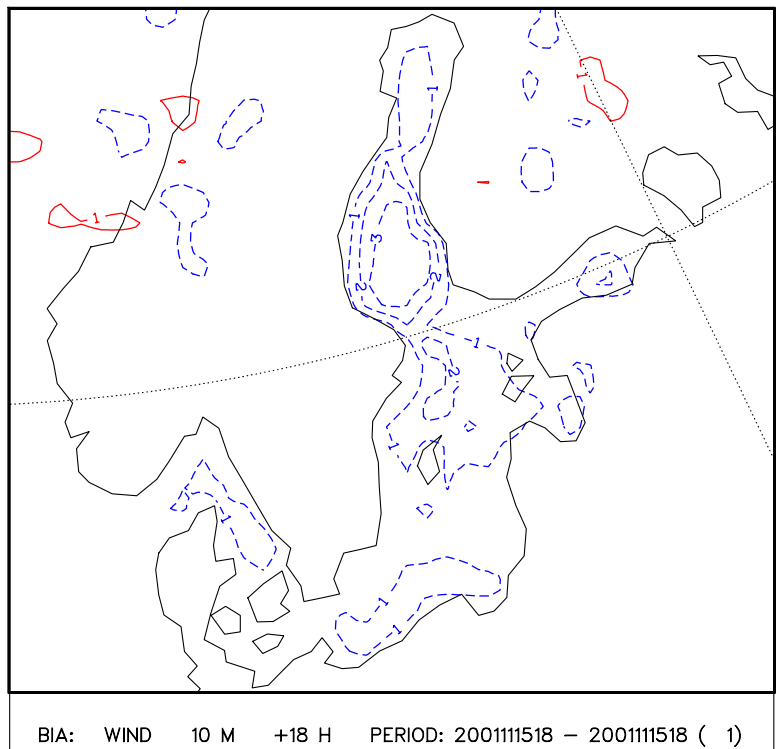


Figure 9: Difference in  $V_{10m}$  between ECA and ENO (ECA - ENO) 18 h forecasts valid at 18 UTC 15 November 2001. Contour interval: 1 m/s. The zero isoline not plotted, negative values indicated with dashed lines.

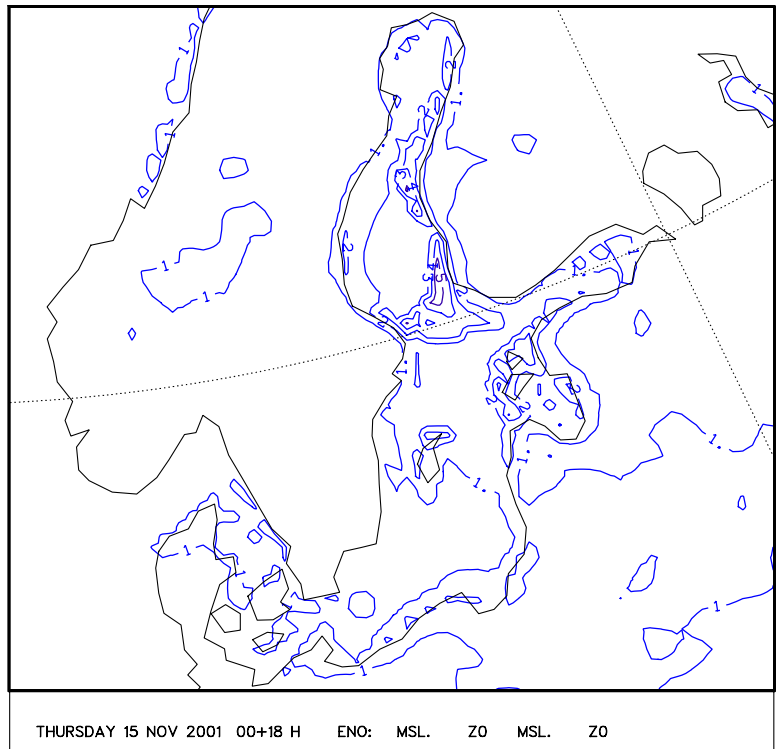


Figure 10: Roughness length for 18 UTC 15 November 2001, as from the ENO experiment. Contour interval: 1 mm.

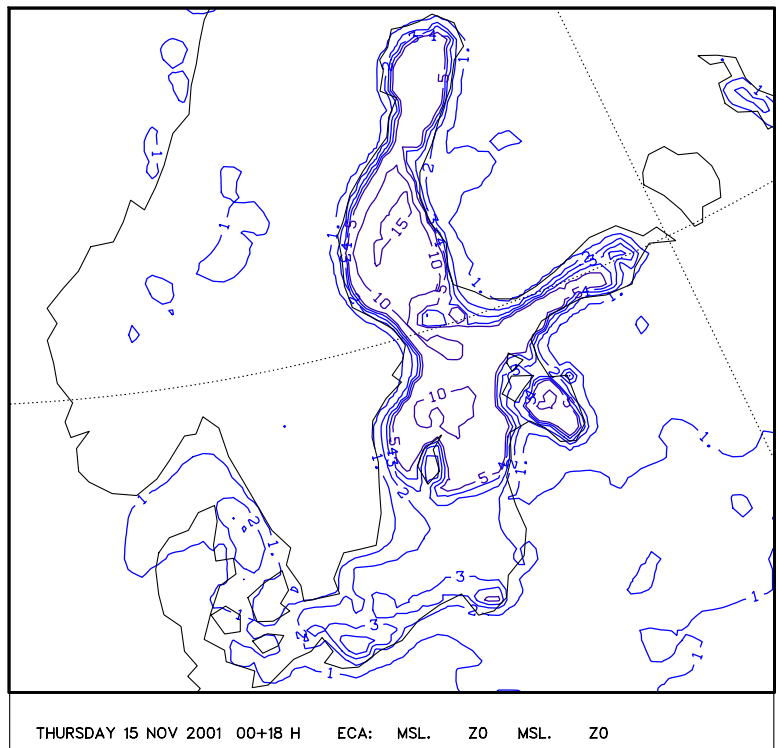


Figure 11: Roughness length for 18 UTC 15 November 2001, as from the ECA experiment. Contour interval: 1 mm for values 1-5 mm and 5 mm for values larger than 5 mm.