THE ACCURACY OF FIMR WAVE FORECASTS IN 2002–2005
Laura Tuomi

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Antti Kangas, Jussi Leinonen and Hanna Boman
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THE ACCURACY OF FIMR WAVE FORECASTS IN 2002–2005
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ABSTRACT
In this report the operational wave forecasting system used at the Finnish Institute of Marine Research (FIMR) since the end of 2001 is described. The accuracy of the operational wave forecasts is evaluated by comparing the model results against buoy measurements in the Baltic Sea for the years 2002–2005. The accuracy of the forecast significant wave heights is good when compared to measurements in the middle of the Northern Baltic Proper. However, the wave model is unable to describe to the full extent some special features of the wave fields in the narrow bays of the Baltic Sea like the Gulf of Finland. The accuracy and the resolution of the forcing wind fields, as well as the resolution of the wave model grid, have a considerable effect on the accuracy of significant wave heights as well as on other parameters, such as peak period and peak wave direction.

Keywords: wave modelling, WAM, forecast accuracy, Baltic Sea

1. INTRODUCTION
The third-generation wave model WAM (WAMDI 1988, Komen & al. 1994) was developed at the end of 1980's by an international group of scientists. Since its development it has been used in several Institutes around the world as a forecast and research model. WAM can be used in global forecasting as well as in coastal limited area forecasting with resolutions from tens of kilometres to a few hundred metres. As forcing data, only surface wind fields from an atmospheric model are used.

WAM is based on the spectral energy balance equation, which equates the evolution of the wave spectrum to the sum of local wind input, wave dissipation, weakly non-linear wave-wave interaction and the propagation of waves from non-local sources. The model solves the two-dimensional wave variance spectrum $F(f,\theta)$ through integration of the transport equation

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

where $f$ is frequency, $\theta$ is the direction in which the waves propagate and $c_g$ is the group velocity of the waves. The source function $S$ is given by

$$S = S_m + S_{nd} + S_{ds} + S_{bt}$$

where $S_m$ represents the physics of the wind input, $S_{nd}$ non-linear wave-wave interactions, $S_{ds}$ dissipation due to white-capping and $S_{bt}$ bottom dissipation.

WAM was implemented in the Baltic Sea area at the beginning of the 1990's. In the first test cases, using a 21km resolution grid, the agreement between modelled and measured significant wave heights was poor. This was considered to be mostly due to the coarse reso-
lution of the forcing wind field (Kahma & al. 1997). Wind fields for these first tests were taken from Finnish Meteorological Institute’s (FMI) weather forecast model HIRLAM (High Resolution Limited Area model) which had a resolution of 0.5° (55km) at that time. The Baltic Sea is so small in size that the marine wind speeds could not be accurately predicted using such a coarse resolution. In addition to this, WAM had a finer resolution than the atmospheric model, and it was therefore necessary to linearly interpolate the coarse resolution wind fields to its grid. This caused the wave grid cells in the proximity of land to have wind forcing affected by land or the land-sea transition. Although several different methods were tried to diminish the effect of land-biased winds in sea areas, the results showed such poor agreement with measured values that the use of WAM as an operational wave forecasting model was not considered at that time to be worthwhile.

At the end of the 1990’s an improvement in the resolution of the FMI’s atmospheric model made it possible to reconsider the use of WAM in operational wave forecasting. The updated FMI-HIRLAM model forecast wind fields with a 0.2° (22km) resolution which was sufficient to describe the basic features of the wind fields over the Baltic Sea. A project, funded by the Finnish Ministry of Traffic and Communication, was started in 1998 to couple the HIRLAM model with WAM. This was inspired by the EU-project ECAWOM (Lionello & al. 1997) that suggested that coupling an atmospheric and a wave model leads to a better description of surface winds over sea areas. In the coupled HIRLAM-WAM model the lowest-level wind fields from the atmospheric model were transferred to the wave model and the sea surface roughness was transferred from the wave model to the atmospheric model. When the sea surface roughness calculation was made taking into account the surface wave fields, the accuracy of the surface wind fields over sea areas was improved.

This improvement in the accuracy of surface wind fields also improved the wave model results. The accuracy of the wave forecasts was further improved by the small wind input time step, allowing the wave model to better take into account variations in time in the input wind fields (Järvenoja & Tuomi 2002). Operational runs with the coupled model were started in November 2001 and continued until the end of 2002. The forecast area covered the Baltic Sea and the North Sea. Difficulties in keeping up with changing super-computer systems ended the operational runs of the coupled HIRLAM-WAM model. Since December 2002 WAM forced by surface wind fields, but with no feedback to the atmospheric model, has been used as the FIMR operational wave model.

The FIMR wave model setup that takes into account the special features of the Baltic Sea is described in this report. The accuracy of the wave forecast in the years 2002-2005 is evaluated, comparing model forecasts to wave measurements. Special attention is paid to various aspects affecting the forecast accuracy in the Baltic Sea.

2. OPERATIONAL WAVE MODEL SET-UP

FIMR runs WAM operationally for the Baltic Sea area. In the years 2002-2005 WAM was run with a 0.2° (~22km) resolution in shallow water configuration. For the year 2002 the model was run with 24 angular and 25 frequency bands (0.042 – 0.414 Hz). In the year 2003 10 frequency bands were added to better capture the short waves in the Baltic Sea (35 frequency bands (0.042 – 1.073 Hz)). Forecast runs are made four times a day with a 54-hour forecast length. The output parameters are significant wave height, peak and mean wave direction, peak and mean wave period. All output parameters are given as integrated parameters of the total sea state as well as separated values for wind sea and swell. The wind
The accuracy of FIMR wave forecasts in 2002–2005

forcing for the operational wave model is taken from FMI’s weather forecast model HIRLAM (Unden & al. 2005). The HIRLAM model has been developed in co-operation between eight European countries since 1985. Since 2003 FMI has also acted as the Lead Centre for the RCR (Regular Cycle with the Reference) runs, in which capacity it has the special duty of running the official reference version of the HIRLAM model as its operational weather forecast model.

The wave model grid is constructed in such a way that it takes into account the special features of the Baltic Sea. The small size of the Baltic Sea sets a limit for the resolution of the wave model as well as for the resolution of the forcing wind fields (Tuomi & al. 1999). A rotated grid with a 0.2° (~22km) resolution was created for the wave model in the late 1990’s (Fig. 1). This resolution was found to be the coarsest resolution with which the waves in the open sea areas of the Baltic Sea could be properly described by WAM. Also the geometry of the Baltic Sea and its narrow gulfs make the grid geometry, as well as a small enough resolution, important (Pettersson 2004). The rotation and the resolution of the grid were chosen to be the same as that used in FMI-HIRLAM at that time. In this way there was no need to interpolate the wind fields in space, and the problems with land-affected wind speeds near coastal areas were reduced.

The archipelago in the northern part of the Baltic Sea and the complex structure of the coastline has to be taken into account in the wave model grid. The irregularities of the shoreline and the sheltering islands are handled by approximating an average shoreline (Kahma 1981), which is then used to make the grid for the wave model. There are also areas like the archipelago between Åland main island and the mainland of Finland open for waves travelling from the Northern Baltic Proper to the Bothnian Sea and vice versa. Using this kind of grid leads to modelled significant wave heights that are too high in the archipelago as well as in the southern Bothnian Sea or in the Northern Baltic Proper, depending on the propagation direction of the waves. To obtain reasonable wave fields in these areas with coarse resolution grids requires coding the archipelago as land, i.e., impassable for waves.

The Baltic Sea has an ice cover every winter. In average winters the Bay of Bothnia, the Gulf of Finland, the Gulf of Riga, and parts of the Northern Baltic Proper freeze. Even in the mildest winters, the Bothnian Bay and the eastern part of Gulf of Finland will have an ice cover. In the FIMR wave forecasts, sea ice is taken into account by coding grid cells having an ice concentration of over 30% as land. This ensures that the wave model uses correct fetches for the wave growth from the ice edge. Naturally, waves are not forecast for areas having an ice cover. The ice concentrations are kept constant for the whole forecast length of 54 hours.
The wave forecasts are presented on FIMR’s web page as forecast maps for the whole Baltic Sea (Fig. 2) and as time series for selected points (some of them buoy locations). Special customised forecast services are also provided.

![Wave forecast map for the Baltic Sea. Significant wave height is marked with colours, wave direction with arrows. Areas covered with ice are shown in white.](image)

**Fig. 2.** Wave forecast map for the Baltic Sea. Significant wave height is marked with colours, wave direction with arrows. Areas covered with ice are shown in white.

### 3. WAVE MODEL COMPARISONS FOR THE YEARS 2002–2005

The wave model results are compared to measurements made at two locations (Fig. 3): in the middle of the northern Baltic Proper (NBP) (59°15' N, 21° 00' E) and off Helsinki (HKI) (59° 57'54" N, 25° 14'06" E). The measurements are made by FIMR using Directional Waveriders. Measurements in the northern Baltic Proper have been carried out since September 1996, excluding ice seasons. The depth at the measuring site is 100m. Off Helsinki measurements have been made in the 1980’s and early 1990’s. From November 2001 the measurements have been made in co-operation with the Finnish Maritime Administration and the Port of Helsinki. The depth at the measuring site is 62m.

![Location of the two FIMR wave buoys in the Northern Baltic Proper (NBP) and off Helsinki (HKI).](image)

**Fig. 3.** Location of the two FIMR wave buoys in the Northern Baltic Proper (NBP) and off Helsinki (HKI).

The comparisons between model and buoy data have been made for these two locations using all available measurements. Data from the wave buoys is only available during the ice-free season. The Gulf of Finland is frozen every winter, so a typical period for wave measurements at the Helsinki location is from the beginning of May until the end of December. In the Northern Baltic Proper the measurement season varies from year to year. In some winters the ice edge reaches the location of the NBP wave buoy and the buoy has to be taken out, which was the case in winters 2002, 2003 and 2005. In some years the wave buoy can stay at the NBP location for the whole winter, which was the case for 2004 in the period discussed here.

#### 3.1 Forecast accuracy

The quality of the FIMR wave forecasts is presented in Figure 4 showing the measured significant wave heights at the NBP and HKI sites compared to the 6-hour forecasts. The accuracy of the wave forecast is good, the bias being slightly negative at both locations. This means that the model tends to slightly underestimate the significant wave heights. The underestimation of significant wave height is larger at the HKI site. The Gulf of Finland, where the HKI buoy is located is only 60km wide in its narrowest parts. The weather fore-
cast model with a resolution of 22km has only a few sea points within the Gulf, and the modelled wind speeds near the coasts are affected by the smaller values over the land. The accuracy and sufficient resolution of the forcing wind field have been reported to play a major role in the wave forecast accuracy in small basins (e.g. Cavalleri 1997).

The accuracy of FIMR wave forecasts in 2002–2005

Fig. 4. Significant wave height from 6-hour forecasts (WAM) compared to measurements in the northern Baltic Proper (NBP) and off Helsinki (HKI). Buoy locations are shown in Figure 3.

Fig. 5. Bias and rms error throughout the whole forecast length at six hour intervals at (a) NBP and (b) HKI.

The decrease in the forecast accuracy of significant wave heights with increasing forecast length can be seen in Figure 5. The bias and root mean square (rms) error between measured and modelled values at the NBP and HKI sites is shown for the whole 54 hour forecast length at six hour intervals. At both locations the bias is negative and smallest at the beginning of the forecast. The bias is larger at HKI than at NBP, as described earlier. The accuracy of the wave forecast is good for the first 18 hours of the forecast. After that, the rms error starts to grow, while the bias remains almost the same throughout the forecast. The growth of error in the wave forecast is mainly due to the growth of error in the forcing wind fields. Similar behaviour in the accuracy of the forecast HIRLAM 10m wind fields has been shown, for example, by Järvenoja (2005).
3.2 Effect of wind field accuracy on the wave forecast accuracy

As mentioned earlier, the accuracy of the forcing wind field has a significant effect on the accuracy of the wave forecast. To evaluate the effect of wind field accuracy on the wave model results in the Baltic Sea, the wave model was run with two different sets of wind fields having the same horizontal resolution. These wind fields were taken from two operational HIRLAM suites run simultaneously at FMI in December 2003, namely, ENO (Eerola 2002) and RCR (Kangas & Sokka 2005). RCR-HIRLAM is a newer version of the HIRLAM model with changes in the physics and parameterisation schemes intended to improve the model results. In Figure 6 can be seen the comparison of measured significant wave height at NBP against the forecast significant wave height using ENO and RCR winds.

When significant wave height is forecast using RCR winds it is usually smaller than when forecast using winds from ENO-HIRLAM. At the highest peaks the accuracy is better when ENO winds are used, even though some of the highest peaks tend to be slightly overestimated. In Figure 7 the forecast 10m wind speeds from ENO- and RCR-HIRLAM are compared with measurements at a height of 31m at FMI’s coastal weather station Utö. No correction to the wind speeds were made due to the different levels of model and measurement heights. The same pattern is seen in the comparison of wind speeds. The winds forecast by RCR-HIRLAM are usually lower than those forecast by ENO-HIRLAM. At the peaks the accuracy of the ENO winds is slightly better than that of the RCR winds.

![Fig. 6. Significant wave height from 6-hour forecasts calculated by WAM using wind forcing from ENO-HIRLAM (blue) and from RCR-HIRLAM (red). Buoy data from NBP are shown with a black line.](image)

![Fig. 7. 6-hour forecasts of wind speed at 10m height from ENO-HIRLAM (blue) and RCR-HIRLAM (red). Measured wind speed at a height of 31m at FMI’s coastal weather station Utö is shown with a black line.](image)
To further illustrate the effect of the accuracy of atmospheric forcing on wave forecasts, the measured significant wave height at NBP is plotted against the 6 hour forecasts separately for the years 2002, 2003, 2004 and 2005 (Fig. 8). For these years the wave model version and the wave model grid have remained the same, but there have been several changes and upgrades in FMI-HIRLAM. In 2002 the coupled atmosphere-wave model described in Section 1 was used to make the wave forecasts. In 2003 the wind forcing for the wave model was taken from ENO-HIRLAM, i.e., the same version of the HIRLAM model that was coupled to the wave model in 2002. Since January 2004, wind fields from RCR-HIRLAM have been used. The international Hirlam project is constantly developing the HIRLAM model, and several updates and improvements to the RCR-HIRLAM were made in years 2004 and 2005. The different characteristics in the forecast significant wave heights for each year can clearly be seen in Figure 8. Unfortunately there were only a few cases of high significant wave heights measured by the NBP wave buoy in 2002. For this reason it is difficult to fully evaluate whether the accuracy of high significant wave heights was better in 2002 than in 2003, as suggested by the experiments with the coupled model in 2001. When significant wave heights of over 4 m are compared in the years 2003 and 2004, it can be seen that they tend to be over-predicted in 2003, whereas in 2004 almost all are under-predicted. This behaviour is already seen in Figure 6 showing the differences of the simultaneous wave forecast runs using two different sets of wind fields, i.e., ENO-HIRLAM in 2003 and RCR-HIRLAM in 2004. Although the accuracy of significant wave heights of over 4m is poor in 2004 the scatter is significantly reduced compared to earlier years. The further improvements in HIRLAM model physics and parameterisations after 2004 have improved the quality of the surface wind fields and thus of the wave results, as can be seen by the comparison for the year 2005.

3.3 Wave model features affecting forecast accuracy

Although wind field accuracy still remains the main reason for errors in the wave forecasts, the formulation of the physics, numerics and parameterisations in the wave model also have an effect on the results. The improvement in wind field accuracy in recent years has made it possible to identify errors in the wave forecasts caused by the wave model itself. In 2002 the accuracy of significant wave heights of under 1m was poor, as can be seen in Fig. 8. This was mainly due to the frequency range used in the wave model in that year. This frequency range was designed for the prediction of waves with coarse resolution in oceans, where neglecting small wave lengths has no significant effect on the results. In the Baltic Sea it is also important to have the high frequencies present in the wave spectra. A lack of high frequencies in the model frequency range can lead to too low significant wave heights in a growing wind sea, as can be seen in Figure
9. The growth of wind waves in the model starts when wind speeds reach high enough values to grow wave energy within the given frequency range. In the case presented in Figure 9, for example, the wind waves started to grow only after the wind speed had reached about 5 m/s. Extending the frequency range to 1.073 Hz in 2003 enabled the model to calculate wave growth with low wind speeds, thus leading to a better description of significant wave heights.

Fig. 9. In 2002 high frequencies were missing from the wave model spectra. Wind waves only started to grow when wind speeds reached high enough values (~5 m/s in this case). This led to an underestimation of significant wave heights in a growing wind sea (dashed line). Adding high frequencies to the frequency band improved the prediction of significant wave heights (solid line).

In addition to the accuracy of significant wave height, it is also important to know the accuracy of other parameters produced by the wave model, such as wave direction and peak period. In Figure 10 the modelled wave direction at the spectral peak is compared to those measured at NBP and HKI. The scatter in wave direction is quite large at both sites. At NBP the accuracy is better than at the HKI site. The geometry of the Gulf of Finland causes a steering of wave direction into the direction of the axis of the gulf. WAM is unable to reproduce this behaviour, and at the HKI location the modelled peak directions tend to follow the wind direction rather than the measured wave direction (Pettersson 2004). However, the accuracy of the peak directions was shown to slightly improve when a higher resolution grid was used for the Gulf of Finland. Some of the scatter in the peak wave direction is also caused by the inability of the wave model to predict accurately the amount of swell energy in the wave spectra. This leads to situations where the modelled wind sea directions are compared to measured swell directions. This will be discussed further later in this Section.

Fig. 10. Comparison of 6-hour forecasts of wave direction at the spectral peak against measurements in the Northern Baltic Proper (NBP) and off Helsinki (HKI).
In addition to a better description of peak directions, the higher resolution wave model grids also affect the prediction accuracy of the significant wave heights in the Gulf of Finland. In Fig. 11 the significant wave height predicted by the 22km resolution and 11km resolution models using the same atmospheric forcing are plotted against the measurements at the HKI site. The accuracy of the predicted significant wave height improves when a higher resolution is used. However, in narrow gulfs and near coastal areas, the accuracy and sufficient resolution of the atmospheric model is as important as the resolution of the wave model in producing accurate significant wave heights.

Figure 12 shows the comparison of modelled and measured peak periods. The scatter in the peak periods is quite large. The peak period from buoy and model spectra corresponds to the frequency with maximum energy. The difference in the resolution of the frequency bands of model and buoy spectra causes some of the scatter seen in the results. The frequency bands in buoy data have equal spacing, whereas in the wave model the frequency resolution decreases towards higher frequencies. However, this does not entirely explain the scatter in the results, especially at the HKI location, where measured periods of 10–12s are clearly underestimated by the model. In these cases the buoy measurements show the peak period of the swell, whereas the model has the highest energy in the growing wind waves. This can be seen in Figure 13, where measured spectrum at the HKI location is compared to the modelled one. WAM clearly underestimates the amount of swell in the spectrum, and shows only one swell peak at ~0.23Hz, whereas the buoy has two swell peaks at 0.17Hz and 0.23Hz. The wind sea part in frequencies of over 0.4Hz is overestimated by the wave model. One possible explanation for this is that the wind fields that originally produced the swell were underestimated, thus leading to underestimated wind wave energy and later swell energy. It is also possible that the wave dissipation source term, which is the least known of the source terms, may dissipate swell energy too quickly from the wave spectra (Alves & Banner 2003). However, more detailed analysis is needed to explain this behaviour to its full extent.

![Fig. 11. Significant wave height predicted by the 22km resolution (dashed line) and 11km resolution (solid line) wave models compared to measurements made by the Helsinki wave buoy in August 2002.](image-url)
SUMMARY

WAM has been in operational use at FIMR since November 2001. The operational model has been set up to take into account the special features of the Baltic Sea, such as the irregular shoreline and archipelago and ice during winter time. The forecast accuracy of significant wave height is good in open sea areas. The main reason for inaccuracies in forecast significant wave heights in the open sea areas are the inaccuracies in the forcing wind fields. However, in narrow gulfs the coarse resolution of operational wave model has an additional effect on the underestimation of significant wave heights. The comparison of the whole forecast length of 54 hours shows that the modelled significant wave heights fit the observations very well in the first 18 hours of the forecast. After that, the difference between measurements and forecast values increases. Peak wave direction and peak period are not as accurately forecast by the wave model as the significant wave heights. In addition to the factors affecting the accuracy of the significant wave heights, peak direction and peak period seem to be more sensitive to wave model features such as the resolution of the frequency bands, grid geometry and the formulation of the wave model physics.

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References

The accuracy of FIMR wave forecasts in 2002–2005


SEA LEVEL FORECASTING FOR FINLAND’S COAST FOR THE YEAR 2007

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ABSTRACT

In this paper we introduce a sea level model known as Wetehinen and study its sea level modelling performance on the Finnish coast for the year 2007. Wetehinen is a 2-dimensional vertically integrated hydrodynamical model, which is applied to the Baltic Sea region with an open boundary to the North Sea. It is forced by sea-level air pressure, surface wind speed and direction. It can be used to forecast the sea level by using meteorological forecasts, at the moment up to +132 hours ahead. The model results are compared to the tide gauge measurements, and the RMS errors for different locations and different forecast lengths are calculated. The RMS errors of the nowcast values were 8–10 cm, increasing to 10–19 cm for the +132 hour forecasts. In the low water cases the RMS error remains nearly the same as the average RMS error for the whole dataset, but in the high water cases the error is nearly doubled. Also the effect of the situation analysis on the RMS error of the forecasts was inspected, and it was found that the hand-made forecasts have the RMS error less than 40% of the model RMS error.

Keywords: Wetehinen, sea level, modelling, Baltic Sea, forecasts, year 2007

1. INTRODUCTION

The Baltic Sea is a semi-closed sea area, whose mean depth is only 55 m and maximum depth 450 m. The local maximum sea level variation on the Finnish coast is about 330 cm. Short-term sea level variations, on a time scale of an hour to a few days, are mainly controlled by local meteorological processes. Wind conditions, air pressure and transient water movements such as seiches play an important role. Other factors, such as precipitation, evaporation and astronomical tides have a minor effect. The water balance variations of the Baltic Sea, caused mainly by inflow and outflow through the Danish Straits, affect the sea level on time scales longer than about two weeks. The variation in the Baltic Sea level has been studied earlier, for example by Lisitzin (1974b) and Johansson & al. (2001).

The Baltic Sea has certain features that make its sea level variation differ from that of the ocean. The Baltic Sea level can differ from that of the North Atlantic and the North Sea by about half a metre because the wind stress in the shallow channels of the Danish Straits can create a large sea surface tilt, and the water cannot restore freely to the North Sea level. The Danish Straits alternate tidal waves, effectively preventing them from entering the Baltic Sea; therefore tides do not dominate the sea level height. In the Baltic Sea, water movements are restricted by topography and land masses, introducing an important feature, seiches. The surface tilt can be large due to the wind stress and shallow depth. These features must be taken into account in the Baltic Sea level modelling in order to obtain reliable sea level forecasts.
Hydrodynamical modelling of the Baltic Sea using numerical models has been done at the Finnish Institute of Marine Research (FIMR) since the 1970's, for example by Häkkinen (1980), Jokinen (1977) and Andrejev & al. (2000). Nowadays the results from the various different numerical sea level models are used together with tide gauge measurements in operational sea level forecasting. The forecasts are used in commercial ship traffic, leisure boating and flood combatting for example. Reliable forecasts, as well knowledge of the forecasts’ error limits are essential for the users.

In this paper we study the forecast error of one of the models, known as Wetehinen, for the year 2007. Wetehinen is a 2-dimensional vertically integrated sea level model. The Wetehinen's now and forecast errors are calculated based on hindcast simulation using two different atmospheric forcing for the year 2007.

Along with the sea level observations, the results from different sea level models are analyzed to make manual forecasts. In 2007 the manual forecasts were made operationally daily in the period of January—May (not based on hindcast results); their accuracy was also examined and their error was calculated.

The year 2007 was a special year for water level studies. The water level in the whole Baltic sea was exceptionally high in January, and during a winter storm new sea level records were measured at Rauma and Föglö on the 16th of January. Another, shorter, high water situation occurred in the middle of May. At the end of February and beginning of July two low water situations occurred. The sea level for the rest of the year was within the normal range of variation (Boman 2008).

2. SEA LEVEL MODEL AND HINDCAST SET-UP

Wetehinen is a vertically-integrated sea level model for the Baltic Sea. The model has been developed in FIMR for sea level modelling, and is used operationally to forecast the sea level on the coast of Finland. The model is calibrated for the Finnish coast by using Finnish tide gauges (total 13). The governing modified shallow water equations are derived from the Navier-Stokes equation and the continuum equation by using the hydrostatic and Boussinesq approximations (Haidvogel & Beckman 1999).

\[
\frac{\partial U}{\partial t} - f V = -g H \frac{\partial \eta}{\partial x} - H \frac{\partial P}{\partial x} + \nabla^2 V U + \tau^w - \tau^b \tag{1}
\]

\[
\frac{\partial V}{\partial t} + f U = -g H \frac{\partial \eta}{\partial y} - H \frac{\partial P}{\partial y} + \nabla^2 V H + \tau^w - \tau^b \tag{2}
\]

where \( U \) and \( V \) are the vertically-integrated velocities in the \( x \) and \( y \) directions, \( H \) is the water depth, \( f = 2 \Omega \sin \phi \) is the Coriolis parameter, \( g \) is the gravitational acceleration, \( \eta \) is the water level (the deviation from the mean water level), \( A = 1.5 \times 10^4 \text{ m}^2\text{s}^{-1} \) is the horizontal eddy coefficient, \( P \) is the air pressure divided by the water density, \( \tau^w = \rho_{\text{air/water}} c_D \frac{1}{\rho_{\text{water}}} \) is the wind stress, \( \rho_{\text{air/water}} \) is the air density divided by the water density, \( c_D = 1.3 \times 10^3 \) is the wind drag coefficient, \( u_{\text{wind}} \) is the wind velocity, \( \tau^b = \rho H^2 U^2 \) is the bottom friction and \( r = 10^6 \text{m}^2 \) is the bottom friction coefficient.

The equations are discretized on a Arakawa C-grid. The grid size is 6 nm (about 11*9.6km), and the data for the bottom topography and the coastline is averaged from IOW (Leibniz-
Institut für Ostseeforschung Warnemünde) 1

nm bathymetry data (Seifert & al. 2001). The
model domain consists of 111 x 131 grid
points, which cover the whole Baltic Sea re-
gion.

The spin-up time for the model was two weeks
and the time step was 100 s.

The atmospheric forcing consists of sea-level
air pressure, surface wind speed and wind di-
rection. For the first simulation the atmos-
pheric forcing was taken from HIRLAM
(High Resolution Limited Area Model (Unden
& al. 2002)) forecasts provided by FMI (Fin-
nish Meteorological Institute). The HIRLAM
forecast used consisted of forecast values up to
+54 hours in 3-hour steps; these were interpo-
lated to one-hour intervals in the Wete
hinen model. HIRLAM was run four times a day (at
00, 06, 12 and 18 UTC), and the input atmos-
pheric forcing therefore consisted of 365 * 4 =
1460 HIRLAM forecasts, of which 10 were
not available for sea level modelling. The pre-
vious Wete
hinen run was used as a starting
point for the next run. The second simulation
was forced by the ECMWF forecast (Persson
& Grazzini 2005). The ECMWF forecasts
were available once a day at 00 UTC from
July to December, altogether 183 forecasts
(one missing). The ECMWF forcing consists
of forecast values up to 132 hours ahead at the
beginning at 3-hour interval and after +60
hour at 6-hour interval.

The inflow into and outflow of water from the
Baltic Sea was taken into account by using sea
level forecasts for the north of the Danish
Straits. The sea level forecast was provided for
FIMR by the BSH (Bundesamt für
Seeschifffahrt und Hydrographie) Operational
Circulation Model (BSHcmod (Dick & Kleine
2001)). The sea level values for Grenaa on the
Danish coast and Viken on the Swedish coast
were extracted from the BSH forecasts and the
sea level was linearly interpolated between the
two locations. The BSH values were reduced
by 25 cm because of different reference sys-
tems and a possible steric effect (due to the
appreciable difference in salinity and tempera-
ture).

The Wete
hinen model sea level between
Grenaa and Viken was forced to new values
every 15 minutes. The BSHcmod sea level
forecast time span was insufficient for some of
the Wete
hinen simulations: a few hours too
short for the HIRLAM evening (18 UTC)
model simulations and about three days too
short for ECMWF simulations. In such cases
the last available values were used for the rest
of the simulation.

3. MODEL RESULTS

In order to characterize the error of the fore-
cast given by the Wete
hinen model and its
variability, we performed various analyzes on
the measured and forecast data. The Wete
hinen model data consists of the HIRLAM
forced simulations for the whole year 2007
and the ECMWF forced simulations from July
to December. Throughout the validation pro-
cess, we mainly used two statistical measures
for the error: most importantly, the root-mean-
square error (RMSE), defined as

\[
\sqrt{\frac{1}{N} \sum_{k=1}^{N} (f_k - m_k)^2}
\]

and secondarily, the (related) standard devia-
tion of error

\[
\sqrt{\frac{1}{N} \sum_{k=1}^{N} (f_k - m_k - \mu)^2}
\]

where \(f_k\) and \(m_k\) denote the forecast and mea-
sured water level values at the same time and \(\mu\)
denotes the mean error (bias)

\[
\frac{1}{N} \sum_{k=1}^{N} (f_k - m_k)
\]

The RMSE error is of particular interest in the
evaluation of an operational model such as
Wete
hinen, as it provides an estimate of the
expected error of the water level forecast to
the end-user of the data. Thus, it can be used as a measure of the average reliability of the model. The standard deviation is a similar measure, but eliminates the bias, or systematic error, \( \mu \) from the RMSE, giving a measure of the variability of the forecast error.

While examination of the above-mentioned errors for all Finnish tide gauge locations and times over the year does yield some degree of understanding of the performance of the model, it is certainly more fruitful to inspect the spatial and temporal variability of the errors. From an operational standpoint, it is most important to report the variability of the error at coastal locations, that is, whether and by how much the typical error on the coasts of the Gulf of Finland differs from that in the Gulf of Bothnia. We selected three Finnish tide gauge locations for closer inspection: Kemi, Föglö and Helsinki. The map of Finland’s coast with the relevant tide gauges is shown in Figure 1. They were chosen for their locations on the coast of Finland: Kemi at the end of the Bay of Bothnia, Föglö in the Archipelago Sea and Helsinki in the Gulf of Finland. Vaasa (in the Quark) and Hamina (at the end of the Gulf of Finland) were also included in the geographical inspections. We also studied the seasonal variability of the forecast error, and the effects of the forecast length and the actual (measured) water level on the error.

Figure 2 shows the RMS error of forecast for the different months of the year for the five sites. The most prominent feature of the figure is the disproportionately large error for January at each location. This corresponds to the stormy weather and high average water levels in January 2007; evidently the performance of the Wetehinen model decreases in extreme conditions. During the late spring and summer months the RMS error is smallest, increasing towards winter months as the storms and low pressure systems become more frequent and stronger in the Baltic Sea region. The average RMSE values for Kemi, Föglö and Helsinki are 13.9, 13.7 and 14.3 cm, i.e., the differences between these three locations are small. During the first quarter of the year the sea level was high and record-breaking levels were measured on the Finnish coast. The Wetehinen had a large bias in its results during those months: if the first three months are neglected from the analysis the values for April–December are 9.4, 7.7 and 8.5 cm respectively. In this case the model RMSE values are smallest in areas with the smallest sea level variation, and vice versa.

In Figure 3 we present the seasonal variability of the forecast as a scatter plot. The RMSE and standard deviation are shown on the horizontal and vertical axes of the plot, respectively, and the points denote seasonal averages at each of the selected locations. The different clusters illustrate the seasonal difference in error: in general the winter months seem to have been more prone to error. The conspicuous outliers in this figure are the January data points, when the error was largest. The spring and summer months show tighter clusters, with summer data producing consistently small errors, while the autumn data are much more scattered.
Fig 2. The RMS error of forecast for the different months of the year for five sites.

Fig. 3. The seasonal variability of the forecast.
The measured and nowcast (+1...+6 hour forecast for HIRLAM and +1...+24 hour forecast for ECMWF) water levels at the Föglö measurement station in the Åland archipelago of southwest Finland are shown in Figure 4. Inspection of the time series shows that Wetehinen is able to predict significant rises in the water level that correspond to observed events, but not always to the full extent of the real conditions. The error is most visible in January, when the forecast Föglö sea level was 25 to 40 cm lower than that observed. The error can be explained in part as due to errors in the forcing data: in January–March the BSHemod forecast sea levels were 10 to 15 cm lower compared to the tide gauge measurement at Grenaa, Denmark, near the Danish Straits. For the rest of the year the error was clearly smaller, but it can be seen that the Wetehinen model gives too conservative results, that is, on the average the forecast values are too low for the high water cases and correspondingly too high for low water.

The effects of forecast length (i.e., the time between the beginning of the forecast and the actual forecast moment) for July–December 2007 at the different sites are shown in Figure 5. Surprisingly, this effect is, at the beginning, rather small compared to the initial error: the predictions are, on the average, almost as reli-
Sea level forecasting for Finland’s coast for the year 2007

able for +48 hours as for nowcast. The error grows fastest at Kemi, especially after +48 hours. The RMS error at the +130-hour forecast time is double that of the nowcast value. At Föglö and Kemi, the RMS error grows linearly with increasing forecast length. At Föglö the error grows from 8 cm to 10 cm in 130 hours, at Helsinki from 9 to 13 cm and at Kemi from 10 to 19 cm in the same period. The HIRLAM-forced simulations have a slightly smaller RMSE than the ECMWF forced simulations.

In Figures 6 and 7 we show the effect of the length of the forecast on forecast RMSE in high and low water cases. The notable periodic oscillation (6 hours for HIRLAM forcing, 24 hours for ECMWF) remains unexplained, it could be due to the diurnal errors in the atmospheric forcing data, but must be further investigated before conclusions can be drawn.

For high water cases (the upper 10% of the June—December 2007 tide gauge measurements) the model RMS error is 50% larger compared to the whole dataset. The error grows only slightly faster than in normal sea level conditions, at Föglö from 15 to 16 cm and at Kemi from 13 to 30 cm in 130 hours. It should be noted that the RMSE varies greatly with time in the ECMWF simulation, and reliable values are difficult to extract. The model’s forecast ability is weaker in high water cases.

![High water (max 10%)](image1)

![Low water (min 10%)](image2)
The picture is not as simple in low water cases. For these, the model RMS error at the beginning is smaller than in normal sea level conditions at Föglö and Helsinki, but slightly larger at Kemi. The error grows faster, from 5 to 10 cm at Föglö in 130 hours and from 12 to 26 cm at Kemi. In low water situations, the model can forecast the sea level nearly as well as it can during normal conditions.

The +52 hour HIRLAM RMS error histogram for Helsinki for the year 2007 is shown in Fig. 8. The error is skewed to the right because the data for the beginning of the year have a 25 to 40 cm bias. If the biased data are neglected, the error is normally distributed. The picture is similar for Kemi and Föglö. The histograms do not depend much on the forecast length; the distributions are just slightly more spread out for longer time span-forecasts.

![Fig. 8. The RMS error histogram for Helsinki for 2007. Low and high water case histograms are also shown.](image)

The low and high water situation histograms are also shown in Figure 8. In these cases too, the error is normally distributed. The 90% confidence limits (5% of the lowest and 5% of the highest values) for the model results are almost the same for +6, +24 and +54 h forecasts. At Kemi the limits are -32.0...+13.2, at Föglö -15.7...+5.8 cm and at Helsinki -33.6...+6.6 cm. These numbers are more comparable when they are divided by the sea level variation range, when the following numbers are obtained: Kemi 13.8%, Föglö 12.4% and Helsinki 16.9%. The model performance is worst for Helsinki; this is mainly because the errors in modelling the amplitude and timing of the seeiche for the Gulf of Finland – Baltic Proper.

4. MANUAL FORECASTS

The manual forecast is a forecast that was hand-made by an expert, based on sea level observations and models. The models used in the analysis were the HIRLAM-forced Wetehinen (note that the ECMWF forcing was not available in a suitable format), the old 2D water level model developed at FIMR (Jokinen 1977), the OAAS model run at FIMR (Andreyev & al. 2004), the DMI (Danish Meteorological Institute) North Sea - Baltic Sea ocean model BSHemod (DMI 2005) and the SMHI (Swedish Meteorological and Hydrological Institute) HIROMB (High Resolution Operational Model of the Baltic Sea (Funkquist 2001)). The manual forecasts were made over the period January–May 2007 for all the Finnish tide gauge locations (total 13). The analysis below is based on 101 manual forecasts for each location that were made in operational forecasting in January–May 2007. The forecasts were made at around 4 pm. local time (not depending on the model run times) and the maximum forecast length was 54 hours.

Figure 9 shows the time dependency of the RMS error of the forecasts for Kemi, Föglö and Helsinki. The manual forecast RMS error is relatively small for the first 48 hours. Here it should be noted that this data set is from the January–May period and also includes the most difficult months of January and February. The error can be expected to be larger than it would be for the whole year.

The error for Föglö is less than 6 cm for the first 48 hours, which about one third of the Wetehinen model results with HIRLAM forcing for the same period. For Kemi and Helsinki the difference is smaller, but the manual forecast error is still more than 2.5 times smaller than the model results.
Fig. 9. The RMS error on the manual forecasts as a function of forecast age in January–May 2007.

Clearly, the error depends on the location; it is smallest for Föglö (4.9 cm, average RMSE for +0...+54 h forecasts), larger for Helsinki (7.8 cm) and largest for Kemi (9.4 cm). The corresponding values for the Wetehinen model are: Kemi 18.2 cm, Föglö 19.1 cm and Helsinki 19.6 cm. The manual analysis aims at reducing long-term error (bias) and improving the forecasting accuracy of short-term variability. At Föglö the long term error is often dominant, and is easy to remove. For this reason the forecasts are improved the most there, and less at the ends of the Gulf of Finland and Gulf of Bothnia (Kemi).

As found earlier with the model results, the RMS error does not increase drastically with time. After 48 hours the error increase rate is significantly increased due to the lack of HIRLAM-based results and the end of the BSHcmod forcing data.

In Figures 10 and 11 the histograms of manual forecast error and Wetehinen model error are shown for January–May 2007. The manual analysis reduces the long-term bias well in all cases, and the errors are nicely distributed around zero. The spread is also reduced. The 90% error limits (5% of the lowest and 5% of the highest values) for the manual forecast for Kemi are -14...+16 cm, for Föglö -7...+7 cm and for Helsinki -12...+11 cm. These numbers are more comparable when they are divided by the sea level variation range. The results are then 9.2%, 8.1% and 9.5% respectively.

Fig. 10. The RMS error histogram of the manual forecasts in January–May 2007.

Fig. 11. The RMS error histogram of the Wetehinen model forecasts in January–May 2007. The y-axis is scaled to be comparable with Figure 10.
5. DISCUSSION

The analysis described in this article provided an insight into the performance of the Wetehinen model, as well as of the manually-tuned forecasts, and the seasonal and location-dependent changes in performance. The sea level models offer an efficient tool for operational forecasting with sufficient accuracy in most cases. In special events, such as flooding or rapid changes in the sea level, the manual forecasts provide improved accuracy and an error estimation.

Further work should be done to find out the end-users' minimum requirements in order to further develop the sea level forecasts. Also work should be done to determine the accuracy of the timing of the forecast values, for example the expected time of the flood peak.

It is important to notice that the location affects both the model and manual forecast errors. In the Archipelago Sea they both obtain clearly better results than at the ends of the Gulf of Finland and the Gulf of Bothnia, due to the smaller sea level variations and weaker seiche effects in the Baltic Proper. The time of the year also affects the forecast accuracy indirectly through the greater sea level variation in autumn and winter. During large sea level variation periods, the forecast error is increased.

At the present, the forecast length is +132 hours when the ECMWF atmospheric forcing is used. The error at the end of the forecast (+132 hour) is naturally larger than at the beginning. Based on the experience gained during manual forecasting, the error is found to be significantly larger when the forecast track of a low air pressure system changes. Still, the forecast gives valuable information about expected sea level changes, especially when the shortcomings of the long-term forecasts are properly taken into account. The forecasts users have expressed a need for longer timespan forecasts, but these are not yet available in sufficient accuracy. This is because wind direction and speed, as well as air pressure are hard to forecast accurately over a long time-period. Tests with 10 day ensemble forecasts have been made, and testing should be continued in order to find out if useful extra information on the sea level forecasting can be obtained from such forecasts.

It is recommended that an analysis of the sea level model performance be made yearly to monitor the accuracy and reliability of the forecasts.

References


