VATTEN – Journal of Water Management and Research 70: 19–29. Lund 2014

MODELING THE WAVE CLIMATE IN THE BALTIC SEA

Modellering av vågklimat i Östersjön

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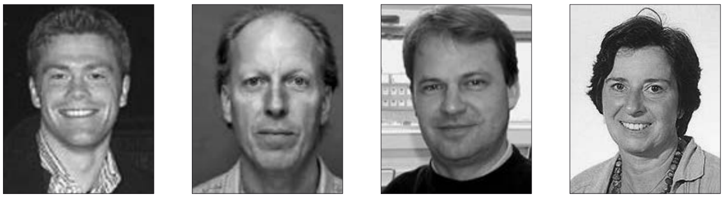

Abstract

Based on a 6-year simulation of the wave conditions for the Baltic Sea the wave climate at five locations along the Swedish SE coast was constructed. Using the WAM wave model to hindcast the waves between Jan 1st 2004 and Dec 31st 2009 the parameters significant wave height, direction of wave propagation, and spectral wave peak period were extracted from the time series and assembled in a wave atlas. The model was forced with point source wind measurements from meteorological stations in coastal areas around the southern Baltic Sea. To accommodate for differences in winds on land and over water the wind measurements were corrected through a logarithmic expression originating from experiments on the American Great Lakes. Validation of the model results against buoy measurements in the Baltic Sea showed that the chosen approach was able to reproduce the general trends and overall statistics of the wave climate, even if single events could be less well represented. Larger wave heights were generally underestimated. The resulting wave atlas is primarily intended to be used in practical applications and as guidelines for design in and around the five selected locations. The results can also be used as input to more detailed computer models of the nearshore processes.

Key words – wave model, wave climate, WAM, wave atlas, Baltic Sea

Sammanfattning

Baserat på modellberäkningar över sex år av vågförhållanden i Östersjön beräknades ett vågklimat för fem platser längs den svenska sydostkusten. Vågmodellen WAM användes för att beräkna vågorna mellan 1 januari 2004 och 31 december 2009. Parametrarna signifikant våghöjd, vågutbredningsriktning och vågperiod extraherades från tidsserien och presenteras som en vågatlas. Input till modellen utgjordes av punktvisa mätningar av vindar ifrån meteorologiska stationer i kustområden runt södra Östersjön. Skillnader mellan vindar över land och vatten kompenserades genom ett logaritmiskt uttryck som härrör från fältmätningar på de amerikanska Stora Sjöarna. Valideringen av modellens resultat mot mätningar i Östersjön visade att den valda metoden kunde reproducera de allmänna tendenserna och statistiska egenskaperna hos vågklimatet, även om enstaka händelser kunde vara missvisande. De större våghöjderna blev i allmänhet underskattade. Den resulterande vågatlasen är främst avsedd att användas i praktiska tillämpningar och som riktlinjer för projektutformning i och runt de fem utvalda platserna. Resultaten kan också användas som input till mer detaljerade datormodeller av fysikaliska kustprocesser.

Introduction

The Baltic Sea is relatively shallow, with an average depth of only 55 m, but at its deepest parts it reaches 450 m (Östersjöportalen, 2011). The Baltic Sea can be sub-divided into the Sea of Bothnia to the north and the southern Baltic Sea to the south. The highest individual recorded wave in the Baltic Sea was 14 m high, and was measured south of Åland on Dec 22nd 2004 (SMHI, 2010). The significant wave height at the time was 7.7 m. Such high waves are rare in the Baltic as the enclosed nature of the basin means that all wave generation must take place within the basin itself, and is therefore limited by the fetches of the basin. In the Baltic Sea the longest fetches are approximately 800 km. The average values of the monthly significant wave heights, calculated from available buoy measurements, for three locations in the Baltic Sea can be seen in Figure 1. The locations of the three buoys are shown in Figure 4.

Objectives, scope, and limitations

This study has two main objectives. The first one is to assess the effects of forcing the WAM wave model with point source wind measurements from meteorological stations in coastal areas instead of, as customary, using wind fields generated by meteorological models. Each wind station will be assigned an area of influence over which its measurement is assumed to be valid, and by combining the areas a wind field over the Baltic will be created. This approach has been used by e.g. Blomgren, et al. (2001) with satisfactory results. The reasons for choosing point-source measurements rather than the conventional approach are several:

- It is of scientific interest to know how well the model can simulate waves from to point measurements.
- In practical applications one does not always have access to wind fields generated from meteorological modelling.
- Like all models, meteorological models have their weaknesses. By using actual measurements the assumptions and simplifications used by the meteorological models can be avoided.

Some of the downsides of using point measurements are:

- The measurements are local and stand risk of being influenced by surrounding topography and/or buildings.
- Local disturbances will then be transferred onto the entire area of influence.
- A representative way of merging measurements from different stations into one wind field must be found. This can prove difficult if several weather systems are affecting the modelled area at the same time and the scale of a particular system is much smaller than the modelled area.

In the present study, model performance will be evaluated with respect to measured significant wave height, peak period, and direction of wave propagation.

If an acceptable model performance is achieved when forced by point source measurements a second objective will be introduced. Using winds between 2004 and 2009 to force the model, the medium-term wave climate at Falsterbo, Ystad, Hanöbukten, the southern tip of Öland, and south of Nynäshamn will be established. The locations chosen can be seen in Figure 2, along with latitudes, longitudes, and the water depths used by the model at the locations.

The study will only consider waves within the Baltic Sea, so Skagerrak and Kattegat will be excluded from the studied area. As the final aim of the study is the description of waves in the southern Baltic Sea the Sea of Bothnia will also be excluded. These exclusions were shown through simulations not to affect the calculated waves in the Baltic Sea (Irminger Street, 2011). The present paper is to a large part based on this M.Sc. thesis (Irminger Street, 2011).

Materials and Methods

The WAM model

The WAM model is a so called 3rd generation wave model. No in-depth description of the differences between 1st, 2nd and 3rd generation models will be given here. For detailed descriptions see e.g. Komen, et al. (1994) or Jensen (1994). It suffices to say that earlier generations were limited in their modelling of wave-wave interaction by either neglecting it or requiring a priori assumptions for the wave spectrum shape. This meant that model development became site specific and non-universal. In 3rd generation models the spectrum is

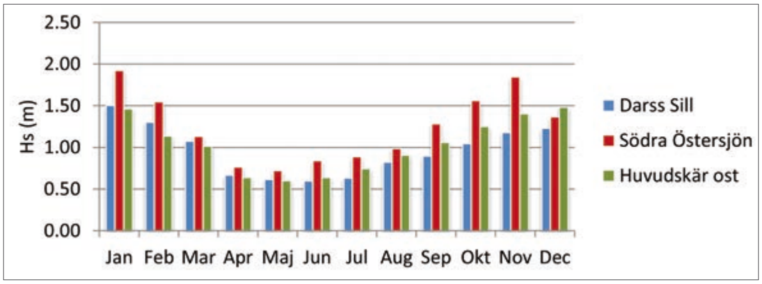

Figure 1. *Average monthly significant wave heights for three locations in the Baltic Sea. The values are based on available buoy measurements.*

Figure 2. *Locations for which a wave atlas were constructed.*

free to take any shape and is therefore considered universal.

The distribution of energy density for a wave field will depend on both the wave frequency and the direction of propagation. For WAM to handle this, the directional and frequency spectrums must be discretized by the user, stating the number of directional and frequency bins (= intervals) used in a run along with the lowest frequency the user wishes to employ. By discretizing the directional and frequency spectrums the WAM model can produce a 2D energy density spectrum at each model grid point and time step. The energy density spectrum is represented by an N x M matrix, in which N represents the directional bins and M the frequency bins.

The fundamental equation used in WAM is an energy balance known as the transport equation (TE). The TE shows how energy shifts within a system by stating that the change of energy is equal to the sum of all source and sink terms inside the system subtracted by the net energy leaving the system as waves are crossing the system boundaries. The transport equation is written as,

$$\frac{\partial E}{\partial t} + \vec{c}_g \cdot \vec{\nabla} E = \sum S_i \qquad (1)$$

where E is the two-dimensional energy density spectrum with respect to wave frequency and direction of propagation at each grid point and time, c_g is the group wave velocity, S_i is the combined source or sink terms adding or taking energy to/from the system. For the WAM model the included source and sink terms are: S_w-input of energy from the drag the wind exercises on the water surface (the only energy input to the system), S_{ds}-loss of energy through dissipation from white-capping and depth-limited breaking of waves, S_{nl}-non-linear redistribution of energy within the spectrum due to wave-wave interaction by which energy will be moved from higher frequencies to lower causing a lowering of the peak frequency and a more narrow-banded energy spectrum as time elapses, S_{bf}-energy loss due to bottom friction and percolation, which is only relevant when modelling in shallow water.

The model setup in the study area

For this particular study the model was run in shallow water mode and refraction was included. The properties of the directional and frequency bins may be summarized as: number of directional bins (N) = 24, span of each directional bin = 15 deg., number of frequency bins (M) = 30, lowest frequency/period = 0.05 Hz / 20 s.

In order to run WAM, the model requires at least two input data files; the bathymetry of the modelled area and the wind field acting over the same area. In addition to this, currents and ice coverage can also be included, but are not in this study.

A high-resolution, spherical bathymetric grid of the Baltic Sea region was obtained from the Leibniz Institute for Baltic Research (IOW). The grid stretched from latitudes 53.30°–66.00° and longitudes from 9.00°–31.00° (degrees given as decimal degrees). The resolu-

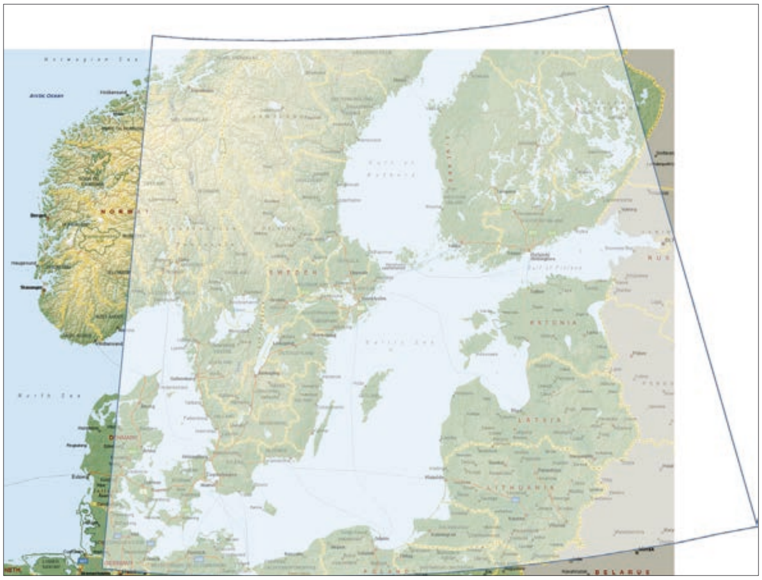

Figure 3. *Area covered by the original 2x1 minute bathymetric grid.*

tion of the grid was 2 minutes in longitude and 1 minute in latitude, equal to 1/30th and 1/60th of a degree. The full grid coverage can be seen in Figure 3.

From Sweden five meteorological stations (Falsterbo, Ölands södra udde, Hoburg, Gotska sandön and Svenska högarna) along the east coast were used. Winds were collected and supplied by the Swedish Meteorological and Hydrological Institute (SMHI) on a 3 h basis for the period 1961–2009, although not all stations have the full period coverage. The locations of all stations and their periods of measurements are illustrated by Figure 4 and Figure 5.

From Germany two meteorological stations (Arkona and Fehmarn) located along the German north coast were used. The data was supplied by the Deutscher Wetterdienst (DWD) on a 3 h basis for the period 2004–2010.

From Latvia three meteorological stations (Liepaja, Kolka and Pavilosta) located along the Latvian western coast were available. One of the stations, Pavilosta, was

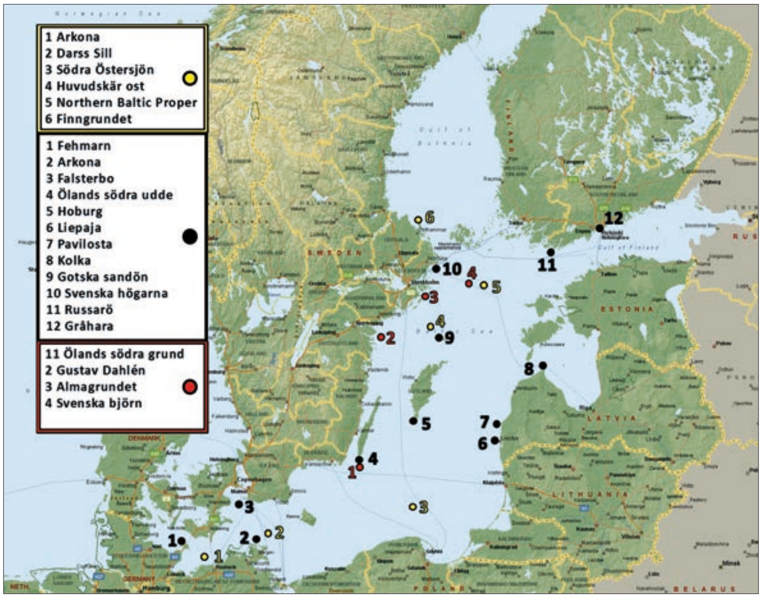

Figure 4. *Location of meteorological stations (black), wave buoys with recordings during the period 2004–2009 (yellow), and other wave buoys (red).*

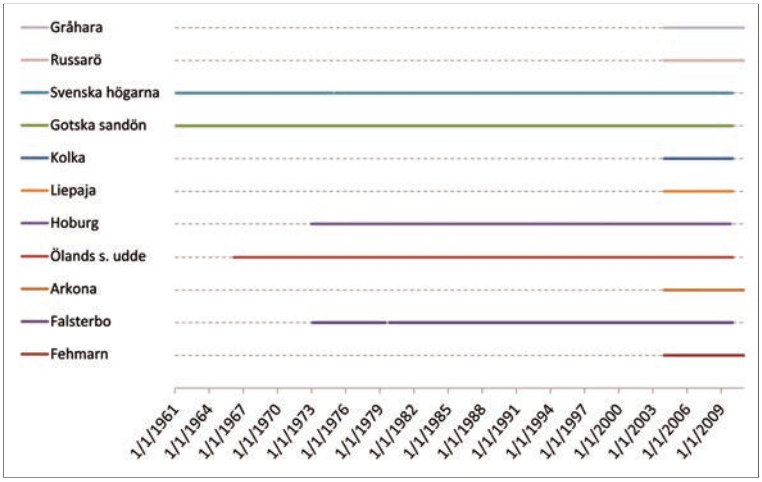

Figure 5. *Periods of available wind measurements.*

quickly deemed unreliable and excluded from this study.

From Finland two meteorological stations (Gråhara and Russarö) located in the Gulf of Finland were employed. The data was supplied on a 3 h basis by the Finish Meteorological Institute (FMI) over the period 2004–2009.

Even if ice coverage of sea areas has a major impact on wave propagation, effectively acting as if these areas were land, ice data was not included in this study. This was primarily due to the fact that the area of main interest was the southern Baltic Sea, where ice cover is less frequent (SMHI, 2009a). In addition when using results from medium-term modelling for future planning it is highly relevant to see how the Baltic reacts to winds under ice-free conditions, as one cannot always count on ice being present in the future to protect against waves. Currents typically have only a minor impact on the wave climate on the open sea, and were not included in the study.

Wave measurements from six wave buoys were available from SMHI, in total covering the period 1978–2010. Out of the six, three had coverage during the 2004–2009 period. These buoys were Södra Östersjön, Huvudskär Ost, and Finngrundet. The locations and periods of measurements of all the buoys are illustrated by Figure 4 and Figure 6, respectively. The available measurement parameters used in this study were the significant wave height (H_s), the direction of wave propagation, and the peak period (T_p). Measurements were done as 10 min averages every hour.

From Germany two wave buoys (Darss Sill and Arkona) were available from the DWD, covering the period 2004–2010. Unfortunately the only measurement parameter available from the German buoys was H_s.

From Finland one wave buoy (Northern Baltic Proper) was available from the FMI, covering the period 2008–2009. As the buoy did not cover the full period 2004–2009 this buoy was not used in the study. No wave data from Latvia were used.

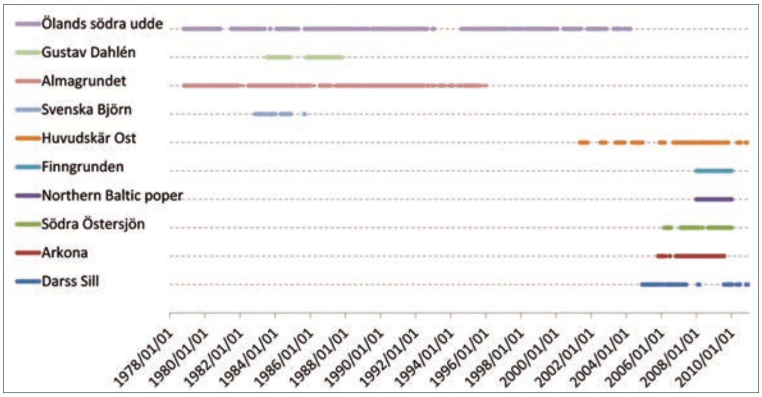

Figure 6. *Periods of available wave measurements.*

Data analysis

With reference to the much more extensive report presented by Irminger Street (2011) only a very brief discussion about the data analysis will be given here. The results from the Swedish stations showed that winds were prevailingly south-western at most of the stations. Svenska Högarna experienced more northern winds than the other stations, but even so about 50 % of all winds at all five stations were in the range S–SW–W, showing that the wind stations were generally affected by the same weather systems. With respect to wind speed all the Swedish stations presented similar characteristics, with a maximum speed of approximately 30 m/s (Ölands Södra Udde is extreme with 39 m/s) and an average of approximately 6.0–7.0 m/s. Svenska Högarna, the most northern station, was a little bit windier with an average of 7.5 m/s. The German wind stations showed very similar patterns to those seen at Falsterbo, with mainly W and SW winds.

Latvian wind speed measurements seemed suspiciously low compared to Swedish and German measurements. The Gulf of Finland showed to be slightly calmer than most of the other stations with average wind speeds at 5.8 and 6.6 m/s and maximum speeds at 21.2 and 23.7 m/s for the two stations. Three reliable wave buoys from the southern Baltic Sea have data coverage for the period 2004–2009. These are Darss Sill, Södra Östersjön and Huvudskär Ost.

Preparation of data for model run

Using the original 2*1 minute spatial resolution was found not to be reasonable from a computational run-time perspective. A coarser, more appropriate grid size was 12x12 minutes, or 0.2x0.2 decimal degrees. At the southern end of the Baltic Sea this corresponded to a longitude step of ~13 km, whereas at the northern end it corresponded to ~9.4 km. The latitude step remained ~22.3 km at both ends. The new grid allowed for acceptable computational run times, while still maintaining a sufficient degree of detail, and the resulting grid points can be seen in Figure 7. As the scope of this study was limited to the southern Baltic Sea, it was desirable to leave the Sea of Bothnia out of the grid to further reduce the computational time. Thus, the final bathymetric file was limited to only include grid points south of latitude 60.31° as shown in Figure 8). Also, Kattegat/Skagerrak north of the Öresund Strait and the Danish Belts were excluded from the model.

Allocations of areas of influence to wind measurements

The wind measurements supplied by national meteorological services were point-source measurements, so in order to use them to force WAM they must be allocated to areas of influence. The sum of the individual areas of influence must cover the entire area modeled. When allocating areas of influence to the stations the midway

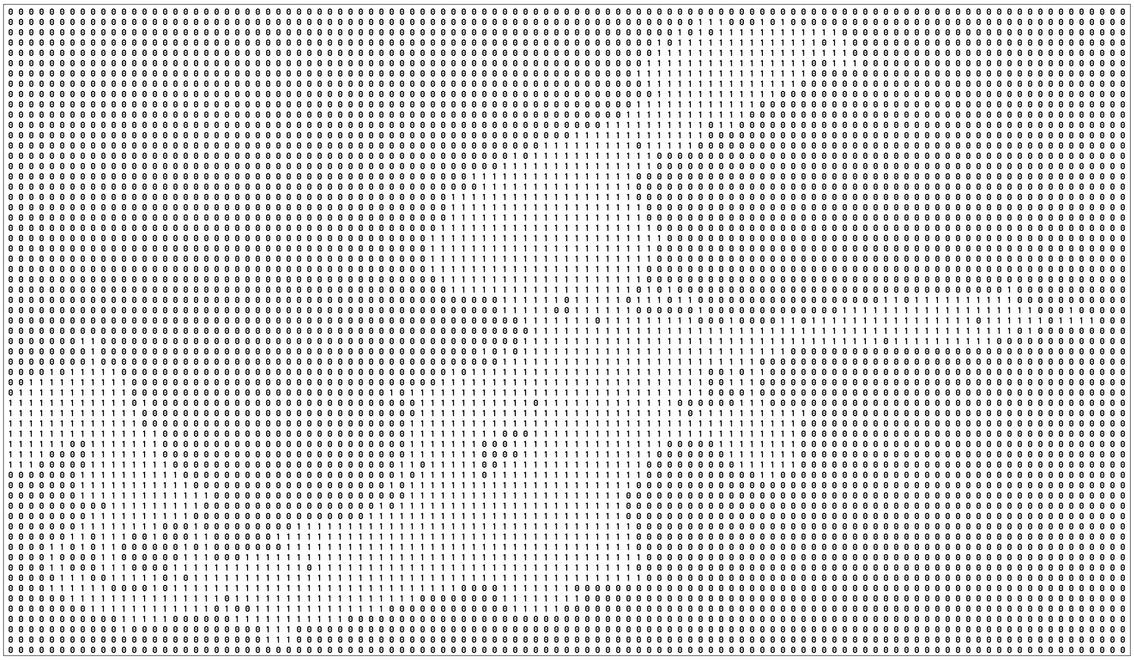

Figure 7. *The full resulting 12'x12' bathymetric grid used when running the model, where '0' denotes land cells and '1' denotes water cells.*

Figure 8. *The resulting area used when the Sea of Bothnia, Kattegat/Skagerack, and the Danish Belts were excluded.*

points between adjacent stations were found and marked (Figure 9) and the dots surrounding each station were connected to form a preliminary area (Figure 10). This created a number of polygons between which non-allocated triangular areas arose, so the center-point of each such triangle was located and the surrounding areas were extended to meet in the center-point (Figure 11 and Figure 12). Once the boundaries had been found, minor manual adjustments were made to assure that area limits fell on model grid points.

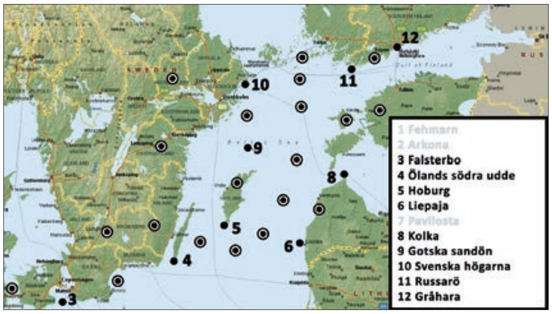

Figure 9. *Find and mark the half-way point between all measuring stations.*

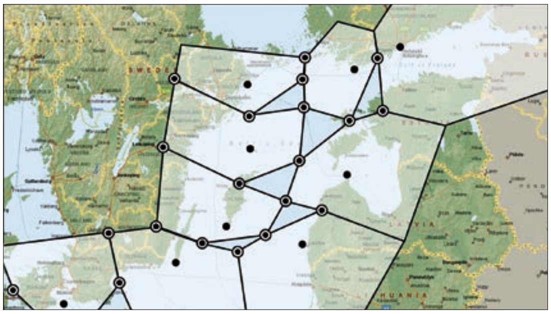

Figure 10. *Connect the half-way points of each station, forming an area of influence.*

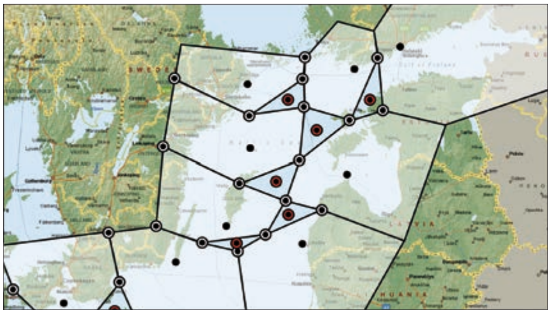

Figure 11. *Mark the center-point of the triangles that form between the areas of influence.*

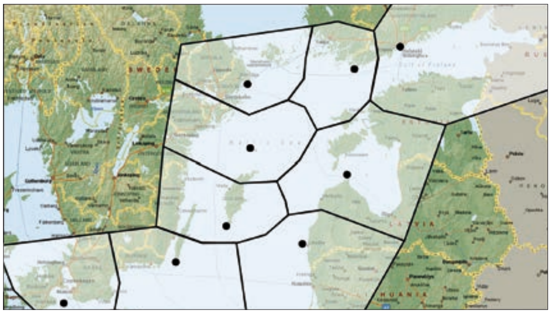

Figure 12. *Let the areas join together in the center-points, forming the final areas of influence.*

Results

Model validation

In January of 2005 a severe storm passed over southern Sweden. The storm, named Gudrun, had gusts of up to 42 m/s and was the most destructive storm ever recorded in Sweden (SMHI, 2009b). A storm of this magnitude presented a good opportunity of evaluating how the model reacted to extreme events. Several time periods were used for wave model validation (Irminger Street, 2011), but in the interest of space, only results from the storm Gudrun will be discussed here.The validation of the model was done with respect to significant wave height, peak period, and direction of wave propagation.

For this study, when comparing model results with measurements, two types of linear regressions were used: one where the linear regression was forced through origo (dashed line in Figure 13) and one where the intercept of the linear equation was free to assume any value (dotted line in Figure 13). The forced regression made it possible to compare the scatterplots against each other while the free regression showed if there were any tendencies in the modeled results. Figure 13 gives examples of such scatter plots for the storm Gudrun. In an attempt to compensate for possible misrepresentations of the local wind measurements three different wind input setups were used to force the model:

1) The 10-meter equivalent wind speeds. This setup showed how well the model represented reality when forced with "raw" point measurements from coastal areas;
2) All wind speeds were increased by 20 %. This derived from an often occurring underestimation of wave heights seen in several wave modeling studies. The value 20 % has some basis in previous experiences, but should be considered as arbitrarily chosen for this study.
3) Available literature suggests that overland wind speed measurements should be converted to equivalent open water velocities. This was done here using empirical results from the American Great Lakes (CEM, 2006).

While the dashed line showed that the overall agreement between buoy measurements and modeled wave heights appeared good, the dotted line indicated the tendency of overestimating small waves and underestimating large waves. In order to numerically compare the setups their scatterplots are presented in Figure 13. For the Storm Gudrun Setup 2 gave the best fit with a R^2 value of 0.81. The free regression showed next to no tendency to differ from that of the forced regression.

In conclusion it seems as if the model captured the storm event well. This indicates that land measurements seem to be well suited for forcing the model under strong wind conditions in the Baltic Sea, possibly due to an increased homogeneity of the wind field during storms.

Calculation results

Based on the results of the validation runs, of which only one set is shown here, it was concluded that local wind measurements can indeed be used to force the wave model and find wave climate statistics, if modified according to Setup 3. Setup 1 consistently gave too low results and was quickly abandoned, but the choice between Setup 2 and Setup 3 was not as easy. Setup 2 gave better results most of the time, but had a tendency to heavily overestimate the top portion of the wave heights. As this is the part of greatest interest for the wave statistics it was seen as too uncertain to include these waves. Setup 2 was therefore abandoned, leaving Setup 3 as the final choice. Neither the results from comparison of propagation directions nor peak periods were to the disadvantage of Setup 3.

The resulting calculated significant wave heights at the five selected locations discussed above are presented in Figures 14 to 16. The significant wave height has been presented in three different ways, intended for three different types of applications. First the average values of

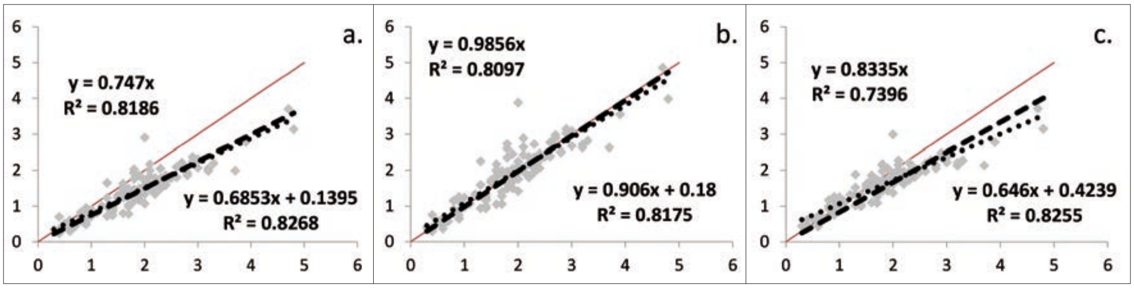

Figure 13. *Scattergrams of H_s for the storm Gudrun. Horizontal axis = measured values. Vertical axis = calculated values. Panel a. is for Unchanged wind, panel b. for Wind increased +20 %, and panel c. for Logarithmic expression. The dashed line is forced through origo, the dotted line is free to assume any intercept value in the linear regression equation, and the solid red line has a slope of 1:1.*

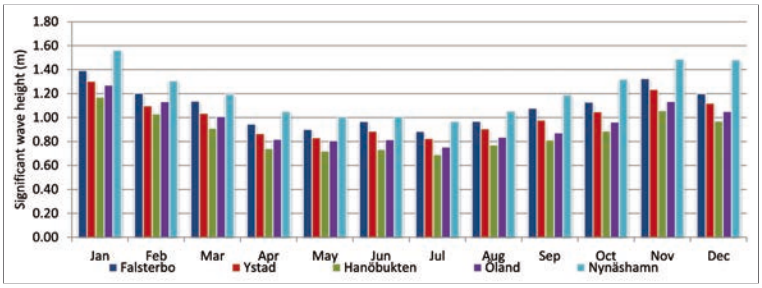

Figure 14. *Calculated monthly average significant wave heights.*

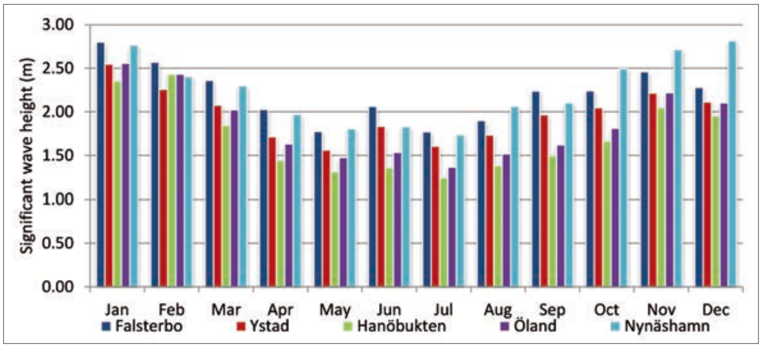

Figure 15. *Calculated average of top 10 % monthly significant wave heights.*

H_S are presented on a monthly basis, illustrating typical conditions. After this, the average value of the top 10 % of H_S are presented, intended to illustrated rough but not extreme conditions. Finally, the maximum model results for H_S are presented, intended to be used as guidance on extreme events in design situations.

For the average values of H_S (Figure 14), it is striking how similar the temporal variation of wave height patterns are at all five locations, clearly suggesting that the winds used to force the model were indeed similar over the entire area. The figure also shows that April to August is generally a period of lower waves, while November to February is a period of higher waves and that the sheltered areas of Hanöbukten and near Öland experience lower waves than the more exposed and open areas around Falsterbo, Ystad, and Nynäshamn. The highest average waves were seen at Nynäshamn, just as the strongest winds were measured at Svenska högarna. Nynäshamn is also the location with the longest fetch. These results lend credibility to the model output.

For the rough weather conditions, illustrated in Figure 15, the annual cycle is similar to that of the average waves, but with a noteworthy exception. In June both Falsterbo and Ystad suffer from rough weather waves that are more than half a meter higher than those at Hanöbukten. These higher waves demonstrate how locally strong winds seem to be reoccurring in June at the southern tip of Sweden. The locally high waves become even more pronounced when looking at the maximum wave heights, illustrated in Figure 16, were it can be seen that the maximum value for Falsterbo is 2 m higher than that of Hanöbukten in June.

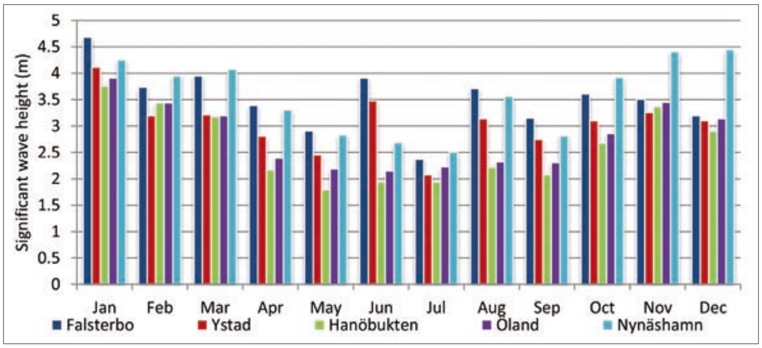

Figure 16. *Calculated monthly maximum significant wave heights.*

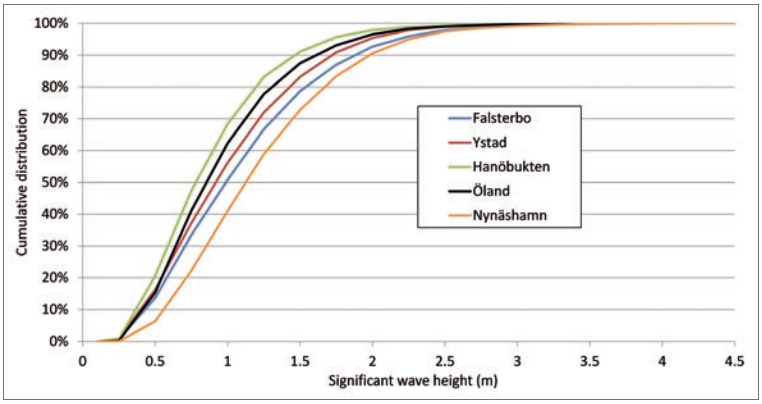

Figure 17. *Cumulative distributions of the wave heights in the 6-year time series at the five selected locations.*

In a design situation it is rare to build a structure or a system to withstand very extreme events, as this would become unreasonably expensive. It is therefore desirable to determine how large a percentage of the incoming waves that will exceed any given H_S, and to this end the cumulative distributions of the wave heights at the five locations have been presented in Figure 17. The figure shows how the limiting H_S exceeded by *e.g.* 20 % of the waves (cumulative distribution = 80 %) at Hanöbukten is 1.25 m while at Nynäshamn it would be 1.75m. Reversing the reading of the graph one can also conclude that a structure withstanding a 2 m wave would withstand 97 % of the waves at Hanöbukten, but only 91 % of the waves at Nynäshamn.

Both the average values, the maximum values, and the seasonal variations of H_S are in good agreement with results found in previous studies of waves in the Baltic Sea (e.g., Blomgren et al., 1991; Jönsson, et al. 2002; or Tuomi et al, 2011)

The directions of propagation are also calculated in the model. In the interest of space, they are however not shown here. Just as expected the different stations show very similar results. During June to December 60–70 % of the propagation is on the eastern half of the compass, with a majority of the waves going towards E or NE around the southern tip of Sweden and NE or N along the east coast. During the late winter and spring there is a shift in propagation regime with an increase in propagation towards W and S, culminating in March/April, after which the propagation directions once more turn eastward and complete the annual cycle.

The peak periods, both as maximum and average values, were also given by the model. Due to the large spread of the peak period scatter clouds in the validation process it is not straightforward to interpret these results for assessing the applicability of the model to accurately predict wave periods. The results showed a large similarity between the different stations and over the different months, indicating that the wave period varies little in space as well as in time. Maximum periods varied between 7 and 10 s, with slightly higher values for Öland and Nynäshamn. Average periods varied between 4 and 5 s for all stations.

Discussion and conclusions

The validity of the results presented above must be considered as high. Four different validation runs were performed, of which only one was presented here, to fully understand the response of the model to varying circumstances, and the resulting regression lines showed that the average values of H_S and direction of propagation were represented well. This was also seen when comparing the monthly average values of model and measurements at Södra Östersjön and Huvudskär Ost. Even so, the top-portion of the wave heights were consistently underestimated, so it is likely that the results for rough weather illustrated in Figure 15 are a little low. This becomes especially important when using the cumulative distribution of the waves presented in Figure 17, as the accuracy of the top-portion of the waves is crucial for the applicability of the graph. The uncertainty of the higher waves means that the distribution is not accurate enough to be used for actual design, but it is still illustrative of how the waves are distributed. When it comes to the lower wave heights the model gave a consistent overrepresentation, probably due to the shape of the logarithmic expression used to increase the winds.

When simulating the direction of wave propagation the model showed minor discrepancies with the timing of shifts in direction, but no real difficulties in calculating the general pattern. One possible concern to the validity of the results at the selected locations is the fact that all validation was done in deep water, where the effects of refraction were minor. The selected model points are in depths of around 10–15 m, so some refraction might have occurred for longer wave periods. A rough assessment of the refraction effect was obtained by looking at the propagation directions at a grid cell one grid step south of each model point, where the water was deeper, and then comparing the differences between the two cells. The technique was crude and was only done for a limited amount of values, but it seemed as if the waves were turned by refraction in the expected direction. Based on this the wave directions are considered as reliable.

The greatest uncertainties of model results lay with the peak periods. Timeline plots of the modeled and measured peak periods showed how the model followed the general trend of the measurements well, especially for the chosen wind setup, so based on this there was little reason to doubt the model results. At the same time the scatterplots showed a substantial spread, but still reasonably high values on the regression coefficients. The combined assessment of this is that the timeline plots were good enough not to doubt the average values, but that results from short or individual events are more uncertain.

As a concluding remark the model results are believed to give reliable and solid guidelines on the wave climate at five locations along the Swedish east coast. They can be used as good and reliable estimates for a range of different applications, but as guidelines they should not be considered exact representations of reality.

Acknowledgments

We would like to thank Marcus Flarup of the SMHI, Thomas Bruns of the DWD and Heidi Pettersson and Asko Huttila of the FMI for providing the wind and wave data measurements.

References

Publications

Blomgren, S., Larson, M., Hanson, H. (1999) Numerical modelling of the wave climate in the Southern Baltic Sea, Journal of coastal research (17)2, pp. 342–352.

CEM 2006. Coastal Engineering Manual. US Army Corps of Engineer Research and Development Center, Report EM 1110-2-1100, Vicksburg, MS, USA.

Irminger Street, S. (2011) Wave Atlas of the South-Eastern Coast of Sweden – A 6-year simulation of waves using local wind measurements from meteorological stations around the Baltic Sea. Dept.of Water Resources Engineering, Lund University, Lund, Sweden. MSc Report TVVR 11/5007.

Jensen, R. (1994) Spectral wave modelling technology. Costal Engineering Technical Note 9.

Jönsson, A., Broman, B., Rahm, l. (2002) Variation in the Baltic Sea wave field¸ Ocean Engineering 30 (pp 107–126).

Komen, G.J., Cavaleri, L., Dinelan, M., Hasselmann, K., Hasselmann, S., Jansen, P.A.E.M. (1994) Dynamics and Modelling of Ocean Waves, Cambridge, Press Syndicate of the University of Cambridge.

Östersjöportalen (2009) Östersjöns form, areal och volym, Retrieved 2011-04-17 from Östersjöportalen webpage: http://www.itameriportaali.fi/sv/tietoa/yleiskuvaus/sv_SE/muoto_ala_tilavuus/

SMHI (2009a) Isförhållanden i Östersjön, Retrieved 2011-05-10, from Swedish Meteorological and Hydrological Institute webpage: http://www.smhi.se/kunskapsbanken/oceanografi/isforhallanden-i-ostersjon-1.7024

SMHI (2009b) *Gudrun – Januaristormen 2005*, Retrieved 2011-04-17 from Swedish Meteorological and Hydrological Institute webpage: http://www.smhi.se/kunskapsbanken/meteorologi/gudrun-januaristormen-2005-1.5300

SMHI (2010) Vågor i svenska hav – Faktablad 46. Swedish Meteorological and Hydrological Institute.

SPM (1984) Shore Protection Manual (pp. 3–30). Washington: US Army Corp of Engineers.

Tuomi, L, Kahma, K.K., Pettersson, H. (2011) Wave hindcast statistic in seasonally ice-covered Baltic Sea, Finnish Meteorological Institute, Helsinki

Vännman, K. (2002) Matematisk statistik. Lund: Studentlitteratur.