BOREAL ENVIRONMENT RESEARCH 15: 295–300 © 2010
ISSN 1239-6095 (print) ISSN 1797-2469 (online) Helsinki 30 June 2010

Depth induced breaking of wind generated surface gravity waves in Estonian coastal waters

Victor Alari and Urmas Raudsepp

Marine Systems Institute at Tallinn University of Technology, Akadeemia Rd. 21, 12618 Tallinn, Estonia

Received 1 Mar. 2008, accepted 29 May 2009 (Editor in charge of this article: Timo Huttula)

Alari, V. & Raudsepp, U. 2010: Depth induced breaking of wind generated surface gravity waves in Estonian coastal waters. *Boreal Env. Res.* 15: 295–300.

Depth-induced wave breaking is a key term for wave energy dissipation in the action balance equation of the third generation spectral wave models, and becomes an essential consideration in modelling wave behaviour in shallow water and near the coast. Neglecting this sink function leads to an overestimation of significant wave heights. Current paper addresses the importance of depth induced wave breaking, using the SWAN wave model, at two locations in Estonian coastal waters in case of NNW storms — the first site is the Harilaiu Bank, situated in the north-west of the Saaremaa Island while the other one is Tallinn Bay. We performed simulations using SWAN with two different setups, i.e. the depth induced wave-breaking accounted and not accounted. The computed wave height in the first case was smaller than in the second case with maximum difference of 4.8 m in the Harilaiu Bank and 2.3 m in Tallinn Bay. Previous studies using the WAM model suggest that remarkable wave maxima exist in these regions due to focusing of wave rays e.g. due to topographic refraction of surface waves. As these maxima were reproduced by SWAN when depth-induced wave breaking was turned-off, we conclude that the maxima simulated by WAM can be an artefact of the model.

Introduction

The length of the Estonian coastline is about 3780 km. Although the coast of Estonia is not as staggered as are the Finnish and Swedish coasts, it still contains numerous shallows and islands. Consequently, modelling the wave regime of Estonian coastal waters requires a model that is capable of modelling the processes involved in shallow water wave propagation and dissipation over complex bathymetry. The least understood aspect of the physics of wave evolution, as it pertains to spectral modelling, is the dissipation source function. In shallow water, three terms contribute to the dissipation source function: dissipation due to surface processes (white-capping), dissipation due to bottom friction and depth-induced wave breaking. Understanding and modelling depth induced wave breaking and other processes are thus critically important in achieving an accurate representation of the principal sink function in the energy (or action) balance equation.

Soomere (2003, 2005) analyzed the typical and extreme wave regimes off the north-western Saaremaa Island and Tallinn Bay using a third generation spectral wave model WAM (Komen 1994). The extreme storm in the former case was 25 m s^{-1} NNW wind blowing steadily over the Baltic Sea within eight hours. The latter case was NNW wind with the speed of 23 m s^{-1} blowing

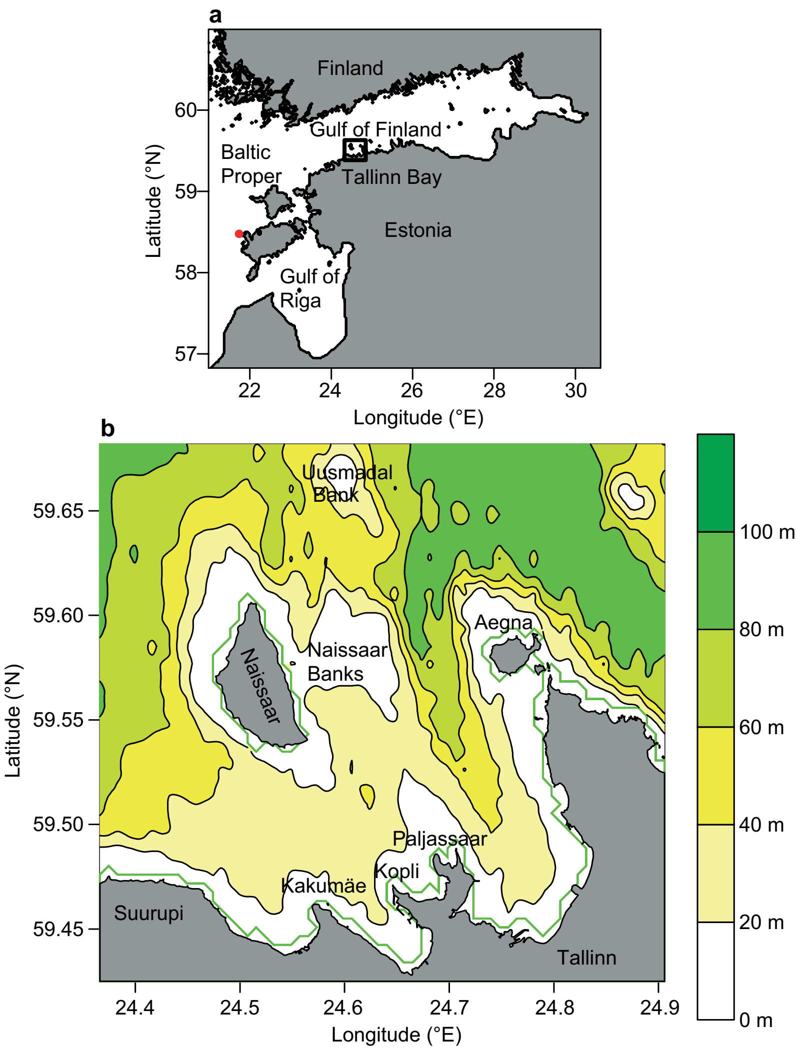

Fig. 1. (**a**) Location of the Harilaiu Bank (red dot). (**b**) Bathymetry of Tallinn Bay.

steadily for six hours. Soomere (2003) found that several wave height maxima occurred near the Saaremaa and Hiiumaa Islands with the most intensive ones occurring at the Harilaiu Bank (Fig. 1), where significant wave heights grew up to 9.8 m. In Tallinn Bay, several wave height related maxima occurred near the Aegna Island, Paljassaare and Kopli Peninsulas and at shallows in Tallinn Bay (Fig. 1). He explained these maxima as topographic refraction of the surface waves. However, the WAM wave model does not include a sink function for depth-induced wave breaking (Komen 1994) and the effect of triads is also not considered — although less significant than depth-induced wave breaking in the present case.

The objective of this study was to repeat numerical experiments of Soomere (2003, 2005) in Estonian coastal waters using the SWAN model — a third-generation spectral shallow water wave model (Booij 1999, Holthuijsen 2007) — and to compare obtained results with those of Soomere obtained with the WAM model (Soomere 2003, 2005). Wave patterns at the Harilaiu Bank and Tallinn Bay are of great importance. The Harilaiu Bank is close to the Kiipsaare Cape, a peninsula which is being fast eroded due to beach processes induced by wave activity. Tallinn Bay on the other hand has the most intense shipping activity in Estonia and, therefore, an accurate presentation of its typical and extreme wave properties are of great importance. The SWAN model was validated for significant wave heights in small Küdema Bay, (north-western Saaremaa Island) by Alari *et al*. (2008).

Numerical model

SWAN is a third-generation phase-averaged spectral wave model developed at the Delft University of Technology, the Netherlands (Booij *et al*. 1999). In SWAN, the waves are described with the two-dimensional wave action density spectrum, whereas the evolution of the action density, N, is governed by the time-dependent wave action balance equation, which in Cartesian coordinates reads:

$$\frac{\partial N}{\partial t}+\left(\vec{c}_{\mathrm{g}}+\vec{U}\right)\nabla N+\frac{\partial c_{\sigma}N}{\partial\sigma}+\frac{\partial c_{\theta}N}{\partial\theta}=\frac{S_{\mathrm{tot}}}{\sigma} \quad (1)$$

The first term represents the local rate of change in action density; the second term denotes the propagation of wave energy in the two-dimensional geographical space with c_{g} being the group velocity and U the ambient current. The third term represents the effect of shifting the relative frequency due to variations in depth and mean currents. The fourth term represents the depth-induced and current-induced refraction. The quantities c_{σ} and c_{θ} are the propagation velocities in spectral space (σ, θ) with σ and θ representing the relative frequency and the direction of propagation respectively. The right-hand side contains the source term S_{tot} that represents all physical processes that generate, dissipate or redistribute wave energy. In shallow water, six processes contribute to S_{tot}:

$$S_{\mathrm{tot}} = S_{\mathrm{wind}} + S_{\mathrm{nl3}} + S_{\mathrm{nl4}} + S_{\mathrm{wc}} + S_{\mathrm{bot}} + S_{\mathrm{db}} \quad (2)$$

These terms denote respectively the energy input by wind (S_{wind}), the non-linear transfer of wave energy through three-wave (S_{nl3}) and four-wave interactions (S_{nl4}), and the decay of waves due to white-capping (S_{wc}), bottom friction (S_{bot}) and depth-induced wave breaking (S_{db}).

In the surf zone, the dissipation of wave energy due to depth-induced wave breaking becomes stronger than the wave decay due to bottom friction or percolation (Massel 1996). The modelling of energy dissipation, due to breaking in the wave train, is usually based on four main assumptions (Massel 1996): (1) dissipation is equivalent to dissipation in a bore connecting two regions of uniform flow; (2) dissipation is proportional to the difference between the local energy flux and the stable energy flux; (3) the breaking wave height is saturated, i.e. the wave height is proportional to the local water depth and the proportionality coefficient is assumed to be constant across the surf zone; (4) dissipation is controlled by the presence of surface roller.

Following the previous, in SWAN total dissipation due to depth-induced wave breaking is modelled as dissipation of a bore, applied to the breaking waves in a random field in shallow water. The wave period used is calculated from zero and the first moment of the variance density spectrum. The tunable coefficient e.g. the breaking parameter is set to 0.73. (Holthuijsen 2007).

For the north-western coast of Estonia, the model is exposed to NNW wind (direction 330°) having the strength of 25 m s^{-1} blowing steadily over the Baltic Sea. The model topography is based on Seifert *et al*. (2001) with the resolution of 1´ along latitudes and 2´ along longitudes. The number of spectral frequencies is 40. The spectral frequencies are distributed logarithmically on the frequency range of 0.04–1 Hz and 12 spectral directions are also used.

Calculations of Tallinn Bay wave field were carried out using a triple nested model. The coarse Baltic Sea model had resolution of 1´ along latitudes and 2´ along longitudes. The medium grid for the Gulf of Finland (GOF) had a resolution of 0.5´ along latitudes and 1´ along longitudes, with the boundary conditions obtained from the coarse Baltic Sea model. The high resolution Tallinn Bay model is 0.25´ along latitudes and 0.5´ along longitudes and the boundary conditions were obtained from GOF model. The model is forced with the NNW wind blowing at 23 m s^{-1}. The spectral resolution is the same as for north-western Estonia. In the case of the high resolution Tallinn Bay model, the number of spectral directions is 24.

Two calculations for north-western Estonia and Tallinn Bay were made. The first calculation was with depth-induced breaking activated and

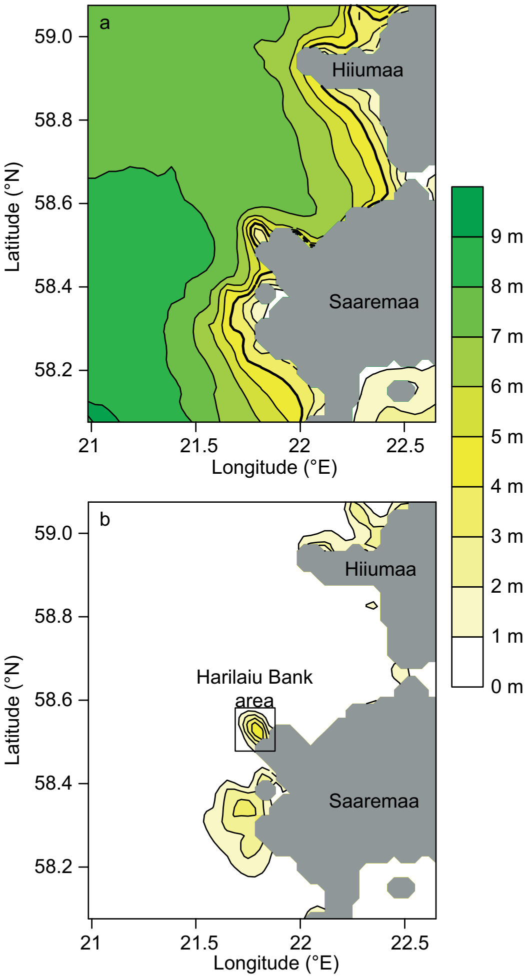

Fig. 2. (**a**) Significant wave height in the coastal zone of the Hiiumaa and Saaremaa Islands in case of an extreme (25 m s^{-1}) NNW storm. (**b**) Difference between depth induced breaking not activated and depth induced breaking activated. The 4 m isoline is contoured bold. Colour bar holds for **b** as well.

the second one was with depth-induced breaking not-activated. The analyzed and visualized fields represent saturated wave fields.

Results

Harilaiu Bank

The significant wave height can grew as high as 8 m offshore and even 9 m when moving farther towards the open sea (Fig. 2). Approaching the coast, the significant wave height decreases. Only in some parts of the NW Saaremaa Island, the significant wave height remains over 6 m. When comparing the topography of this region with the other areas where the significant wave height starts to decrease farther away from coast, it becomes clear, that here large water depths are closer to the coast.

Calculations with depth-induced breaking turned off presents areas near the coast where the significant wave height increases (Fig. 2b). The largest increase in the significant wave height up to 4.8 m forms at the Harilaiu Bank. It means that the maximum significant wave height at theHarilaiu Bank is 7.4 m in the case of depth-induced wave breaking turned off. South of the Harilaiu Bank forms an area where the significant wave height grows more than 3 m in the case of depth-induced breaking turned off. Third area where an increase in the significant wave height is seen is located NW of the Hiiumaa Island, where the increase is over 1 m. Other coastal areas do not show an increase of the significant wave height. As the water depth in the other areas starts to decrease quite far away from the coast and smoothly (no significant slope), we may conclude that bottom friction mainly dissipates waves there instead of depth-induced wave breaking. On the open sea, the difference between the calculations with depth-induced wave breaking and without it is, as expected, negligible.

The wave-height maxima as depicted in Soomere (2001: fig. 2, 2003: fig. 4) are not present in calculations with SWAN (Fig. 2a) in the case of activated depth-induced wave breaking. In Soomere (2001, 2003), the maximum significant wave height grew up to 9.8 m and 10.5 m at the Harilaiu Bank, respectively. Calculations with SWAN in present work show that the maximum significant wave height near the Harilaiu Bank does not exceed 3 m, but grows to 9 m on the open sea. The latter coincides well with Soomere (2001, 2003).

Soomere (2001, 2003) also reports that the maximum wave heights owing to topographic refraction accumulate in a certain time phase of a storm. The analysis of time series of the significant wave height at the Harilaiu Bank (Fig. 3) calculated with the non-stationary mode of

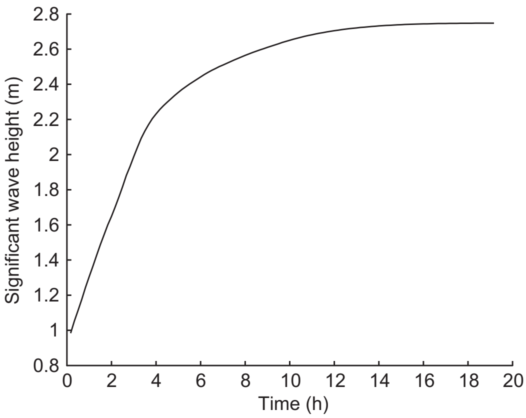

Fig. 3. Dependence of significant wave height on wind duration at the Harilaiu Bank.

SWAN does not show any anomalous wave-height growth at any time. The wave height grows to 2.6 m within about 9 hours and then becomes saturated.

Tallinn Bay

Although Tallinn Bay is well sheltered by two islands (Naissaar and Aegna) and many shallows (*see* Fig. 1), high waves may penetrate into the bay in case of NNW winds (Fig. 4a). The significant wave height may be as high as 3 m in the bay interior and up to 4 m to the west of the Naissaar Island, which is about 1 m less than reported by Soomere (2005). Areas north of the Aegna Island and shallows between Aegna and Naissaar islands exhibit significant wave heights less than 3 m. Areas near the peninsulas of Suurupi, Kakumäe, Kopli and Paljassaar exhibit the significant wave heights less than 2.5 m. The lowest significant wave heights, less than 1 m, occur between the mainland and the Aegna Island. In general, the significant wave height calculated for the Tallinn Bay interior with SWAN is about 0.5 m smaller than in Soomere (2005).

The results of using the SWAN model with depth-induced breaking inactive show an increase in wave height north of the Aegna Island and on the north-western coast of the Naissaar Island, near the peninsulas of Kopli, Paljassaar and Kakumäe, and at Naissaar Bank and the Uusmadal Bank, as well as at Suurupi

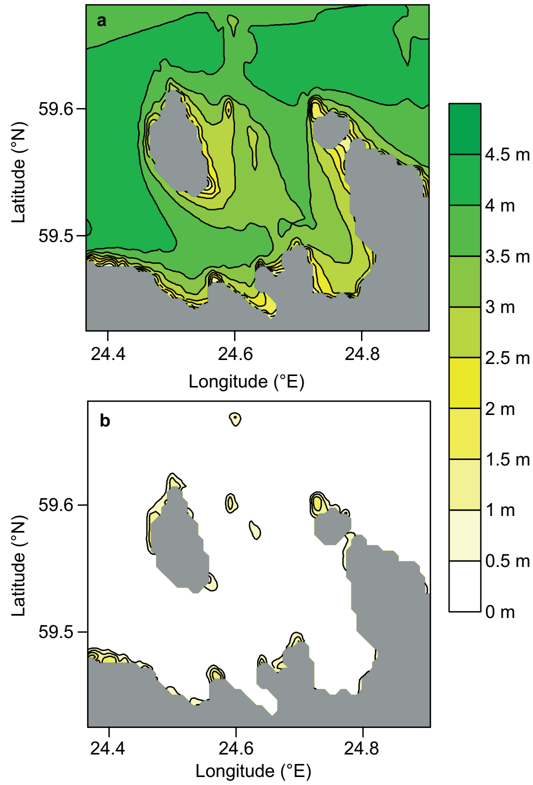

Fig. 4. (**a**) Significant wave height in Tallinn Bay and adjacent sea area in case of an extreme (23 m s^{-1}) NNW storm. (**b**) Difference between depth induced breaking not activated and depth induced breaking activated. Color bar holds for **b** as well.

(Fig. 4b; *see* also Fig. 1 for exact locations). The increase in the significant wave height north of Aegna is 1.8 m, 1.1 m at the Keskmadal Bank, 1.4 m at the Naissaar Bank, 2 m at the Kakumäe Peninsula, 1.5 m at the Kopli and Paljassaare peninsulas. The highest increase occurs near the Suurupi Peninsula, where the non-breaking case presents significant wave height increase of 2.3 m. Central Tallinn Bay, also west of the Naissaar Island and other areas, where the water depth is greater than 20 m do not show increase in the significant wave height. As compared with the increase of the significant wave at the Harilaiu Bank in case of depth-induced breaking turned off, Tallinn Bay exhibits almost two times lower increase, however, there are more areas where the significant wave height increases. The lower increase of the significant wave height is probably due to lower background values of the significant wave height in Tallinn Bay (and in the Gulf of Finland) as compared with those at the Harilaiu Bank (and in the Baltic Proper).

Conclusions

Three possible sources of errors in wave modelling suggested by Komen *et al*. (1994) are: (1) inadequate wind input, (2) inadequate numerical schemes and resolutions, and finally (3) inadequate model physics. In this paper, we compared SWAN wave model results with and without depth-induced wave breaking to address the effect of depth-induced wave breaking in the Estonian coastal waters.

The results of modelling with SWAN indicate that depth-induced wave breaking plays a key role in the dissipation of waves at the Harilaiu Bank and in Tallinn Bay. In the case of NNW storms, depth-induced wave breaking reduces the significant wave height up to 4.8 m at the Harilaiu Bank and up to 2.3 m in Tallinn Bay. Hence, the maxima in these areas are not caused by topographic refraction, as suggested by Soomere (2003, 2005). Although WAM is a widely used and verified model against measurements in deep water (Komen *et al*. 1994), it does not reproduce the wave fields near shore, as shown here. The WAM model is intended for deep water applications, and cannot be realistically applied to coastal regions with horizontal scales smaller than 20–30 km and water depth smaller than 20–30 m (e.g. Booij 1999). The reduction of the significant wave heights due to depth-induced breaking at the Harilaiu Bank and in Tallinn Bay clearly shows that the results obtained with WAM can lead to large overestimation of wave heights, as WAM can not be expected to obtain realistic values in this kind of depths, especially in extreme conditions.

In conclusion, the wave height maxima at the Harilaiu Bank and Tallinn Bay (Soomere 2003, 2005) are an artefact of the WAM model — confirming the fact that WAM was never intended to reproduce wave fields near shore. Let us remind ourselves that maximum wave heights can be up to 1.8 times larger than significant wave heights, hence the calculations by Soomere (2001, 2003) lead to the maximum wave height of 18 m at the Harilaiu Bank. Thus the conclusions by Soomere are likely incomplete.

Acknowledgments: We are grateful to Dr. Gennadi Lessin and Kai Ristikivi for the help in preparing the figures, and to anonymous referees for their crucial comments and suggestions.

References

Alari V., Raudsepp U. & Kõuts T. 2008. Wind wave measurements and modelling in Küdema Bay, Estonian Archipelago Sea. *J. Mar. Syst*. 74: S30–S40.

Booij N., Ris R.C. & Holthuijsen L.H. 1999. A third-generation wave model for coastal regions. 1. Model description and validation. *J. Geophys. Res*. C104: 7649–7666.

Holthuijsen L.H. 2007. *Waves in oceanic and coastal waters*. Cambridge University Press, Cambridge.

Komen G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S. & Janssen P.A.E.M. 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge.

Massel S. 1996. *Ocean surface waves: their physics and prediction*. World Scientific Publication, Singapore.

Seifert T., Kayser B. & Tauber F. 2001. A high resolution spherical grid topography of the Baltic Sea, revised edition. In: *Baltic Sea Science Congress 2001: Past, Present and Future — A Joint Venture*, Abstract Volume, Stockholm University, p. 298.

Soomere T. 2001. Wave regimes and anomalies off northwestern Saaremaa Island. *Proc. Estonian Acad. Sci. Eng*. 7: 157–173.

Soomere T. 2003. Anisotropy of wind and wave regimes in the Baltic Proper. *J. Sea Res*. 49: 305–316.

Soomere T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res*. 10: 103–118.