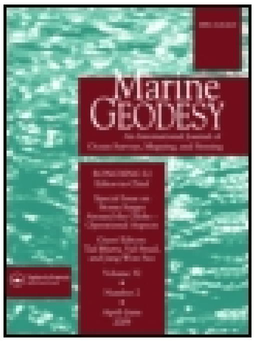

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GIS Modeling of Wave Exposure at the Seabed: A Depth-attenuated Wave Exposure Model

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Several studies have documented relationships between wave exposure and distribution, density, and size of marine species. Hence, this factor is at a high level in the hierarchical habitat classification system EUNIS and is one of the Water Framework Directive water typology criteria of coastal waters. Isæus (2004) has developed a continuous simplified wave model (SWM) that has been applied to several Nordic countries. Here we refine this model by introducing depth-attenuation, giving us the advantage of a model for wave exposure as it will actually work at the seabed. The values of the depth-attenuated model SWM(d) are approximately similar to the SWM model in shallow areas but noticeably lower in deep areas. The two models were compared in an analysis of the distribution of seabed substrate in the Stockholm archipelago. Using the depth-attenuated wave exposure instead of the SWM model as predictor in substrate modeling improved these models considerably.

Keywords Depth attenuation, GIS modeling, seabed substrate, wave exposure

Introduction

Mapping coastal marine biodiversity has become a priority for coastal zone managers. For years, studies have documented relationships between wave action and marine benthic habitats and communities (Lewis 1964; Crothers 1976; Sjøtun and Fredriksen 1995; Bruntse et al. 1999; Fonseca et al. 2002; Krause-Jensen et al. 2003; Bekkby and Isæus 2008; Bekkby et al. accepted). As a consequence, wave action is found at a high level in the hierarchical habitat classification system EUNIS (Davies and Moss 2003) and is one of the Water Framework Directive water typology criteria of coastal waters (Moy et al. 2003).

Even though wave effects on marine habitats and communities have been measured quantitatively (Jones and Demotropoulos 1968; Doty 1971; Norton et al. 1977; Schultze et al. 1990; Christie et al. 2003; Norderhaug 2004), these effects have rarely been studied in an objective and reproducible manner (however, see Ekebom et al. 2003; Lindegarth and Gamfeldt 2005; Burrows et al. 2008). Consequently, knowledge of biological effects

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of waves has been difficult to interpret and transfer to other areas and studies. In addition, wave exposure is rarely quantified as a high resolution spatial variable.

Wave activity varies over time and space. However, in this approach, we define the term "wave exposure" as the long-term wave climate that varies geographically but has a stable pattern over time. Effects from wave exposure is reflected in the patterns of shore organism distribution (Lewis 1964), and this fact has been used to construct biological wave exposure indices (Ballentine 1961; Lewis 1964; Dalby et al. 1978). The "Simplified Wave Model" (SWM) developed by Isæus (2004) provides a spatially distributed estimate of wave exposure in an ecologically relevant way by using easily obtained physical parameters of fetch and wind speed. The model has been validated in the Stockholm archipelago (Isæus 2004) and has been applied in the Norwegian mapping program on marine biodiversity (Rinde et al. 2006) and in Swedish research projects (Eriksson et al. 2004; Sandström et al. 2005).

One of the advantages of the SWM is that it is a continuous, or step-less, model. Such models seem to be superior to categorical models when it comes to explaining the variability in total, algal and faunal richness (Lindegarth and Gamfeldt 2005). The SWM may be applied to large regions at quite high resolution (e.g., 10 m), which is too demanding for more computationally intensive numerical wave models (e.g., WAM, WAMDI Group 1988; SWAN, Booij et al. 1999).

However, SWM is a surface model, as it does not include attenuation of wave energy with depth. Unpublished data have indicated this is a problem for analyses and prediction of marine benthic species and habitats, in particular for those found in deep waters. Hence, the aim of this paper is to present a refinement to the model of Isæus (2004), estimating wave exposure as it will actually work at the seabed. Here we present the theory and the practical implementation of the changes. Also, the performance of the Isæus (2004) surface model and the depth-attenuated models SWM(d) is compared in an analysis of the distribution of seabed substrate in the Stockholm archipelago (Svenska Högarna nature reserve).

Theory of Depth-Attenuation

Wave exposure is a complex concept. Conceptually it should be related to the velocity of the water movement associated with the orbital motion of waves (Lindegarth and Gamfeldt 2005; Resio et al. 2003) or with the square of this orbital velocity, that is, with the kinetic energy of the wave field. The wave orbital velocity, in turn, is closely related to the wave height (for small-amplitude waves the two are linearly related). Any location in the ocean is exposed to a wide spectrum of waves of different amplitudes, frequencies and wavelengths. However, for practical estimates of wave exposure, the concept of "significant wave height" (and thus significant wave motion or wave energy) can be applied (Pond and Pickard 1983; Resio et al. 2003). The significant wave height has traditionally been defined as the mean amplitude of the one-third largest waves or, more recently, as four times the root-mean-square amplitude of the wave field at a given location. Simplified expressions that predict this significant wave height (as well as the significant wave period and frequency) as a function of various environmental parameters have been developed based on scaling laws. For applications in semi-enclosed ocean regions where the wind fetch (the distance over which the wind blows from land to a given point in the ocean) is expected to act as a limiting factor on wave height, dimensional scaling predicts (Eq. 1):

$$H_{m0} = \frac{k}{\sqrt{g}} * \sqrt{F} * W, \tag{1}$$

where H_{m0} is the significant wave height, F is the fetch (in meters), W is the near-surface wind speed (in meters per second), g is the acceleration due to gravity, and k is the wave number.

Isæus (2004) examined various functional relationships between fetch and near-surface wind speed by correlating these with a biological index constructed from observed zonation patterns of a set of sea shore organisms. In constructing a Simplified Wave Model exposure index (SWM), he obtained a best correlation between the biological index and the product between fetch and wind speed averaged over 16 compass sectors (Eq. 2):

$$\mathrm{SWM} = \frac{1}{16}\sum_{i=1}^{16} F_i * \bar{W}_i. \tag{2}$$

Here F_i is the fetch in direction i and W_i is the wind strength in direction i. The overbar on W indicates that a long-time average has been taken. Although this “best-fit” expression does not hold the dimensional form of significant wave height, Isæus (2004) found that the prediction skill of his model was equal to or better than the skill for a similar expression involving the product of fetch and the square of wind speeds which is related to the square significant wave height, that is, to the significant wave energy.

Since the model of Isæus (2004) already has been used extensively and calibrated in Scandinavian studies, we take this as a starting point to examine the depth attenuation of wave exposure. We make the common assumption (Defant 1961; Kundu 1990) of small-amplitude waves for which the depth dependence of the wave height for a single wave of wavelength λ and wave number $k = 2\pi/\lambda$ goes as (Eq. 3)

$$h(z) = \frac{h(0)}{Cosh[kH]} * Cosh[k(z+H)], \tag{3}$$

where H is the ocean depth and $h(0)$ is the wave amplitude at the surface (z is negative below the level of the time-mean sea surface). This form of the depth attenuation has been experimentally verified in numerous laboratory studies (see, e.g., Defant 1961) and is today used in most state-of-the-art numerical wave models (e.g., the SWAN model, Booij et al. 1999).

We will here limit ourselves to deep-water waves for which the wavelength is smaller than roughly two times the ocean depth (e.g., figure 12.4 in Pond and Pickard 1983). For such waves the depth dependence reduces to the simple form (Eq. 4)

$$h(z) = h(0) * \exp(k * z), \tag{4}$$

where the wave number k is related to the wave angular frequency ω via the dispersion relationship (Eq. 5):

$$k = \frac{\omega^2}{g}. \tag{5}$$

Knowledge of the dominant or peak wave frequency and corresponding wave number at a given location in the ocean thus gives us a way to estimate the decay of wave exposure with depth. The immediate advantage of limiting the model to deep-water waves in this preliminary study is that it allows us to obtain an estimate of the peak wave frequency, that is, the frequency of the most energetic wave, from wind speed and fetch via the JONSWAP spectrum for fetch-limited waves (Hasselman et al. 1973) (Eq. 6):

$$\omega p = 22\left(\frac{g^2}{F * W}\right)^{1/3}. \tag{6}$$

By substituting the expression in Eq. (2) for an average value of $F{*}W$ into Eq. (6), we have an expression of the depth-attenuation of wave exposure, Eq. (7),

$$\mathrm{SWM}(z) = \mathrm{SWM}(0) * \exp(k_p * z), \tag{7}$$

with Eq. (8)

$$k_p = 22^2 * \left(\frac{1}{\mathrm{SWM}(0)}\right)^{2/3} * g^{1/3}. \tag{8}$$

As mentioned above, the dispersion relationship for deep-water waves (as well as the simplified expression for depth-attenuation in Eq. (4) roughly holds for wavelengths smaller than two times the ocean depth. The theory may be modified to take finite bottom depths into account (see, e.g., Resio et al. 2003, pg. II-2–47 for an ad hoc procedure), but here we proceed to make a first exploration of these ideas based on the deep-water assumption.

Comparing the SWM and the Depth-attenuated Model SWM(d)

Our aim is to evaluate whether the depth-attenuated model is able to improve the prediction skills of spatial seabed substrate models. The model test area (59°N 19°E) is part of the Swedish nature reserve Svenska Högarna in the Stockholm archipelago. The area is typical for the outer central coast of the Baltic, with depths down to approximately 100 m (Figure 1).

We begin by comparing the prediction of wave exposure from the original surface model (SWM, Isæus 2004) with the new formalism taking depth-attenuation into account, SWM(d). Both models were fed data on average wind direction and strength for the period 1990–2000 from a station located within the study area (data provided by the Swedish Meteorological and Hydrological Institute). For estimates of the depth-attenuation, a digital depth model was produced through TIN modelling (i.e., Triangular Irregular Network) from depth curves (0, 3, 6, 10, 15, 20, 30, 50 m) and depth points (provided by the Swedish Sea Mapping Authorities; map no 613, ref. 010207-02-02039/235-61D3-04). The depth data available for the deeper areas were sparse due to military restrictions. Consequently, the digital depth model is less accurate in these deep areas than in the rest of the study area. The equations for the depth-attenuated wave model were programmed as an Avenue script (i.e., the script language of ArcView 3.x). The script was run in ArcView 3.3 using the “Spatial Analyst” extension. All calculations, both for the surface model and the depth-attenuated model, were done at a spatial resolution of 25 m.

The two different estimates of wave exposure are shown in Figures 2 and 3. The original surface model (Isæus 2004) predicts a wave exposure index ranging from ultra sheltered to exposed (values estimated by Isæus 2004; classification similar to Rinde et al. 2006). The seabed wave exposure model, that is, the model which includes depth-attenuation, predicts seabed exposure values that are approximately similar to the surface model in shallow areas, but noticeably lower in deeper areas (Figure 4). This is as expected, as the effect of the depth-attenuation gets larger with increasing depth. A particularly noticeable difference between the two models can be seen to the west-northwest of the archipelago. Here the

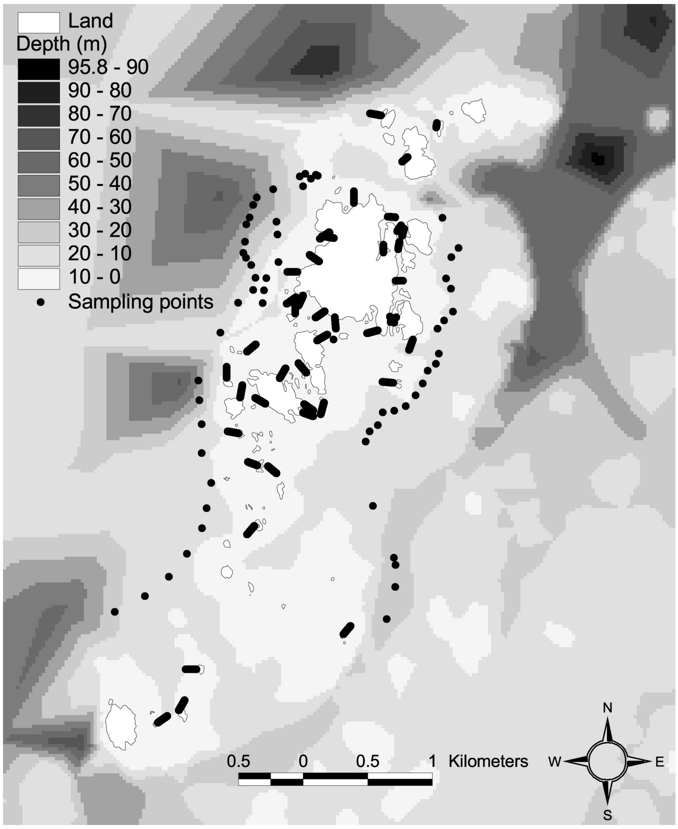

Figure 1. The digital terrain model showing the depths in the test area (the Swedish nature reserve Svenska Högarna outside Stockholm, Baltic Sea, 59°N 19°E). The model is interpolated using data purchased from the Swedish Mapping Authority. The spatial resolution is 25 m. The depth data available for the deeper areas (northwestern part) were sparse due to military restrictions. Consequently, the digital depth model is more inaccurate is these areas than in the rest of the area.

surface model predicts a distinct lee zone due to the islands' ability to shelter this region from winds originating from the east-southeast. The depth-attenuated model suggests that the levels of wave exposure *at the seabed* in this region also is considerably influenced by the actual bottom depth there.

Testing the New Formalism in Substrate Modeling

The incorporation of depth-attenuation of the wave field clearly predicts different exposure levels at the seabed in deeper areas of this region. Does this difference actually influence our ability to model the seabed substrate distribution? We examined this question by analyzing the probability of finding rock, sand, soft sediment, and mixed sediment (more details in Isæus et al. 2007) using our information on surface wave exposure and depth-attenuated exposure together with information on three other typical influential factors, namely depth, slope, and aspect. Based on the digital depth model described above, slope and aspect were calculated using standard functions available in ArcGIS 9.0. Slope identifies the maximum

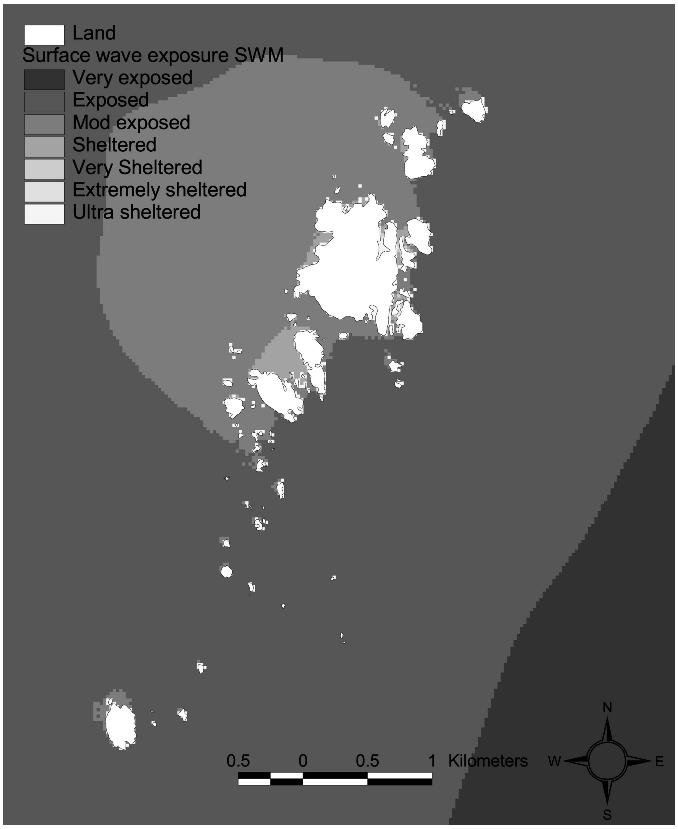

Figure 2. The simplified wave model (SWM; Isæus 2004), showing the surface wave exposure applied to the test area (the Swedish nature reserve Svenska Högarna outside Stockholm, Baltic Sea, 59°N 19°E). The spatial resolution is 25 m.

rate of change from each cell to that of its neighbor's (in degrees). Aspect identifies the steepest down-slope direction (in compass direction, 0 is north, 90 is to the east, etc.).

In total, 104 sites were visited (42 through diving and 62 by using an Ekman sediment grabber), and data were sampled down to 44 m depth. The distance between sampling points ranged from 0.5 to approximately 270 m. In total, 6,863 sampling points (Figure 1) were defined according to the coverage of each of the four substrate types.

We analyzed the statistical influence of surface wave exposure and depth-attenuated wave exposure together with depth, slope, and aspect by using Generalised Additive Models (GAM, 2 degrees of freedom for the smoothing spline function) in S-PLUS 2000. This data set was binomial (presence/absence), and more than 25% coverage of a substrate type was defined as presence. As a tool for model selection, we used the Akaike Information Criterion (AIC; see Burnham and Anderson 2001) in GRASP (an extension to S-PLUS 2000; Lehmann et al. 2002; Lehmann et al. 2004). The predicted probability models were validated using a cross-validation method (a ROC test; Fielding and Bell 1997) based on the presence/absence data. The cross-validation was made with five subsets (folds) of the entire dataset (5-fold cvROC).

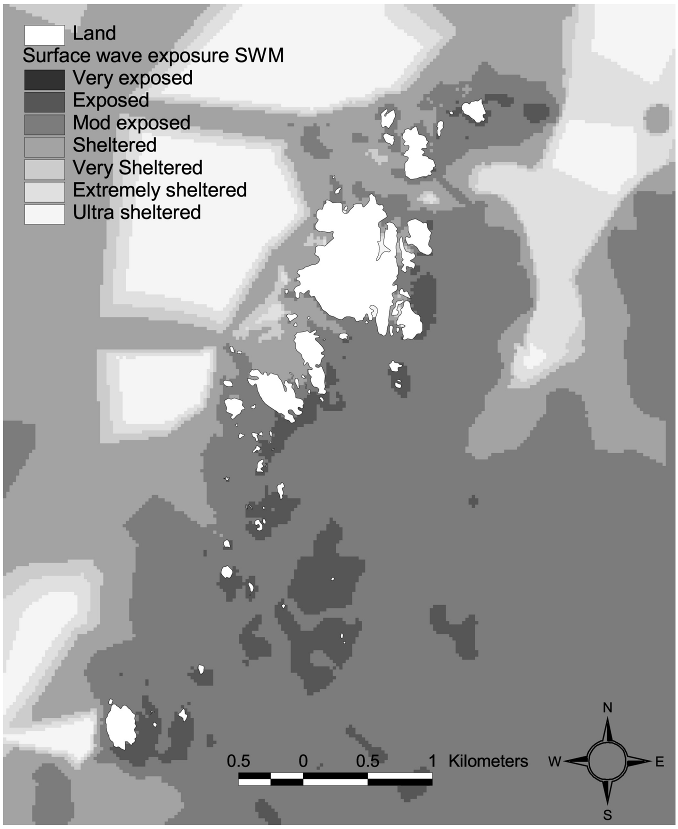

Figure 3. The wave exposure model including depth-attenuation, SWM(d) applied to the test area (the Swedish nature reserve Svenska Högarna outside Stockholm, Baltic Sea, 59°N 19°E). The spatial resolution is 25 m. The depth data available for the deeper areas (northwestern part of Figure 1) were sparse due to military restrictions. Consequently, the depth-attenuated wave exposure model is more inaccurate is these areas than in the rest of the area.

The statistical analyses show that the discrepancy from the best model (the Δ value of Table 1), was high (at minimum 46.9) for the models using the (surface) SWM model instead of the depth-attenuated wave model SWM(d). Consequently, the substrate model using the depth-attenuated wave exposure is regarded as considerable better than the substrate model using the surface model.

Discussion

The idea of seabed substrate and ecology being controlled by bottom rather that surface exposure conditions is logical and appealing. This work represents the first approach to refine the SWM model of Isæus (2004) by taking into account the attenuation of the surface wave field with depth, thus providing a measure for wave exposure at the seabed. In our statistical analyses, we found that the depth-attenuated wave exposure model contributed as a significant predictor, together with depth, slope, and aspect, in reliable predictions of substrate types. Using the depth-attenuated wave exposure instead of the surface model

Table 1

The results of the AIC model selection. The response variable was sediment type occurrence (presence/absence). More than 25% coverage of a substrate type was defined as presence. Predictor variables were depth, slope, aspect, wave exposure (SWM, Isæus 2004) and depth-attenuated wave exposure, SWM(d). cvROC is the cross-validation method used. Δ is the discrepancy from the best model

Model	Rock	Sand	Soft sediment	Mixed Sediment
1. Depth, slope, aspect, SWM(d)	AIC = 7757.4	AIC = 4604.8	AIC = 926.6	AIC = 8726.3
	cvROC = 0.77 Δ = 0	cvROC = 0.80 Δ = 0	cvROC = 0.94 Δ = 0	cvROC = 0.67 Δ = 0
2. Depth, slope, aspect, SWM	AIC = 7856.6	AIC = 4730.5	AIC = 973.5	AIC = 8926.1
	cvROC = 0.77 Δ = 99.2	cvROC = 0.76 Δ = 125.7	cvROC = 0.94 Δ = 46.9	cvROC = 0.68 Δ = 199.8
3. Slope, aspect, SWM(d)	AIC = 8020.6	AIC = 4759.6	AIC = 1006.8	AIC = 8820.8
	cvROC = 0.73 Δ = 263.2	cvROC = 0.79 Δ = 154.8	cvROC = 0.93 Δ = 80.2	cvROC = 0.67 Δ = 94.5
4. Slope, aspect, SWM	AIC = 8531.2	AIC = 5116.1	AIC = 991.8	AIC = 9158.4
	cvROC = 0.71 Δ = 773.8	cvROC = 0.73 Δ = 511.3	cvROC = 0.94 Δ = 65.2	cvROC = 0.62 Δ = 432.1

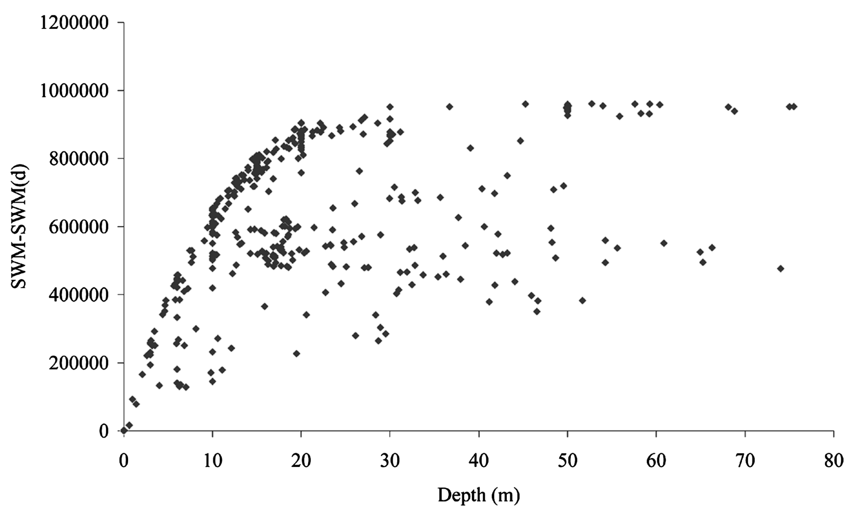

Figure 4. A sample of 400 randomly selected data points were used to illustrate how the difference between the surface model SWM and the depth-attenuated wave exposure model SWM(d) (y-axis) varies with depth (x-axis). The relationship between the values on the y-axis and the wave exposure classes presented in Figures 1 and 2 is found in Rinde et al. (2006).

of Isæus (2004) thus improved the models considerably, and the validation showed a high degree of precision.

The depth-attenuated wave exposure model does not fully reproduce the effects of bathymetry on wave attenuation. The model captures the decline in wave amplitude with increasing depth but takes no account of, for example, the effects of very shallow water on waves. In addition to modifying the dispersion relationships of waves (as mentioned above), shallow regions next to the coast may cause waves to break and lose energy (as included by, e.g., Thomas 1986). The reason for ignoring this and other effects of bathymetry (e.g., refraction) in the SWM model is that bathymetry is often not available at a high quality in coastal waters. The modeling approach was originally developed for application to large coastal areas irrespective of the availability of bathymetric data, and the SWM model may be used for producing high resolution wave exposure grids (5–25 m) for large coastal areas (countries) at a reasonable cost and at a quality useful for research (Eriksson et al. 2004; Sandström et al. 2005; Westerbom and Jattu 2006; Bekkby et al. accepted) and management purposes (e.g., Rinde et al. 2006; Bekkby and Rosenberg 2006).

Even though the proposed depth-attenuated wave exposure model clearly has several shortcomings, the theoretical basis is sound. One should therefore expect the model to provide an improved estimate of wave exposure at the seabed. The new model has not been evaluated through dedicated field measures or tested as thoroughly as the original Isæus (2004) model. However, we have here presented a first test against the original surface model in a study modeling seabed substrate types. The results, showing considerable improvement in predictive skills, are encouraging.

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