EUSeaMap

Technical Report No. X

Energy data and thresholds

Contents

1 Introduction

Energy exerted on the seabed can be characterised in a variety of ways that account for effects due to waves or tidal currents, or their combined effects. For example, waves can be characterised by their height, period, or orbital velocity of water particles that varies with depth. Currents can be characterised by measures such as tidal current magnitude or kinetic energy over a tidal cycle. One variable common in ocean modelling to capture the effects of both waves and tides and also their combined effect on the seabed is bed shear stress. Bed shear stress is a measure of the force exerted by waves and/or currents on sediments by the water movement over the seabed.

Comment [AC1]: Remove/reword since we don't use bed shear stress.

Energy regimes resulting from wave action and tidal currents have similar, but not always the same, effects on biological community character. Their relative importance varies significantly from one place to another, being quite different in a macrotidal[1] system such as the Channel compared to wind-dominated areas such as the Western Mediterranean. In coastal areas, the two variables typically work together; their separate effects are often difficult to distinguish and for simplicity they are combined for application in the EUNIS classification scheme.

Energy layers were calculated for the North and Celtic Seas, the western Mediterranean Sea and the Baltic Sea. For the North and Celtic Seas and the western Mediterranean Sea, kinetic energy models at the seabed were calculated for waves and currents. For the Mediterranean Sea bed shear stress was also calculated. For the Baltic Sea significant wave height and SWM (simplified wave model) layers were calculated and combined into a seamless layer in which significant wave height was recalculated to corresponding SWM values. This approach is necessary in the Baltic Sea since wave exposure can vary at a small spatial scale in coastal areas with a complex coastline, particularly archipelagos, in a way that is poorly described by large-scale oceanographic models.

Biologically relevant thresholds for energy were defined for the North and Celtic Seas and the Baltic Sea. Thresholds for energy regimes in the Mediterranean Sea were not defined since it was not possible to discriminate different energy levels associated to the habitat types. For the Baltic Sea two energy thresholds were defined; between high and moderate wave exposure and between moderate and low wave exposure. Comment: Information about thresholds for the North and Celtic Seas to be added by JNCC.

[1] In macrotidal areas the difference between mean high water springs and mean low water springs is between 4m and 6m.

2 Data layer preparation

2.1 North and Celtic Seas

Two layers were developed for the North and Celtic Seas, kinetic energy at the seabed due to waves and currents.

The EMODNET bathymetry data set was used as the primary bathymetry source; this data was merged with SeaZone data captured in the coastal wave models. The resolution of the EMODNET bathymetry is 0.0020833°. GEBCO data has also been used to cover those areas lying outside the extent of the SeaZone and EMODNET data coverage. Figure X shows the bathymetry coverage for the whole model area.

2.1.1 Kinetic energy model for waves – North and Celtic Seas

The primary source of wave data is from the 12km resolution ProWAM model, which covers the area 48°07'N to 62°53'N and 11°50'W to 12°50E. Beyond the western limit of the ProWAM model, the water depths are greater than 150m and consequently, the seabed KE term due to waves will be comparatively small. In MB102 (ABPmer 2010), wave disturbance probability calculations were extended beyond the limit of ProWAM, as far as 24°W, by inferring comparable values of wave period from the NOAA product Wavewatch III. A similar approach has been applied to wave heights in areas beyond the limit of ProWAM, leading to an estimate of the seabed wave KE in those regions. In coastal areas along the European coastline and in particular the Kattegat Sea interpolated wave heights were adjusted to take account of breaking in shallow water. In all places where wave height is greater than 0.8* Water Depth, wave height was reduced to 0.8 * Water Depth. This adjustment compensated for the lack of wave breaking which would have occurred if a local scale wave model had been used.

2.1.2 Kinetic energy model for currents – North and Celtic Seas

The National Oceanographic Centre (NOC) High Resolution Continental Shelf Model (CS20) has been used wherever possible, followed by the Continental Shelf Model (CS3/CS3X). For those parts of the project area not covered by either of these two models, information has been obtained from the North East Atlantic (NEA) model.

2.2 Western Mediterranean Sea

In the northern part of the western Mediterranean basin (roughly north of Balearic Islands) an energy model was built on PREVIMER[2] wave and current models (WAVEWATCH III at resolution of 10km and MENOR model at 1km respectively). The Mediterranean model was run at a time step of three hours for a period of three years (2001 and 2007-2009). Methods used to combine the effects of waves and currents for bed shear stress were based on Soulsby (1997). 90 percentile of the maximum bed shear stress is shown in figure 1. The energy layers developed for the Mediterranean

[2] PREVIMer Coastal observations and forecasts www.previmer.org

were eventually not used in the seabed habitat model after threshold analysis showed that the models were too coarse and there were insufficient field biological data available to be able to classify energy regimes in the Mediterranean (section 3.2).

The interactions between waves and current are non-linear. Soulsby, 1997:

$$\tau_m = \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_w + \tau_c} \right)^{3.2} \right]$$

$$\tau_{cw} = \sqrt{[(\tau_m + \tau_w|\cos\varphi|)^2 + (\tau_w|\sin\varphi|)^2]}$$

where

τ_m represents the average shear stress in the current direction
τ_{cw} is the maximum shear stress generating during a wave period
φ is the angle between the current and wave directions

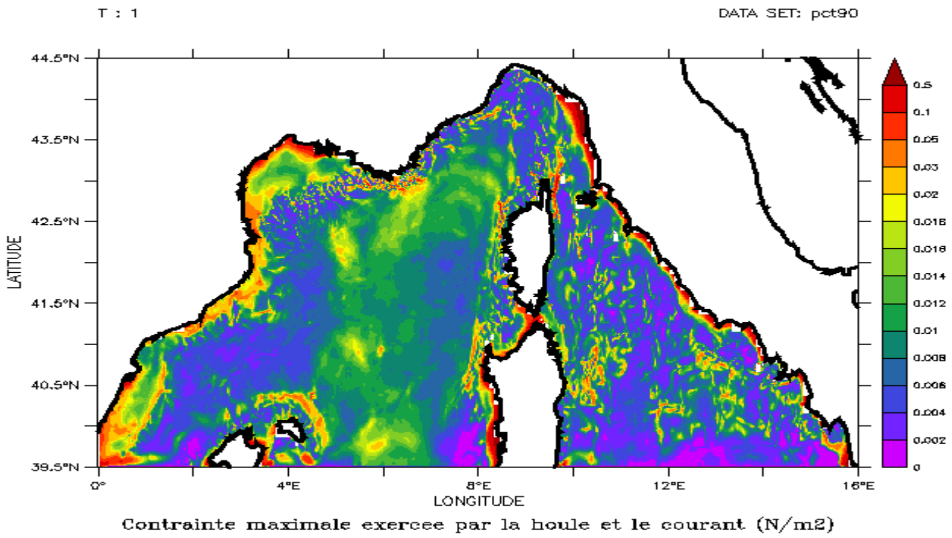

Figure 1. 90 percentile of the maximum bed shear stress due to the combined effects of waves and currents generated during a wave period.

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2.3 Baltic Sea

Two wave models have been developed for the Baltic: a coastal wave exposure model; and a model to be applied away from the coast. This dual approach is necessary because in coastal areas with a complex coastline, particularly archipelagos, the wave exposure can vary at a small spatial scale in a way that is poorly described by large-scale oceanographic models. In order to better describe energy in such areas of the Baltic Sea, the oceanographic wave model is complemented with a simpler fetch based model, SWM (Simplified Wave Model, Isaeus 2004). The energy layers were finally merged by recalculating mean significant wave height from the oceanographic model to corresponding SWM values. The final energy layer for the Baltic Sea was created from SWM-layers of very high spatial resolution for the coastal areas and mean significant wave height of lower spatial resolution for the open sea. The oceanographic model~~Significant wave height~~ is described in section 2.3.1 below. SWM is described in section 2.3.2 and the recalculation and merging of the layers is described in section 2.3.3. Kinetic energy at the seabed was also calculated but not used in the final model since significant wave height corresponds best to SWM. Kinetic energy at the seabed is described in section 2.3.4.

2.3.1 Wave model – Baltic Sea

The applied wave model is based on the MIKE 21 SW modelling system. MIKE 21 SW is a state-of-the-art third generation spectral wind-wave model developed by DHI. The model simulates growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. In this version of the model, the fully spectral formulation is used. This formulation is based on the wave action conservation equation. The basic conservation equations are formulated in polar spherical co-ordinates for large-scale applications.

The fully spectral model includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations
- Wave-current interaction (not included since this is mainly important in local coastal areas)
- Effect of time-varying water depth

The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action.

For the present purpose, DHI's operational Northern Europe wave model, which forms part of DHI's water forecast service www.waterforecast.com, has been used. This model is based on MIKE 21 SW as described above and covers UK waters and part of the North Atlantic, the North Sea, the Belt Sea and the entire Baltic Sea. A section of the model area is shown in figure 2. The model mesh has a resolution of approximately 4 km to 20 km in the area of interest (finest in the Danish waters and coarsest in the Bothnian Bay).

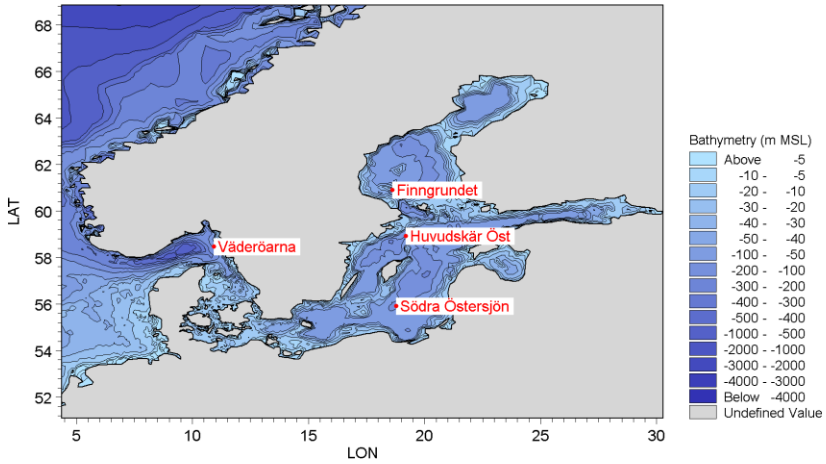

Figure 2. Section of applied MIKE 21 SW wave model showing model domain and location of measurement stations.

The model has been run in hindcast mode for a 3-year period from 1 January 2007 to 31 December 2009. The model is driven by wind fields from a meteorological model (Vejr2 and StormGeo's meteorological models), and also by open boundary conditions from a larger scale wave model. During the 3-year simulation period, wave parameters in terms of significant wave height and peak wave period were saved for every hour in every mesh element. For the present purpose only results from eastern Skagerrak/Kattegat to the Baltic Sea were used.

The wave model has been validated mainly on a case by case basis in connection with specific projects. In the present context the performance of the model has been checked by comparing model results to wave observations from SMHI in the stations Finngrundet, Huvudskär Öst, Södra Östersjön and Väderöarna. The comparisons are made for a 1-2 month period in autumn 2009, where events with high waves may be expected. In figure 3 and 4 the comparisons are shown. It is observed in the two figures that the model results compare well with the observations.

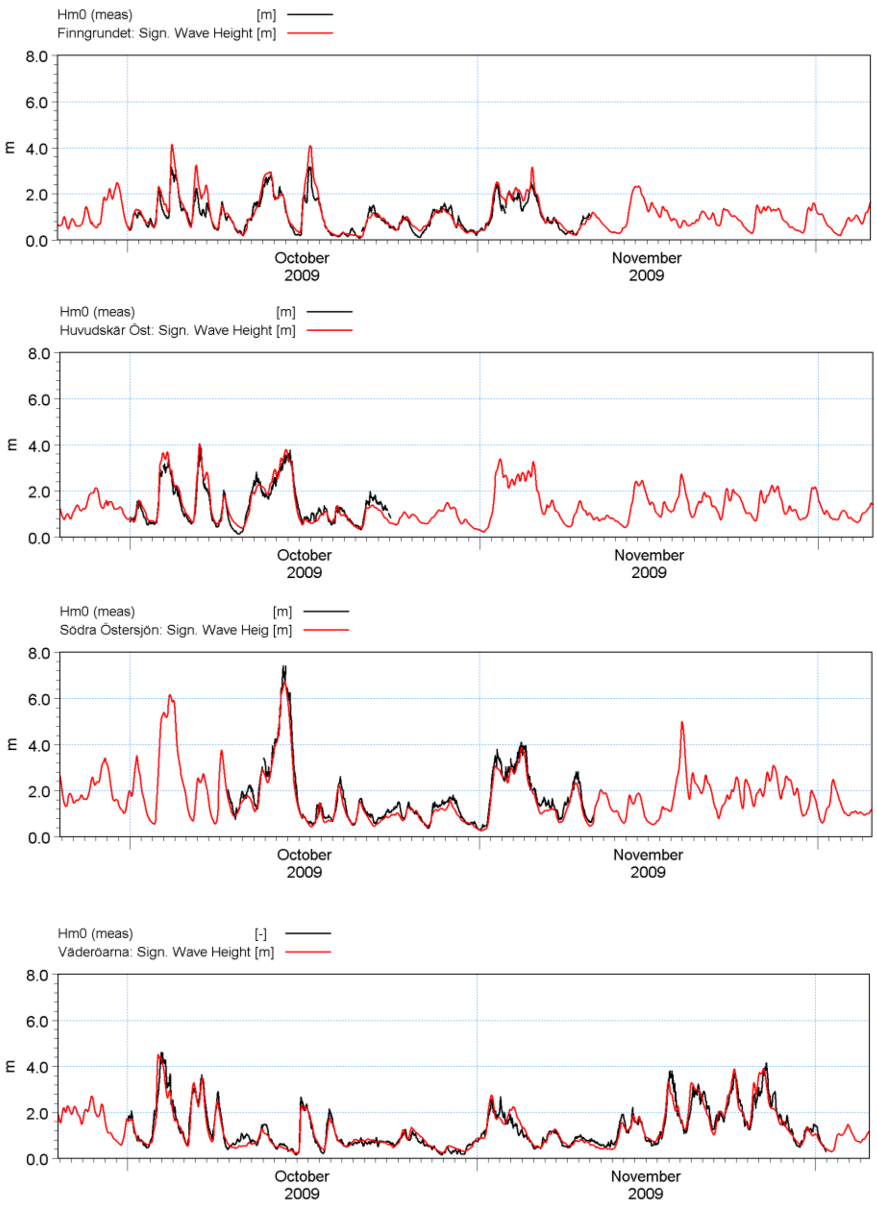

Figure 3. Comparison of observed (black line) and modelled (red line) significant wave height

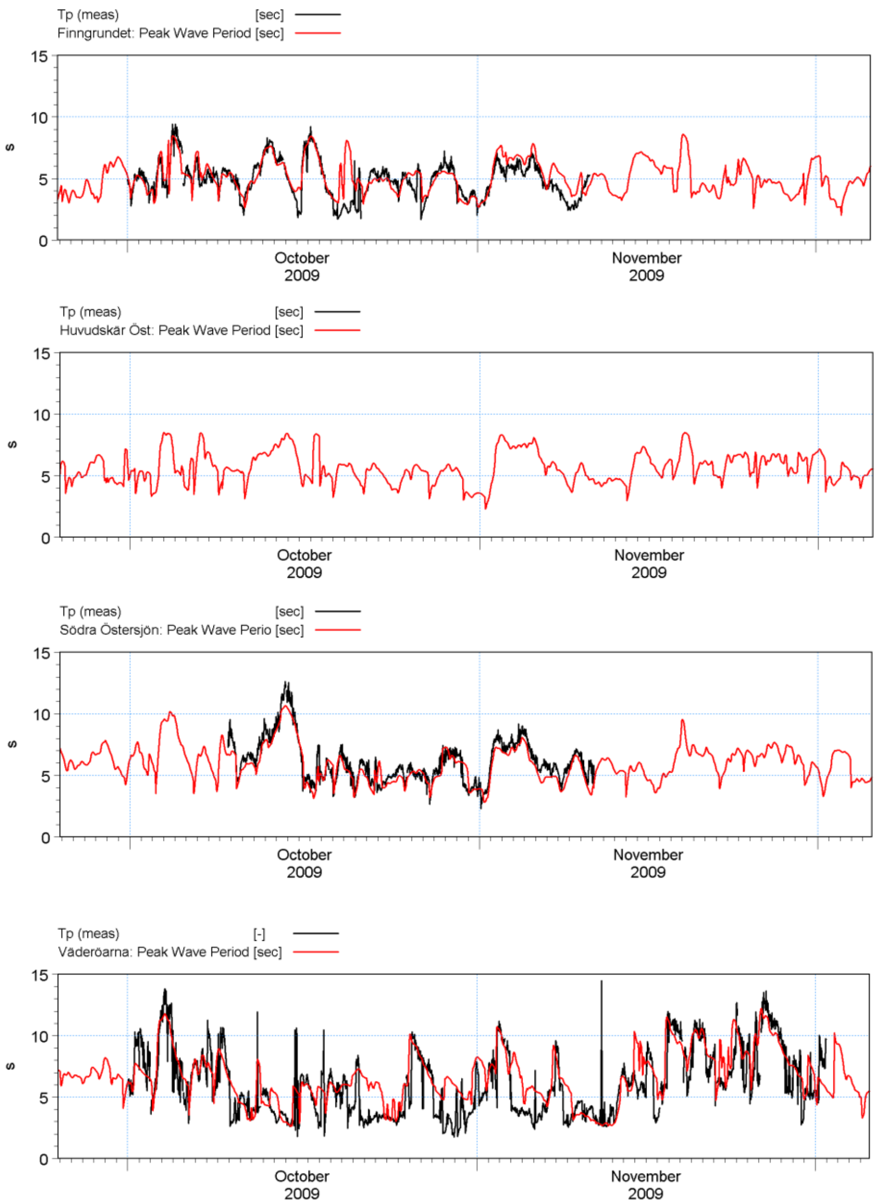

Figure 4. Comparison of observed (black line) and modeled (red line) peak wave period

The SWM layers (described in section 2.3.2) only cover coastal areas. ~~For this purpose m~~Mean significant wave height ~~was selected, since this layer~~ corresponds best to SWM and was therefore selected for open sea areas in the merged energy layer for the entire Baltic Sea. ~~.~~The mean value of mean significant wave height for the years 2007, 2008 and 2009 was calculated and a GIS layer was created.

2.3.2 Simplified Wave Model – Baltic Sea

SWM was calculated with the software WaveImpact 1.0, which is fully described by Isæus (2004). The method is termed simplified since it uses the shoreline and not the bathymetry as input for describing the coastal shape. This is an adoption to the fact that bathymetry data of sufficient spatial resolution is often unavailable or confidential and therefore of restricted use. The method has been proved useful in several papers (Bekkby et al., 2009; Bekkby et al., 2008, a-c; Bekkby and Isaeus 2008; Eriksson et al., 2004; Florin et al., 2009; Sandman et al., 2008; Sandström et al., 2005; Snickars et al., 2010; Soldal et al., 2009; Sundblad et al., 2009).

To ensure long distance effects on the local wave exposure regime, a nested-grids technique was used. In this case a coarse grid (500 m cell size) covering the major part of the Baltic Sea was used to support finer grids (100 m cell size) with input fetch values. These 100 m grids further provided input fetch values for the final 25 m grids (used in the SWM calculations). The extents of the 25 m grids were set to include coastline features that affect fetch locally, to overlap between each grid pair and to be of manageable size.

The fetch is calculated for every sea grid cell of the map. An advantage of using such a grid solution is that the values of adjacent cells can be used as input data, which facilitates the simulation of the patterns of refraction and diffraction. The wave exposure was calculated for mean wind conditions represented by hourly wind data for the five-year period between September 1, 2002 and August 31, 2007. Wind data were retrieved from the British Metoffice Unified Model, by the Interdisciplinary Centre for Mathematical and Computational Modelling, University of Warsaw. A total of 26 locations were used. For some grids there were several wind stations available. For those grids, the most representative wind station was selected. For the calculations, the wind data were divided in sixteen compass directions, each representing an angular sector of 22.5°.

The SWM was calculated by multiplying the value of each cell in the corresponding fetch grid by the mean wind speed for each wind direction separately, resulting in sixteen new grids. Finally the mean value of all grids was calculated in an overlay analysis. The separate SWM grids (25 m cell size) were integrated into three seamless descriptions of wave exposure along the coasts of Russia, Latvia, Lithuania, Germany and Denmark. In turn, these grids were integrated with earlier calculated grids for Sweden, Finland, Estonia and Poland into a seamless SWM-coverage for the Baltic coasts.

Calculation of SWM for the Baltic Sea is described in more detail in Isaeus and Wijkmark, Wave Exposure Calculations for the Baltic Sea, Aquabiota report 2010:02.

2.3.3 Conversion of mean significant wave height to SWM and merging with SWM

In order to recalculate mean significant wave height layer to SWM a regression was performed using data points in overlapping areas. Data points with SWM values under 100,000 were not included since SWM and mean significant wave height differ drastically in areas with such low values due to the difference in spatial resolution between the models. In total 22639 overlapping points were included in the regression, equation below.

$Y = 826787\ X^{1.2017}$
$R^2 = 0.5593$

where

Y = SWM
X = mean significant wave height

The mean significant wave height layer was transformed to SWM using the equation above.

The SWM and wave height layers were merged in GIS (ESRI ArcMap). It can be assumed that SWM is more accurate than wave height in coastal areas and archipelagos and that wave height is the most accurate layer in the open sea. The use of fetch based wave exposure models in coastal environments is supported a study by Hill et al. 2010 pointing out fetch based indices as the best predictors for occurrence and cover of algal genera and community-level patterns. Since the SWM layer also has a much higher spatial resolution it is more suitable for use in areas with complex coastlines and islands. In areas with SWM values over 500,000, the transformed wave height layer determines the value of the merged layer and in areas with lower values the SWM layer determines the value of the merged layer. The layer is shown in figure 5 below.

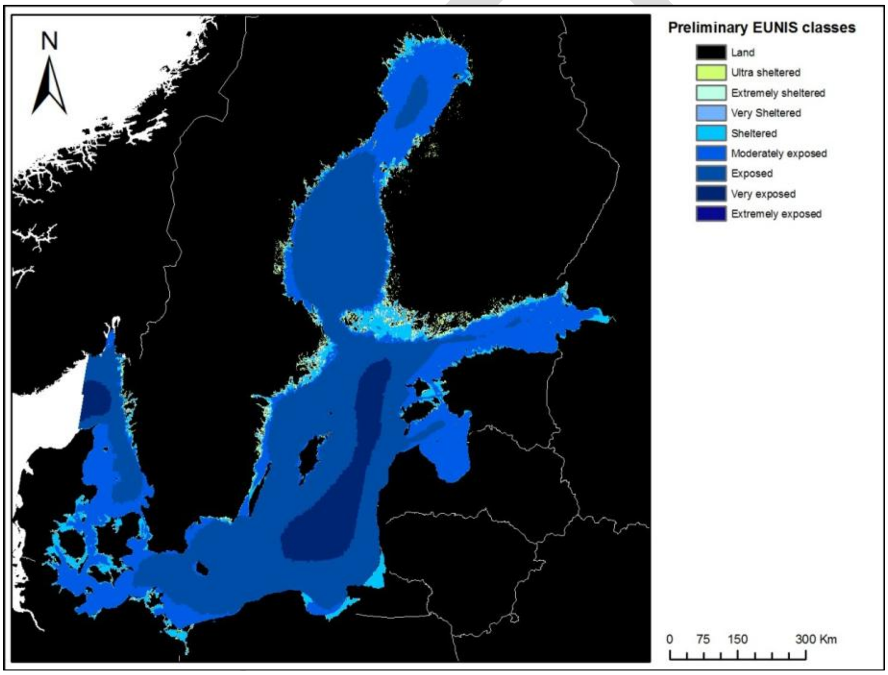

Figure 5. SWM layer for the Baltic Sea. SWM values for open sea areas are derived from recalculated significant wave height.

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2.3.4 Kinetic energy at the seabed

For the Baltic Sea kinetic energy at the seabed was calculated as both the wave induced kinetic energy and the current induced kinetic energy. However kinetic energy at the seabed was not used in the final merged energy layer for the Baltic Sea since significant wave height corresponds better to SWM.

The kinetic energy at the seabed is calculated as both the wave induced kinetic energy and the current induced kinetic energy. In the former case the kinetic energy is based on the wave orbital velocity at the bottom and in the latter case the kinetic energy is based on the current speed at the bottom.

The calculation of the kinetic energy induced by waves is based on the modelled wave parameters, i.e. significant wave height and peak wave period, as well as on the local water depth.

The calculation of the kinetic energy induced by current is based on modelled current velocities. The applied current model, or hydrodynamic model, is based on the MIKE 3 modelling system developed by DHI. The MIKE 3 model is a dynamic time-dependent 3-D baroclinic model for free surface flows. The mathematical foundation of the model are the Reynolds-averaged Navier-Stoke's equations in three dimensions, including the effects of turbulence and variable density, together with conservation equations for mass, heat and salt, an equation of state for the density, a turbulence module and a heat exchange module. The equations are solved on a Cartesian grid by means of the finite difference techniques. The hydrodynamic model provides a full 3-D model representation of the water levels, flows, salinity, temperature and density within the modelling domain.

3 Development of Thresholds

3.1 North and Celtic Seas thresholds

The effect of energy at the seabed – to be completed by JNCC.

3.2 Western Mediterranean Sea thresholds

The effect of energy is a pivotal factor in determining the development of specific habitats such as rhodolith beds (Maerl) in the circalittoral as the intensity of the currents will enhance the rolling motion of specific red algae over sediments thereby stimulating the production of the algal concretion over the sediment granule resulting in the rhodolith (Bressan & Babbini, 2003). At the same time the effect of bottom currents together with other factors such as river inputs and other oceanographic factors will also contribute over very long terms to the deposition of specific sediment types and granulometries resulting in different habitat types (Tunesi & Peirano, 1985; Morri et al. 1986). Bibliographic data indicates that the coastal detritic and muddy detritic assemblages of the upper circalittoral are strongly influenced by the intensity of the bottom current typologies. In the first case medium constant currents contribute to the deposition of gravelly and sandy substrata originating from the nearby coast and infralittoral features (i.e. predominant local rocks, debris from mollusc shells, or dead bryozoan or Melobesiae) while in the second case currents of lower intensity contribute to the deposition of mud formed by terrigenous deposits over a detritic bottom (Pérès & Picard, 1959)".

To this effect, an attempt was made to use the modelled energy layers to:

a) define energy threshold values for rhodolith beds versus coastal detritic bottoms, because both habitats occur on the same type of substrate category and may be defined on the basis of differing energy levels. The resulting energy thresholds can therefore be used to model these two habitats in the final model.

b) define the energy range values for two soft bottom habitats (coastal detritic and muddy detritic) occurring in the upper circalittoral and occurring on two different substrate types. The threshold values obtained by comparing the energy layer against known distributions of these habitats could therefore be used as a second “proxy” variable to model these habitats in case substratum data entering into the model should not be exhaustive enough to do so in the first instance (each habitat-assemblage would first be modelled based on the respective substrate category and its location in the upper circalittoral [as defined by the 0.01% light layer], and subsequently the modelled habitat distribution would be checked against the defined energy threshold values).

Information regarding all types of rhodolith associations was considered for the purpose of the validation procedure and all available rhodolith association types were grouped under one category. The validation was carried out taking into account the distribution of Maerl, Facies of free Peyssonneliaceae and non-specified rhodolith associations for four location in France (Antibes-Cape d’Ail, Cannes, Ciotat and Marseilles); rhodolith, coastal detritic and muddy detritic assemblages in Italy (Tuscan archipelago and Ligurian sea) and coastal detritic, coastal detritic rhodolith and Maerl in Spain (Baleari Archipelago). All rhodolith associations were grouped together

The validation was carried out by considering only the habitat polygons characterized by a size >= 20 pixels so as to enhance the possibility that only the polygons with a high spatial significance be used with respect to the scale of elaboration. The resulting collected number or records for the various habitat types amounts to 137 but only 28 polygons of size >= 20 pixels were considered in the analysis process (Table 1).

Table 1. Habitat polygons falling within energy layers.

Habitat	N° of polygons falling in the energy layer (Avg and Pct90)	N° of polygons with >= 20 pixels (Avg and Pct90)
Muddy Detritic	26	4
Coastal Detritic	56	12
Rhodolith associations	55	14
Total	137	28

Results of the zonal statistics of the above polygons with respect to all the modelled bottom current energy layers (minimum, maximum, average and 90th percentile), constructed on 1 Km resolution, were plotted in scatter plots. The mean values of the average and of the 90th percentile energy layers were further analysed and an attempt was made to identify cut off points for high, medium and low energy for the three habitat types (all rodolith associations, coastal detritic, muddy detritic). The scatter plot of the entire habitat datasets against the average modelled energy layer, as illustrated in figure 6 below, indicates that it is not possible to discriminate different energy levels associated to the three different assemblage types. The polygons of the muddy detritic (cod 2) and rhodolith associations (cod 5) are characterised by similar minimum energy values and the rodolith associations are also characterised by similar average to medium-high energy values as those of the coastal detritic (cod 1) polygons. A similar trend is also observed when plotting the polygons against the 90th percentile modelled energy layer.

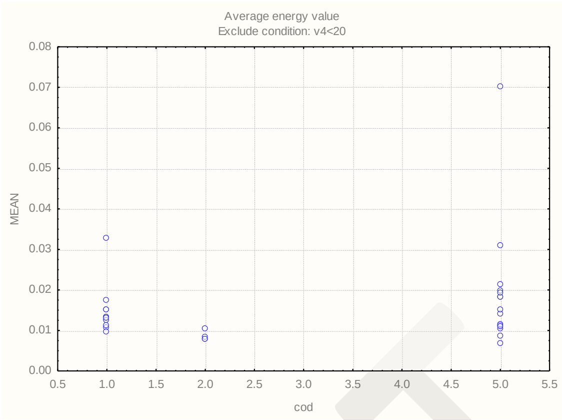

Figure 6. Scatter plot of the energy values for coastal detritic (cod 1), muddy detritic (cod 2) and rhodolith associations (cod 5) in Italian, French and Spanish waters using the model for average (bottom current) energy values.

A further attempt was also made to analyse the distribution of these polygons against the modelled energy layer involving both bottom currents and wave energy, but no significant energy differences were found capable of differentiating any of the three habitat types. It is likely that the coarse resolution of the modelled energy layer as well as the consistent data gap of the model for the inshore coastal areas hinders the application of this approach.

The results of the modelled energy output against the distribution of known habitats that are influenced by currents carried out in this specific exercise do not allow concluding on any specific energy threshold value with which to attempt modelling the three habitat categories. As a result, the initial attempt to consider mapping rodolith beds in the Western Mediterranean based on modelled energy values was abandoned. Similarly no energy threshold value was identified to differentiate coastal detritic from muddy detritic habitats, though these two habitat types can be modelled based on the substrate typology and their distribution in the circalittoral and upper circalittoral zone.

3.3 Baltic Sea thresholds

In the present analysis, the threshold between high and moderate energy was defined by the occurrence of *Fucus*-dominated communities at < 3 m depth. High energy shores typically lack dense communities of the large perennial *Fucus* species, at least in the uppermost meters. Instead, these shores are typically dominated by communities of more disturbance-tolerant filamentous algae. *Fucus* may occur deeper; hence we only looked at the presence of *Fucus* in the uppermost meters.

The threshold between moderate and low energy was defined by the occurrence of species-rich charophyte- and phanerogam communities typical for low-energy shores. The definition was set to presence of at least 5 species from these groups occurring together, which excluded low-diverse communities of more hardy species such as *Zostera marina*, *Ruppia* sp., *Potamogeton pectinatus*, *Potamogeton perfoliatus* and *Chara aspera* that occur also in higher energy.

The field data set used to set the threshold values came from a total of 902 diving transects from the Swedish and Finnish coasts, 70 from the oligo- and 832 from the mesohaline salinity zones. The data was compiled from a number of different studies, using a standard method for monitoring of phytobenthic communities in the Baltic Sea (Kautsky 1992; HELCOM 1999). In short, diving transects were placed perpendicular to the shoreline, from the shore to the deepest occurrence of macroalgae or plants and the substratum type and surface cover of all algae, plants and sessile animals were noted within depth sections in a 6-10 m wide corridor along the transect line.

For the threshold analyses, each transect section from the diving transects was classified into preliminary EUNIS classes using the BalMar tool (Backer et. al 2004, Alleco 2005). Exposure values for each transect was extracted from SWM grids with 25 m cell size, in order to get as correct value as possible for the threshold analysis.

The maximum SWM value recorded for a transect including a community type (shallow *Fucus* or species rich charophyte/phanerogam communities) was used as the upper limit of the fuzzy threshold, after removing a few extreme outliers that where apparently the result of errors in SWM layer. The 90 percentile of transects including the type was used as the lower limit of the fuzzy threshold. For both the thresholds, the 90 percentile represented an energy level below which the community type was occurring commonly, so this percentile level was regarded to be relevant.

The result from the threshold analyses is shown in Table 2. The max and 90 percentile values were generalized to the nearest 10 000 since this was regarded to be the relevant degree of precision in the datset.

Thresholds for the Baltic Sea were defined using SWM (Simplified Wave Model) ranges in two coastal areas for selected species of macro algae and vascular plants.

A dataset of 19059 data points in total was used. The data were collected during scuba diving surveys and contains both transect and point data. Transects contain several data points.

The data were collected in two areas along the Swedish Baltic coast; the counties of Östergötland (approximately 58° N) and Västernorrland (approximately 63° N). Of the 19059 points in total, 16263 were collected in Östergötland and 2795 were collected in Västernorrland. Exposure values were extracted from SWM grids with 25 m cell size.

Fifteen species of vascular plants and algae from the genera *Callitriche*, *Ceratophyllum*, *Chara*, *Zostera*, *Ranunculus* and *Potamogeton* were investigated. Outliers were removed manually for some of the species. The threshold between sheltered and moderately exposed was defined as the interval between the maximum wave exposure values for the species *Ceratophyllum demersum*, *Chara aspera*, *Pomatogeton perfoliatus* and *P. filiformis*. To establish the threshold between moderately exposed and exposed the maximum exposure values for the species *Zostera marina* and *Potamogeton pectinatus* were used.

Sheltered/moderately exposed threshold

The threshold between sheltered and moderately exposed was set to the SWM interval 40 000 to 80 000 based on maximum exposure values for the species used (table 3.3).

Moderately exposed/exposed threshold

The threshold between moderately exposed and exposed was set to the SWM interval 160 000 to 240 000 based on maximum exposure values for the species used (Table 2).

Table 2 **The defined thresholds for energy levels in the Baltic Sea. The values are fetch values from the SWM model. The last column shows the threshold values used in the model.** **Maximum SWM values for each species used for the thresholds.**

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Comment [AC4]: The SWM merged w DHI model version of the layer used? (see section 2.3)

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Species	Threshold	Maximum SWM	n
Ceratophyllum demersum	Sheltered/Moderately exposed	40002	853
Chara aspera	Sheltered/Moderately exposed	60212	158
Pomatogeton perfoliatus	Sheltered/Moderately exposed	64030	991
Potamogeton filiformis	Sheltered/Moderately exposed	81904	77
Zostera marina	Moderately exposed/exposed	174506	526
Pomatogeton pectinatus	Moderately exposed/exposed	208379	519
>25% cover			
Pomatogeton pectinatus	Moderately exposed/exposed	238594	1913

	Definition	Statistica	SWM value	Threshold value
High/moderate	Occurrence of *Fucus* communities at < 3 m depth	Max 90 percentile	673 000 522 000	680 000 520 000
Moderate/low	Occurrence of species-rich (>4 species) of charophytes/ phanerogams	Max 90 percentile	79 000 44 000	80 000 40 000

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