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Comparing the ecological relevance of four wave exposure models

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ABSTRACT

Wave exposure is one of the main structuring forces in the marine environment. Methods that enable large scale quantification of environmental variables have become increasingly important for predicting marine communities in the context of spatial planning and coastal zone management. Existing methods range from cartographic solutions to numerical hydrodynamic simulations, and differ in the scale and spatial coverage of their outputs. Using a biological exposure index we compared the performance of four wave exposure models ranging from simple to more advanced techniques. All models were found to be related to the biological exposure index and their performance, measured as bootstrapped R^2 distributions, overlapped. Qualitatively, there were differences in the spatial patterns indicating higher complexity with more advanced techniques. In order to create complex spatial patterns wave exposure models should include diffraction, especially in coastal areas rich in islands. The inclusion of wind strength and frequency, in addition to wind direction and bathymetry, further tended to increase the amount of explained variation. The large potential of high-resolution numerical models to explain the observed patterns of species distribution in complex coastal areas provide exciting opportunities for future research. Easy access to relevant wave exposure models will aid large scale habitat classification systems and the continuously growing field of marine species distribution modelling, ultimately serving marine spatial management and planning.

1. Introduction

Wave exposure is one of the main physical factors forming the marine environment in a region. Many studies have documented relationships between wave action and the distribution, abundance, diversity, composition and productivity of benthic and rocky shore communities (e.g. Lewis, 1964; Sjøtun and Fredriksen, 1995; Fonseca et al., 2002; Christie et al., 2003; Burrows et al., 2008; Bekkby et al., 2009; Hill et al., 2010; Norderhaug and Christie, 2011; Pedersen et al., 2012). Wave exposure is typically an integrative measure of the hydrodynamic conditions at a site, with both mechanical and process related influence on nearshore plants and animals (Lewis, 1964). Consequently, several qualitative and quantitative estimations of wave exposure have been developed (Ballantine, 1961; Dalby et al., 1978; Ekebom et al., 2003; Isæus, 2004; Lindgren, 2011). For instance, low to moderate wave exposure levels may have a positive effect on algae through moving fronds maximising the area available to trap light, as well as maintaining a high nutrient flow (Lobban and Harrison, 1994). Wave exposure also influences rocky shore communities by varying the amount of water that is washed upon the shore, thereby vertically structuring the intertidal community (Lewis, 1964). However, since the choice of exposure measure can affect ecological inference (Lindegarth and Gamfeldt, 2005), objective, reproducible and quantitative exposure indices are needed for comparison across studies.

Wave exposure may be modelled with methods ranging from simple cartographic to more advanced numerical wave models incorporating a range of physical processes and their interactions.

Cartographic models originated from an ecological need to explain biological distributions (Lewis, 1964). They are based on relatively basic calculations and use a small set of easily accesible input information, usually the coastline and wind data (e.g. Ekebom et al., 2003; Burrows et al., 2008). Such fetch-based models measure the length of open water associated with a site, thereby obtaining a simplified estimate of the potential wave energy for a

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specific set of study sites along the coastline (Ekebom et al., 2003). Burrows et al. (2008) presented a fetch-based method for obtaining wave exposure estimates for larger areas, potentially allowing macroecological predictions of community structure. However, simple, straight line-based fetch measures can be improved by using bathymetry to account for loss of wave energy from bottom friction (Hill et al., 2010). Although straight line-based approaches have been shown to explain ecological characteristics, they fail to incorporate diffraction, i.e. topograchically induced alterations in wave direction, potentially reducing their applicability in narrow straits, sounds and archipelagos (Ekebom et al., 2003).

A wind and fetch-based exposure model which incorporates algorithms for diffraction was developed by Isæus (2004). The first generation model, the "simplified wave model" (SWM), utilizes wind strength, fetch and empirically derived algorithms to mimic diffraction. A second version, the "frequency based wave model" (FWM), incorporates wind frequency and includes the effect of bathymetry by simulating loss of energy due to friction at the seafloor to better match wave theory. Consequently, FWM utilizes large parts of linear wave theory otherwise reserved for numerical models. Although extensively used for mapping the distribution of species and habitats in Scandinavia (e.g. Westerbom and Jattu, 2006; Bekkby and Isæus, 2008; Bekkby et al., 2008a, 2009; Florin et al., 2009; Sundblad et al., 2009; Snickars et al., 2010; Sundblad et al., 2011; Bergström et al., 2013; Sundblad et al., in press), SWM has not been compared with other wave exposure modelling techniques.

More advanced numerical wave models are well founded on physical wave theory and are derived from a theoretical perspective of how waves "behave", rather than from an ecological need to explain biological distributions. These models are based on wind forcing, diffraction, wave-to-wave interactions and loss of energy due to friction and wave breaking. Numerical wave models are often incorporated within hydrodynamic general circulation models and used operationally for forecasting the sea state (Hasselmann et al., 1988; Booij et al., 1999; Smith et al., 2001). The inclusion of the vast number of wave processes in the calculations makes them computationally intensive, which imposes ocean-wide simulations to be made at rather coarse resolutions. Their applicability along complex coast lines or inshore environments is, therefore, normally limited due to poor spatial coverage. Although it is entirely possible to set up local high-resolution numerical wave models a complicating factor, in terms of being easily accessible and user-friendly, is the need of rather intricate input data (e.g. local wave spectral data) for a proper initiation of the model. In the context of ecological studies, the use of this type of wave model is therefore often not feasible.

In this study, four methods, ranging from simple straight-line based to numerical wave models, are compared in relation to a biological exposure index. The index integrates the basic exposure levels at a site and the biology of the shoreline, thereby reflecting both the ecological relevance of the models as well as their ability to describe the predominant wave climate. The tested wave exposure models were, in increasing order of complexity; the BioEx model (Rinde et al., 2004), SWM (Isæus, 2004; Wijkmark and Isæus, 2010) and the further developed FWM, and the numerical STeady-state spectral WAVE model (STWAVE; Smith et al., 2001).

2. Materials and methods

2.1. The biological exposure index and study area

The biological exposure index used in this study was developed as an integrated measure to estimate the average wave exposure on rocky shores using species composition and abundance at the particular site, as the biota is thought to reflect average conditions over a period of time (Kruskopf and Lein, 1997).

Biological exposure indices have been frequently used in Norway. From six possible counties we selected the county of Sogn og Fjordane on the west coast of Norway as the study area for this comparison (Fig. 1), as this was the only region in which the biological data were satisfyingly well georeferenced. This is a highly productive marine area with high species and habitat diversity. It is characterized by a heterogeneous bathymetry and a wide range of wave exposure levels.

The biological exposure index in the study area was developed by Kruskopf and Lein (1997). Field data were collected during autumn 1996 and included randomly selected stations ($n = 103$) with rocky substrate, i.e. solid rock or big stones, and varying slopes ($<60^\circ$). At each station, the percent cover or number of individuals of the dominant species that were easily identifiable and known to respond to exposure were estimated and subsequently scaled to intervals of ten, ranging from 0 (not present) to 70 (very abundant). The species community consisted of 14 algae, 1 lichen and 6 animals. A preliminary measure of exposure, ranging from zero (<1 km to nearest shoreline) to six (at least one sector, 10° wide, towards the open sea), was assigned to each station based on the longest stretch of open sea before it meets land. Regression polynomials were fitted between the scaled abundance measures and the preliminary exposure values for the 21 common perennial species. All polynomials were significant at the 0.05 level, except *Fucus distichus* f. *anceps* ($p = 0.08$). The variance explained ranged from 20 to 86% with a median of 71%. The final biological exposure index was then calculated through a reciprocal process, whereby the fitted relationships were used to predict the expected abundance values. The predicted values were then used to fit new polynomials, and the process was repeated until stable values were reached, i.e. a maximum of 10% of the stations change exposure value with the smallest change of 0.25 (Kruskopf and Lein, 1997). Kruskopf and Lein (1997) compared the resulting biological exposure index which, hence, is a quantitative measure ranging between 0 and 9, with similar indexes developed in two other areas from the Norwegian coast. No difference in exposure estimates was detected (Wilcoxon paired tests), suggesting that the Sogn og Fjordane exposure index can have a more general application and that it accurately reflects the ecological composition at different levels of exposure.

2.2. The wave exposure models

The four wave exposure models ranged from very simple cartographic techniques to more complex wave models. All models produce continuous rasters as output, in this study with a spatial resolution of 50 m. Wind data were obtained from the Norwegian Meteorological Institute.

The BioEx model is a modification of the method developed by Baardseth (1970) and was designed to facilitate a geographical presentation of the exposure over large regions. It was applied in the pilot period of the (Norwegian) program for mapping of marine coastal biodiversity (Rinde et al., 2004). The model was in 2006 replaced by the SWM model, described below, which is still used in the program. BioEx is based on information about the frequency, strength and direction of winds weighted by the level of openness (given as 1–3 open 10° sectors) in each of 12 directions (i.e. 3 sectors per direction). BioEx is calculated as the sum of the index developed at three spatial scales; local (sectors with a radius of 500 m), fjord (7.5 km radius) and ocean (100 km radius). When summing the three different values, ocean exposure is weighted ten times higher than fjord exposure, which in turn is weighted ten times higher than local exposure. The resulting value