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Wave climate off the Swedish west coast

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ABSTRACT

This paper presents and discusses the wave climate off the Swedish west coast. It is based on 8 years (1997–2004) of wave data from 13 sites, nearshore and offshore, in the Skagerrak and Kattegat. The data is a product of the WAM and SWAN wave models calibrated at one site by a wave measurement buoy. It is found that the average energy flux is approximately 5.2 kW/m in the offshore Skagerrak, 2.8 kW/m in the nearshore Skagerrak, and 2.4 kW/m in the Kattegat. One of the studied sites, i.e. site 9, is the location of a wave energy research site run by the Centre for Renewable Electric Energy Conversion at Uppsala University. This site has had a wave power plant installed since the spring of 2006, and another seven are planned to be installed during 2008. Wave energy as a renewable energy source was the driving interest that led to this study and the results are briefly discussed from this perspective.

1. Introduction

Ocean wave energy has the potential to contribute large amounts of renewable energy to the world's societies [1]. Today several technologies have been tested at large scale and in real sea conditions, see e.g. [2–4], and some are nearing a commercial stage. In order for the wave energy converters (WECs) to be competitive, they have to be adapted to the local wave climate. The more detailed knowledge one has of the wave climate of a particular site, the easier it is for developers of wave energy systems to optimize the technology and make it competitive.

The present study describes the specific wave climates at 13 locations off the west coast of Sweden, in the continuation of the North Sea called Skagerrak and Kattegat. It summarizes 8 years of wave data covering the years from 1997 to 2004. The investigated sites are spread out over varying depth and distance from land, from north to south in order to provide a comprehensive picture of the overall wave climate of the Swedish west coast. The wave climate of the sites are presented in terms of significant wave height, energy period, dominating wave directions, energy flux, annual energy distribution, the occurrence of extreme wave conditions, and statistical hundred-year waves. The model wave data has been calibrated with on-site measurements carried out by Uppsala University at one of the studied nearshore sites, i.e. site 9, see Fig. 2. The results are discussed from a wave power perspective, as this was the driving interest that led to this study and since this perspective raises questions and visualizes aspects that are critical to wave power technology.

It is well known that the wave climate off the west coast of Sweden is relatively calm in comparison to the coasts facing the oceans of the world. The Norwegian coast, only 300 km to the west, has an average wave climate with an energy flux up to an order of magnitude higher [5]. Moreover, the average total deepwater wave power resource along the Atlantic coasts of Europe amounts to about 290 GW [6]. Yet in spite of this it has been presumed that the available wave power resource of the Skagerrak can still be a viable source of renewable energy from a technical and economical perspective, mainly attributed to the high density of energy in ocean waves [7]. When the results of this paper are discussed from the perspective of a wave energy converter (WEC) the technology in mind is that described by Danielsson et al. [8] and Leijon et al. [9]. In brief the WEC consists of a linear generator of limited stroke length. The generator is located on the seabed and is connected, via a line, to a point absorber on the surface. The discussed points are, however, with few exceptions valid and important for all wave energy converters known to the authors.

Although some recent studies have been carried out on the wave fields and wave energy resource of the Baltic sea, see e.g. [10–12], the documentation that can be found on the wave climate of Skagerrak and Kattegat is fragmented in time and sparse in spatial resolution. Documentation on the wave climate off the Swedish west coast saw most activity in the 1980s during the Swedish Wave Measuring Programme. The measurements were carried out by the Swedish Meteorological and Hydrological Institute (SMHI) using Wave rider buoys and Echo sounders [13,14]. Registrations of the wave climate along the west coast are limited to four locations and

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concentrated on two areas: Trubaduren, Fladen, and Läsö near Gothenburg; and Väderöarna further north. The measurements on these sites have not been carried out simultaneously, but rather each station has been running for a few years with some overlap. The longest time series are found at Trubaduren covering the years from 1978 to 2004 [15], though the available documentation only covers the period from 1 October 1978 to 28 February 1986 [14]. The information from Trubaduren is given only in the form of scatter diagrams. The measurement station Väderöarna is of special interest here since it can be compared to one of the measurement sites in this paper, i.e. site 4, see Fig. 2. During the time period from 1 April 1980 to 13 January 1981 the documented average significant wave height, *Hs* (sometimes given as H_{m0} to show its origin in spectral analysis) at Väderöarna was 2.46 m, and the mean wave period was 5.42 s. The highest expected wave for a 100 year period at the same location was calculated to 18.3 m, however, as the author points out; the calculation is based on less than one year of measurements, which gives a rather low reliability [14]. As a rough estimate, the mean energy flux in the Skagerrak region of the Swedish west coast has been calculated to be about 6 kW/m [13]. In Jönsson et al. [16] a hindcast model has been used to calculate the wave fields in the Baltic Sea and around Sweden. This hindcast study used data for one year (1999) and the results are compared to wave measurements made by the Swedish Meteorological and Hydrological Institute. A comprehensive report on the Swedish wave energy research up until 1987 can be found in Claesson [5].

2. Wave data

The wave data that this study has been based on was purchased from Fugro OCEANOR of Norway. The data consists of time series of relevant wave parameters representing every 6-h time period during the years 1997–2004. The data have been collected through the combined information from on-site wave-buoys, satellites, and a wave and wind model, WAM [17], run by the European Centre for Medium-range Weather Forecast. The information from the wave-buoys is used to calibrate the satellite altimeter data, and the satellite data is, in turn, used to calibrate the WAM model. Five of the studied points are located near shore at depths of approximately 15–30 m. At these locations, where the geography of sea floor and coastline will have a larger impact on the waves, the SWAN (Simulating Waves Nearshore) model has been used on the calibrated WAM data and a detailed description of bathymetry and coastline has been used. For a more thorough description of the wave data generation see Barstow et al. [18]. During the spring of 2005 the Swedish Centre for Renewable Electric Energy Conversion of Uppsala University deployed a wave measurement buoy at site 9 [19]. Collected wave data from continuous measurements of that buoy were used to calibrate the data generated by the SWAN model in order to increase the accuracy of the modeled nearshore data. A qualitative view of the result of the calibration, in terms of significant wave height, energy period, and energy flux, is seen in Fig. 1. The result shows that the only significant difference between measured and simulated values is for the energy period at very small wave heights. This is due to the poor frequency response of the wave measurement buoy at low frequencies, as well as to difficulties in the simulations of very weak sea states. In other words, the uncertainties are greater in both measurements and simulations during weak sea states.

3. Extreme wave calculations

Extreme wave calculations have been performed according to the recommendations of the International Association for Hydraulic Research [20]. Data sets have been chosen from all sites through the peaks over threshold method (POT), and the threshold level resulting in the best goodness of fit has been chosen throughout. The data has been fitted, by means of maximum likelihood, to the truncated three-parameter Weibull distribution:

$$F(Hs) = 1 - \exp\left[-\left(\frac{Hs - A}{B}\right)^C + \left(\frac{Hs_0 - A}{B}\right)^C\right] \quad (1)$$

where *F* is the cumulative distribution function (CDF), *Hs* is significant wave height, Hs_0 is the threshold significant wave height, *A* is the location parameter, *B* is the scale parameter, and *C* is the shape parameter. The truncated three-parameter Weibull distribution was chosen over the non-truncated case because, as shown by quantile–quantile plots, it proved more stable towards the highest waves where the regular three-parameter Weibull distribution in general overestimated the wave heights. The General extreme value distribution was also evaluated but suffered the same drawback as the regular three-parameter Weibull distribution. The Kolmogorov–Smirnov test was used to evaluate the goodness of fit between the data and the distribution. The resulting significance level is above 95% for all sites with the exception of site 3 for which the significance level is 87%.

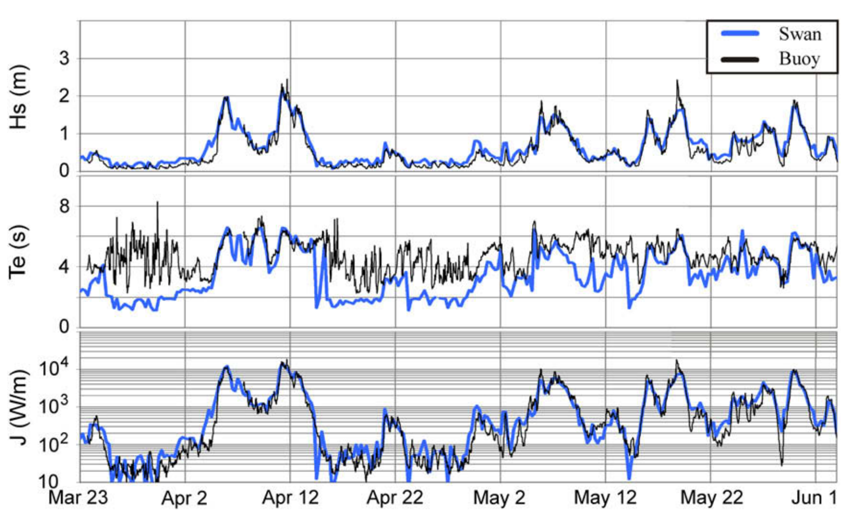

Fig. 1. Comparison between the wave parameters simulated by the SWAN model and those measured by a wave measurement buoy located at site 9. *Hs* is significant wave height, T_E is energy period, and *J* is energy flux.