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Wave power variability over the northwest European shelf seas

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HIGHLIGHTS

- ▶ We simulate the wave climate of the NW European shelf seas over a 7 year period.
- ▶ We apply a high resolution 3rd-generation wave model.
- ▶ We quantify spatial patterns of uncertainties in estimating the wave power resource.
- ▶ Uncertainty is considerably greater over winter months.
- ▶ There is a positive correlation between winter wave power and the NAO.

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ABSTRACT

Regional assessments of the wave energy resource tend to focus on averaged quantities, and so provide potential developers with no sense of temporal variability beyond seasonal means. In particular, such assessments give no indication of inter-annual variability – something that is critical for determining the potential of a region for wave energy convertor (WEC) technology. Here, we apply the third-generation wave model SWAN (Simulating Waves Nearshore) at high resolution to assess the wave resource of the northwest European shelf seas, an area where many wave energy test sites exist, and where many wave energy projects are under development. The model is applied to 7 years of wind forcing (2005–2011), a time period which witnessed considerable extremes in the variability of the wind (and hence wave) climate, as evidenced by the variability of the North Atlantic Oscillation (NAO). Our simulations demonstrate that there is much greater uncertainty in the NW European shelf wave resource during October–March, in contrast to the period April–September. In the more energetic regions of the NW European shelf seas, e.g. to the northwest of Scotland, the uncertainty was considerably greater. The winter NW European shelf wave power resource correlated well with the NAO. Therefore, provided trends in the NAO can be identified over the coming decades, it may be possible to estimate how the European wave resource will similarly vary over this time period. Finally, the magnitude of wave power estimated by this study is around 10% lower than a resource which is used extensively by the wave energy sector – the Atlas of UK Marine Renewable Energy Resources. Although this can partly be explained by different time periods analysed for each study, our application of a third-generation wave model at high spatial and spectral resolution significantly improves the representation of the physical processes, particularly the non-linear wave-wave interactions.

1. Introduction

To reduce greenhouse gas emissions and aid sustainable development, there is an urgent need to support our electricity generating capacity through the development of low carbon technologies, particularly those generated from renewable sources [1]. The ocean is a vast and largely untapped energy resource – wave energy alone has been estimated as around 2 TW globally [2]. A significant portion of this wave energy could be exploited by a range of wave energy converter (WEC) technologies [3], and so wave energy has been highlighted as a key contributor to the future global energy mix. However, progress from full-scale testing to commercialisation of wave energy projects has been relatively slow, partly due to the financial risks associated with uncertainty in quantifying the wave energy resource at a variety of timescales. This is in direct contrast to assessment of the tidal energy resource – tidal currents are largely driven by astronomical forces, and so can be accurately predicted over long time scales [4]. Beyond seasonal trends, waves are largely stochastic, and so it is difficult to quantify the long-term wave resource for a region at a variety of timescales. With likely future changes in the wave energy resource due to climate change [5–7], this uncertainty in resource assessment will increase for proposed future large-scale WEC array scenarios that have been identified in marine energy roadmaps (e.g. [8]).

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One of the most popular data sources used by developers for quantifying the UK wave energy resource is the Atlas of UK Marine Renewable Energy Resources [9]. Similar wave resource assessments have been made for Europe [3], the Black Sea [10], the Baltic Sea [11], the Canary Islands [12], Australia [13], China [14], the United States [15], and globally [2]. Regardless of the accuracy of such studies in terms of data quality and availability, and the spatial, temporal, and spectral resolution of the underlying wave models, most assessments provide potential developers with only averaged quantities such as the annual mean significant wave height and wave power, and give no indication of temporal variability beyond seasonal means [16]. Of the few studies which do analyse how the temporal distribution of wave energy resource at seasonal and inter-annual scale affects site selection, Cornett [17] analysed variability of the global resource at a relatively coarse ($1.25° \times 1°$) model resolution, and Liberti et al. [18] provide a study of wave variability for the Mediterranean. Akpinar and Komurcu [10] provide a thorough resource assessment for the Black Sea, examining monthly, seasonal, and annual distributions of wave height and wave power. However, most studies give no indication of the inter-annual variability of the wave resource, something that is critical for even a superficial assessment of the wave energy potential of a region. Further, the suitability of a particular location cannot be matched to a particular WEC technology [19], since these resource assessments provide no information on the spectral properties of the waves. Rather, relatively expensive high-resolution nested model studies [20], or expensive *in situ* monitoring programmes [21], are required to make even an initial assessment of the wave energy potential of a region. The present research aims to address such issues by providing a thorough assessment of the wave energy potential of the NW European shelf seas, a region where many wave energy projects are under development. In particular, this study focusses on temporal variation of the wave resource over seasonal and inter-annual timescales, and assesses the spectral properties of the waves for a range of contrasting locations.

2. Study region

The NW European shelf sea has been selected for this study as it is one of the most energetic shelf sea regions in the world [2,22]. Due to its large wave energy resource, and the prominence of European nations (particularly the UK) in developing wave energy technologies [3], many wave energy test sites exist, and many wave energy projects are under development throughout this region, with selected sites shown on Fig. 1, and further details provided in Table 1. These eight locations form the basis of the detailed site-specific resource assessment in Section 4.2, and further details of the sites can be found in Bahaj [1], Reeve et al. [6], Mouslim et al. [23], Beels et al. [24] and Aquamarine Power [25]. These sites are located in regions of considerable variations in water depths and wave exposures, and so enable a contrast in wave properties to be made for a wide range of environments. In addition to being a suitable region for exploitation of the wave energy resource, the oceanography of the northwest European shelf seas is well documented, and extensive datasets are available, including wave buoy data, to validate models of the region. Further, since many countries have coastlines bordering the NW European shelf seas, this increases the relevance, and hence impact, of this study.

The NW European shelf seas, located on the northeastern margin of the North Atlantic, are generally shallower than 200 m (Fig. 1). The Celtic Sea, Malin Sea and northern North Sea are exposed to Atlantic waters, with water depths in the range 100–200 m, with the exception of the deeper (600 m) Norwegian Trench in the northeastern North Sea. The Celtic Sea borders the Irish Sea to the north, a semi-enclosed water body. To the east of the Celtic Sea, the English Channel connects to the southern North Sea; and to the south of the Celtic Sea lies the Bay of Biscay.

The climate of the NW European shelf is dominated by the atmospheric polar front [26]. The instability of this front causes depressions to form, tracking across the North Atlantic and following a preferred route which passes between Iceland and Scotland. There is considerable variation in the wind climate around the NW European shelf seas, but the strongest winds generally emanate from the west and south, and the mean winds from the southwest [27]. Wind speeds tend to be highest to the northwest of the British Isles (closest to the depression tracks), decreasing towards the south and east. An annual cycle of higher wind speeds in winter and lower speeds in summer reflects the seasonally varying strength of the large-scale atmospheric circulation [26]. The strong background flow leads to high mean wave energy over the shelf seas and the variability results in a wave climate with considerable extremes [28]. Considerable interannual variability in the synoptic-scale circulation over the Atlantic is described by the North Atlantic Oscillation (NAO) index [29], and a previous study has demonstrated that there is a positive correlation between the NAO and the mean wave power for an area off the north coast of Scotland [30]. In regions of the shelf seas exposed to the Atlantic, the orbital velocity of the longer-period (swell) waves penetrates to the sea bed [31]. Where fetch length is sufficient, the wave distribution over the shelf seas broadly maps to the wind distribution [28]. Due to the dominant southwesterly wind direction, many regions of the NW European shelf seas are relatively sheltered from wind effects and hence experience relatively low wave energy, particularly the western seaboard of the North Sea (sheltered by the UK land mass) and the northern half of the Irish Sea (sheltered by Ireland).

3. Methods

3.1. Wave model

The third-generation spectral wave model SWAN (Simulating Waves Nearshore) was used to simulate wave climates over the North Atlantic, including the NW European shelf seas. SWAN is an Eulerian formulation of the discrete wave action balance equation [32]. The model is spectrally discrete in frequencies and directions, and the kinematic behaviour of the waves is described by the linear theory of gravity waves. SWAN accounts for wave generation by wind, non-linear wave-wave interactions, white-capping, and the shallow water effects of bottom friction, refraction, shoaling, and depth-induced wave breaking.

The evolution of the action density N is governed by the wave action balance equation which, in spherical coordinates, is [32]

$$\frac{\partial N}{\partial t} + \frac{\partial c_\lambda N}{\partial \lambda} + \frac{\partial c_\phi N}{\partial \phi} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \tag{1}$$

where c_λ and c_ϕ are the propagation velocities in the longitude (λ) and latitude (ϕ) directions, σ is frequency, θ is wave direction, and S_{tot} represents the source terms, i.e. generation, dissipation, and non-linear wave-wave interactions. For this application, the wave energy spectrum at each grid point was divided into 40 discrete frequency bins and 45 discrete direction bins for both scales of model simulation (North Atlantic and NW European shelf seas – see Section 3.3). The lowest modelled frequency was 0.05 s^{-1} (period T = 20 s), and the highest frequency resolved by the model was 2 s^{-1} (T = 0.5 s). Outside of this range, the wave spectrum was imposed, hence the effects of lower and higher frequencies are included in the simulations [33].

Version 40.85 of SWAN was run in third-generation mode, with Komen linear wave growth and whitecapping, and quadruplet