The influence of wind gustiness on estimating the wave power resource

Goward Brown, Alice; Neill, Simon; Lewis, Matthew

International Journal of Marine Energy

Published: 10/11/2013

Publisher's PDF, also known as Version of record

International Journal of Marine Energy 3–4 (2013) e1–e10

Contents lists available at ScienceDirect

International Journal of Marine Energy

journal homepage: www.elsevier.com/locate/ijome

The influence of wind gustiness on estimating the wave power resource

Alice J. Goward Brown *, Simon P. Neill, Matt J. Lewis

School of Ocean Sciences, Bangor University, Menai Bridge, Isle of Anglesey LL59 5AB, UK

ARTICLE INFO

Keywords:
Wave power
Wave climate
Wave model
High frequency variability
North sea

ABSTRACT

There are many uncertainties associated with the wave models used to generate regional wave energy resource assessments. One of these sources of uncertainty is the temporal resolution of the wind input. Wave models are typically forced with 3-hourly synoptic wind fields. In reality, winds are highly turbulent and exhibit high spatial and temporal variability. Therefore, by using 3-hourly wind fields to force wave models, much of the high frequency nature of the wind climate is not captured, and this could lead to substantial errors when estimating the wave energy resource of a region. Until now, research has focused on the importance of spatial model resolution, with little attention given to the importance of temporal resolution. Here, we use the SWAN wave model to simulate an idealised storm event within an idealised model domain characteristic of the North Sea. The extent to which fluctuating wind affects wave power is examined, with a test case where wind, in the absence of gustiness, was input as the control. Wave power is a function of the wave period and the square of wave height, both of which are altered as a result of high frequency wind input. Our results indicate that, for this idealised study, the inclusion of wind variability at sub-hourly time-scales can lead to a difference in wave height of up to 35%, which corresponds to a difference of up to 56% in simulated wave power. Consequently, understanding and accurately simulating the high frequency nature of winds can improve the accuracy of regional wave energy resource assessments.

* Corresponding author.
E-mail address: a.j.gowardbrown@bangor.ac.uk (A.J. Goward Brown).

2214-1669/$ - see front matter
http://dx.doi.org/10.1016/j.ijome.2013.11.007

1. Introduction

Increased awareness of the need to combat climate change through reducing carbon emissions has driven government investment in the development of low carbon technologies [1]. The energetic environment of our shelf seas provides us with an opportunity to exploit the tidal and wave energy resource, and it has been estimated that the global wave power resource is around 2TW [2]. However, progress is slower for wave technology than it is for tidal stream technology, due to the stochastic nature of the wave resource. Tidal currents are primarily driven by astronomical forces which allow them to be predicted with accuracy over long time periods [3,4]. In contrast, the wave energy resource is difficult to quantify beyond seasonal trends. Waves are largely driven by the prevailing wind field. The fluctuations within this wind field impact the wave resource – this change is particularly evident in the seasonality of the wave resource, which is much more energetic during winter months in contrast to the summer months [5]. Upfront investment is required to support developments in marine renewable technologies. The ability to accurately quantify the resource, and to understand the environment of proposed wave energy extraction sites, is important for developers and investors. Increased awareness of developments in the marine renewable energy industry is reflected in the scientific literature [6]. In particular, oceanographic modelling has an important role in advancing the development and progress of the marine renewable industry, since such models can be used to quantify the resource over various timescales, and so aid site selection. Models are validated using in situ and experimental data, and model outputs help inform our understanding of the natural environment. However, when comparing these model outputs to observed data, it is often found that wave models have difficulty accurately predicting extreme wave height values, and that wave models often underestimate larger wave events [7–9]. Being able to reduce wave model uncertainty is important so that we can have more confidence in wave model results – and so have more confidence in simulated wave energy resource assessments. A resource popular with developers is the Atlas of UK Marine Renewable Energy Resources [10]. However, this product only provides developers with mean wave power, and does not include detailed spatial and temporal variability beyond seasonal timescales; Neill and Hashemi [5] show that it is important to consider inter-annual variability when assessing the wave energy resource over long time periods, for example when considering long term trends in climatic indices such as the North Atlantic Oscillation. Wave growth occurs when the wind speed exceeds the phase speed of the waves [11,12]. Traditionally, wave models are forced with 3-hourly synoptic wind fields; subsequently, high frequency wind gusts and their impact on the wave climate, are not being captured. The aim of our idealised study is to determine the importance of high frequency wind forcing on the simulated wave energy resource. The results of this study are also relevant to model simulations of wave-induced sediment transport, and for quantifying mean and extreme wave impacts on coastal structures.

2. Theory

2.1. The study region

The model region selected for this study is the North Sea, a semi-enclosed basin with an area of 575,000 km^2 located between the United Kingdom, the European continent and the Scandinavian peninsula. Neill and Hashemi [5] demonstrated that, although the wave energy resource of the North Sea is relatively modest, there is low inter-annual and intra-seasonal variability in the resource compared to other regions of the northwest European shelf seas; the North Sea could therefor be a reliable wave energy resource. However, the North Sea is known for its stormy nature and attempts have been made previously to accurately model extreme wave heights in this area [8,13,14]; application of this work to the wave power industry has not yet been considered. Beels et al. [15] investigated the wave power resource of the North Sea and compared it with the north and south coasts of the UK. They concluded that, whilst the North Sea is certainly not as dynamic as the other shelf sea regions which surround the UK, areas to the west of Norway in particular do exhibit a certain amount of wave energy potential. Defining high frequency wind fluctuations will be more important for areas with less energetic wave climates, like the North Sea, than it would be for areas already earmarked for first generation wave energy extraction. As wave energy technology improves, the development of devices in less dynamic environments is likely to increase. In addition, wave energy devices in more quiescent environments will not need to be engineered to withstand the storms which more exposed shelf sea regions are subject to. Subsequently, through being able to accurately quantify the wave resource, we can help provide a clear pathway for future wave energy extraction.

2.2. The wave energy resource

Surface waves are a dominant oceanographic feature, driven by the prevailing wind. Fluctuations within this wind field will have a subsequent impact upon the wave energy resource [11]. Typically, wave models are forced with 3-hourly wind fields, and so higher frequency fluctuations within the wind field are not captured. Past research highlights concerns in the extent of wave variability which is not being resolved by wave model outputs [11,14,16,17]. Wind generated waves can be subject to changes as a result of external forcing such as the fluctuations in the North Atlantic Oscillation, although the extent of this influence depends upon location [5,18,19]. These low- and high-frequency fluctuations need to be accounted for in the design of marine renewable energy technologies, in order to engineer the most efficient turbines, and to aid in site selection. Understanding wave influence and extent is also useful in determining some of the forces which marine current turbines will be subject to over the lifetime of the device.

2.3. Wave models

Increased computing power over the last decade has facilitated the generation of high frequency wind data for use in wave models. Traditionally, wave models are forced with 3-hourly data output from atmospheric models. This raises the following questions: 'How much variability is being missed by this 3-hourly wind forcing?' and 'Does including this high frequency variability have a significant impact on the wave model outputs?' The consequence of wind variability on the growth of wind waves has been previously considered. Results have demonstrated that wave growth rate, and subsequently wave energy, are both affected by high frequency wind variability [11,12,14,16]. This theory has application for storm surge modelling, ocean circulation modelling, and potentially wave forecasting.

3. Methods

There were several stages in this study. A high frequency wind time series was obtained from the FINO-1 research platform in the North Sea and was analysed to determine the distribution of wind variability with respect to the mean. As a result of this analysis, an idealised wind field was generated for a 14 h storm event. This wind field was used to force the wave model SWAN in order to understand the importance of increasing wind variability and the impact that this variability has on simulated wave heights and wave power estimates.

3.1. The SWAN wave model

SWAN (Simulating WAves Nearshore) is a third generation wave model, and was used in this study to simulate the impact of high frequency wind fluctuations on the wave climate of an idealised domain. The SWAN model accounts for refractive propagation, is driven by boundary conditions and winds, and includes the processes of wind generation of waves, whitecapping, non-linear wave–wave interactions, depth-induced wave breaking, and bottom dissipation [20].

3.2. Data sources

3.2.1. Wind data

The wind data used for analysis was obtained from the FINO-1 research platform in the German Bight. The data set is comprised of wind speed and direction at 1 min temporal resolution for the whole of 2007.

3.3. Analysis of real wind data

In order to correctly apply the results from the initial idealised experiments, wind variability needs to be characterised. Wind direction and wind speed data from the German Bight, was used for this analysis. The wind speed measurements from 30 m above sea level at the FINO-1 platform were extrapolated to 10 m above sea level using the method proposed by Karagali et al. [21]. The extrapolation is based upon a logarithmic relationship between the wind speed at 30 m and the height of the sea surface (Eq. (1)), where $U2$ is the wind speed at the height we are extrapolating to, $U1$ is the original wind speed, $z2$ is the height of the new wind speed, $z1$ is the height of the old wind speed, and $z0$ is the sea roughness length.

$$U2 = U1\,\log\frac{\left(\frac{z2}{z0}\right)}{\log\frac{z1}{z0}} \tag{1}$$

After extrapolation, a 3-hourly average of the wind speed was created to compare against the original data in order to investigate the variability which is not resolved by the 3-hourly wind fields, see Fig. 1.

The 3-hourly wind averaged data and original 1-min wind data were statistically analysed to determine the relationship between high frequency wind data and 3-hourly averaged wind data. The normal distribution of the high frequency fluctuations and the 3-hourly averaged wind field data was checked using both the t-test and z-test statistical methods. For both of these tests, a significance level of 5% was used. Being able to characterise the wind data in this way is important for future work, where randomly sampled mean wind speed data will be applied to real wind data in order to generate a higher resolution wind field to force a SWAN model.

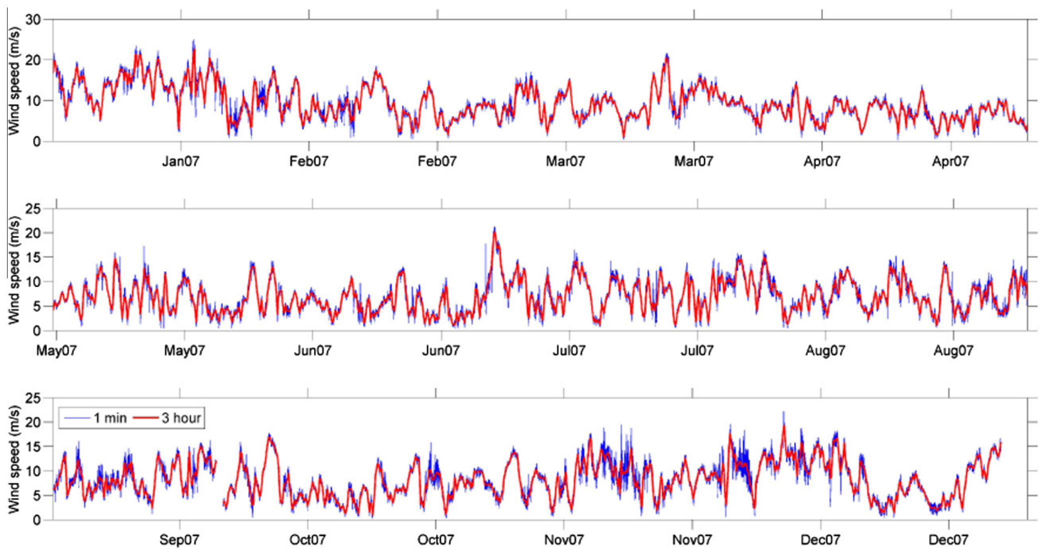


Fig. 1. 3 hourly averaged wind data (red line) plotted against the original 1 min data (blue line) for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Modelling the effects of a synthetic wind field within an idealised North Sea model domain

SWAN was forced using a simulated wind field with varying gustiness for a 14 h storm event over an idealised North Sea model domain, similar to that used in previous research [22], where the width of the domain is 550 m, the length is 1000 km, and the (constant) depth is 75 m. This size of model domain was used in order to observe the effect of potential temporal wind variability on a simulated storm wave climate. Using a method similar to other such studies [12,16], a Gaussian function was used to represent the temporal variability of the magnitude of the wind storm event (Fig. 2). The wind was initially input at 2 m/s, reaching a maximum of 22 m/s and returned to 2 m/s over the duration of the 14 h storm event. Onto this curve, a percentage of the wind speed between 0% and 90% was applied at each time step, representing wind variability or 'gustiness'. Time steps of 5 min, 30 min and 1 h were simulated for comparison. To maintain a fair test in this idealised case, the wind gusts were applied above and below the mean wind speed systematically so that a true assessment can be made. It was important that the mean wind input was unchanged for each of the tests. The resultant significant wave height and wave period outputs were then averaged over the whole model domain, and the spread of data observed. This method is intended to simulate potential temporal uncertainty effects on a synthetic wave climate. This information was then used to calculate the wave power using Twidell's equation for wave power, Eq. (2) [23].

$$P = \frac{\rho g^2 Hs^2 Te}{64\pi} \tag{2}$$

Importantly, wave power (P) is related to the square of the significant wave height (Hs) multiplied by the wave period (Te). Subsequently, even small changes to the wave height will result in a two-fold impact on wave power.

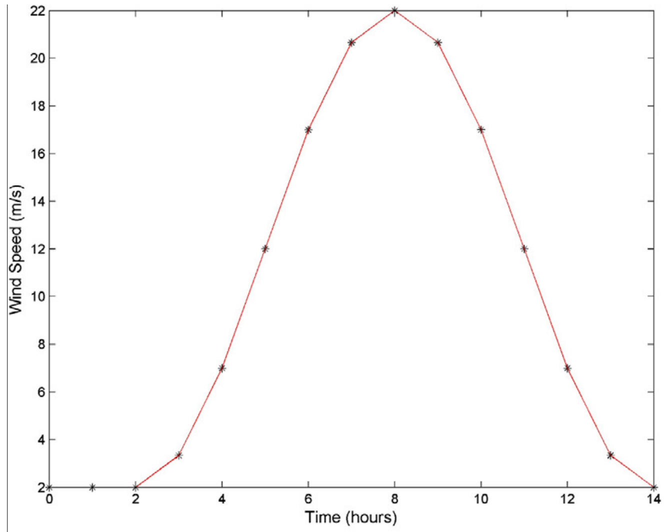
4. Results

4.1. Real wind data

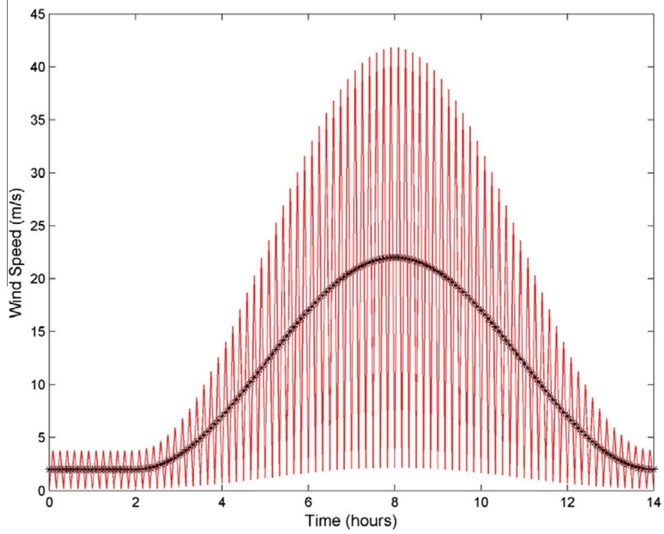
From our analysis of the FINO-1 wind data, it is possible to see that by only inputting 3-hourly wind data into wave models, much of the high frequency variability is not being resolved (Fig. 1). In particular, there is more wind variability not being captured during winter months, in contrast to summer months (Fig. 3). This is important to consider, since it is during winter months that the UK experiences a peak in the wave power resource [24]. Our analysis of wind data showed it to be normally distributed, and as such allowed the use of a Gaussian distribution for the generation of the synthetic wind data. The extent of variability around the 3-hourly mean was also examined: the minimum amount of wind variability about the mean during this time period was 29%, and the maximum amount of variability about the mean was 100%. As such, in the next stage of this study we considered gustiness values between 10% and 90% about the mean.

4.2. Impact of synthetic wind variability on simulated wave power and wave orbital velocity

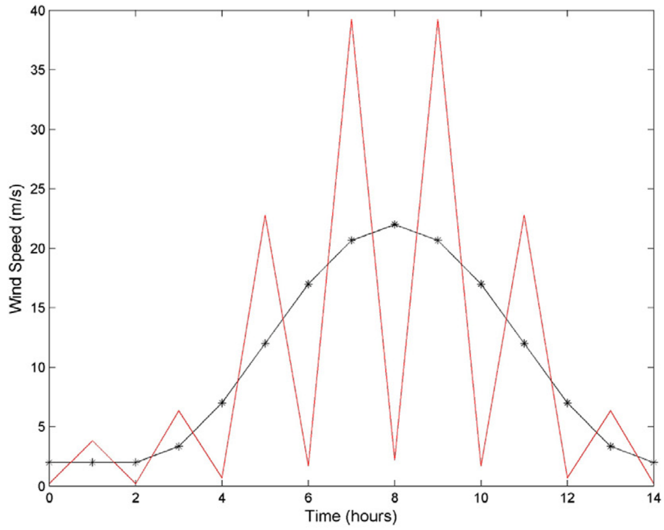
In this idealised experiment, two questions were addressed: 'What is the impact of reducing the wind time step on the simulated wave variables?', and 'To what extent does wind variability influence the simulated wave power?' The maximum wave height for each test is displayed in Table 1. From these results, it is possible to calculate the percentage difference between these maximum values for each test. The difference in values as a result of changing the model time step could be as large as 35%. Similarly, if the time step remains constant, the largest difference in wave heights as a result of changing the extent of variability around the mean was 17%. Using the maximum values of wave height and wave period for each test, the maximum impact that changing wind time step has on the wave power over the domain was calculated, demonstrating that without the use of higher frequency wind input in wave model simulations, wave power could be underestimated by up to 56%.



(a) Mean wind field input with no variability



(b) Mean wind field input with 90% variability for a 5 minute timestep



(c) Mean wind field input with 90% variability for a 60 minute timestep

Fig. 2. Examples of wind input.

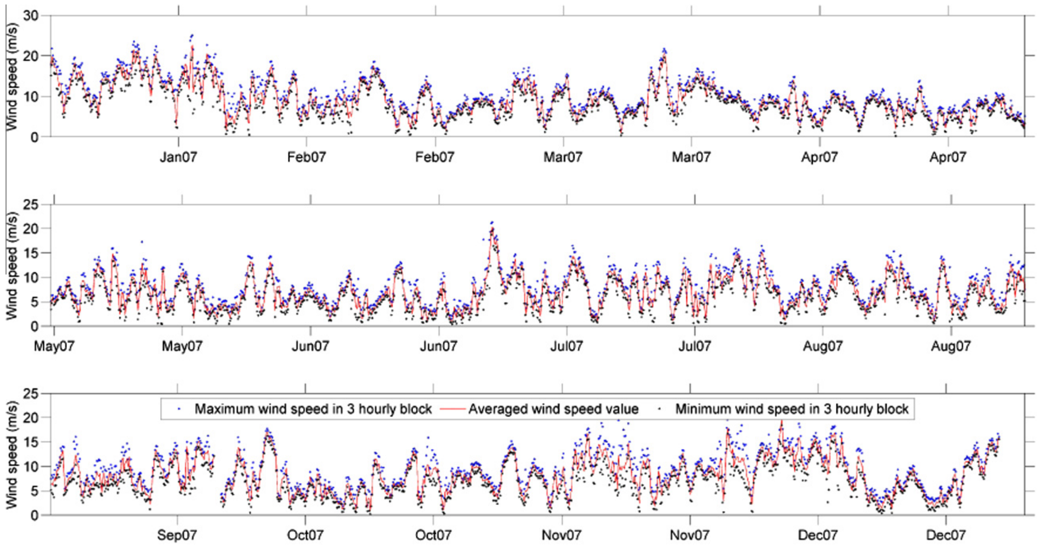


Fig. 3. Maximum and minimum 1 min wind speed values observed over each 3 h period during 2007.

Table 1
Maximum wave height output in metres for all tests.

Wind variability %	Wind time step (min)			
	5	30	60	180
Control (0)	4.40	4.47	4.29	3.64
10	4.45	4.41	4.37	3.54
20	4.43	4.42	4.32	3.46
30	4.46	4.47	4.34	3.38
40	4.51	4.53	4.44	3.29
50	4.58	4.61	4.51	3.21
60	4.70	4.71	4.63	3.19
70	4.86	4.85	4.77	3.24
80	5.03	5.03	4.94	3.35
90	5.24	5.23	5.14	3.49
Overall maximum	5.24	5.23	5.14	3.64

The results have been converted into wave power values to be plotted (Fig. 4). The results clearly show the relationship between wind input and wave power. As the wind variability about the mean wind speed increases, the spread of potential values for the simulated wave power similarly increases. These values initially appear to be negligible for low values of wind variability (<50%). However, it is important to remember that small changes in wave height will have a two-fold impact on the calculated wave power. As the wind input time step decreases, so does the spread of the potential wave power results, thereby leading to more accurate simulations of the wave power resource. Subsequently, quantifying these stormy weather patterns is important for establishing more accurate wave power estimates.

The key message shown by Fig. 4 is that the inclusion of high frequency wind variability in wave models increases the spread of potential values for simulated wave power and wave height. This, combined with the reduction in the wind time step, narrows the spread of results, enabling more accurate wave power estimates. As such, it can be summarised, that high resolution wind input is crucial for improving confidence in wave power estimations. In addition, changes in the wave climate will also affect wave orbital velocities and associated bed shear stress [25]. Changes in wave orbital velocities could be an important consideration for tidal turbine efficiency in strong tidal flow regions such as the Pentland Firth, and changes in bed shear stress could have important impacts on the sediment dynamics of shallow exposed regions, such as Dogger Bank in the North Sea.

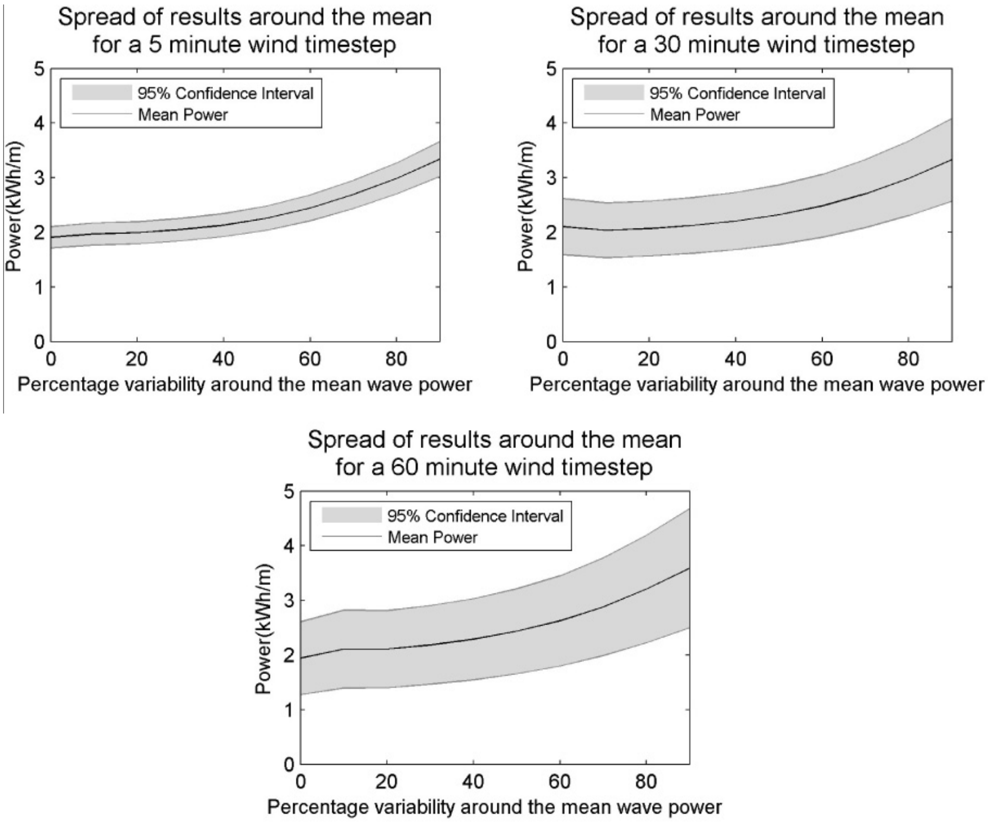


Fig. 4. The spread of values for wave power and wave height as a result of varying gustiness.

5. Discussion

The aim of this study was to investigate how altering the wind input influences modelled wave parameters. As you would expect, changing the wind time step narrowed the spread of potential values for significant wave height. Subsequently, by using higher frequency wind data, more confidence can be placed in wave power estimations. Using sub-hourly wind data, we found a maximum difference in the mean wave power of 23%. Similarly, using wind fields with a wind time step of less than 3 h shows a maximum difference in wave power values of 56%. Furthermore, the high frequency wind data obtained from the FINO-1 research platform suggests that wind variability around the mean wind values could be as large as 100%. Although this data was obtained from just one area in the North Sea, it is likely that this considerable variability is being missed from wind recorded elsewhere, particularly in more exposed regions such as the North Atlantic. Our results show that by not accounting for these extreme values of wind variability, wave heights could be underestimated by up to 17%. Spring, summer, early autumn and December extreme wind values lie relatively close to the mean, whilst during late autumn and winter the spread of extreme values around the mean increases (see Fig. 3). In general, results show that the greatest amount of uncertainty lies within the winter months. Using wind input with this degree of uncertainty during what would be the most productive time of year for the wave power industry, wave heights will not be correctly modelled, and this could effect the wave power estimates for a region. This idealised study has provided the foundation for future work which will apply high frequency wind gusts to two-dimensional wind fields, enabling us to model a more realistic scenario which will include directional input over a longer time period. It is hoped that through this work we will be able to solve the problem of extreme wave height under-prediction by wave models and, alongside other studies [5], aid wave power development by helping to more accurately quantify the wave power resource, enabling more confidence to be placed in wave power estimates.

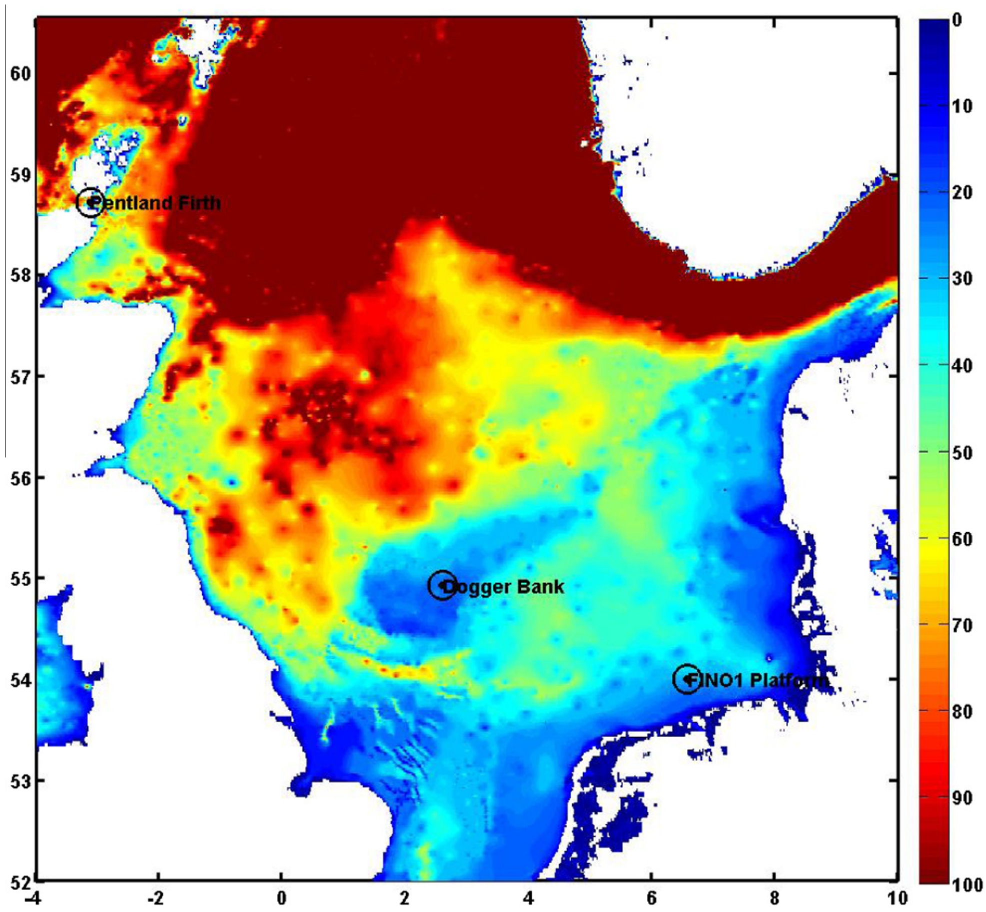


Fig. 5. Domain and bathymetry for the North Sea. The locations of the FINO-1 research platform, Dogger Bank and the Pentland Firth are indicated.

5.1. Future work

5.1.1. Applied study: high frequency wind input

This investigation can be applied to a more realistic North Sea wave model. Once the relationship between the variability within the wind speed and wind direction data have been analysed, it can be applied to wind data for the whole of the North Sea to obtain an accurate spatial representation of the wind field. SWAN can be forced with this wind field and run for a year or longer to produce annual wave power estimates for the North Sea. In order to get an accurate representation of the North Sea environment, accurate variable bathymetry data can be input into the SWAN model (Fig. 5). SWAN allows the selection of areas within the domain for the output of data. As such, it could be interesting to obtain outputs from a number of locations across the domain to see how the wave field develops over an annual cycle. This data could then be applied to estimate wave effects on structures, for example tidal energy turbines in the Pentland Firth, or on the suspension and movement of sediment around sandbanks (e.g. Dogger Bank, North Sea). The influence of tides on the wave resource has not yet been included in this study, and is likely to be a natural step forwards with this research.

6. Conclusion

By forcing wave models with high frequency wind, more accurate representations of the wave environment should be created, which will aid predictions of the wave power resource. In future, this can be applied to resolving the stress of extreme wave scenarios on marine current turbines and correctly determining the impact of marine current turbines, on for instance, features such as offshore sandbanks [26]. Much more research needs to go in to making both tide and wave models as accurate as possible in order to reduce the uncertainties within the model results. In order to truly demonstrate the available wave resource, there are also many other variables which need to be looked at, such as wave–current interactions and multi-directional wind input. Future research will endeavour to accurately model and determine the extent of marine interaction with tidal turbines and their subsequent feedback mechanisms. This work will include the combination of currents and all wave conditions for local scale spectral test cases.

Acknowledgments

Thanks to the British Oceanographic Data Centre (BODC) for supplying the GEBCO bathymetry data, and to the BMU (Bundesministerium fuer Umwelt, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) and the PTJ (Projekttraeger Juelich, project executing organisation) for the FINO-1 wind data. Additionally the authors are grateful to Olaf Outzen and Friederike Kinder for their help with gaining access to appropriate wind data. The model simulations were made possible by access to High Performance Computing (HPC) Wales. This work was undertaken as part of PhD research into the feedbacks between tidal stream array operation and the marine environment and as such wish to acknowledge the financial support of Fujitsu in partnership with HPC Wales.

References

[1] A. Bahaj, Generating electricity from the oceans, Renewable and Sustainable Energy Reviews 15 (7) (2011) 3399–3416.
[2] K. Gunn, C. Stock-Williams, Quantifying the global wave power resource, Renewable Energy (2012).
[3] J.D. Boon, Secrets of the tide: tide and tidal current analysis and applications, storm surges and sea level trends, Horwood Pub Limited, 2004.
[4] I. Bryden, G. Melville, Choosing and evaluating sites for tidal current development, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 218 (8) (2004) 567–577.
[5] S.P. Neill, M.R. Hashemi, Wave power variability over the northwest European shelf seas, Applied Energy 106 (2013) 31–46.
[6] R. Ahmadian, R. Falconer, B. Bockelmann-Evans, Far-field modelling of the hydro-environmental impact of tidal stream turbines, Renewable Energy 38 (1) (2012) 107–116.
[7] G. Muraleedharan, C. Lucas, C. Guedes Soares, N. Unnikrishnan Nair, P. Kurup, Modelling significant wave height distributions with quantile functions for estimation of extreme wave heights, Ocean Engineering 54 (2012) 119–131.
[8] P. Stansell, Distributions of extreme wave, crest and trough heights measured in the north sea, Ocean Engineering 32 (8) (2005) 1015–1036.
[9] A. Akpınar, G.P. van Vledder, M. İhsan Kömürcü, M. Özger, Evaluation of the numerical wave model (SWAN) for wave simulation in the black sea, Continental Shelf Research (2012).
[10] ABPmer. (2008) Atlas of uk marine renewable energy resources, available at: http://www.renewables-atlas.info, 2008 (Online).
[11] E. Bauer, R. Weisse, Determination of high-frequency wind variability from observations and application to north atlantic wave modeling, Journal of Geophysical Research 105 (C11) (2000). pp. 26 179–26 190.
[12] L. Cavaleri, G. Burgers, Wind gustiness and wave growth, KNMI Memorandum OO-92–18 (1992) 62 (1992).
[13] C. Guedes Soares, M. Scotto, Modelling uncertainty in long-term predictions of significant wave height, Ocean Engineering 28 (3) (2001) 329–342.
[14] R. van der Grinten, J. de Vries, H. de Swart, Impact of wind gusts on sea surface height in storm surge modelling, application to the North Sea, Natural Hazards (2012) 1–14.
[15] C. Beels, J.C.C. Henriques, J. De Rouck, M.T. Pontes, G. De Backer, H. Verhaeghe, Wave energy resource in the North Sea, Proceedings of the 7th European Wave and Tidal Energy Conference (2007).
[16] S. Abdalla, L. Cavaleri, Effect of wind variability and variable air density on wave modeling, Journal of Geophysical Research 107 (C7) (2002) 3080.
[17] A.V. Babanin, V.K. Makin, Effects of wind trend and gustiness on the sea drag: Lake George study, Journal of Geophysical Research: Oceans (1978–2012) 113 (C2) (2008).
[18] G.P. Harrison, A.R. Wallace, Sensitivity of wave energy to climate change, IEEE Transactions on Energy Conversion 20 (4) (2005) 870–877.
[19] D. Reeve, Y. Chen, S. Pan, V. Magar, D. Simmonds, A. Zacharioudaki, An investigation of the impacts of climate change on wave energy generation: The wave hub, cornwall, UK, Renewable Energy 36 (9) (2011) 2404–2413.
[20] N. Booij, R. Ris, L. Holthuijsen, A third-generation wave model for coastal regions. 1. Model description and validation, Journal of Geophysical Research 104 (C4) (1999) 7649–7666.
[21] I. Karagali, M. Badger, A.N. Hahmann, A.B. Peña, C. Hasager, A.M. Sempreviva, Spatial and temporal variability of winds in the Northern European Seas, Renewable Energy 57 (2013) 200–210.
[22] N. Carbajal, Two applications of Taylor's problem solution for finite rectangular semi-enclosed basins, Continental Shelf Research 17 (7) (1997) 803–817.
[23] J. Twidell, T. Weir, Renewable Energy Resources, Taylor & Francis, 2003.
[24] S. Hartwell-Naguib, R. Benwell, M. O'Brien, J. Bird, F. Grahan, J. Wright, J. Evans, N. Davies, The Future of Marine Renewables in the UK – Energy and Climate Change, available at: http://www.parliament.uk/parliament.uk/ecc, 2012 (Online).
[25] R. Soulsby, Dynamics of Marine Sands: A Manual for Practical Applications, Thomas Telford, 1997.
[26] S.P. Neill, J.R. Jordan, S.J. Couch, Impact of tidal energy converter (TEC) arrays on the dynamics of headland sand banks, Renewable Energy 37 (1) (2012) 387–397.