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An investigation of the impacts of climate change on wave energy generation: The Wave Hub, Cornwall, UK

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ABSTRACT

In this paper a generic methodology is presented that allows the impacts of climate change on wave energy generation from a wave energy converter (WEC) to be quantified. The methodology is illustrated by application to the Wave Hub site off the coast of Cornwall, UK. Control and future wave climates were derived using wind fields output from a set of climate change experiments. Control wave conditions were generated from wind data between 1961 and 2000. Future wave conditions were generated using two IPCC wind scenarios from 2061 to 2100, corresponding to intermediate and low greenhouse gas emissions (IPCC scenarios A1B and B1 respectively). The quantitative comparison between future scenarios and the control condition shows that the available wave power will increase by 2–3% in the A1B scenario. In contrast, the available wave power in the B1 scenario will decrease by 1–3%, suggesting, somewhat paradoxically, that efforts to reduce greenhouse gas emissions may reduce the wave energy resource. Meanwhile, the WEC energy will yield decrease by 2–3% in both A1B and B1 scenarios, which is mainly due to the relatively low efficiency of energy extraction from steeper waves by the specific WEC considered. Although those changes are relatively small compared to the natural variability, they may have significance when considered over the lifetime of a wave energy farm. Analysis of downtime under low and high thresholds suggests that the distribution of wave heights at the Wave Hub will have a wider spread due to the impacts of climate change, resulting in longer periods of generation loss. Conversely, the estimation of future changes in joint wave height-period distribution provides indications on how the response and power matrices of WECs could be modified in order to maintain or improve energy extraction in the future.

1. Introduction

The Wave Hub project is a wave energy research project for testing arrays of wave energy converter devices being developed at a location 10 miles offshore from the north coast of Cornwall, in the south west of the UK, at about 50m water depth, see Fig. 1. The project is designed to accommodate up to four different wave energy converter (WEC) technologies to generate wave power, which will be connected to the national grid to supply electricity for thousands of homes (www.wavehub.co.uk). The Wave Hub is being constructed as part of the broader effort to develop renewable energy technology with the intention that CO_2 and other greenhouse gas emissions will be reduced, thereby mitigating the climate change associated with burning fossil fuels. However, as wave energy is generated by surface wind forcing, which will change in response to alterations in the atmospheric climate, wave energy generation at the Wave Hub may in turn be affected by climate change.

In order to accurately predict the long-term energy yield for a wave farm, it is essential to take natural variability and climate change into account. Reliable long-term predictions of the Earth's atmospheric evolution over the period of many years are not available. For this study we have used climate simulations based on specific scenarios defined by the IPCC (Intergovernmental Panel on Climate Change). The aim of this study is to quantify the relative changes in wave energy power and WEC energy yield corresponding to the different future climate scenarios, as well as to evaluate the statistical significance of those changes. This knowledge will give a better understanding of the possible changes in wave energy generation at the Wave Hub due to climate changes, while the methodology can be extended to other sites and WEC devices.

The current knowledge of how to assess the impacts of climate change on wave energy resource is rather limited. An early study of

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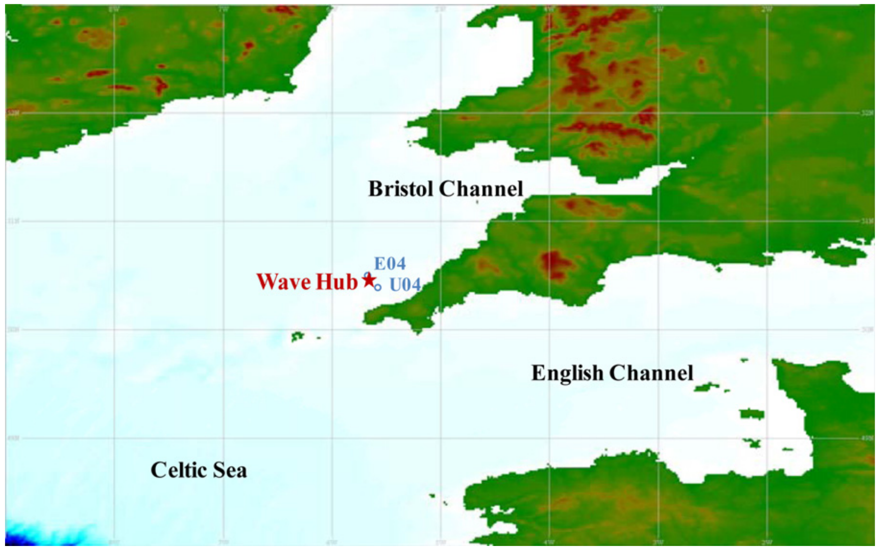

Fig. 1. Location of the Wave Hub site.

the sensitivity of wave energy yield to climate change [1],, suggested that the wave energy resource could be quite vulnerable to wind forcing changes. A simple relationship between wind speed and the Pierson-Moskowitz wave spectrum was used to investigate how changes in wind speed may affect available wave power and expected energy yield from a Pelamis WEC. A parametric model for wind speed was used to generate the joint distribution of wave height and period at the study site so that the energy yield could be calculated according to the given Pelamis power matrix. The results from sensitivity tests illustrated that a 10% increase in wind speed may result in a 60% increase in available wave power and a 20% increase in expected energy yield. However, this method did not take into account the presence of swell waves.

Recently, a more sophisticated analysis of the sensitivity of WEC yield to climate change was presented by [2,3] through a correlative link with the North Atlantic Oscillation (NAO) index. With assumptions of a linear relationship between the WEC yield and the NAO index and positive correlation between the NAO index and changes in the level of CO_2 emissions, the variance of WEC yield was linked to possible changes in CO_2 emissions. Their analysis was specific to a site to the north of Scotland. Their sensitivity tests suggest that changes in annual energy yield arising from anthropogenic climate change may not be detectable amongst the natural variability. As there is a low correlation between available wave power and the NAO index at the Wave Hub site [4],, this method is not directly applicable in this case.

In the present study, we propose a more generic method that is based on numerical wave modelling driven by past/present wind field and future wind scenarios associated with different levels of greenhouse gas emissions. A comparative assessment between a 'control' climate and different climate scenarios has been widely used as a method for assessing the impacts of different emission scenarios for the future [5–8]. Here, we use the time histories of surface winds generated under present-day conditions and in different climate change scenarios to drive numerical wave models and thence to evaluate the relative changes in power generation for a specific wave device with a prior known power matrix. Furthermore, dynamical wave modelling generates time histories of wave conditions which can be used to perform statistical analyses of WEC parameters such as idle time, downtime and maintenance windows.

Here, we have built on the results of [9] which employed a third generation wave model, WAVEWATCH III (WW3), to carry out the control and future scenario wave climate simulations at the Wave Hub site. This paper is organised as follows: Section 2 introduces the methodology and details of the data; Section 3 presents the results of available energy resource, WEC energy yield and downtime for the control case; Section 4 presents the impacts of future change in those parameters by comparison of future scenarios to present/control condition, followed by conclusions and discussions in Section 5.

2. Methodology

2.1. Climate model

This study uses the Global Climate Model (GCM) and Regional Climate Model (RCM) wind output provided by the Max Planck Institute for Meteorology at resolutions of 1.875° × 1.875°and

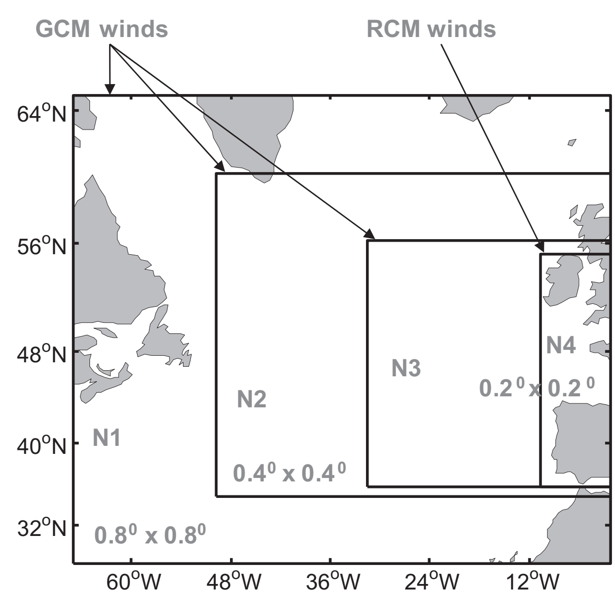

Fig. 2. Framework of four nested domains (N1-N4). Wave simulations on N1, N2 and N3 domain are forced with GCM wind forcing while the N4 domain is driven with RCM wind forcing (adapted from [9]).

0.2° × 0.2°, respectively. The datasets consist of a 40 year time-series (1961-2000) of wind fields for the present and two 40 year (2061-2100) time-series for the IPCC future scenarios A1B and B1 [10],, which represent intermediate and low greenhouse gas emissions respectively.

2.2. Wave modelling

WW3 is a third generation wave model developed at NOAA/NCEP in the spirit of the WAM model [11,12]. The model solves the spectral action density balance equation without any pre-defined shape of wave energy spectrum.

The WW3 model, (Version 2.22) [13], was setup within a one way downscaling framework, as shown in Fig. 2, for this study. Four nested domains were used to provide downscaled wave conditions at the Wave Hub site. The first level domain N1 uses 0.8° by 0.8° resolution covering the North Atlantic from 67°W to 2°W in longitude and from 28°N to 65°N in latitude, the intermediate level domains N2 and N3 have the resolutions of 0.4° by 0.4° and 0.2° by 0.2° respectively, covering part of North Atlantic Sea and Celtic Sea. The fourth level domain, N4, which is the smallest scale and centred at the Wave Hub, has the same resolution as N3. For domains N1, N2 and N3, the model was forced by GCM wind conditions, but for domain N4, higher resolution RCM wind conditions were used to improve the accuracy, (see Fig. 3). Wave parameters, including significant wave height H_s and mean wave period T_m at the Wave Hub site, at 3-hourly intervals from the N4 domain, are used for further analysis presented in this paper, whilst further details of the wave modelling can be found in [9].

2.3. WEC performance assessment

The available wave power is directly related to wave height and wave period. Following [14] this may be estimated empirically with

$$P = 0.49H_s^2T_e \tag{1}$$

where H_s is the significant wave height; T_e is the wave energy period defined in terms of moments of the wave spectrum:

$$T_e = \int_0^\infty f^{-1}S(f)df \Big/ \int_0^\infty S(f)df \tag{2}$$

where f is the frequency and $S(f)$ is the wave spectrum density.

The mean wave period T_m output from the WW3 model is defined as [13,15],

$$T_m = 2\pi \iint \sigma^{-1}F(\sigma,\theta)d\sigma d\theta \Big/ \iint F(\sigma,\theta)d\sigma d\theta \tag{3}$$

where σ is the angular frequency; θ is the wave direction and $F(\sigma,\theta)$ is the two- dimensional spectrum density. As, by definition, the following relationship holds:

$$\sigma = 2\pi f \tag{4}$$

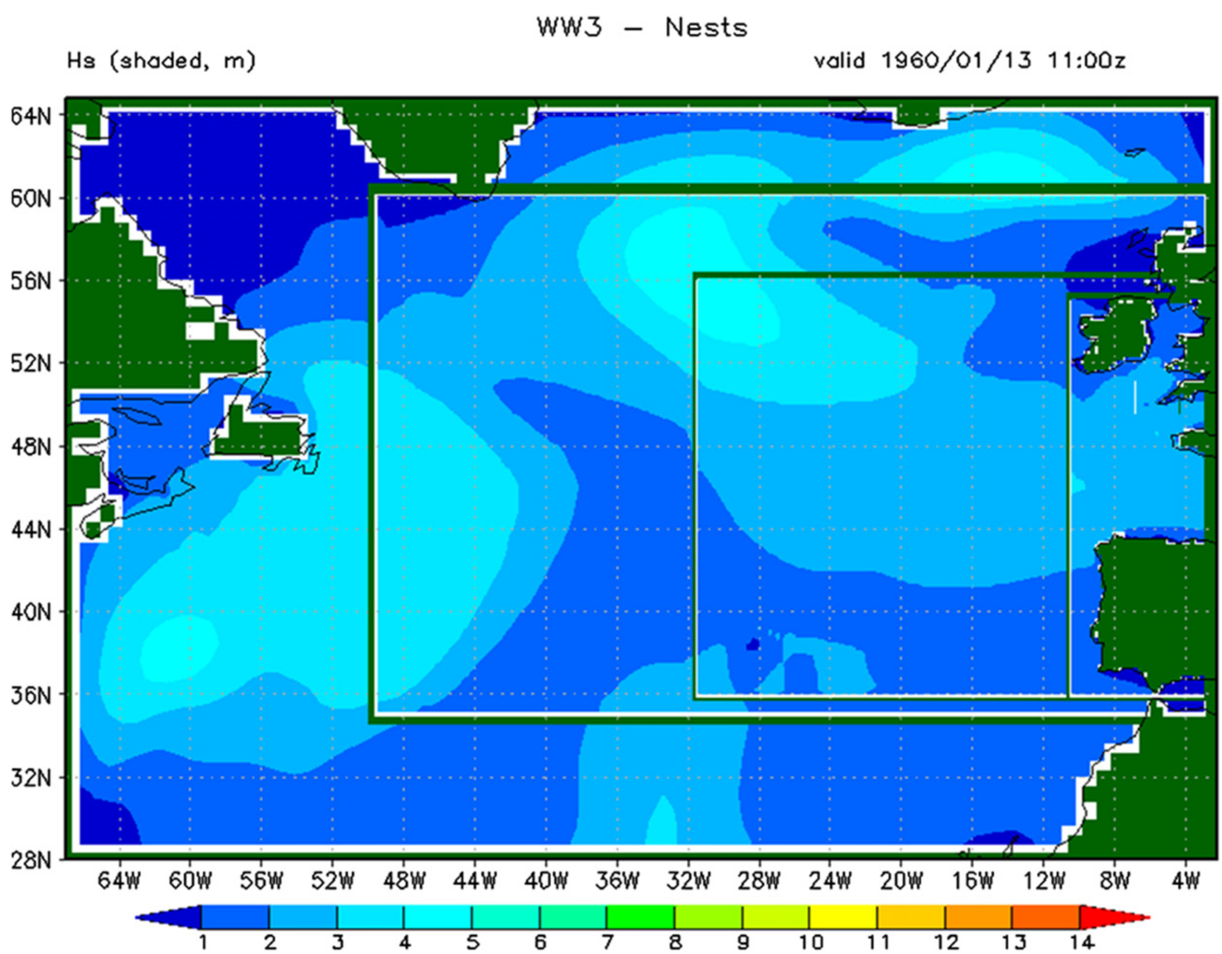

Fig. 3. Overlapping wave height field from four computational domains simultaneously.

Significant wave height (H_{sig}, m) \ Power period (T_{pow}, s)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
0.5	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle	idle
1.0	idle	22	29	34	37	38	38	37	35	32	29	26	23	21	idle	idle	idle
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	-	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	-	-	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	-	-	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	-	-	-	739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5	-	-	-	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	-	-	-	-	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	-	-	-	-	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	-	-	-	-	-	750	750	750	750	750	750	750	750	676	613	584	525
7.5	-	-	-	-	-	-	750	750	750	750	750	750	750	750	686	622	593
8.0	-	-	-	-	-	-	-	750	750	750	750	750	750	750	750	690	625

Fig. 4. Pelamis Power Matrix (adapted from www.pelamis.co.uk).

we can see that T_m is equivalent to the energy period T_e. Hereafter, we use T_e.

It should be noted that Equation (1) gives the theoretical available wave power, but the actual wave power yield will depend on particular WEC devices rated by their wave power generation matrices as well as by their performance matrices which consider the variation of the device performance in response to wave directionality and spectral width [16]. Power generation and

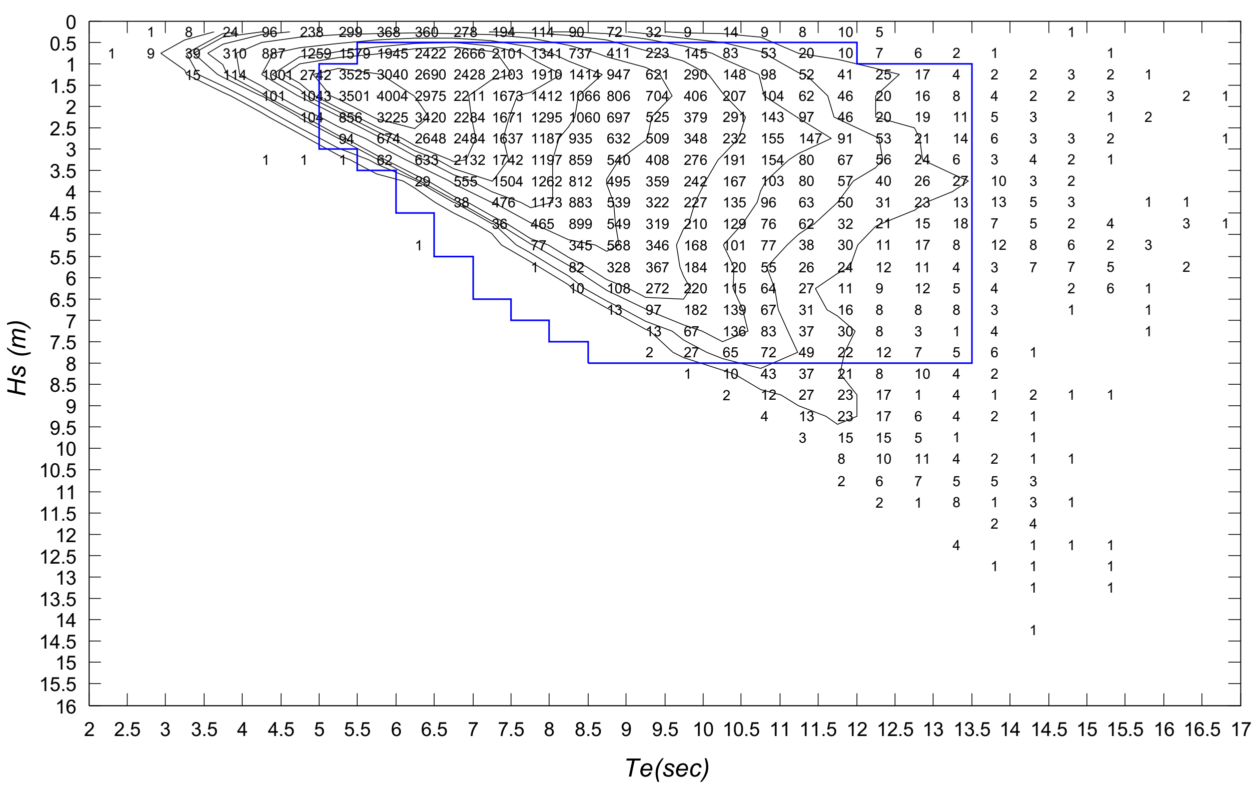

Fig. 5. Joint occurrences of H_s–T_e embedded with effective Pelamis power box under control condition.

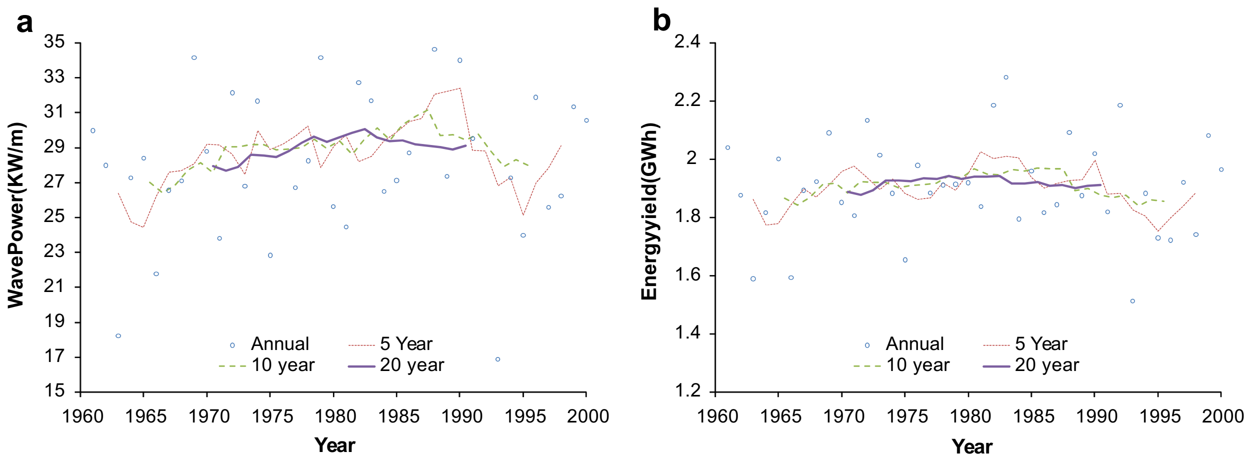

Fig. 6. Annual, 5-year, 10 year and 20 year moving averages of (a) available wave power and (b) WEC energy yield, at the Wave Hub under control condition.

performance matrices are typically derived from numerical experiments validated against measurements made on scale models and hence are related to the theoretical performance of the devices. In this study we take the Pelamis WEC as an example to calculate energy yield. The authors did not have access to performance matrices but power generation matrices are publicly available and were used in this study to provide a fair proxy of the actual wave power yield of the specific device. Using the 3-hourly consecutive wave height and wave period time sequences from the wave model, a joint frequency distribution of H_s and T_e can be generated with fixed partitioning of H_s and T_e (0.5 m and 0.5 s respectively in this study), which matches the corresponding bin of the Pelamis WEC power matrix as shown in Fig. 4. The energy yield from each bin can be calculated from the product of the occurrence of H_s and T_e and the power generation rates defined in the power matrix. The total energy production of the WEC can be calculated from the summations of the energy yield in each bin.

In addition to the WEC energy yield, the downtime is also an important parameter for the description of WEC performance. The downtime can be interpreted in different ways, and here it is defined as the length of time period when the wave height is continuously lower or higher than a specific value. Two threshold wave heights are defined: H_L for lower-threshold wave height and H_H for upper-threshold wave height. The downtime for the wave height below H_L is termed downtime (low), and the downtime for the wave height above the H_H is termed downtime (high). The downtime (low) can be used to indicate either idle time (when the wave conditions generate negligible power) or maintenance windows (when the wave conditions are sufficiently benign to allow maintenance and repair work to be performed). The downtime (high) can be used to indicate the time period when the WEC has to be shut down for the sake of survivability under extreme wave conditions.

2.4. Hypothesis test

With 40 years of continuous wave sequences for both control time-slice (1961–2000) and future time-slice (2061–2100), two groups of 40 annual average results are available for both slices. Therefore, the statistical significance of the differences between these two groups of data can be quantified through the technique of hypothesis testing. To avoid *a priori* assumptions about the distribution of the annual data, the

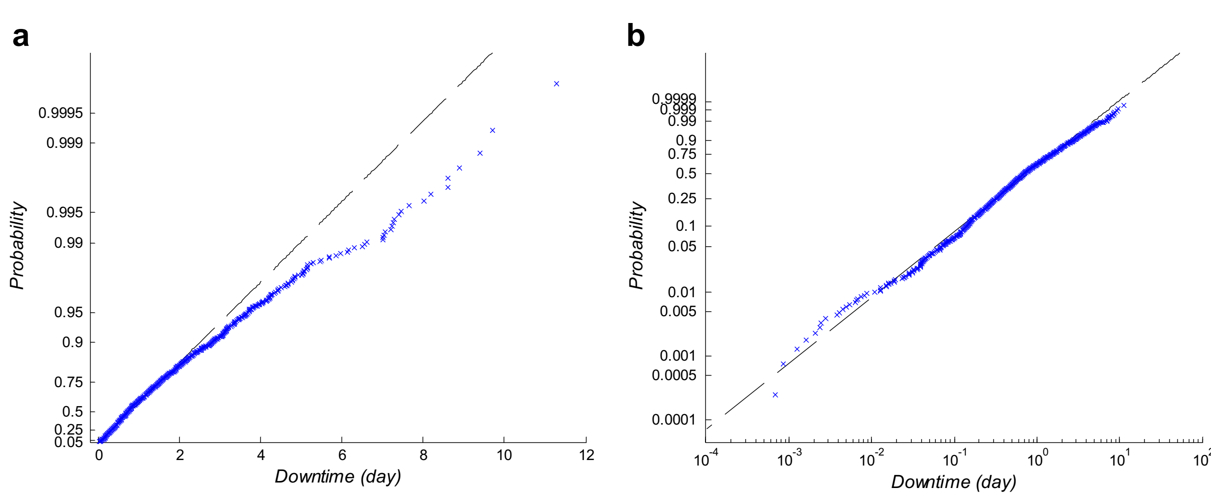

Fig. 7. Distribution of downtime with the lower-threshold of 1.0 m fitted with (a) Exponential distribution and (b) Weibull distribution.

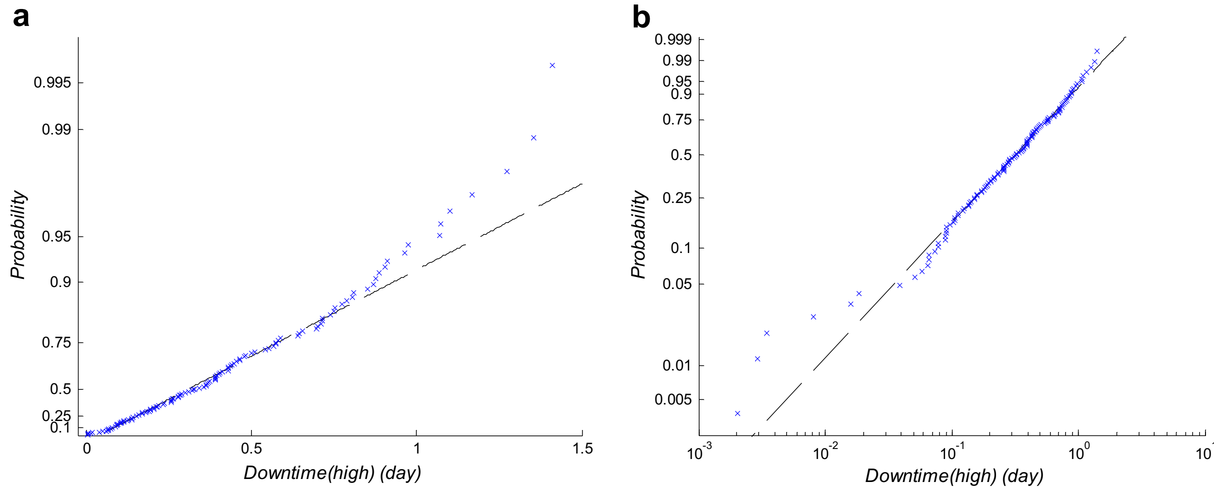

Fig. 8. Distribution of downtime with the upper-threshold of 8.0 m fitted with (a) Exponential distribution and (b) Weibull distribution.

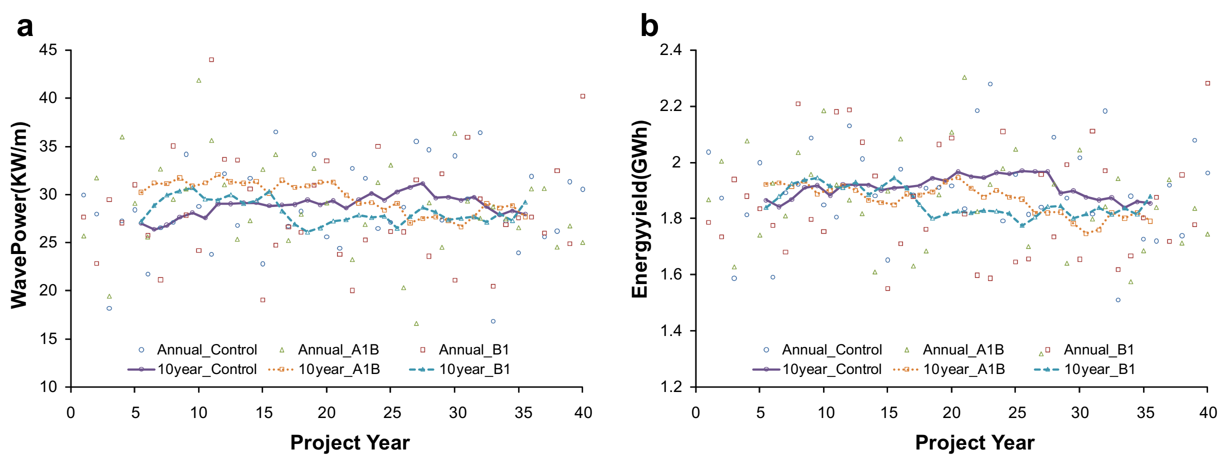

Fig. 9. Annual and 10-year moving averages of (a) available wave power and (b) WEC energy yield under control and future scenarios (A1B and B1).

non-parametric Wilcoxon rank-sum hypothesis test, (see eg [17].), is selected for assessment. This test determines the value of a statistic and the '*p*-value'. The *p*-value is the probability of obtaining a test statistic at least as extreme as the one actually observed, assuming that the null hypothesis is true. In our case the null hypothesis is that there is no difference between the control and future scenario conditions. The null hypothesis is rejected if the *p*-value is smaller than or equal to the significance level. Here, this level is set to 0.05. This is a widely adopted value, giving the probability of rejecting the null hypothesis when it is true as 5% or less.

To investigate the impact of climate change on the long-term energy output, it is helpful to use moving averages which smooth inter-annual variations. For reference in later sections we note that the n-year moving average available power at year N is calculated by,

$$\overline{P_N}^n = \sum_{i=N-\frac{n}{2}}^{N+\frac{n}{2}} P_i \tag{5}$$

Table 1
Relative changes in moving average available wave power.

	1-year		5-year		10-year		20-year	
	Wave power (KW/m)	P-value	Wave power (KW/m)	P-value	Wave power (KW/m)	P-value	Wave power (KW/m)	P-value
Control average	28.53		28.58		28.90		29.01	
Relative change (%) (A1B minus Control)	2.69	0.6896	3.54	0.0780	2.95	0.0271	2.92	0.0137
Relative difference (%) (B1 minus Control)	−0.78	0.4675	-1.45	0.0901	−2.27	0.0398	−3.31	0.0000
Relative difference (%) (B1 minus A1B)	−3.47	0.3944	−4.99	0.0045	−5.21	0.0005	−6.23	0.0000

Table 2
Relative changes in moving average annual WEC energy yield.

	1-year		5-year		10-year		20-year	
	Energy yield (GWh)	P-value	Energy yield (GWh)	P-value	Energy yield (GWh)	P-value	Energy yield (GWh)	P-value
Control average	1.90		1.90		1.91		1.92	
Relative change (%) (A1B minus Control)	−2.16	0.3944	−1.94	0.0328	−2.31	0.0027	−2.37	0.0000
Relative difference (%) (B1 minus Control)	−2.12	0.1795	−2.34	0.0053	−2.76	0.0001	−3.46	0.0000
Relative difference (%) (B1 minus A1B)	0.04	0.7692	−0.41	0.7740	−0.45	0.4556	−1.09	0.0527

3. Results for control case

3.1. Available wave power & WEC energy yield

The first step in the methodology is to test whether the wave climate has been reasonably reproduced by the control wave climate used in this study. Although there are no wave measurements available from 1961-2000 at the study site, some indirect comparison with other work is possible. Using UK Met Office wave data, which was validated against wave buoy measurements in the period 2005–2006, the available wave power at the Wave Hub site was calculated by [4]. By linking the wave height with the 'Index of Westerlies', it was estimated that the long-term (1965–2005) mean wave power was approximately 28 kW/m ± 4 kW/m at offshore point E04 and 21 kW/m ± 6 kW/m at the nearshore point U04 (the positions of E04 and U04 are shown in Fig. 1). The historic trend in potential wave power at a site in the north of Scotland over the period 1954–2005 was investigated in [2]. Using moving averages,

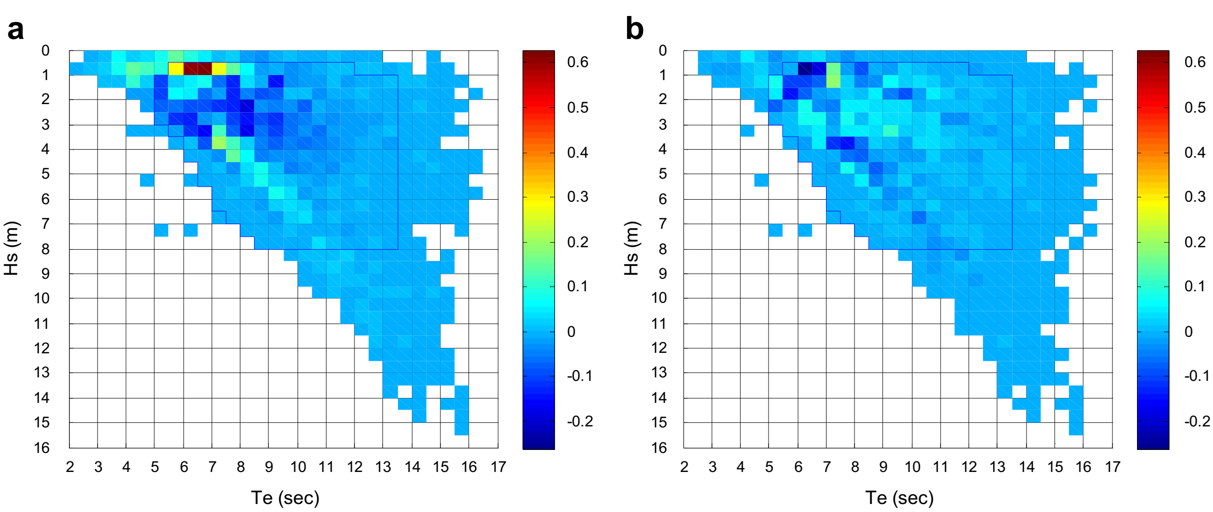

Fig. 10. Change in occurrence frequency between future scenarios and control condtion for scenarios (a) A1B and (b) B1.

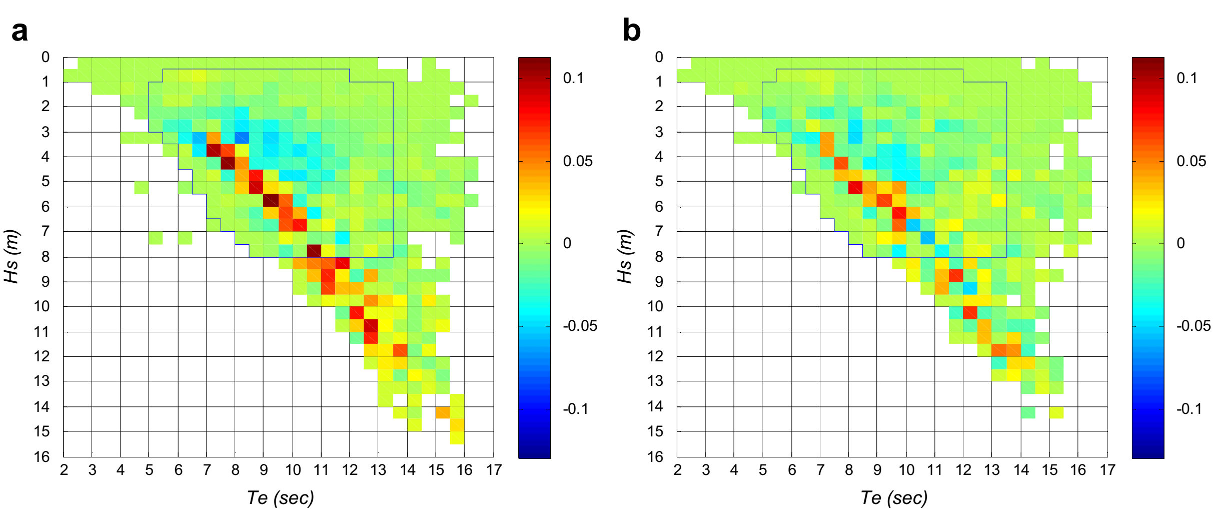

Fig. 11. Change in available wave power (unit: KW/h) between future scenarios and control condtion for (a) A1B and (b) B1.

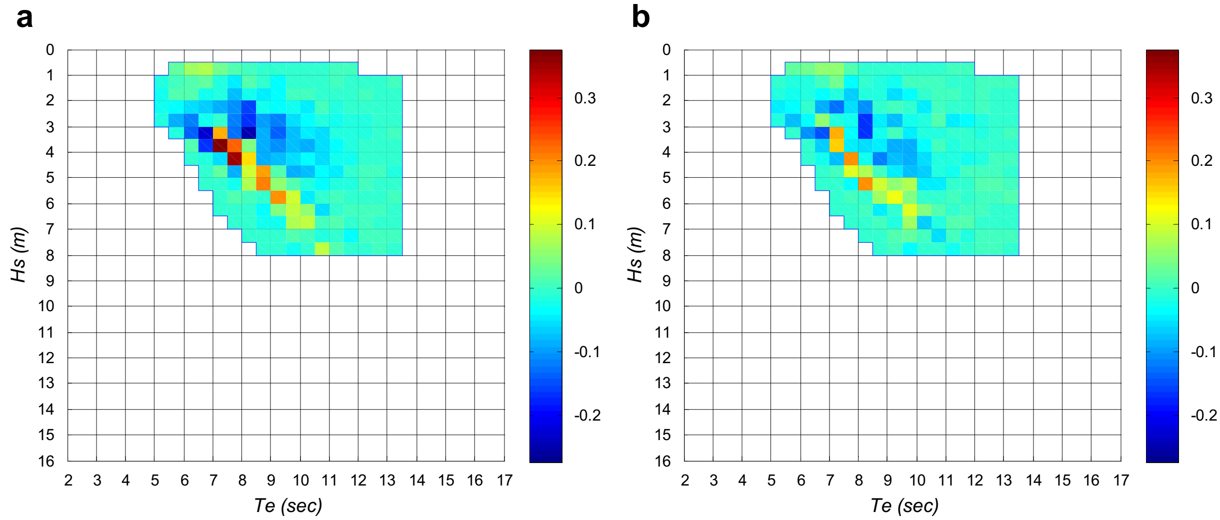

Fig. 12. Change in WEC energy yield (unit: GWh) of effective power matrix between future scenarios and control condtion for (a) A1B and (b) B1.

they found that the annual mean power started to increase around 1970, reached a peak in the early 1990s and then started to decrease. This finding is consistent with the trends in wave height in the North Atlantic Sea [18,19].

In the present study, the H_s–T_e joint distribution based on the WW3 model results is shown in Fig. 5. Applying Equation (1), the annual mean wave power at the Wave Hub is calculated as 28.53 kW/m ± 4.55 kW/m which is comparable to the results found by [4]. The annual mean available power and the 5, 10 and 20 year moving averages, as shown in Fig. 6(a), also illustrate a considerable increase from 1970 to 1990 and then a slight decrease afterwards. In comparison, the trend in energy yield from a Pelamis WEC, as shown in Fig. 6(b), seems less obvious than that in available power. The reduced variability in the WEC energy yield would seem to be due to the smoothing effect of the power matrix combined with the nature of the changes in wave power with respect to the most efficient H_s–T_e combinations for energy conversion.

3.2. Downtime

Downtime provides a useful measure for WEC operators for two reasons. Firstly, at the upper-threshold it gives an indication of the level of 'power outages' due to extreme conditions. Secondly, at the lower-threshold it gives an indication of the length of time associated with calms and minimal power generation. It also gives a useful measure of the availability of conditions suitable for maintenance and repair work. With a 40 year sequence of continuous wave conditions we can calculate the probability distribution of downtime with a given threshold. As an example, Figs. 7 and 8 show the probability distribution of downtime (low) with the lower-threshold of 1.0 m and downtime (high) with the upper-threshold of 8.0 m respectively, fitted with (a) an exponential distribution and (b) a Weibull distribution. The good fit of an exponential distribution for the small downtime values for both cases implies the short downtime episodes are randomly spaced in time. The good fit of the Weibull distribution for large downtime

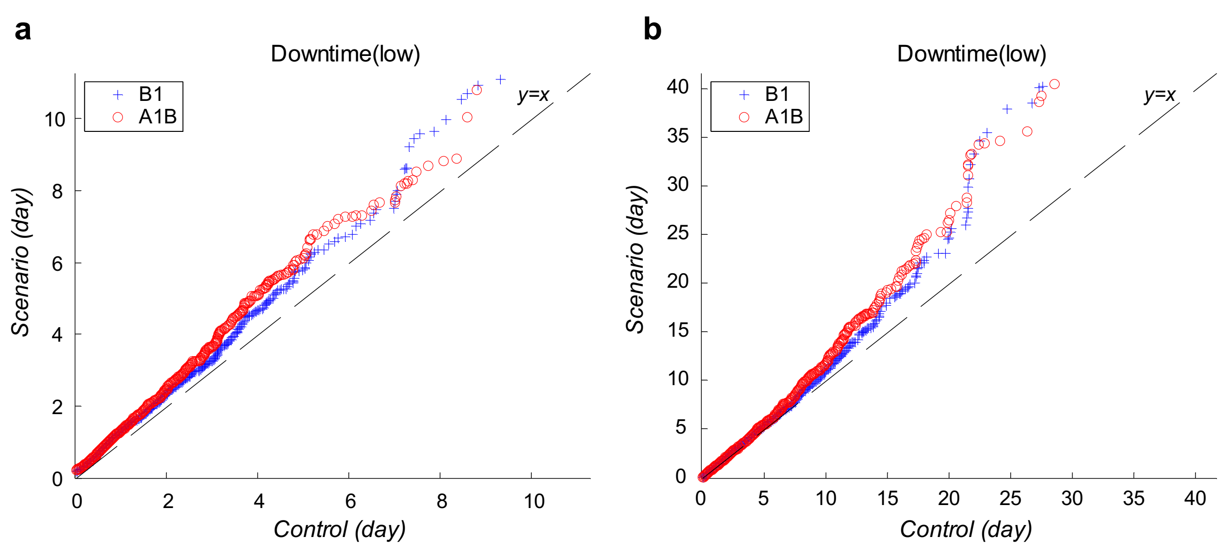

Fig. 13. Comparison of downtime (low) between scenarios and control condition for (a) $H_L = 1.0$m and (b) $H_L = 2.0$m.

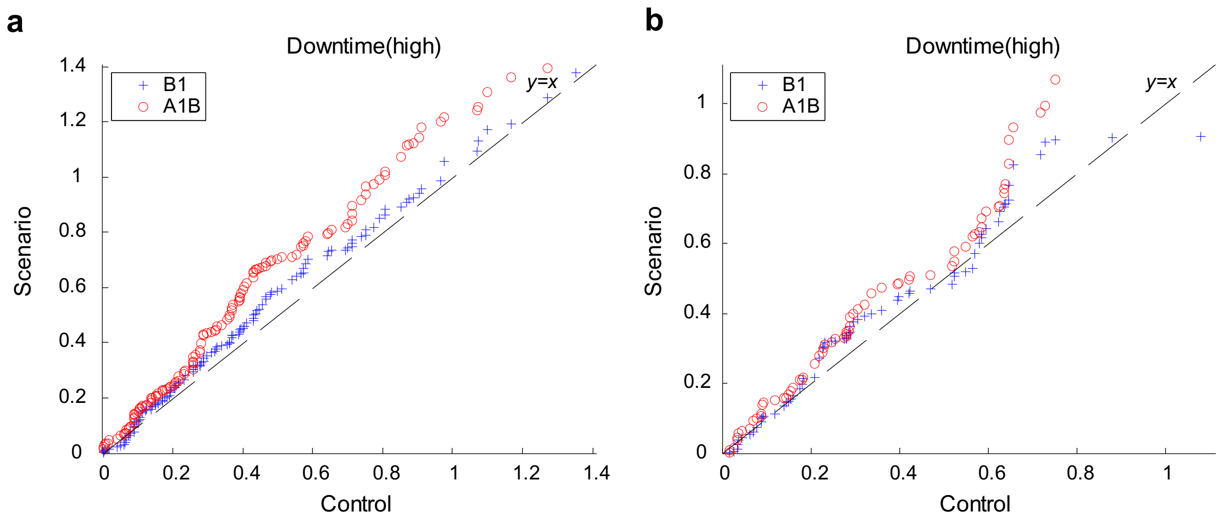

Fig. 14. Comparison of downtime (high) between scenarios and control condition for (a) $H_H = 8.0$m and (b) $H_H = 9.0$m Note: indicate (a) and (b) for Figs. 12–14.

value suggests that the occurrence of long periods of downtime can be predicted by using standard extreme value theory.

The value of downtime can be also used to indicate the spread of wave height, i.e. if downtime (low) increases, it means the occurrence of small waves which is below the lower-threshold increases. Similarly, if downtime (high) increases, it means large waves over the upper-threshold occur more frequently. If both downtime (low) and downtime (high) increase, then there is a broader spread of wave conditions.

4. Results for future changes

In this section we compare the results obtained from the future scenario conditions with those of the control condition.

Fig. 9 shows the annual and 10 year moving averages of (a) mean wave power (b) WEC energy yield under the control wave climate and the future scenarios. Although differences of annual mean values between present and future scenarios seems negligible due to the relatively high natural variability, the changes in moving averages turn out to be significant, as confirmed by hypothesis tests. The relative changes in mean available wave power and their statistical significance, indicated by the *p*-value, are presented in Table 1, while the corresponding results for WEC energy yield are presented in Table 2. From Table 1, it may be seen that the *p*-values for changes in annual mean available wave power between present and future are all larger than 0.05, which indicates the changes in annual mean power are not significant at the 5% level. However, the *p*-value for 10 year and 20 year moving averages are much less than 0.05, and thus are significant. Focussing on the 10 year moving averages, it is evident that the mean available wave power will have a 2.95% increase for the A1B scenario but a 2.27% decrease for the B1 compared to the control condition. As the B1 scenario represents a significant decrease in greenhouse gas emission in the future, the difference between the A1B and B1 scenarios of more than 5% implies that efforts to reduce the greenhouse gas emissions may have an unintended adverse effect on the natural wave power, although this might not be immediately detectable due to natural variability. However, there is a different conclusion to be drawn from the statistical changes in WEC energy yield. From Table 2, we can see that the difference of energy yield between A1B and B1 scenarios is very small and not statistically significant, although they both have a 2–3% decrease compared to the control condition.

In order to explain the changes in available wave power and energy yield, the future changes in occurrence frequency of waves in each H_s–T_e bin under (a) A1B scenario and (b) B1 scenario, are plotted in Fig. 10. It can be seen that more waves with low height and more waves with greater steepness will occur for both scenarios. By weighting each bin by the factor $H_s^2 T_e$ to represent the potential power output in each bin, changes in available power under (a) A1B and (b) B1 scenarios, may be calculated and are shown in Fig. 11. From Fig. 11 it is clear that more wave energy is contained in waves with a relatively large steepness, particularly for the A1B scenario. However, due to the relatively low efficiency of wave energy extraction by the WEC for the steeper waves, as shown in Fig. 12, the energy yield may not be increased. This is why the available wave power increases but the energy yield decreases for the A1B scenario. It also explains why the difference in available wave power between A1B and B1 is quite large while the difference in energy yield is rather small. Fig. 13 shows a comparative plot of the distribution of downtime (low) with the thresholds of (a) $H_L = 1.0$m and (b) $H_L = 2.0$m for scenario versus control condition. The figure clearly illustrates that the expected downtime (low) will increase for the future scenarios, meaning a greater occurrence of small waves. Similarly, Fig. 14 shows the corresponding comparative plot of the distribution of downtime (high) with the thresholds of (a) $H_H = 8.0$m and (b) $H_H = 9.0$m. It can be clearly seen that downtime (high) is also expected to increase for both scenarios, indicating the frequency of extreme waves at the Wave Hub will increase in the future. The bigger increase for the A1B scenario reflects the impact that the level of greenhouse gas concentration in the atmosphere may have on the intensity and the frequency of extreme storms, which is consistent with conclusions drawn from other studies of the North-East Atlantic (e.g [20].).

5. Discussion and conclusions

This paper presents a generic method to investigate the impacts of climate change on wave energy generation from a wave energy converter (WEC) at the Wave Hub site. The method is illustrated with wave data derived from an earlier study using nested WW3 grids to transform and downscale the wind conditions from global and regional climate models to wave conditions at the Wave Hub site, located off the north coast of Cornwall, UK. The wave climate derived for the period 1961–2000 represents the present/control condition. Those derived for 2061–2100, for the two IPCC emissions scenarios A1B and B1 corresponding to intermediate and low greenhouse gas emissions respectively, represent future scenarios. Future changes in available wave power, WEC annual energy yield as well as WEC downtime for A1B and B1 scenarios have been quantitatively assessed.

The results show that available wave power will increase 2–3% for the A1B scenario with more energy available in waves with greater steepness. In contrast, the available wave power for B1 scenario will be 4–6% smaller than that for the A1B scenario. The WEC energy yield is found to decrease by 2–3% for both A1B and B1 scenarios, mainly due to the upper-limit of exploitable energy from steep waves. Although those changes are relatively small compared to the natural variability, the impacts of climate change may well be important when considered over the lifetime of a wave farm i.e. 10 year or 20 year averages. Statistical analysis of WEC downtime under low and high thresholds suggests that the distribution of wave heights at the Wave Hub will have a wider spread in the future, i.e., there will be a greater occurrence of both small and extreme waves. Depending on the performance characteristics of the individual WEC this may result in greater downtime. If wave devices can be optimised to extract energy from the steep waves more efficiently, it could increase the energy production. Further, as the wave modelling can generate wave climate over the whole computational domain, this method can be also applied to choose an optimal site for a wave farm, in terms of available wave power and/or energy yield.

It would be remiss of us not to point out a number of caveats. Firstly, uncertainties surround the estimation of future changes in wave energy. We have restricted ourselves to two emissions scenarios and one global-regional climate model combination. In reality, greenhouse gas emissions seem quite uncertain and a wide range of emission scenarios exist to account for this uncertainty. Secondly, the different climate models provide outcomes. A multi-model study [21], showed that the uncertainty between different climate models may be at least the same order of magnitude as the effects of climate change itself. Thirdly, the wave model itself may also introduce some uncertainties, although it is believed to be the source of least uncertainty. Finally, actual WEC performance may deviate from that approximated through using the power matrix as a proxy. One way to better quantify these uncertainties is to adopt an ensemble modelling approach. Our proposed methodology is easily adaptable to such a technique as it could be applied to each member of the ensemble in turn.

In conclusion, given the wind input and the power matrix of a WEC, this method can be applied to different sites for any particular WEC. For cases where WEC performance is heavily dependent on wave directionality and/or spectral shape, performance matrices and some additional analysis would be required. The dependence of wave energy extraction on wave steepness found in this paper is specific to the WEC device considered. Whether other devices are similarly affected will depend on the details of their power and performance matrices.

The method may also be applied to different climate change scenarios. The results from the modelling may have potential benefits to the wave farm developers as well as WEC designers. Based on the future climate scenarios, it is possible to estimate the range of wave conditions at a particular site, which is an important parameter in evaluating the economic viability of a wave farm.

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