Climate change might result in increased offshore wind farm accessibility in the North Atlantic

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I. Introduction

OFFSHORE wind is projected to supply a global average of 13% in 2050 [1]. Some regions, such as Europe and China, already have substantial installed capacity of offshore wind farms. Offshore wind operations depend significantly on metocean conditions. Unfavourable weather conditions are among the top three main causes of delays in construction of offshore wind projects, and in some cases can double the planned installation time and cost [2], [3]. Weather delays during maintenance accumulate throughout the wind farm lifespan and create profit losses due to prolonged downtime.

The amount of weather delays can be measured by accessibility, which is the ratio between the time when marine operations are allowed and total time. Vessels' operational limits and local climate combine to determine the level of accessibility for each wind farm.

A. Operational limits

The combination of wind speed, wave height and wave period determine the safety and wellbeing of the crew at different stages of installation and maintenance [6–8]. Interestingly, the relationship between thresholds of these environmental variables and weather delays can be nonlinear: an increase of wind speed limit from 6 m/s to 10 m/s corresponds to 30% shorter weather delays, whereas an increase from 10 m/s to 12 m/s leads to a 15% reduction in delays [2], [9], [10].

Since most maintenance activities require the transfer of technicians on small boats called crew transfer vessels (CTVs), maintenance is more sensitive to wave height. Significant wave height (H_s) limit varies from 1.5 m for small CTVs, to 2 m for Trimarans and Small Waterplane Area Twin Hull CTVs (SWATHs), to 2.5 m for larger service operation vessels (SOVs) [11], [12], [13]. In practice operators make decisions based on the weather forecast and their experience. This might be determined by a combination of wave height and wave period [14] and aim to increase safety and reduce discomfort of the crew [8].

Installation, on the other hand, is performed by larger vessels but requires lifting operations that are more sensitive to wind speeds. Depending on the local climate, operational limits of specific vessels, and type of operation (e.g. seabed preparation, cable laying, heavy lifting or sailing), wave height or wind speed can be more restrictive for the overall installation process [2], [4], [5], [15].

B. Other factors of weather delays

Due to seasonal weather variability, the industry tends to favour certain seasons for installation and maintenance. Spring and summer in most European locations are associated with higher accessibility [3, 4, 14]. Seasonality is more pronounced for operational limits of H_s = 1.5 m and H_s = 2 m than for higher limits, especially in locations with overall harsher conditions [14], [17].

Interestingly, the spatial variability of accessibility is pronounced not only regionally, but also on a much smaller scale. Sites that are only 100 km apart can have an absolute difference in annual accessibility of 5%-19% depending on the wave height limit [17]. This is supported in [18], where authors showed variability of annual accessibility at Scottish wind farm development sites in the range of 15%-70%.

Distance to shore can play a role in weather delays due to longer transit times and harsher and more variable conditions further offshore [3], [4].

C. Climate change trends

Climate change can affect metocean conditions , which, in turn, leads to changes in accessibility of offshore wind farms. The research linking climate change and accessibility is limited, possibly due to the absence of wave parameters in climate models. Coordinated research of wave climate started progressing only recently through the Coordinated Ocean Wave Climate Project (COWCLIP) [19]. This project aggregated wave projections from 10 independent research centres and addressed different levels of uncertainty in these projections.

Data from one of the research centres participating in COWCLIP [20] was used in [12] to assess climate change impacts on maintenance in the Northern North Sea. They found a reduction in accessibility of a Northern North Sea location of up to 7% in late spring-early summer, and a similar increase in autumn. They only studied one location using a single model, so the spatial variation and uncertainties caused by natural variability or choice of the model were not assessed.

Ref. [21] conducted a simulation of climate change impacts on operation and maintenance of offshore wind farms at 7 Northern European locations. They considered trends in wave height and wind speed and found an increase in accessibility of up to 9% for a CTV, variation in accessibility for SOV between −0.5% and 1.5%, and a up to 7% increase in opportunities for lifting operations. The study does not report a detailed methodology for climate simulations but the data they used [22] suggests that a single regional model downscaled from EC-EARTH global climate model was used to force the wave simulation. Despite the wider spatial coverage of the assessment compared to [12], the confidence in the results is low as the impacts of natural variability and accuracy of the climate models were not quantified or reported. Low confidence highlights a lack of assessment of climate change impacts on offshore wind accessibility which this study aims to address using a multi-model wave data ensemble.

II. Methods

D. Data

This study employs a subset of global wave projections from the COWCLIP project [19] that were made available in sub-daily time resolution (Table 1) that is needed for this analysis. The dataset includes wave height produced by either running a numerical wave model WAVEWATCH III (WW3) with surface wind and sea ice as inputs (the so-called dynamical approach) or by statistical downscaling driven by predictors derived from sea surface pressure. The atmospheric and sea ice data for these simulations was obtained from an ensemble of 11 runs of 7 general circulation models (GCMs) from Coupled Model Intercomparison Project 5 (CMIP5) with the high emission scenario RCP8.5.

We assessed uncertainties stemming from the inter-model variability using the robustness measure [23] that was used in COWCLIP project [24]. Shapiro-Wilke test showed that accessibility data does not follow a normal distribution. Hence, the Mann-Whitney test was used to assess the significance of changes between the past and the future, projected by a single model. The overall signal is considered robust if over 50% of the ensemble members agree on significance of change and over 80% of statistically significant models agree on the sign of change [25]. The addition of other ensemble members from the COWCLIP dataset to the current study could improve confidence in the results by assessing uncertainties from the choice of emission scenario or wave downscaling method.

Locations where at least one of the models has sea ice are excluded from this study since the development of offshore wind farms in harsh environments typical for the Arctic is unlikely. It should be noted that climate change is projected to reduce the sea ice extent, which increases the wave activity in the region and increases fetch. This phenomenon could affect the results in the locations neighbouring the excluded area.

All models were interpolated to a 1° x 1° grid using distance-weighted interpolation. Wave simulations forced with the same GCM are considered dependent, therefore

Table 1. Ensemble of GCMs used to produce wave climate.

GCM	Variant	Research centre[a]	Wave model	Time coverage		Resolution		Ref.
				Reference	Future projection	Time (hr)	Space (°)	
EC-EARTH	r12i1p1[b]	NOC	WW3	1970-2005	2081-2100	1	0.7 x 0.5	[20]
EC-EARTH	r2i1p1	ECCC	WW3	1979-2005	2081-2100	1	1 x 1	[33]
INMCM4	r1i1p1	ECCC	WW3			1	1 x 1	
GFDL-ESM4	r1i1p1	ECCC	WW3			1	1 x 1	
MIROC5	r1i1p1	ECCC	WW3			1	1 x 1	
BCC-CSM1-1	r1i1p1	ECCC	WW3			1	1 x 1	
MRI-CGCM3[c]	r1i1p1	ECCC	Regression	1979-2005	2081-2100	6	1 x 1	[34]
MRI-AGCM[d]	SST0	KU	WW3	1979-2005	2079-2100	6	0.56 x 0.56	[35]
MRI-AGCM	SST1	KU	WW3			6	0.56 x 0.56	
MRI-AGCM	SST2	KU	WW3			6	0.56 x 0.56	
MRI-AGCM	SST3	KU	WW3			6	0.56 x 0.56	

[a] The centre that performed wave simulations (NOC - National Oceanography Centre, UK; ECCC - Environment and Climate Change Canada, Canada; KU - Kyoto University, Japan).

[b] r for realization, i for initialization and p for physics

[c] Atmospheric correction and forcing based on sea level pressure.

[d] No atmospheric correction, forcing based on surface wind. SST0-3 refers to different sea surface temperature conditions for RCP8.5.

we apply a weighting approach so each group of ensemble members driven by the same GCM have equal contribution. Simulations forced with different GCMs within the same research centre are considered independent. This is a simplification because different GCMs are not entirely independent and might present similarities. However, this is an assumption often made by the research community despite the lack of a clear weighting approach due to the non-trivial dependence between ensemble members.

In this study, we compared this weighted approach with the unweighted approach and found that the addition of weighting does not change the overall area with robust signal. It does, however, alter the reason for the absence of robustness from the lack of model agreement on significance of change to the lack of agreement on the sign of change and vice versa. All results in this study are presented with the use of the aforementioned weighting in robustness assessment.

E. Accessibility evaluation

This study focuses on $H_s = 2$ m and $H_s = 2.5$ m in the assumption that the development of the industry will lead to a slight increase in operational limits of CTVs, as well as to more widespread deployment of SOVs due to larger size of wind farms and their expansion further offshore. The accessibility in this study is not restricted to daytime only, however, a comparison should be made to assess how the climate change impacts vary with diurnal cycle.

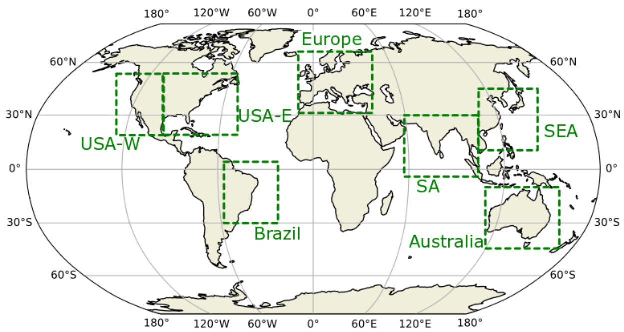

Fig. 1. Regions of offshore wind development

The first step is to split into weather windows ($H_s \leq 2$ m or $H_s \leq 2.5$ m) and waiting periods ($H_s \geq 2$ m or $H_s \geq 2.5$ m). The shortest viable weather window is assumed to be 6 hours long, limited by the smallest temporal resolution of wave simulations (Table 1). This does not affect the applicability of the results to offshore operations since the occasions on which the operators would sail offshore for such a short period of time are rare.

Monthly (annual) accessibility is calculated as the ratio between the total duration of weather windows and the number of hours in a month (year). Monthly accessibility allows for assessing seasonal changes in installation and maintenance patterns on a regional level. Weather windows include the time to sail from port to a wind farm location, perform activities on the wind farm and return to port.

Seasonal changes in accessibility are calculated as an average over all grid cells within each region of OW interest (Fig. 1). The regions are then compared in terms of seasonal changes. Development of offshore wind farms is unlikely in areas further than 300 km from the coastlines. In the future, we will restrict the spatial averages for seasonal analysis to the 0 km-300 km nearshore waters.

III. RESULTS

The spatial patterns of changes in accessibility generally follow the patterns in wave height changes with higher magnitude (Fig. 2 and 3). This intensification in accessibility compared to changes in Hs is especially pronounced in the regions of large teleconnections, El Nino in the tropical South Pacific and North Atlantic Oscillation in the North Atlantic.

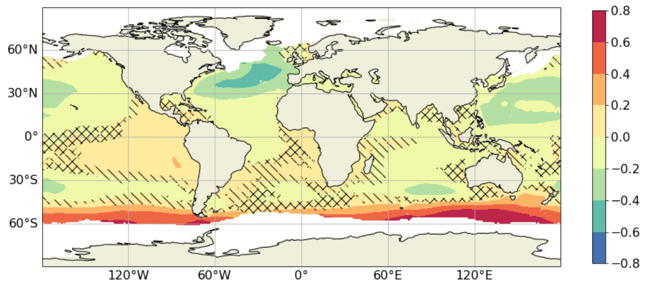

Fig. 2. Projected change in annual mean climatology of significant wave height between 2081-2100 and 1979-2005, weighted ensemble mean.

Robust changes in accessibility are present in the North Atlantic, North Pacific, some parts of Asia and Australia, as well as South America. The current ensemble projects an annual increase in accessibility of up to 9% (30 days) in European and American North Atlantic, an increase of up to 6% (20 days) in the Mediterranean Sea and Japanese, Filipino and Indonesian waters. A decrease of up to 12 % (40 days) is projected in South America, mainly in Brazilian waters and the Southeastern Pacific. In general, the spatial patterns in changes of accessibility for all three operational limits are similar with the smaller magnitude of changes for $H_s = 1.5$ m.

Fig. 4 shows the average monthly regional changes for $H_s = 2$ m and $H_s = 2.5$ m. The overall seasonal pattern for both scenarios is similar, showing an increase in accessibility in the winter months and a decrease in the summer months. This pattern is more pronounced for the US waters. Given that the current accessibility is generally higher in summer months, these results suggest a decrease in the seasonal differences meaning a potential extension of the maintenance season.

IV. DISCUSSION

F. The meaning of changes for the industry

The discussion below is limited to the results in the regions with the robust changes unless stated otherwise. The results agree with the previous findings of [12], [21] in terms of increased accessibility in the North Sea. However, this study shows that changes are not significant enough to attribute them to climate change.

Increased accessibility in major offshore wind development areas can lead to higher comfort of the maintenance crew during transfer, and a decrease in losses due to weather delays. This can be amplified by the development of such technologies as Artemis e-foiler vessel [28] and the Get-Up Safe turbine access system[27], which increase the safety of the crew transfer even within the current climate. Introduction of these technologies has a potential to expand safe and comfortable crew transfer limits, in which case the results for H_s = 2 m and H_s = 2.5 m become more relevant.

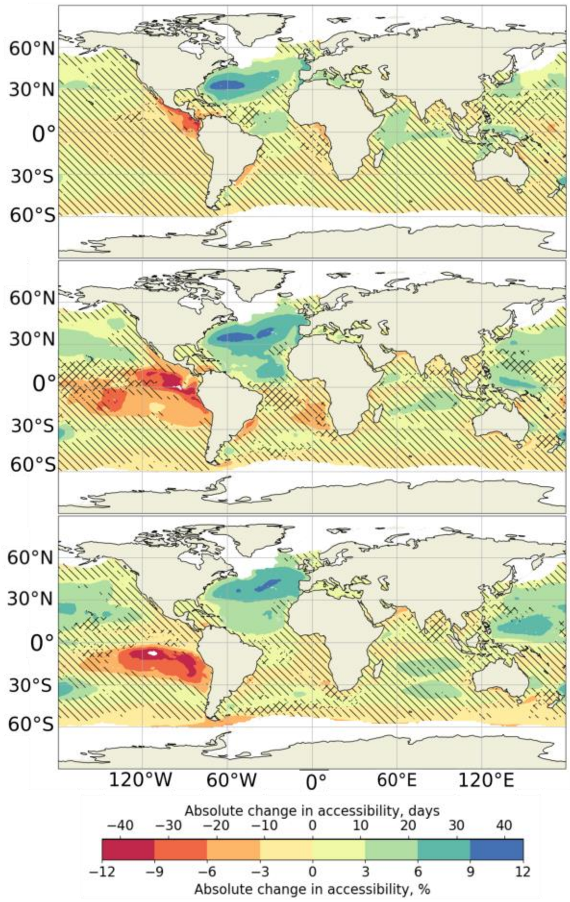

Fig. 3. Projected change in accessibility limited by H_s = 1.5 m (top), H_s = 2 m (middle) and H_s = 2.5 m (bottom) between 2081-2100 and 1979-2005. Single hatches show areas with no change or no robust signal, while double hatches indicate conflicting signal.

Growing density of turbines in some regions, such as Northern Europe and China, can result in a more widespread deployment of SOVs with higher operational limits. Together with the climate change-induced increase in accessibility, this can lead to nearly disappearing problem of weather delays during maintenance. Higher density of wind farms can also alter wave generation and propagation. The wake effect of wind farms reduces the wind for hundreds of kilometres downstream of wind farms [28], [29] which reduces the strength of the ocean wave generation. Additionally, the wind turbine structures change the wave dynamics and potentially reduce the wave height and slow down wave propagation.

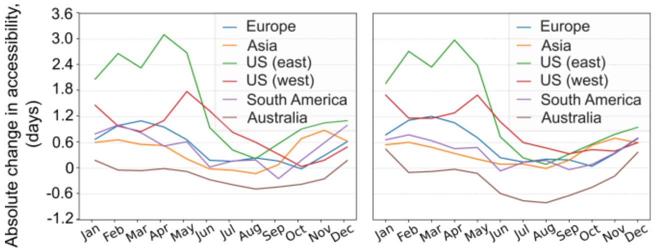

Fig. 5. Change in monthly accessibility limited by Hs=2m (left) and Hs=2.5m (right) between 2081-2100 and 1979-2005

Since the metocean conditions are typically harsher further offshore, the increase in accessibility in the Northern Hemisphere can facilitate development of more remote wind farms. Wind farms further from shore, in deeper waters will predominately be based on floating foundations. There is currently no single procedure for floating foundation deployment, turbine installation, operation and maintenance, which complicates the assessment of potential impacts of climate change on accessibility. One of the strategies for major repairs of floating wind turbines is towing them to port. This operation is limited to 1.5 m ≤ H_s ≤ 2.5 m depending on wave period [14]. We can hypothesize that calming seas might contribute to the acceleration of the floating wind development in such areas as the Iberian Peninsula and the East US coast. Our findings could also be useful for the future deployment of the wave and tidal energy devices as they also require calmer seas for installation and maintenance.

G. Limitations

One of the limitations of this study is the use of accessibility in place of weather windows and waiting periods. The use of weather windows and waiting periods would clarify the differences between impacts on types of maintenance of different duration, such as regular service, minor repair or major repair/component replacement.

Due to high computational demand of this study, we also did not examine the sensitivity of the results to different emission scenarios. Assuming the lower emission scenario means a smaller magnitude of change with a similar pattern of change, the accessibility in the North Atlantic would be expected to either remain unchanged or increase much less with the lower emission scenarios compared to RCP8.5. Limited spatial resolution of the wave projections can also lead to underestimation of extremes and such phenomena as tropical cyclones [30]. This can lead to overestimation of projected availability.

Future work should also include comparison of the projected changes between the wave simulations forced by CMIP5 and CMIP6 GCMs. CMIP6-forced wave projections are still quite limited [31]. As they developed, the increased spatial resolution could reduce the aforementioned inaccuracies in representation of extremes and tropical cyclones.

The authors recognise that wave period and wind speed can also affect accessibility, with the former being more important for service or minor maintenance, and the latter for installation and major repairs that require heavy lifts. We are currently conducting experiments to include wind speed and wave period in the impact assessment. Since the wind speeds are projected to decrease in most nearshore areas [32], the expected results are similar to the current study, showing the increasing accessibility under high emissions scenario.

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