Wave energy potential in the northeast Atlantic: Impact of large-scale atmospheric oscillations

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***Abstract*—Changes in the wave energy potential of the northeast Atlantic are predicted to occur during this century, which may alter future wave energy extraction processes. Large-scale atmospheric oscillations are known to influence the wave climate of the North Atlantic ocean. For this reason, we are interested in the North Atlantic Oscillation (NAO) teleconnection index which is related to large-scale atmospheric circulation. We carried out a statistical analysis of the NAO using an ensemble of EC-Earth global climate simulations that includes historical periods and projected changes by the end of the 21st century. In addition, we analysed the correlation between this teleconnection and the wave energy flux from an ensemble of EC-EARTH driven WAVEWATCH III (WW3) model projections over Ireland and the northeast Atlantic.**

***Index Terms*—WAVEWATCH III, Northeast Atlantic, EC-Earth model, Climate projections, North Atlantic Oscillation.**

I. Introduction

Wave energy conversion depends highly on the average energy available for extraction. Furthermore, it depends on extreme wave heights that may cause damage to Wave Energy Converters (WECs). Changes in wave climate parameters such as wave energy flux (C_gE) and significant wave height (H_s) are related to changes in the wind forcing both locally and remotely. The influence of large-scale atmospheric variability on the wave climate has been extensively studied using different methodologies such as observations from ships, wave hindcasts or reanalysis, satellite altimetry, in situ observations from wave buoys, and ocean weather stations [1]. Regarding our area of interest, it has been shown that the North Atlantic Oscillation (NAO) has a strong correlation with the wave climate of the northeast Atlantic region [2]–[7]. [8] showed a strong correlation between station-derived NAO and significant wave height, wave period and peak direction for winter and spring off the west coast of Ireland using WAVEWATCH III (WW3) driven by ERA-Interim data. [9] showed a strong positive correlation between the 95th percentile of H_s and NAO, but also showed that there is a large uncertainty in the projections of higher percentiles of H_s.

The NAO is associated with the westerly winds across the North Atlantic and its amplitude and phase are manifested in changes to the position and intensity of the Atlantic storm track [10]. The positive phase of the NAO is associated with a stronger pressure gradient due to strengthening of the Icelandic Low and Azores High pressure centres. The stronger pressure gradient creates stronger westerly winds that also create larger waves. A Negative NAO phase is associated with a weaker pressure gradient and slacker westerly winds over the North Atlantic which leads to smaller amplitude waves. A proper understanding of the impact of the NAO on the wave climate is very important for successful wave energy extraction and WEC deployment.

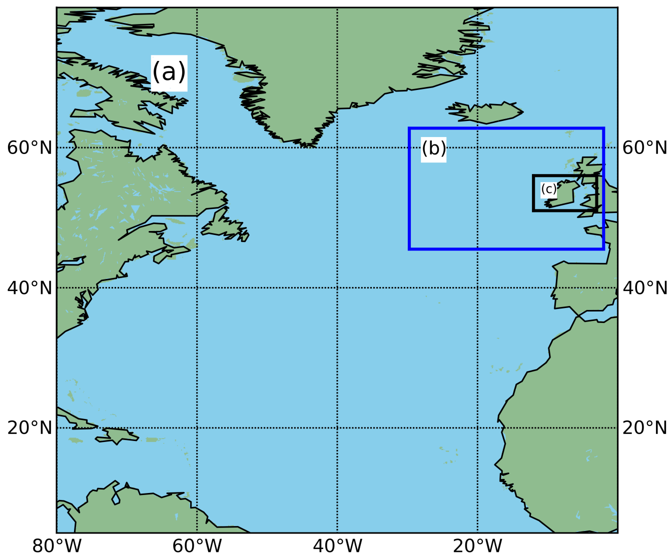

Fig. 1. The WAVEWATCH III model domains used in [11]. This study focuses on the middle grid b) shown by the blue box.

II. Model details

A. EC-EARTH model

The EC-Earth model is one of a variety of Earth System models [12] run under the CMIP5 [13] framework which is created to address scientific questions that arose as a part of the IPCC AR4 process (Intergovernmental Panel on Climate Change 4th Assessment Report) [14], [15]. The EC-Earth mean sea level pressure, wind speeds, and extratropical cyclone characteristics compared well to the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim reanalysis data [16]. This EC-Earth model version 2.3 consists of an atmosphere-land surface module coupled to an ocean-sea ice module [17], [18] with the Ocean Atmosphere Sea Ice Soil coupler (OASIS) version 3 [19]. The atmospheric component of this model is based on the Integrated Forecasting System with a spatial resolution of 125 km and 62 vertical layers up to 5 hPa. The oceanic component is the Nucleus for European Modelling of the Ocean version 2 with a resolution of 110 km [20] with 42 vertical layers and finally the Sea-Ice component is the Louvain-la-Neuve Sea Ice Model (LIM) version 2 [21].

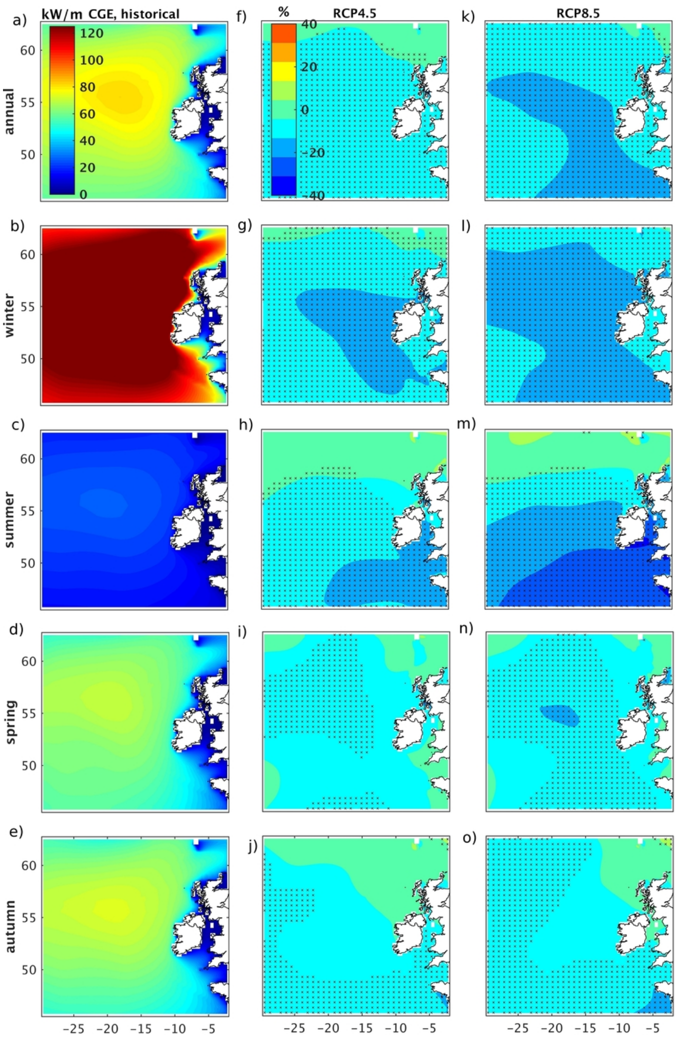

Fig. 2. Ensemble mean (a) annual, (b) winter, (c) summer, (d) spring, and (e) autumn CGE (kW/m) for the historical period (1980–2009). Projected changes (%) of CGE for the period 2070–2099 relative to 1980– 2009 for RCP4.5 (f) annual ensemble mean, (g) winter, (h) summer, (i) spring, (j) autumn and for RCP8.5 (k) annual ensemble mean, (l) winter, (m) summer, (n) spring and (o) autumn ensemble mean. Stippling indicates where the % changes in the future CGE ensemble mean exceed twice the inter-ensemble standard deviation.

The EC-Earth model has been run with two future scenarios or Representative Concentration Pathways (RCPs): RCP4.5 and RCP8.5, where RCP4.5 is a medium/high stabilized at approximately 4.5 W/m^2 after the year 2100 and RCP8.5 is a high pathway with a radiative forcing that reaches over 8.5 W/m^2 by the year 2100 [22]. There are three realizations, each driven by a separate EC-Earth ensemble member ($X = 1, 2, 3$), which make up the wave climate ensemble: each containing one historical (mei$X$) and two future simulations (me4X and me8X) corresponding to the above mentioned RCPs. The historical period is from 1980 to 2009 and the future period is from 2070 to 2099. To conclude there are nine 30-year data sets and with the ERA-Interim hindcast, ten simulations in total.

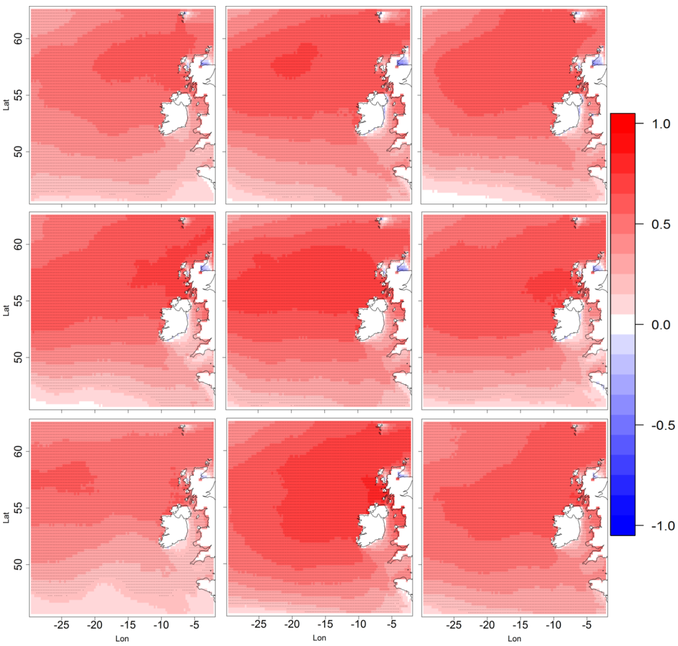

Fig. 3. The Spearman correlation coefficient between the NAO index and the 95th percentile of the wave energy flux (C_gE) for DJFM (DJFM = December, January, February, and March). (a–c) historical period (1980–2009) 3 ensemble members; (d–f) future period 2070–2099 under RCP4.5 and similarly (g–h) is for 2070–2099 under RCP8.5. Correlations statistically significant at the $\alpha < 0.05$ level are dotted.

B. WAVEWATCH III

WW3 [23] is a third generation 'phase-averaged' model that solves the wave action balance equation where conservation of the action density is balanced by source terms that represent physical processes that generate or dissipate waves. The model has been forced with EC-Earth 10 m winds and sea ice fields and ERA-Interim data. The model was run using three grids (see Figure 1). The grid a) covers the North Atlantic with a resolution of 0.75° x 0.75°. Grid b) covers the Northeast Atlantic with a resolution of approximately 0.25° x 0.25°. The grid around Ireland is an unstructured grid with a resolution from 15 km offshore to 1 km nearshore but was not the focus of this study. The focus of our analysis is on the middle grid (b), which covers a large region in the Northeast Atlantic, as opposed to the grid around the nearshore of Ireland (c), which was examined in [11] and [24]. Using grid b) provides an opportunity to examine, in addition to Ireland, the west coast of Scotland and France as areas with high wave energy potential. This research studies the historical and future period of hourly outputted values of the following wave parameter over the northeast Atlantic:

- Energy flux (W/m):

$$C_g E = \rho_w g \overline{C_g} E \tag{1}$$

where $\overline{C_g}$ denotes the averaged group velocity over the frequency-direction spectrum (see [23]), ρ_w is the water density and g is the acceleration due to gravity. E denotes the first moment of the variance density spectra $F(f,\theta)$ and is given as [23]:

$$E = \int_0^{2\pi} \int_0^{\infty} F(f,\theta) df d\theta \tag{2}$$

III. Methodology

The EC-Earth and the WW3 models were used in this study to generate atmospheric and wave datasets. The National Centre for Atmospheric Research (NCAR) NAO station-base time-series were also used.

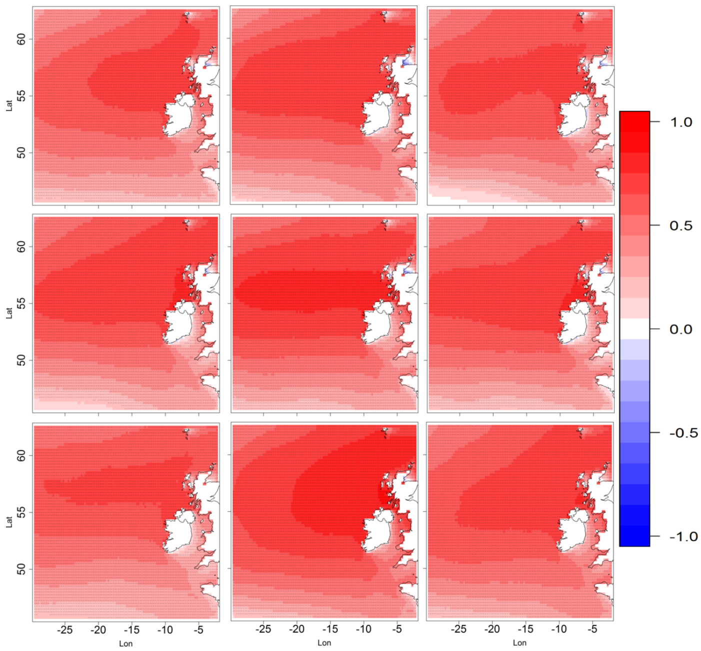

Fig. 4. The Spearman correlation coefficient between the NAO index and the mean wave energy flux ($C_g E$) for DJFM (DJFM = December, January, February, and March). (a–c) historical period (1980–2009) 3 ensemble members; (d–f) future period 2070–2099 under RCP4.5 and similarly (g–h) is for 2070–2099 under RCP8.5. Correlations statistically significant at the $\alpha < 0.05$ level are dotted.

The NAO index is highly dependent on the method used in its definition. The most common definition involves the difference between the Mean Sea-Level Pressure (MSLP) anomalies in the Icelandic Low and Azores High pressure centres. The station-based NAO index is calculated using station observations or gridded reanalysis datasets (using the nearest grid point to the location of interest). We used the monthly observation station-based NAO index by NCAR which was computed using MSLP data recorded in Reykjavik (Iceland) and Ponta Delgada (Azores) and is based on [25]. For each month each stations raw data are normalised separately by the 1864–1983 long term means; the NAO station index is then the difference between the Reykjavik and Ponta Delgado normalised values. EC-Earth MSLP values were extracted using the nearest neighbour remapping algorithm (remapnn) available in the CDO (Climate Data Operators) package [26].

We performed a correlation analysis that measures the strengths of association between two variables and the direction of the relationship. The value of the correlation coefficient varies between +1 and -1. If the value of the correlation coefficient is close to 1, then we have an almost perfect degree of association between the two variables. The closer the value of the correlation coefficient to 0, the weaker the relationship between the two variables. If the correlation coefficient is positive the direction of the relationship is also positive (the variables change in phase) and if the correlation coefficient is negative the direction of the relationship is also negative (the variables change in the opposite direction). Usually, in statistics, there are four types of correlations: Pearson correlation, Kendall rank correlation, Spearman correlation, and the Point-Biserial correlation. We used the Spearman correlation that expresses, through the value of its coefficient, the statistical nonparametric measure of the strength of a monotonic relationship between paired data.

IV. Results

Figure 2 displays the ensemble mean wave energy flux ($C_g E$ described in Equation 1), both annually and seasonally for the historical period 1980–2009, and the subsequent estimated percentage changes (%) for the future period 2070–2099 under the RCP4.5 and RCP8.5 scenarios. The ensemble mean is the mean of the values obtained from either the past or future simulations from different ensemble members, e.g. the future ensemble mean for RCP8.5 is a mean of me81, me82, and me83. As can be seen in Figure 2, there is a general reduction in $C_g E$ across all seasons, with the strongest relative decrease in summer (40%) and the largest decrease in absolute magnitude terms in winter (30 kW/m) off the west coast of Ireland and France. Decreases in spring and autumn are not as significant both in magnitude and statistically. In summer, in the north of the domain above Scotland, an area of statistically non-significant increase (12%) is found related to the increase in the driving 10 m winds to the south of Iceland found in [11].

Figures 3 and 4 shows the Spearman rank correlation coefficient between the station-based NAO index and the 95th percentile of $C_g E$ for DJFM for the historical period (1980 to 2009) and the period 2070–2099 under RCP4.5 and RCP8.5 for each ensemble member. It can be seen that there is a strong positive correlation between the NAO and 95th percentile wave energy flux over the historical period for all ensemble members (Figure 3 (a–c)). The coefficient of correlation between the NAO and average wave energy flux is also positive and slightly higher than for the 95th percentile of wave energy flux (Figure 4 (a–c)). A strong positive correlation was also

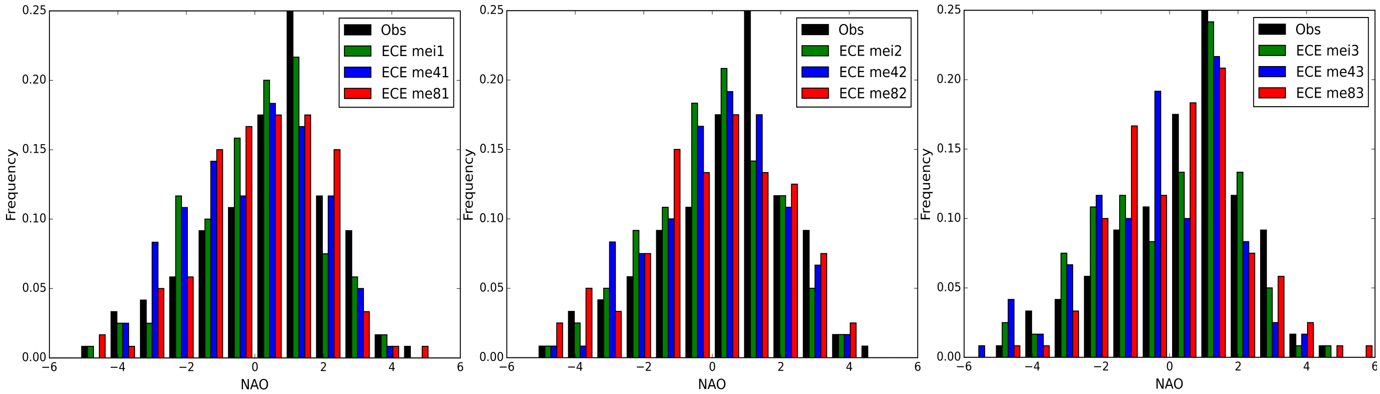

Fig. 5. Histogram of the NAO index for: (left) observations (1980–2009) in black, EC-Earth mei1 (1980–2009) in green, EC-Earth me41 (2070–2099) in blue, and EC-Earth me81 (2070–2099) in red; (middle) shows the same for ensemble number 2; (right) shows the same for ensemble number 3.

found under the RCP4.5 and RCP8.5 scenarios (Figure 3 (d–i)), slightly stronger under the RCP4.5 scenario. The size of the areas of strongest correlation increases off the west coast of Ireland under both RCP scenarios relative to the historical period (Figures 3 and 4). The value of the correlation also increases in the west of Ireland for RCP4.5 for both the mean and 95th percentile. The influence of the NAO loses significance over southern parts of the model domain in each of the ensemble members (historical and future periods), and is strongest to the west and northwest, as can be seen in all panels of Figures 3 and 4. There are large areas to the west and northwest of Ireland showing a correlation coefficient of over +0.7 (significant at the $\alpha = 0.05$ level). Contrary to this, a small area to the east of Scotland shows a negative correlation between the NAO and the 95th percentile of $C_g E$, present in each of the historical realisations. This may be an artifact because this area is close to the WAVEWATCH III domain boundary and is cut off from the wave spectra boundary forcing due to the coastline.

Figure 5 shows histograms of the distribution of monthly mean NAO index (using the months of December, January, February and March; DJFM or winter hereafter and chosen because winds are stronger and wave heights are larger during these months) covering 30-year historical/future periods. The observed NAO and NAO based on the EC-Earth mei$X$ historical simulation are for the period 1980-2009 while the EC-Earth projection data (me4X and me8X) are valid for the period 2070-2099.

V. Conclusion

Despite the decrease in wave energy (Figure 2), the simulations show a likely continuing large energy resource off the coast of Ireland and Scotland (in excess of 70 KW/m annually). There is a continuous stretch of ocean along the Northeast Atlantic, from the north of Scotland down to the west coast of Brittany, France, which has mean annual CGE values exceeding 40–50 kW/m, even with the projected decreases realized. However, this study also shows that the resource is highly variable which should be taken into account when planning WEC deployment and ocean energy extraction. We have a strong positive correlation between the NAO and both mean and 95th percentile wave energy flux off the west coast of Ireland under both RCP scenarios relative to the historical period, with RCP4.5 simulation values slightly stronger than RCP8.5.

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