Title: A 34-year nearshore wave hindcast for Ireland (Atlantic and Irish sea coasts): wave climate and energy resource assessment

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A 34-YEAR NEARSHORE WAVE HINDCAST FOR IRELAND (ATLANTIC AND IRISH SEA COASTS): WAVE CLIMATE AND ENERGY RESOURCE ASSESSMENT

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1. Introduction

The Northeast Atlantic possesses some of the highest wave energy levels in the world and a renewed interest in harnessing this energy has been seen in recent years. Recent studies aimed at quantifying the variability of the wave climate and energy resource in areas of this region, over timescales of a decade or more, have been performed in recent years (for example Gallagher et al. 2013; Boudière et al. 2013; Charles et al. 2012; Dodet et al. 2010). In the operational wave forecasting community, increased attention is being paid to the nearshore (van der Westhuysen 2012), awakened in part by the potential energy resource but also by an increased awareness of coastal hazards and their possible impacts on coastal communities. Improvements in ocean wave forecasting skill (Janssen 2008) and the availability of high-quality global reanalysis datasets, now enable long term regional and local area wave hindcasts to be performed, downscaling to a high resolution in the nearshore.

Additionally, recent studies have shown that in nearshore locations, wave energy extraction levels could be commensurate to those found in the offshore (Folley and Whitthaker 2009). In addition, the cost of transferring power onshore and the accessibility for maintenance can be improved by the proximity to the coastline.

Most wave climate studies for Ireland, have targeted limited nearshore sites (Gallagher et al. 2013; Tiron et al. 2013) and also offshore locations on the Irish West Coast (ESB 2005; Curé 2011; Rute Bento et al. 2012; Cahill and Lewis 2011). The geomorphology of the Irish West Coast is in fact quite heterogeneous and complex. This is likely to introduce significant variability in the wave energy resource for this region (Tiron et al. 2013).

In order to investigate this variability, a high-resolution nearshore 34-year wave hindcast was carried out for Ireland, with a particular focus on the wave energy resource. To complete the wave climate picture, the entire coastline has been modelled, both the Atlantic coast and the eastern seaboard, where the majority of the population is located and where wind-seas dominate.

The wave climate is estimated using the third generation spectral wave model WAVEWATCH III version 4.11 (Tolman 2009), the unstructured grid formulation (Roland 2008). The wave model was forced with directional wave spectral data and 10m winds from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim reanalysis, which is available from 1979 to the present (Dee et al. 2011; Persson 2011). The wave hindcast was validated with data from wave buoys located all around the coast of Ireland and in particular with buoys located in nearshore regions.

Two such areas, which possess steep bathymetry gradients, and complex exposed rocky shorelines, are the southern part of Achill Island on the Co. Mayo coastline and an area centered at Killard point on the Co. Clare coast respectively. For these areas, wave buoy and Acoustic Doppler Current Profiler (ADCP) data for intermediate to shallow depths (50m or less) was obtained from the ESBs WestWave project (WestWave 2013). Additionally, nearshore wave buoy data from other areas with more gentle bathymetric gradients (such as Broadhaven Bay, Co. Mayo) is used to validate the wave model.

2. Construction of the Digital Elevation Model

The quality of the bathymetric data used to build the computational grid greatly influences the accuracy of wave models in the nearshore. Historical seabed surveys have substantial uncertainties which only recently came under the scrutiny of the hydrographic community (Calder 2006). These uncertainties are related to the survey methodology, interpolation of the scattered survey data and any changes in the seabed topography that may have occurred over time, after the bathymetric survey was carried out.

Modern and highly-accurate survey techniques such as light detection and ranging (LIDAR) or multi-beam echosounder (MBES) are currently used to map nearshore areas in campaigns such as the Integrated Mapping For the Sustainable Development of Ireland's Marine Resource (INFOMAR 2006), which is a successor to the Irish National Seabed Survey (INSS), as described in Dorschel et al. (2011). However, it may take several years for mapping of the Irish seabed to be completed.

In the interim, digital elevation models (DEMs) have to combine sets of data with varying degrees of accuracy and resolution. The level of accuracy of a DEM has an impact on the hydrodynamical model, and if not accounted for, could lead to erroneous interpretations of the results (Calder 2006). Recent efforts have been made to construct DEMs with uncertainty estimates (Poti et al. 2012).

The final DEM for Ireland (see Figure 2) was obtained by merging three bathymetric sources (shown in Figure 1):

i. Vector data obtained from OceanWise Ltd., derived from the United Kingdom Hydrological Office (UKHO) admiralty charts. The quality of this data is not uniform, some of the surveys predate modern techniques;

ii. The European Marine Observation and Data Network bathymetric dataset EMODnet (EMODnet 2013). This dataset has a resolution of approximately 500m and blends bathymetric datasets from many sources in Europe. It is constantly updated with new surveys so the quality will continue to improve;

iii. High resolution MBES and LIDAR INFOMAR survey data. Approximately 50 gridded datasets, with resolutions from 2m to 80m were used.

The mismatch between the coarser datasets (EMODnet and UKHO) and high-resolution/high-quality INFOMAR dataset was evaluated on areas of overlap. Differences of more than 20m were observed in some nearshore locations (Tiron et al. 2013). The EMODnet dataset was found to be less accurate than the UKHO data in some nearshore areas on the West Coast. Based on this observation, we have ranked the datasets in the order of accuracy (INFOMAR, UKHO and EMODnet).

To avoid artificial ridges at the boundaries between these datasets (which are likely to induce spurious refraction effects and numerical instabilities in the hydrodynamical model) a blending and smoothing procedure was then applied. The datasets were first gridded on a common grid with a resolution of 50m. Smoothing was applied if the original data was at a finer resolution than the target grid. The overlap areas were excluded from the coarse resolution datasets, based on the ranking mentioned above.

Weights of 10, 5 and 1 respectively, were assigned to each of the datasets and a smoothing kernel with a variable radius based on depth was applied. The radius of smoothing varies between 100m (r_{min}) for depths smaller than 22m (h_0) to 2.5km (r_{max}) in the offshore area:

$$r_{min} + \frac{r_{max} - r_{min}}{2} \left[1 + \tanh\left(\lambda(h - h_0)\right)\right] ,$$

where $\lambda = 0.2$.

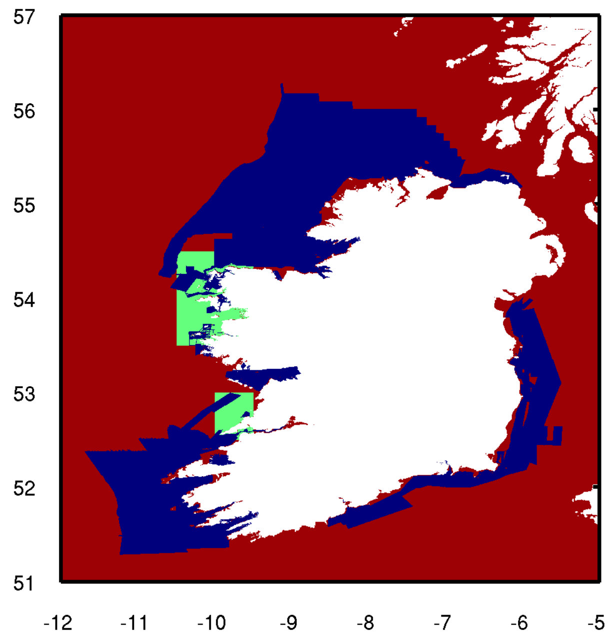

FIG. 1. Bathymetric datasets used in building the DEM for Irish coastal waters: INFOMAR (blue), UKHO (green) and EMODnet (red) bathymetry.

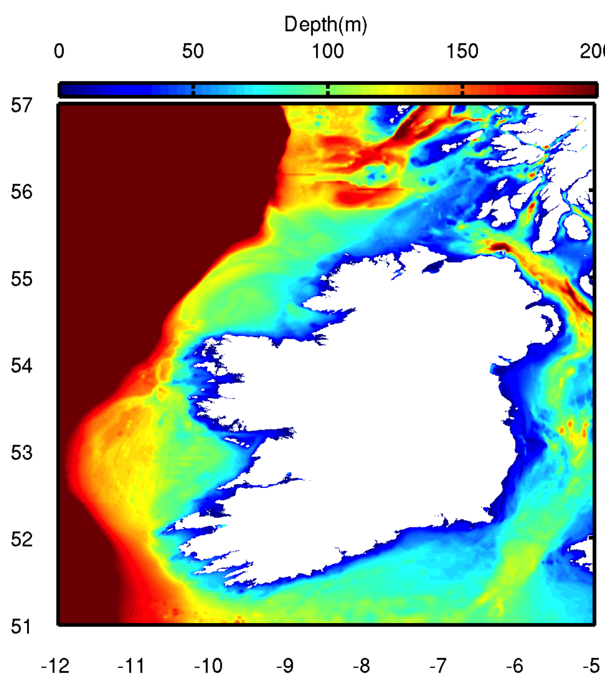

FIG. 2. DEM for Ireland (coastal waters) resulted from merging the bathymetric datasets depicted in Figure 1.

3. Wave Model Set-up

The wave model grid is an unstructured triangular grid with resolution varying from 250m in the nearshore to 10km in the offshore. The coast and island boundaries were derived from the Global Self-consistent Hierarchical High-resolution Shoreline (GSHHS) database (Wessel and Smith 1996), the finest resolution version, smoothed and sampled at approximately 250m. Geo-referenced satellite imagery (LANDSAT 2013) was used to correct the coastline and islands. Indeed, there are some areas on the West Coast of Ireland where a significant mismatch between GSHHS and the shoreline can be seen (see for example Tiron et al. 2013).

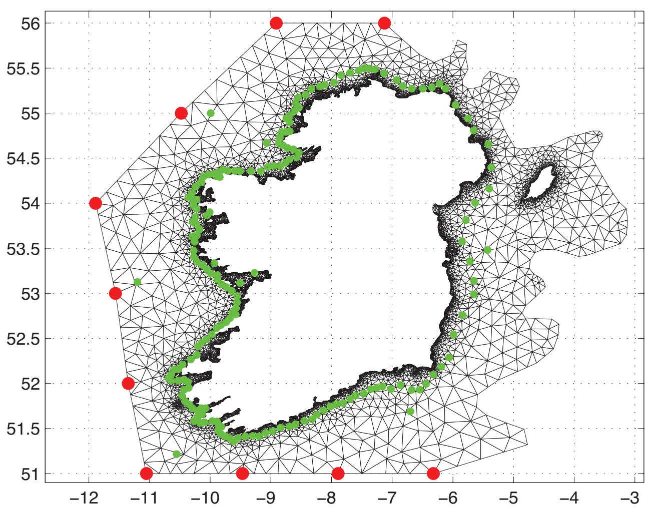

Fig. 3. The wave model grid. Red: ERA-Interim wave model points used for boundary feeding. Green: points where 3-hourly directional spectra outputs were generated.

The resulting grid has approximately 15,000 nodes with a maximum resolution of 250m in the nearshore. The outer boundary of the grid was chosen to align with ERA-Interim wave model grid points (see Figure 3). The boundary feeding was set at grid nodes on segments of the open boundary (in between, and at, the ERA-Interim grid points) where depths were larger than 90m. The spectral domain was discretized in 24 directions and 30 frequencies logarithmically spaced with an increment of 1.1 from 0.0345Hz, which coincides with the resolution of the ERA-Interim wave spectra used to force the model. The temporal resolution of the boundary feeding, and of the 10m ERA-Interim wind forcing fields, is 6 hours (the four standard synoptic times). The spatial resolution of the ERA-Interim winds is approximately 79km (Dee et al. 2011). The parametrization for source terms and dissipation (test 441) formulated in Ardhuin et al. (2010) was employed.

Hourly field outputs were produced for standard mean wave parameters (significant wave height, standard wave periods, directions), the wave energy flux, spectral partitions parameters and wave-ocean layer parameters. Additionally, the directional spectra was saved every 3 hours at the buoy locations and at points on the 60m depth contour, as can be seen in Figure 3.

4. Validation of the Wave Model

The wave model was validated with data from 17 different wave buoys located around the Irish coastline as shown in Figure 4. These buoys vary in depth from 155m to 11m, as described in Table 1. It should be noted that the Irish Marine Weather Buoy Network, maintained by Met Éireann and the Marine Institute (M.I. 2013), has only been in operation since 2001, when the first buoy was deployed. Moreover, buoy data in the nearshore has only become available in recent years, predominantly on the West Coast, targeting potential wave energy testing and deployment sites, as it can also be seen Table 1.

Table 1. Buoy location depth and duration of time series used in comparison with model data. Buoys listed in order of depth.

Buoy	*Location*	*Depth* (*m*)	*Period* (*mm/yy*)
M3	SW of Mizen Head	155	01/03 - 12/12
M1	W of Aran Isl.	140	03/01 - 12/07
BH4	W of Belmullet	100	05/12 - 12/12
M2	E of Lambay Isl.	95	05/03 - 12/12
M4	Donegal Bay	72	04/03 - 11/12
M5	SE Coast	70	10/04 - 12/12
BH3	W of Belmullet	56	12/09 - 01/12
K1	Killard Point	51	11/11 - 01/12
AC1	Achill Isl.	43	11/11 - 08/12
BH1	Broadhaven Bay	38	01/09 - 10/09
K2	Killard Point	36	08/12 - 12/12
SB2	E of Aran Isl.	28	01/10 - 06/10
G1	Galway Bay	22	05/08 - 01/12
AC2	Achill Isl.	21	11/11 - 01/12
SB1	Mace Head	18	04/09 - 09/09
BH2	Broadhaven Bay	11	06/06 - 07/09

The statistical comparison between model and observations for significant wave height (Hs), period and direction is summarised in Table 2. Generally, the model appears to perform well when compared to the measured values. The correlation coefficients for significant wave height are all over 0.94 with the exception of 0.89 for the SB1 buoy (located in Galway Bay, in the shadow of the Aran Islands). A significant bias in Hs can be seen for SB2 (over 40%). This buoy is located in an area where only EMODnet bathymetry was available, with shallow depths of under 20m. Interestingly the correlation coefficient is very good for this location, however the observed discrepancy raises questions regarding the accuracy of the bathymetry dataset in this region and in particular for these depth ranges.

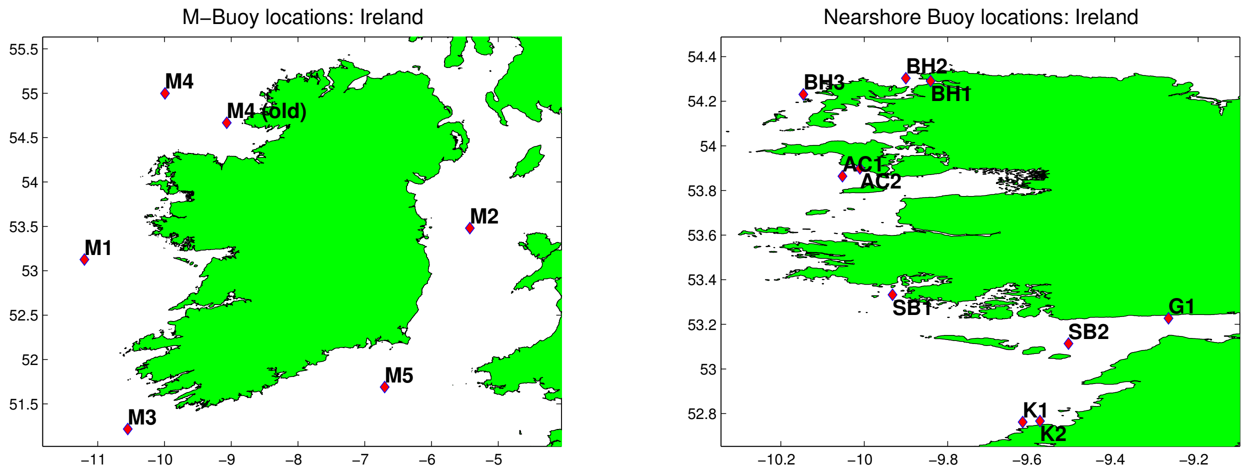

FIG. 4. Locations of the M-buoys from the Irish Marine Weather Buoy Network (left panel) and the nearshore buoys (right panel) used for validation of the wave model hindcast. The buoy availability ranges from periods of a few weeks to almost 10 years, as can be seen in Table 1.

TABLE 2. Comparison between the model and buoy for significant wave height, period and direction: the mean of the buoy (X), the bias, the root-mean square error (RMSE), the correlation coefficient (R) and the scatter index (SI) are shown. Where possible the zero-crossing period and mean direction were used. In some locations only the peak period or peak direction was available. All directional error statistics were calculated using the circular statistics toolbox from Berens (2009). *(* denotes where comparisons were between the buoy and model peak period or peak direction, respectively.)*

	Significant wave height					Period					Direction				
Buoy	*X* (*m*)	*Bias* (*cm*)	*RMSE* (*cm*)	*R*	*SI* (%)	*X* (*s*)	*Bias* (*s*)	*RMSE* (*s*)	*R*	*SI* (%)	*X* (*deg*)	*Bias* (*deg*)	*RMSE* (*deg*)	*R*	*SI* (%)
M3	2.86	-4	45	0.95	16	6.9	0.3	0.8	0.87	11	275	5	13	0.95	15
M1	2.94	-15	46	0.96	16	7.3	0.3	0.9	0.86	12	-	-	-	-	-
BH4	2.87	5	38	0.96	13	6.7	0.2	0.6	0.92	8	292*	9	20	0.7	29
M2	1.19	15	31	0.94	25	4.5	0.9	1.2	0.65	26	189	-15	24	0.77	14
M4	3.11	-1	39	0.97	13	7	0.2	0.7	0.98	19	275	2	13	0.94	15
M4(old)	2.34	-24	55	0.94	23	6.7	0.3	0.9	0.84	13	-	-	-	-	-
M5	1.81	-3	38	0.94	21	5.5	0.1	0.8	0.82	15	231	-6	18	0.84	14
BH3	2.77	11	40	0.97	15	7	0.2	0.7	0.89	10	296*	7	16	0.69	25
K1	4.57	31	53	0.97	12	8	0.0	0.7	0.88	7	291*	4	9	0.74	13
AC1	2.32	-14	34	0.98	15	6.3	-0.1	0.7	0.91	11	270*	5	13	0.68	14
BH1	1.90	2	31	0.97	16	6.2	0.1	0.9	0.86	14	317	4	11	0.83	25
K2	2.44	20	40	0.96	16	6.7	0.0	0.7	0.90	11	292*	-0.5	9	0.75	13
SB2	0.62	-5	17	0.89	27	4.3	-0.4	1.9	0.61	43	259	12	29	0.65	29
G1	0.75	7	18	0.94	25	4.1	-0.3	1.5	0.60	6	-	-	-	-	-
AC2	3.79	-6	43	0.95	11	12.3*	-0.5	1.5	0.76	12	260*	6	12	0.45	12
SB1	0.85	-36	44	0.95	52	4.7	-0.4	1.1	0.71	23	230	6	12	0.70	9
BH2	0.36	1	8	0.97	15	-	-	-	-	-	-	-	-	-	-

5. Analysis

In this section we present a preliminary analysis of the 34 year hindcast for Ireland. We focus on the spatial variability of the wave climate around Ireland, in particular by contrasting the Irish Sea the Atlantic Ocean coasts. The seasonal variability in both Hs (Figure 5) and in the wave energy flux per metre of wave crest (CgE) - Figure 6 is assessed. The interannual variability of the means is represented through the normalized standard deviation (%). It is interesting to note that the overall annual mean and the autumn mean have very similar ranges for both Hs and CgE.

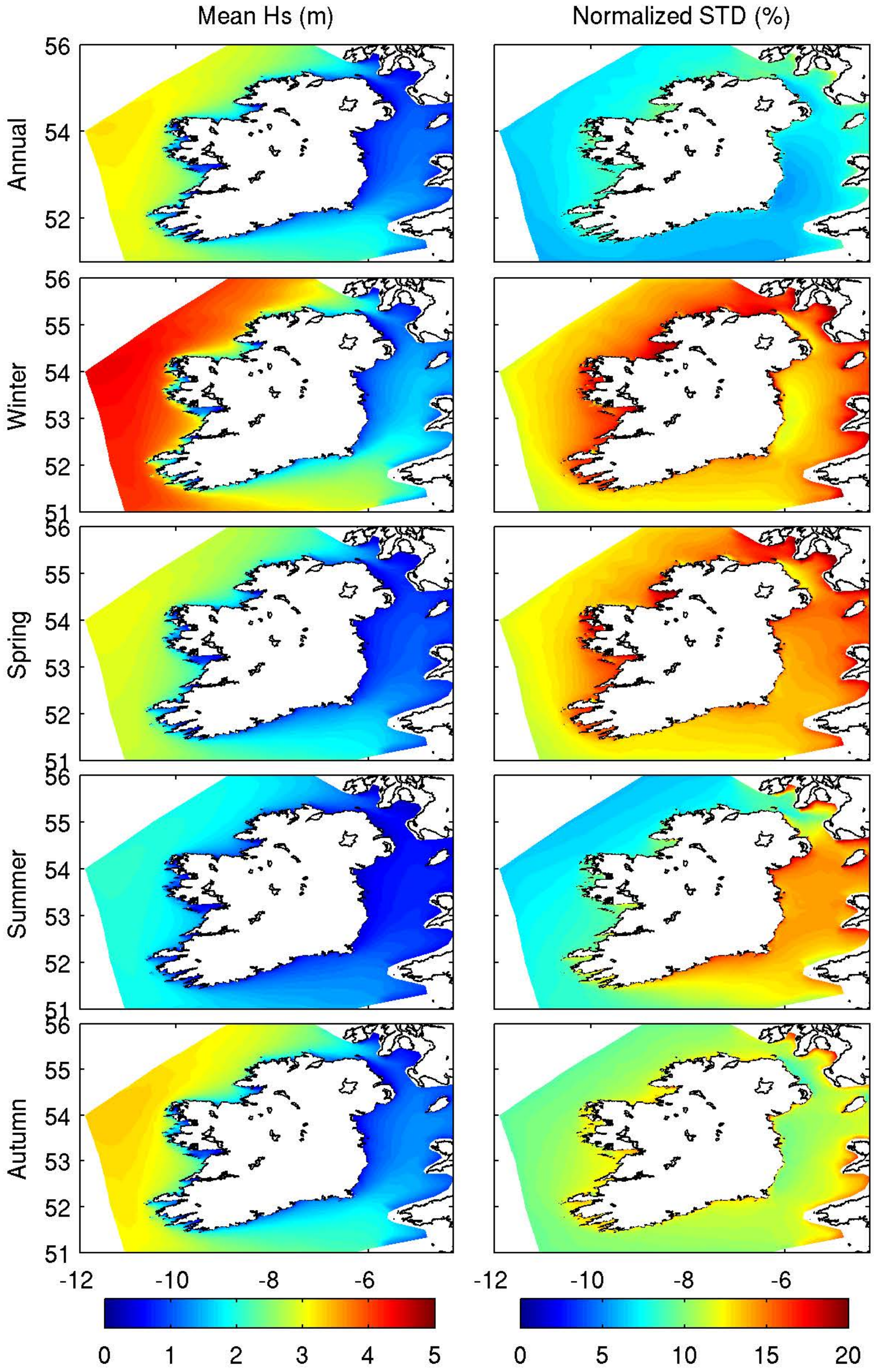

FIG. 5. Wave climate of Ireland 1979-2012. Left panels: annual and seasonal mean significant wave height (m). Right panels: normalised standard deviation of the means (%) which is a measure of the interannual variability.

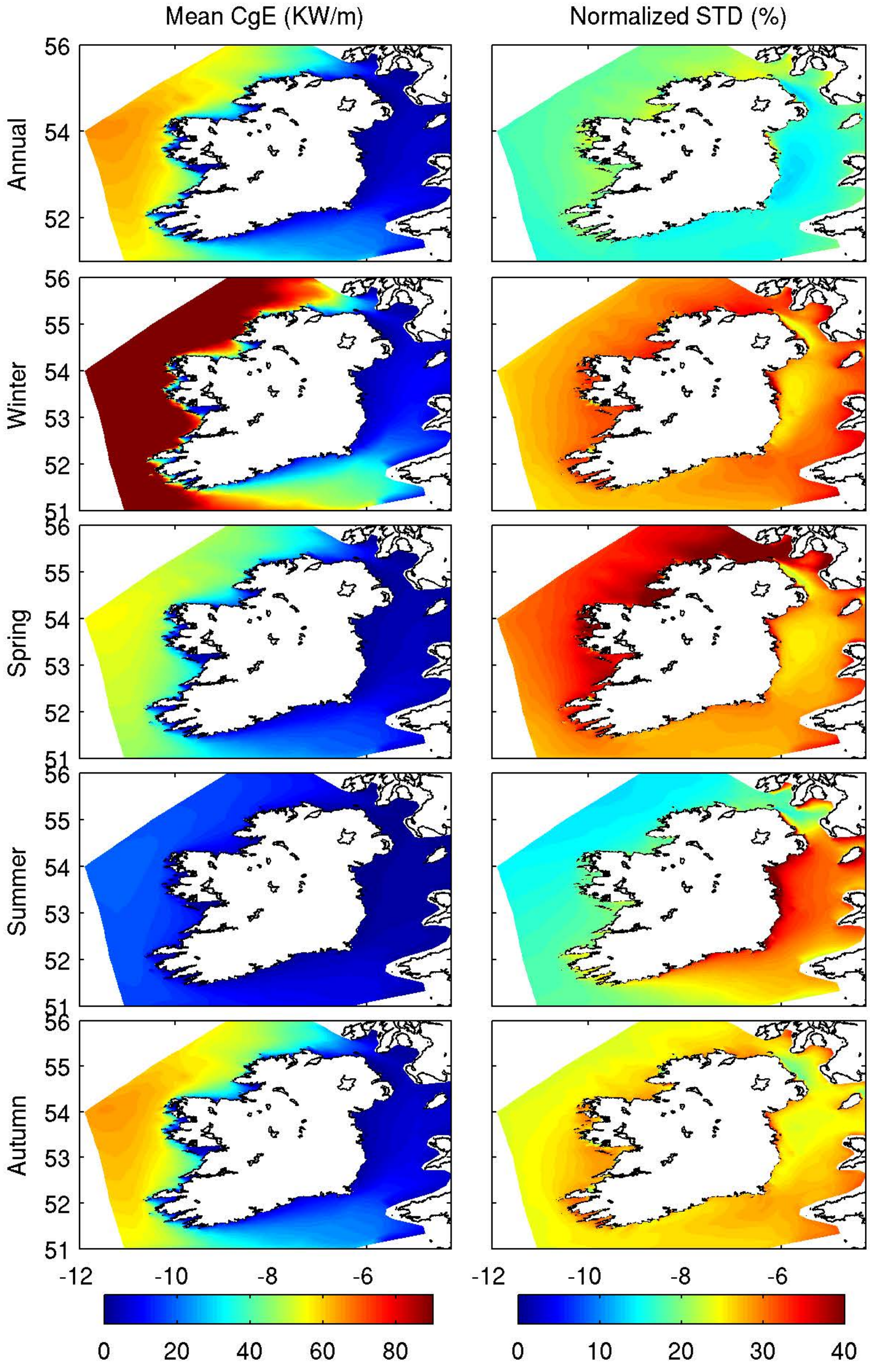

FIG. 6. Wave climate of Ireland 1979-2012. Left panels: annual and seasonal mean wave energy flux (kW/m of wave crest). Right panels: normalised standard deviation of the means (%) which is a measure of the interannual variability of the wave energy resource.

Table 3. Correlation between the 34 year hindcast results (1979-2012) and NAO seasonal averages for significant wave height, energy period and peak direction at the buoy locations specified in Table 1. Correlation coefficients great than ±0.5 are shown in bold. Only correlations significant at higher than 95% by *t* test are displayed. *Winter (December, January, February), spring (March, April, May), summer (June, July, August), autumn (September, October, November).*

	Significant wave height				Period				Direction			
Buoy	*DJF*	*MAM*	*JJA*	*SON*	*DJF*	*MAM*	*JJA*	*SON*	*DJF*	*MAM*	*JJA*	*SON*
M3	**0.65**	0.48	-	-	**0.50**	**0.52**	-	0.39	**0.59**	0.36	-	-
M1	**0.74**	**0.54**	-	-	**0.51**	**0.50**	-	-	0.44	-	-	-
BH4	**0.79**	**0.57**	-	-	**0.53**	**0.53**	-	-	0.39	-	-	-
M2	**0.54**	-	-0.4	-	-	-	-	-	**0.71**	-	-0.4	-
M4	**0.8**	**0.58**	-	-	**0.59**	**0.56**	-	-	**0.53**	-	-	-
M4(old)	**0.81**	**0.58**	-	-	0.48	**0.52**	-	-	-	-	-	-
M5	**0.50**	-	**-0.54**	-	-	-	-	-	**0.56**	-	-	-
BH3	**0.81**	**0.58**	-	-	0.39	**0.50**	-	-	-	-	-	-
K1	**0.81**	**0.63**	-	-	-	**0.51**	-	0.37	0.46	-	-	-
AC1	**0.8**	**0.63**	-	0.37	-	0.44	-	-	0.47	**0.57**	**0.58**	-
BH1	**0.76**	**0.51**	-	-	0.49	**0.53**	-	-	-	-	-	-
K2	**0.80**	**0.63**	-	-	-	**0.50**	-	0.37	**0.5**	0.39	0.41	0.36
SB2	**0.75**	**0.56**	-	-	-	-	-	-	**0.58**	-	-	-
G1	**0.76**	**0.55**	-	-	-	-	-	-	**0.51**	-	-	-
AC2	**0.75**	**0.60**	-	-	-	-	-	-	**0.52**	**0.62**	**0.63**	-
SB1	**0.69**	**0.54**	-	-	-	-	-	-	**0.64**	0.49	-	-
BH2	**0.84**	**0.66**	-	-	-	0.47	0.36	-	0.37	-	-	-

In winter, the Atlantic coast is exposed to highly energetic sea states (mean Hs close to 5m, CgE over 130kW/m) which do not dissipate significantly until very close to the shoreline. In contrast, mean Hs values do not exceed 2m on the Irish Sea coast in any season. The decrease in energy levels from winter to summer is quite dramatic, even though on the West Coast energy levels of up to 20kW/m are maintained in summer months.

The Irish wave climate presents significant interannual variability in terms of Hs: overall less than 15% for the annual means but over 25% in winter and spring. On the Atlantic coast the interannual variability is more pronounced in the nearshore. For CgE, the variability from year to year is markedly larger, as evident in Figure 6. Variability well over 50% in mean CgE annual levels can be seen particularly in spring on the North and West Coast.

This variability can be in fact linked to larger scale atmospheric circulation patterns such as the North Atlantic Oscillation NAO (Barnston and Livezey 1987). Several studies have focused on evaluating correlations between wave climate averages and the various teleconnection indices, such NAO for the Northeast Atlantic region (see for example recent studies by Charles et al. 2012; Le Cozannet et al. 2010; Bertin et al. 2013; Dodet et al. 2010) and also at the Atlantic basin scale (Wang and Swail 2001, 2002).

Positive phases of the NAO are associated with increased wave heights in the Northeast Atlantic. Indeed, local winds play a key role in the Irish wave climate. Furthermore, swells generated in the North Atlantic basin which propagate long distances before reaching Ireland will impact the correlation between wave climate averages and teleconnection patterns such as NAO for this region.

In Table 3 we have evaluated the correlation between seasonal averages of the wave model hindcast and NAO (obtained from Climate Prediction Center 2013) for Hs, energy period (Tm) and peak direction (Pdir). On the Atlantic seaboard of Ireland there is a strong correlation between winter and (to a lesser extent) spring mean Hs values. This correlation persists for Tm and Pdir for these seasons, however to a lesser degree than for Hs. As discussed by (Bacon and Carter 1993), correlation coefficients greater than 0.5 signify a relatively strong connection between the wave climate and teleconnection patterns. As can be seen in Table 3 the Irish wave climate is highly influenced by NAO in winter. The influence of the NAO on the Irish wave climate appears to be more significant than in other Northeast Atlantic regions (for example as estimated by Charles et al. 2012, in the Bay of Biscay).

6. Conclusions

A 34 year, high-resolution, nearshore wave hindcast was performed for Ireland, including both the Atlantic and the Irish Sea. The model was validated with observations from 17 wave buoys around Ireland. The comparison between the observations and the model was found to be excellent. A strong spatial and seasonal variability was found for both significant wave heights and the wave energy flux. We also identified a strong correlation between the NAO teleconnection pattern and wave heights, wave periods and peak direction in winter and also to a lesser extent, in spring.

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