Marine Renewable Energy Resources Atlas for Continental Portugal

Report for the EnergyMare Project (Atlantic area Interreg project Contract Number: 2011-1/157)

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Introduction

Marine renewable energies comprehend a vast number of technologies including tidal, waves and offshore wind technologies. Numerical modelling could contribute to support the development of such activities in several ways. Through atmospheric, waves and hydrodynamic models, the areas with enough energetic resource for these industries could be identified. Furthermore, operation and maintenance services rely on the sea conditions that operational modelling is able to provide through forecasts services. These forecasts could also be valuable for the survivability of the installed devices as extreme events could be identified and thus the possible damages could be reduced by taking measures. Moreover, operational modelling could evaluate the amount of energy would be available and how much could be produced by the devices thus the electric system would be more efficient in accommodating the generated energy.

In these report, the off-shore wind, waves and tidal energy potential would be obtained by exploring the results of numerical models for the Western Iberia region. The report consist on a description of the numerical model applications and the calculations performed with the modelling results to evaluate each marine renewable energy followed by the maps able to describe the resource and a validation of the numerical models with coastal observations.

The numerical models presented in this document have been implemented operationally and their results and forecasts can be accessed at http://forecast.maretec.org/.

Methods

Wind Power

In order to evaluate the wind power density for the development of offshore wind projects, wind intensities and directions were analysed by numerical model forecast for a six-year period (Jun 2009-Jun 2015). Hourly model results were obtained by a MM5 model (Meteorological Model 5; Grell *et al.*, 1994) application based in two nested grids with a horizontal resolution of 27 km and 9 km respectively (Figure 1) implemented by the IST meteorological group (http://meteo.ist.utl.pt; Trancoso, 2012).

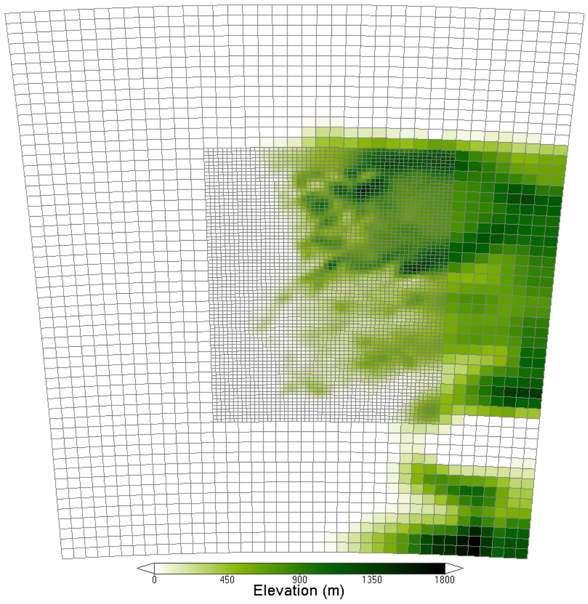

Figure 1 Domains grids for the meteorological model MM5 for the Portuguese mainland application.

Wind velocity model results at 10 m height were interpolated to a 0.06 degrees regular grid (Figure 5). Those values were transposed for 100 m, which is the hub height commonly used by offshore wind developers, i.e. the WindFloat pre-commercial device to be installed in the northern coast of Portugal. The wind profile of the atmospheric boundary layer, until approximate 2 km, is generally is best approximated using the log wind profile equation that accounts for surface roughness and atmospheric stability by using the following formula:

$$u=u_r(z/z_r)^{\alpha}$$

where u is the wind speed at height z, and u_r is the known wind speed at a reference height z_r. The α exponent is an empirically derived coefficient that varies dependent upon the stability of the atmosphere and that according to Hsu *et al*. (1994) would have an optimum value of 0.11 for open water conditions. Replacing the values, wind speeds for the total period and for the different seasons at 100 meters (Figure 6 and Figure 7) were be obtained by applying the following formula:

$$u_{100}=u_{10}(100/10)^{0.11}$$

The seasonal maps (Figure 7) were obtained by the following months' correspondence:

- Spring: March, April, May;
- Summer: June, July, August;
- Autumn: September, October, November;
- Winter: December, January, February.

With the average wind speed, the wind power density (P_{wind}) per m^2 of rotor swept area can be obtained by applying the following formula:

$$P_{wind}= 1/2\rho|U|^3$$

where ρ correspond to the air density 1.225 kg/m^3 and |U| is the modulus of the wind speed. Applying the formula to the 100 m height winds, the average wind power density for the six year period and for each of the seasons were obtained (Figure 8 and Figure 9).

Wave Power

In order to model the generation, propagation and dynamics of the waves reaching the Portuguese continental coast it was used the NOAA WAVEWATCH III (R) Model V3.14.

In the case of the Portuguese coast, swell waves are generated in the western side of the Atlantic Ocean. To simulate the waves arriving to the Portuguese coast, three nested levels with increasing horizontal resolution -0.5, 0.25 and 0.05 degrees- (Figure 2) covering the North Atlantic Ocean (NAt), the southwest part of Europe (SWE) and the Portuguese Continental Coast (PCC) respectively, were defined.

Two bathymetric sources were combined to populate all levels grids: the European Marine Observation and Data Network (EMODnet) Hydrography portal (http://www.emodnet-hydrography.eu) completed by the 30” resolution global bathymetry data SRTM30_PLUS (Becker *et al.*, 2009) for regions where EMODnet data were absent.

The wave energy resource was evaluated for the period 2000-2010. The NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999 with 1 degree of horizontal resolution (NCEP/NWS/NOAA/U.S. Department of Commerce, 2000) was used to feed the wave model with winds intensities and direction.

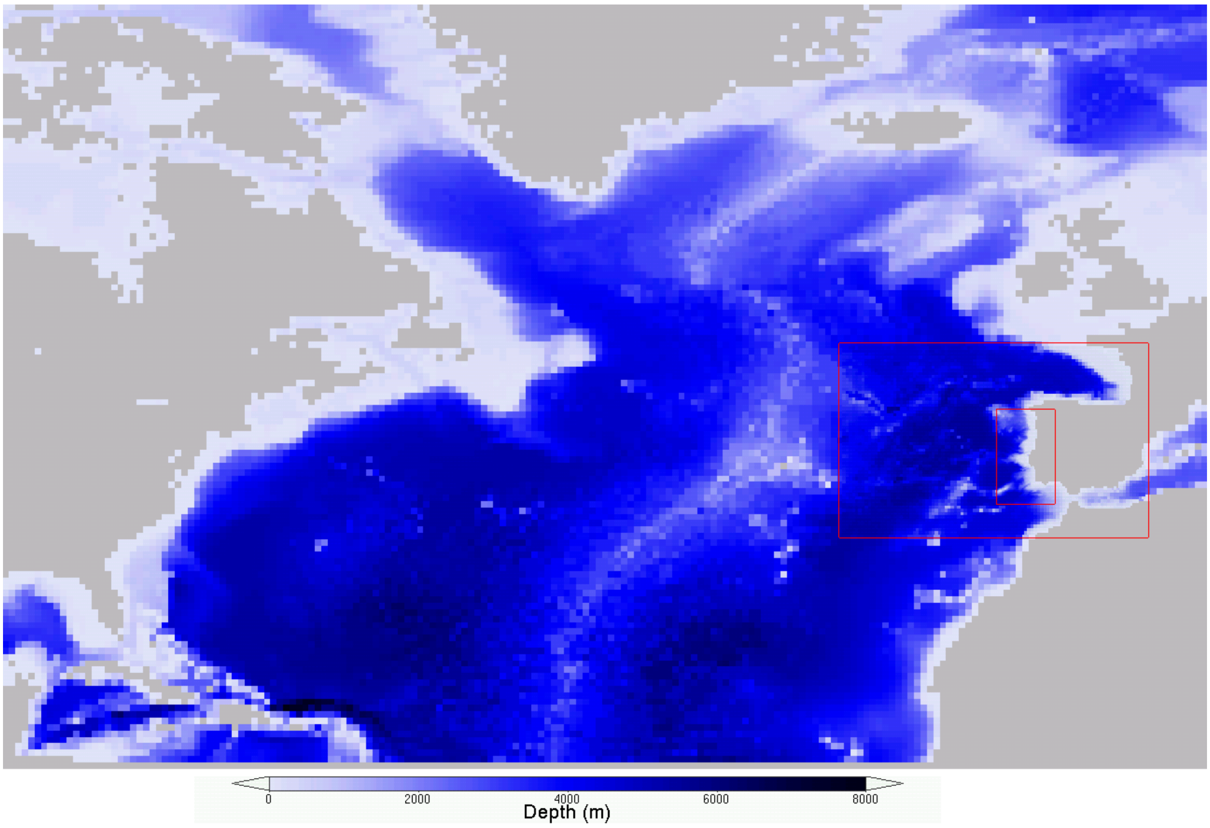

Figure 2 Domains for the waves model WaveWatch III for the Portuguese continental coast application. Nested domains are enclosed by red lines.

For defining the seasonal periods the following criteria, same as for the wind assessment, was applied:

- Spring: March, April, May;

- Summer: June, July, August;
- Autumn: September, October, November;
- Winter: December, January, February.

In Figure 10, the annual significant wave height was obtained for the PCC domain for the period 2000-2010 with larger values found in the open ocean and values around the 2 m in the western Portuguese coast except for the sheltered areas of the Tagus mouth region and the Algarve. Figure 11 shows the seasonal values for the same periods, where a clear contrast between summer and winter periods can be observed.

Wave power (P) was estimated using the formula for deep water, where water depth is larger than half the wavelength:

$$P = 0.49 * H_s^2 * T_m$$

obtaining kilowatts (kW) per meter of wavefront length. Once this formula is applied to the PCC domain for the 2000-2010 period, we obtain the wave power distribution for the study area.

Wave power distribution shows a clear gradient with a NW-SE orientation (Figure 12). Maximum values around 50 kWm^{-1} are found in the open ocean off the Northern coast while minimum values are located in the areas sheltered by geographic features from this direction i.e. the Tagus and Sado estuarine mouths and the Algarve southern coast. On average the Portuguese coastal area has a wave power around 30 kWm^{-1} though this value would present a strong seasonality. Values obtained were in agreement with the ones obtained by Pontes *et al.* (2003). In Figure 13, the wave density power is obtained for each year season, it can be appreciated how spring and autumn values distributions and energy values are similar while maximum are obtained during the winter period and minimum during summer periods.

Tidal Power

In order to evaluate the tidal power for the Portuguese continental coast, an application was ran using the MOHID Water which is part of the MOHID Modelling System (http://www.mohid.com; Neves, 2013). The MOHID is an open source numerical model programmed in ANSI FORTRAN 95 using an object orientated philosophy. This system is being developed since 1985 mainly by the MARETEC group at the Instituto Superior Técnico (IST) which is part of the Universidade de Lisboa. The model adopted an object oriented philosophy integrating different scales and processes. The core of the model is a fully 3D hydrodynamic model which is coupled to different modules comprising water quality, atmosphere processes, discharges, oil dispersion, jet mixing zone model for point source discharges.

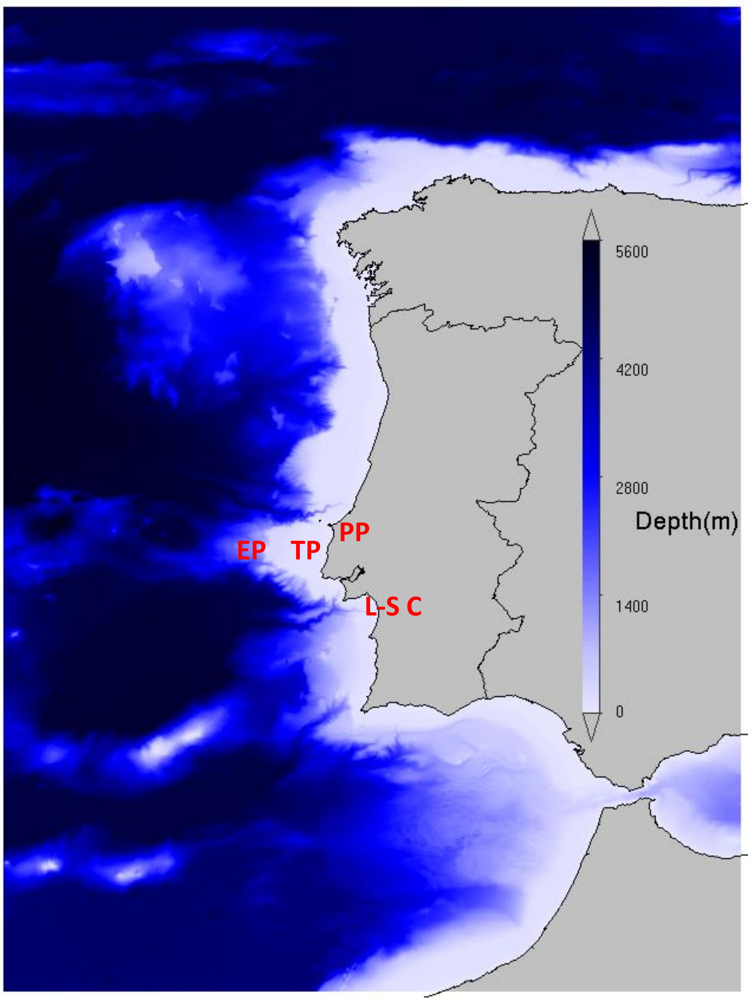

Figure 3 Bathymetry of the West Iberia domain with 0.015° horizontal resolution derived from the EMODnet Hydrography portal. Some areas referred later in the text are identified by the following acronyms: TP (Tagus Plateau), EP (Estremadura Promontory); PP (Peniche Peninsula) and L-S C (Lisbon-Setubal Canyon).

For this particular study, a 2-Dimensional domain covering the West Iberia region comprised by the range of latitudes (33.48N, 45.90N) and longitudes (4.20W, 13.50W) with a grid of 620X828 cells and a horizontal resolution of 0.015° (≈ 1.3 km) was set. That grid has been populated with bathymetric information derived from the EMODnet Hydrography portal (http://www.emodnet-hydrography.eu) (Figure 3). The MOHID water model was forced with the FES2012 global tide model (Carrère *et al.*, 2012) along the ocean boundary for the year 2011.

In order to obtain the tidal power density for the spring and neap periods, the data for each cell had to be processed to identify the maximum current simulated for each spring and neap period. Figure 4 shows an example of the identification process for the Monican01 station located at coordinates (39.51N, 9.64W) for the year 2011. Figure 4 top shows the water levels simulated for that location and the identification of the tidal envelope for those water levels, maximum levels for each spring and neap tidal periods are marked by blue and yellow dots respectively. Once those maximums have been identified, the maximum velocity occurring in the period from the day before to the day after of that maximum is located and stored. From the tidal envelope can also be estimated the tidal range for the spring and neap periods. Maximum velocities and tidal range for the spring tide and neap tide would be later averaged for the whole simulated period.

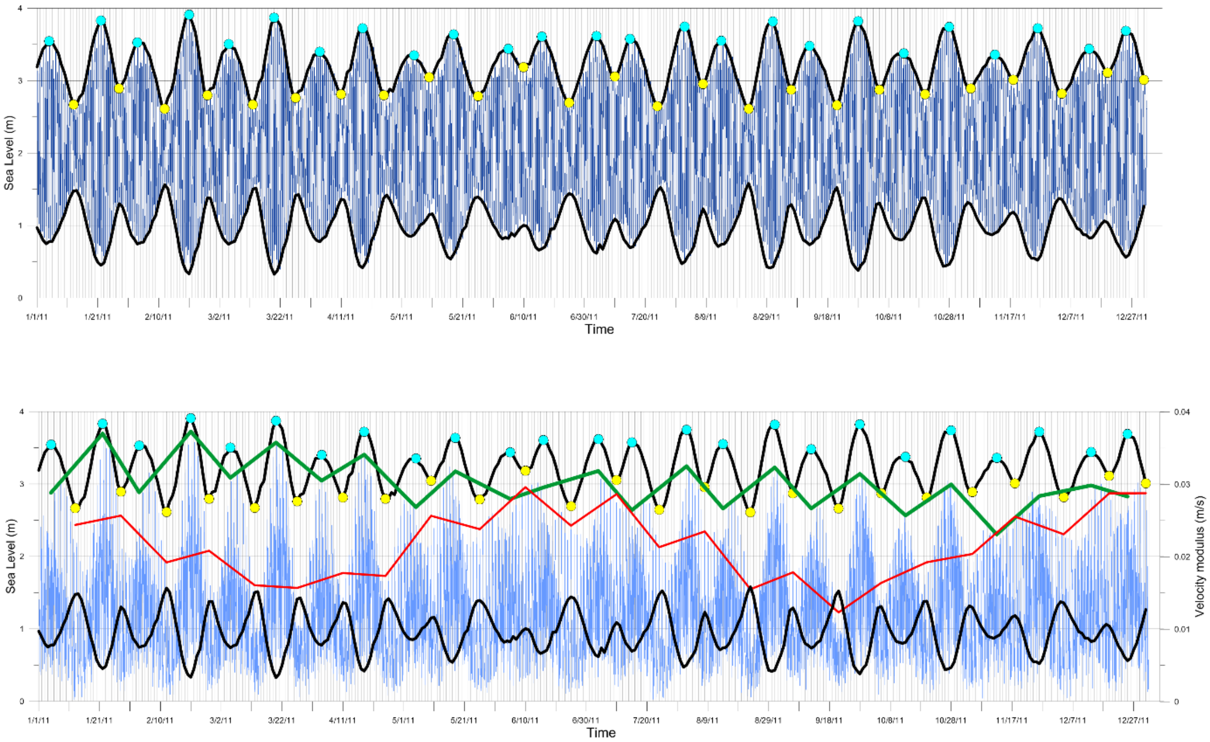

Figure 4 Top - Water levels for the MONICAN01 station for the year 2011 (blue line) and tidal envelope (black lines) identifying maximum water levels for the spring tide (blue dots) and for the neap tide (yellow dots). Bottom – Current velocities associated to the water levels and maximum velocity values associated to the spring tide (green line) and neap tide (red line).

The methodology described above was applied for each cell of the West Iberia domain for the year 2011. Figure 14 and Figure 15 shows the mean tidal range for the spring and neap tides respectively where it can be clearly appreciated a significant difference between both tidal periods and also the sharp tidal gradient taking place in the Strait of Gibraltar. Figure 16 shows the residual velocity for the complete year where some features can be observed including the Strait of Gibraltar strong circulation, the signal of submarine mountains and the currents occurring in the Tagus Plateau in the centre of Portugal and limited in the north by the Peniche Peninsula and the Berlengas Islands, in the south by the Lisbon/Setubal Canyon and in the West by the Estremadura Promontory (Figure 3).

The latter feature has been identified as a diurnal continental shelf wave (CSW) trapped in Tagus Plateau which generation is linked to the coastal bathymetry being the shelf width and slope strength relevant for the growing amplitude of the trapped wave mode (Fortunato *et al.*, 2002; Quaresma and Pichon, 2013). The Tagus Plateau CSW would increase the currents intensities on that region influencing the peak velocities observed during spring and neap tides (Figure 17 and Figure 18) and the energy associated to those velocities (Figure 19 and Figure 20).

To obtain the power potential of the Portuguese Continental coast the values were obtained for one square metre cross-sectional area, therefore using the following formula

$$P = 1/2\rho|U|^3$$

where ρ is the density of water (kg/m^3), and U is the instantaneous current velocity (m/s). For this study a constant density of 1027 kg/m^3 will be used and the velocities would be the peak velocities associated to the spring and neap tides obtaining Figure 19 and Figure 20 respectively.

Tidal power in the Portuguese coast is the less important resource in the open ocean with peak velocities under 1 m/s even during spring tides (Figure 17) for that reason tidal power figures have been represented using a logarithmic scale as maximum values are under 50 W/m while the values estimated for the Strait of Gibraltar due to the barotropic tide would be near the 2800 W/m. Those values are very low when compared to some of the locations in the UK coast with areas with more than 20 KW/m (ABPmer, 2008). The most energetic areas related to tides in the open Portuguese coast, thus excluding estuaries, would be near the Peniche Peninsula and in the southern limit of the Tagus Plateau.

Figures

Wind

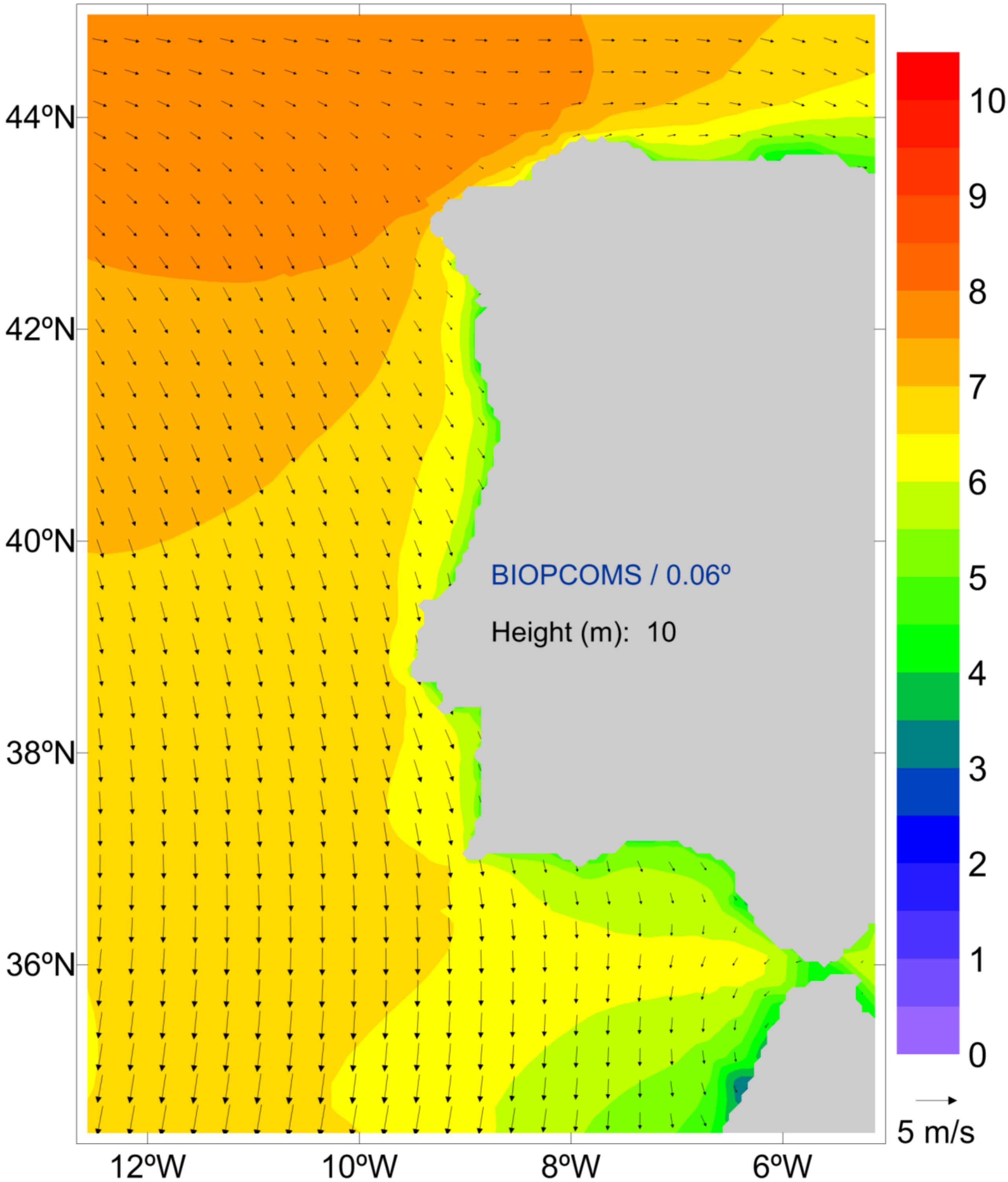

Figure 5 Annual Mean Wind Speed at 10 m in m/s for the Jun 2009-Jun 2015 period. Black arrows indicate the wind direction and intensity.

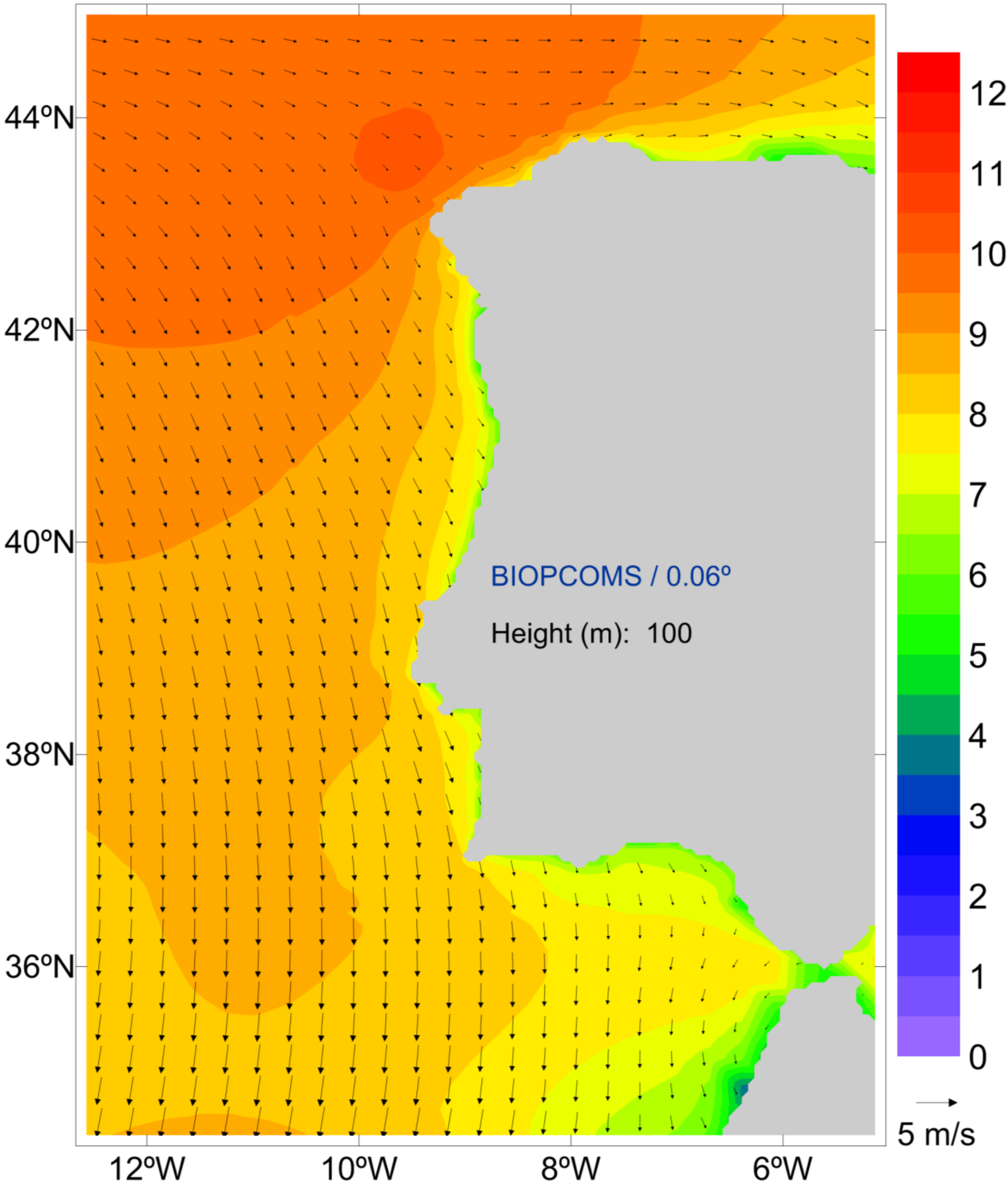

Figure 6 Annual Mean Wind Speed at 100 m in m/s for the Jun 2009-Jun 2015 period. Black arrows indicate the wind direction and intensity.

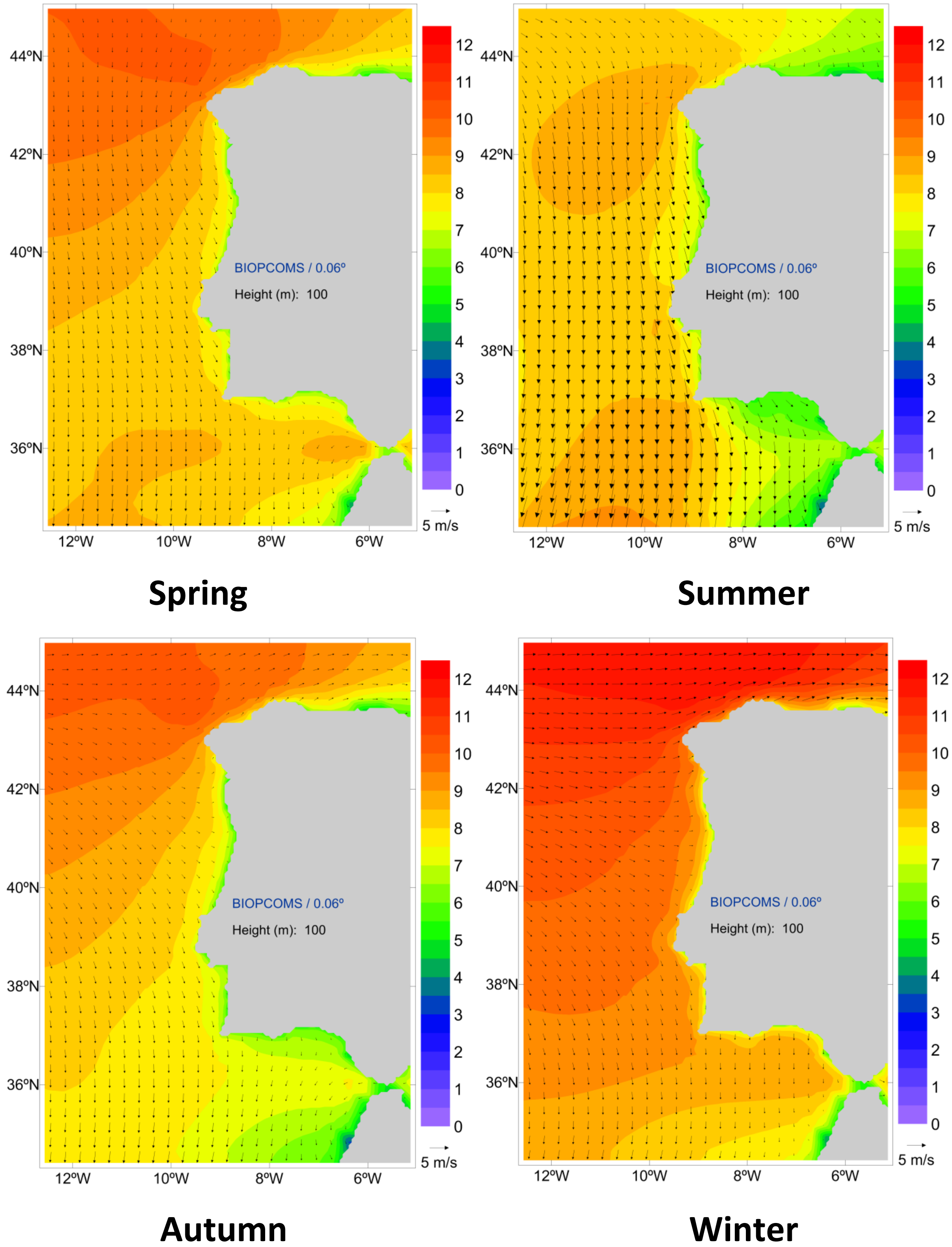

Figure 7 Seasonal Mean Wind Speed at 100 m in m/s for the Jun 2009-Jun 2015 period. Black arrows indicate the wind direction and intensity.

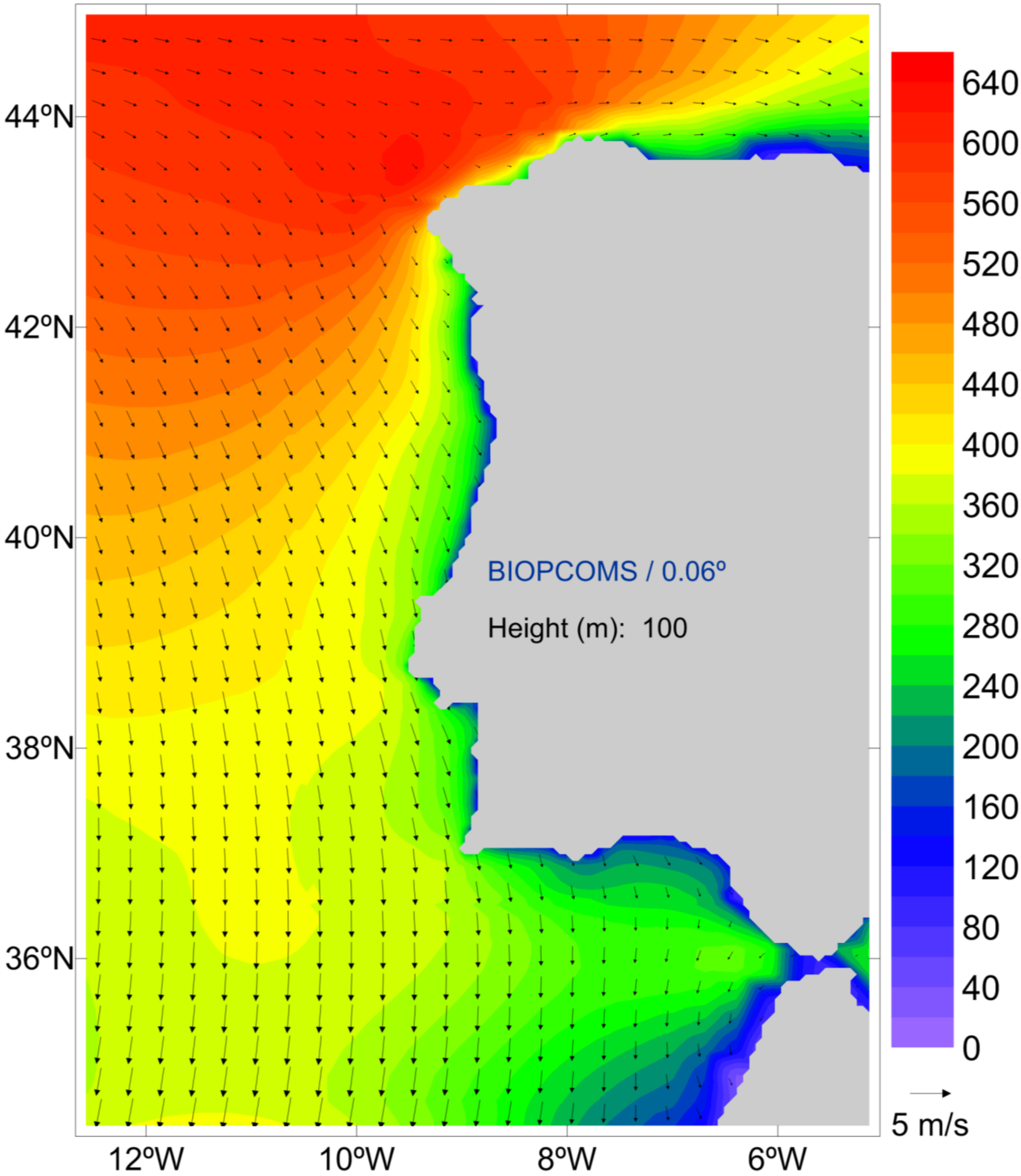

Figure 8 Annual Mean Wind Power Density at 100 m in W/m^2 for the Jun 2009-Jun 2015 period. Black arrows indicate the wind direction and intensity.

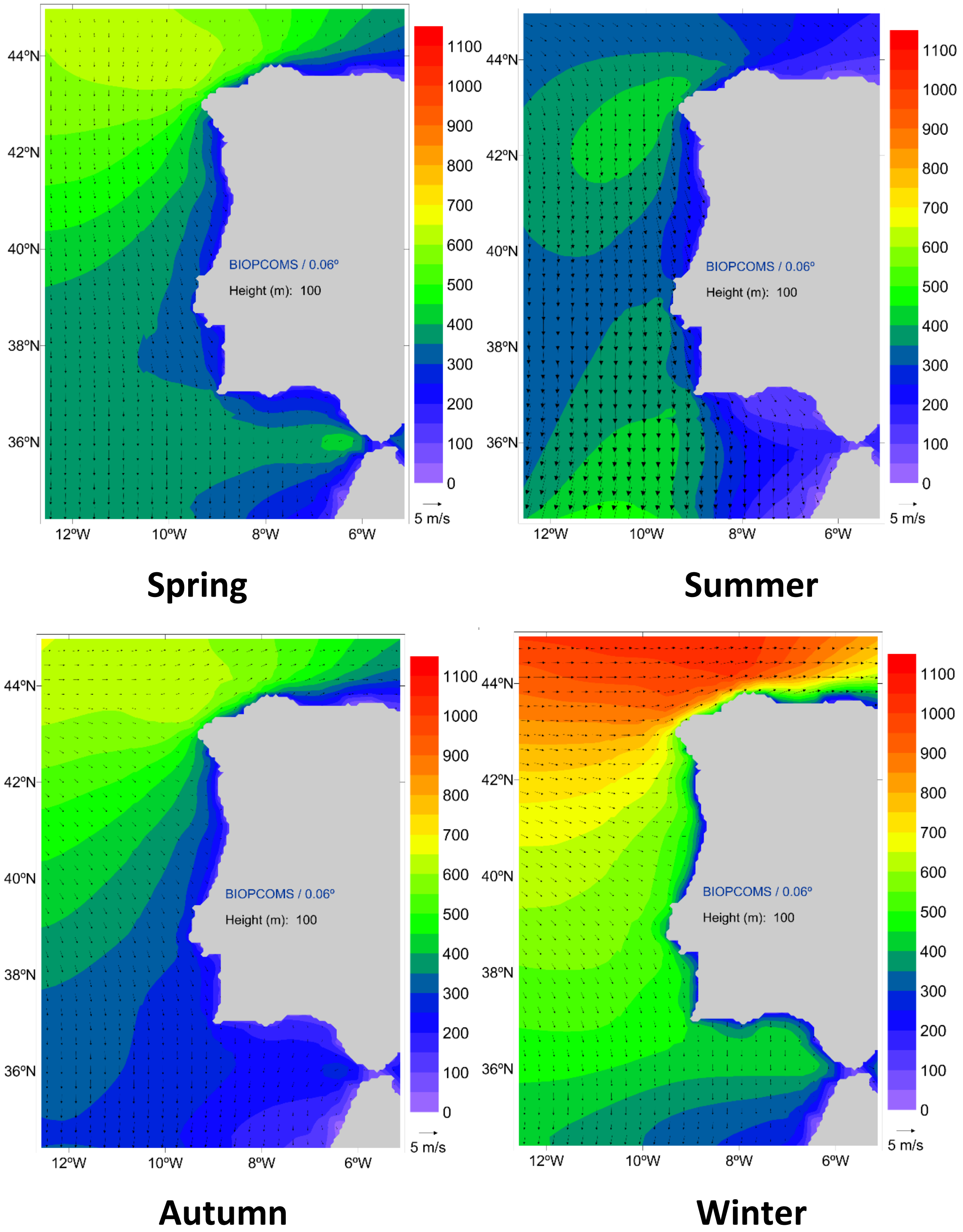

Figure 9 Seasonal Mean Wind Power Density at 100 m in W/m^2 for the Jun 2009-Jun 2015 period. Black arrows indicate the wind direction and intensity.

Waves

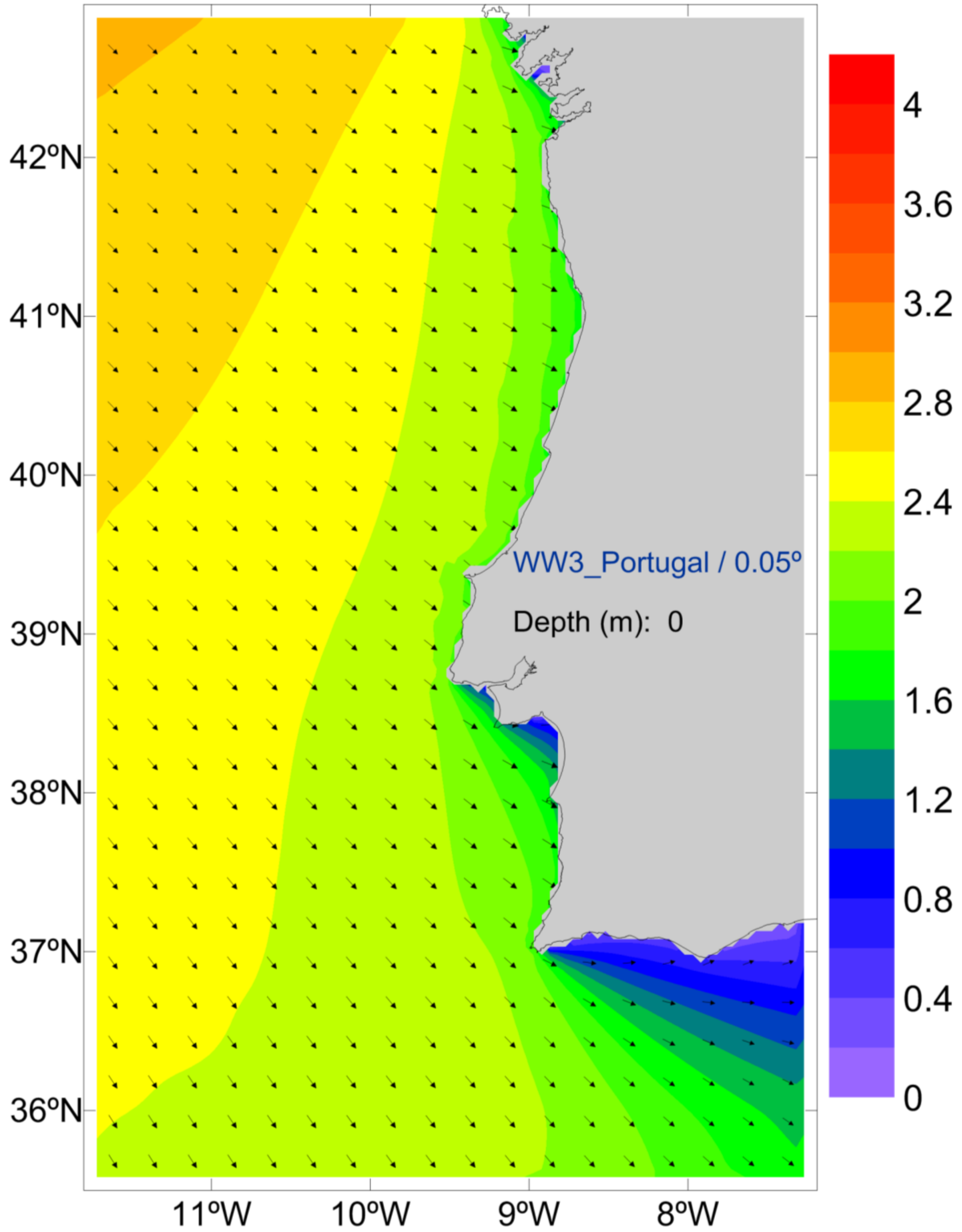

Figure 10 Annual Mean Significant Wave Height (H_s) in m for the 2000-2010 period. Black arrows indicate the mean wave direction.

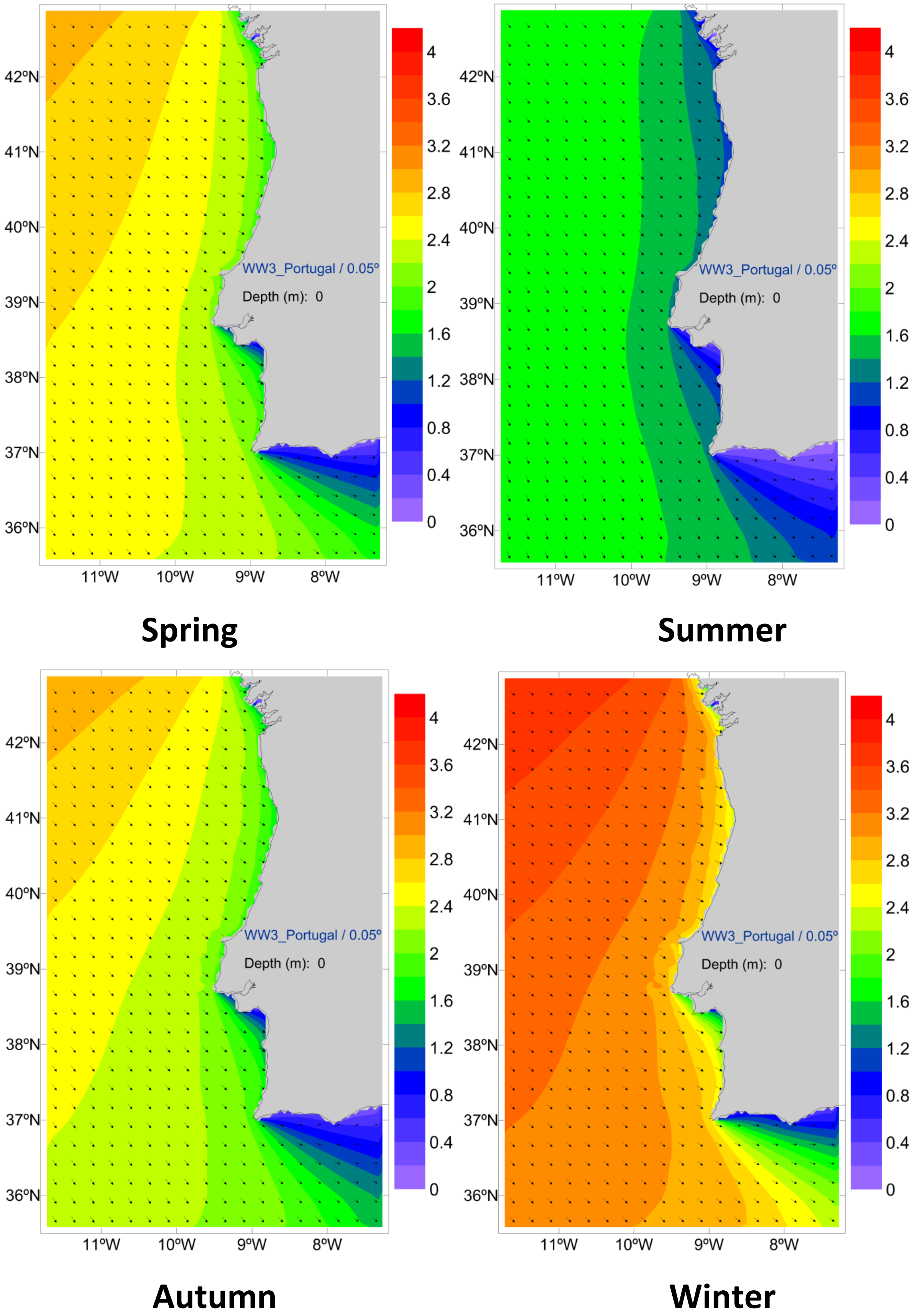

Figure 11 Seasonal Mean Significant Wave Height (H_s) in m for the 2000-2010 period. Black arrows indicate the mean wave direction.

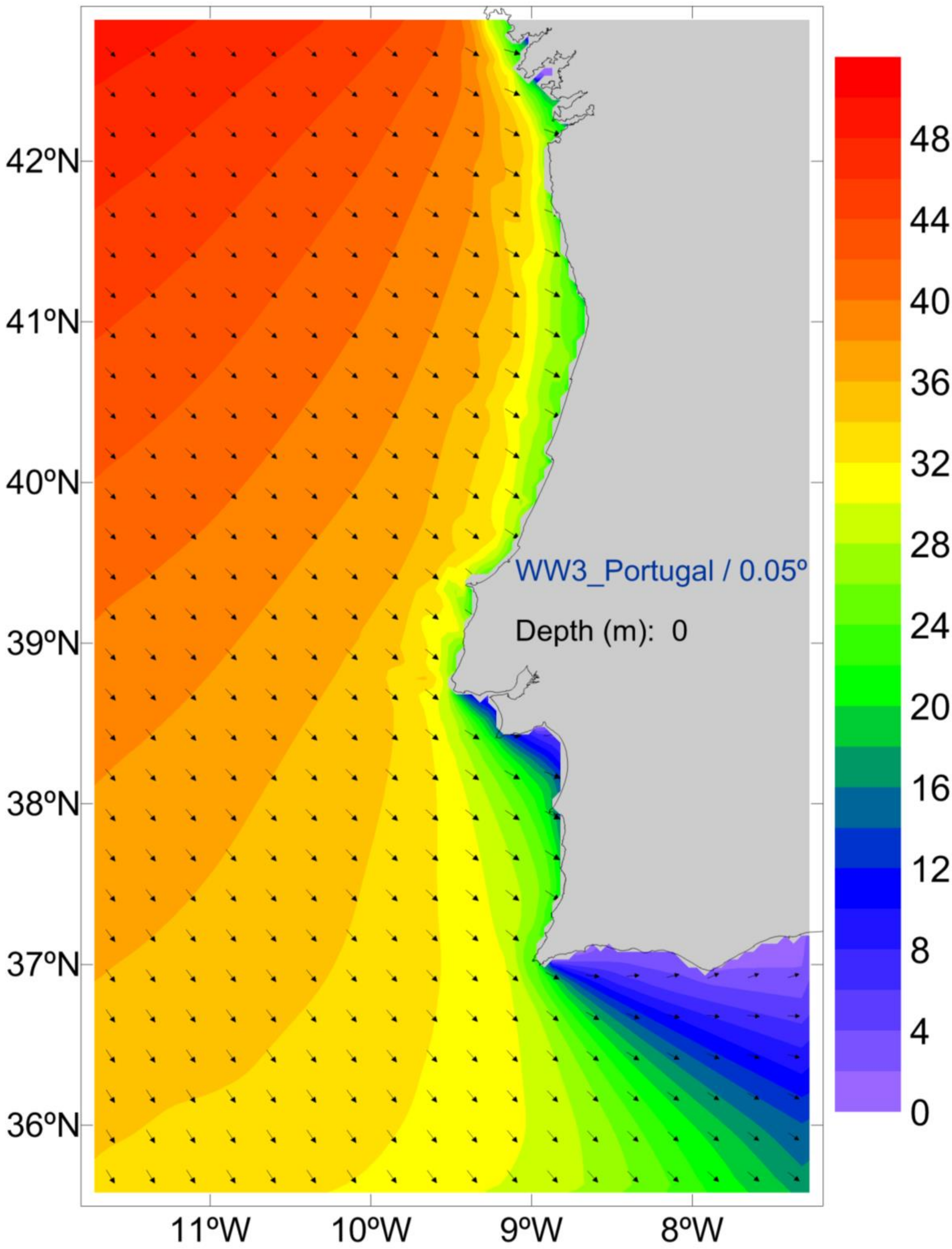

Figure 12 Annual Mean Wave Power Density in kW/m for the 2000-2010 period. Black arrows indicate the mean wave direction.

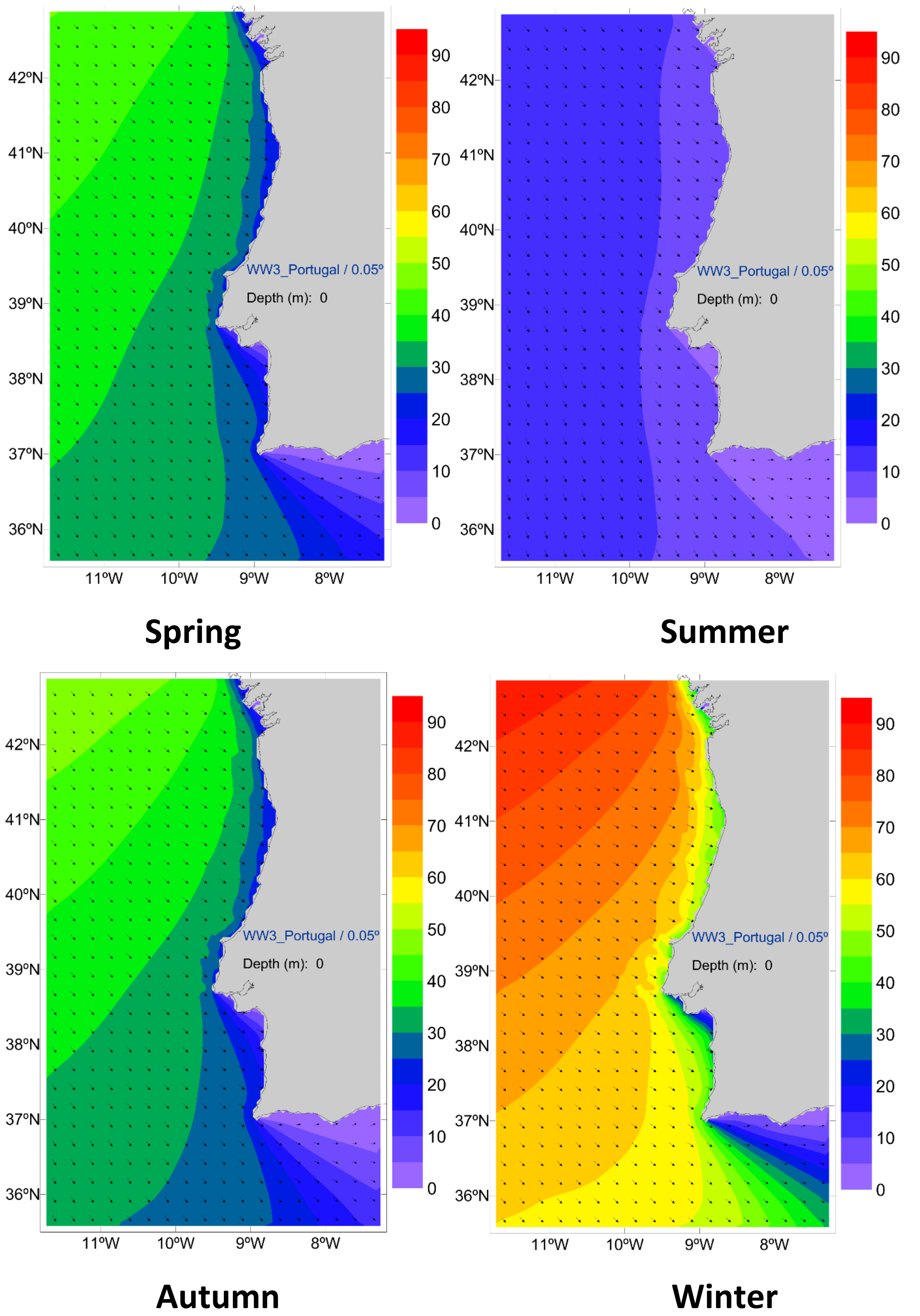

Figure 13 Seasonal Mean Wave Power Density in kW/m for the 2000-2010 period. Black arrows indicate the mean wave direction.

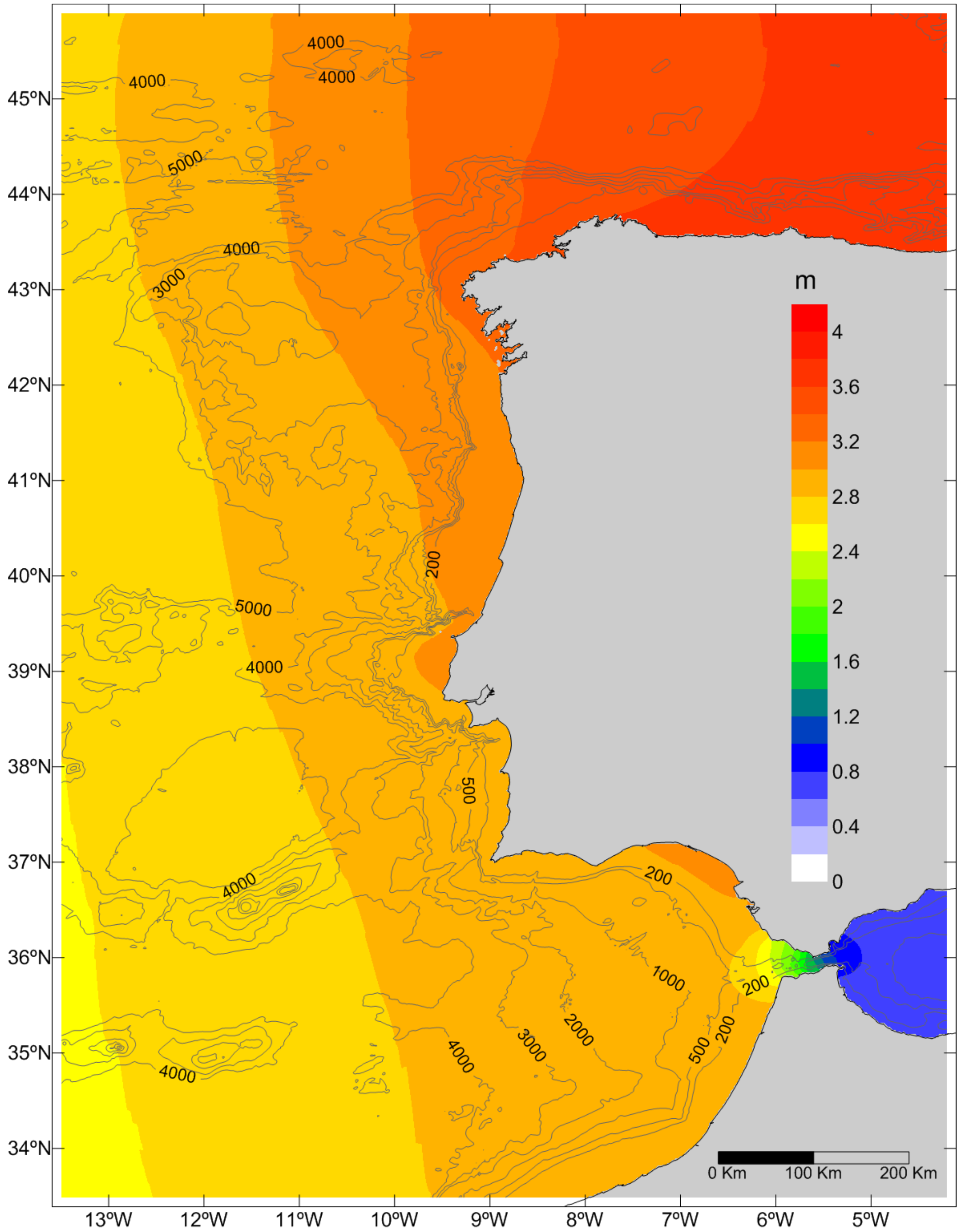

Figure 14 Mean Spring Tidal Range. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

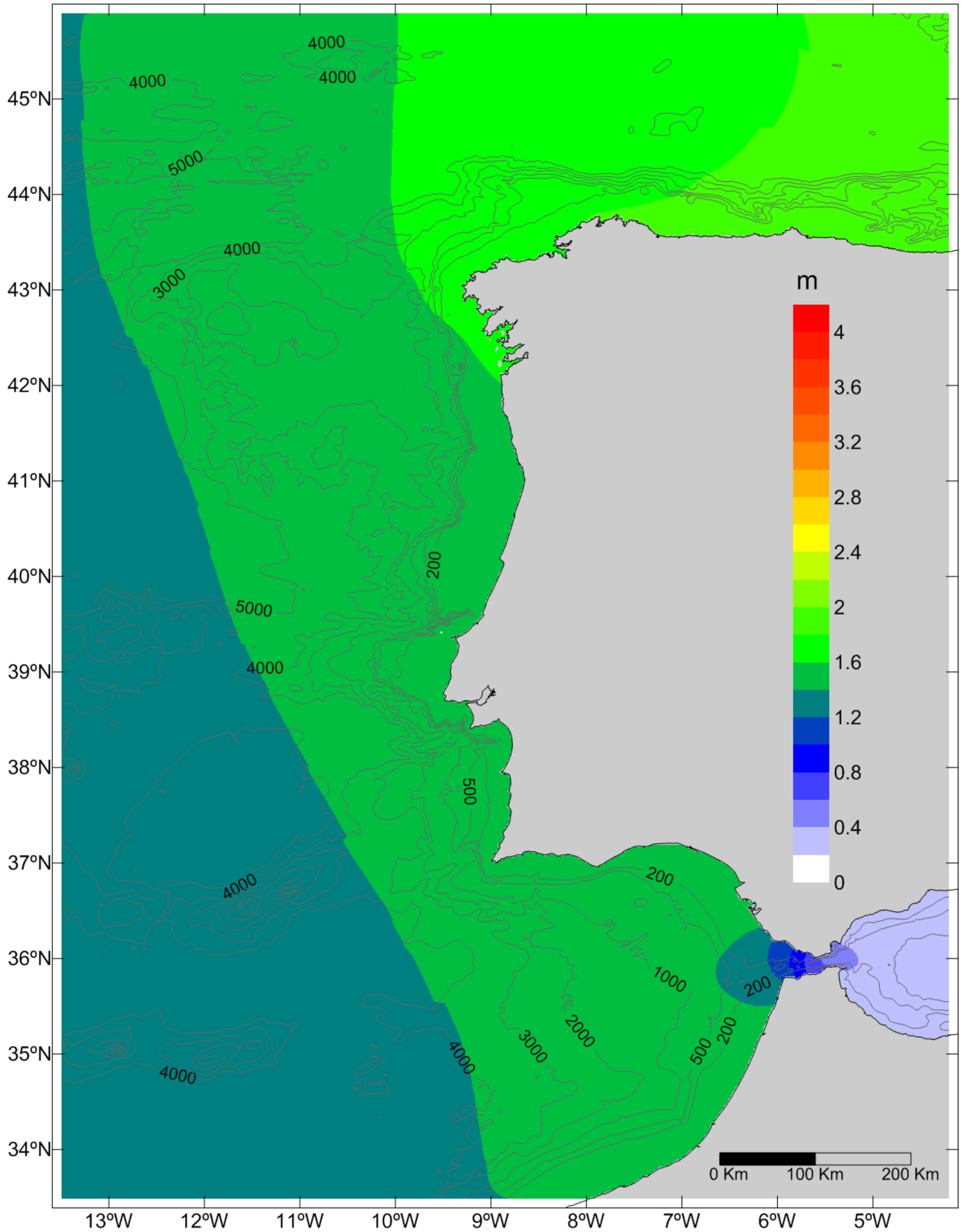

Figure 15 Mean Neap Tidal Range. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

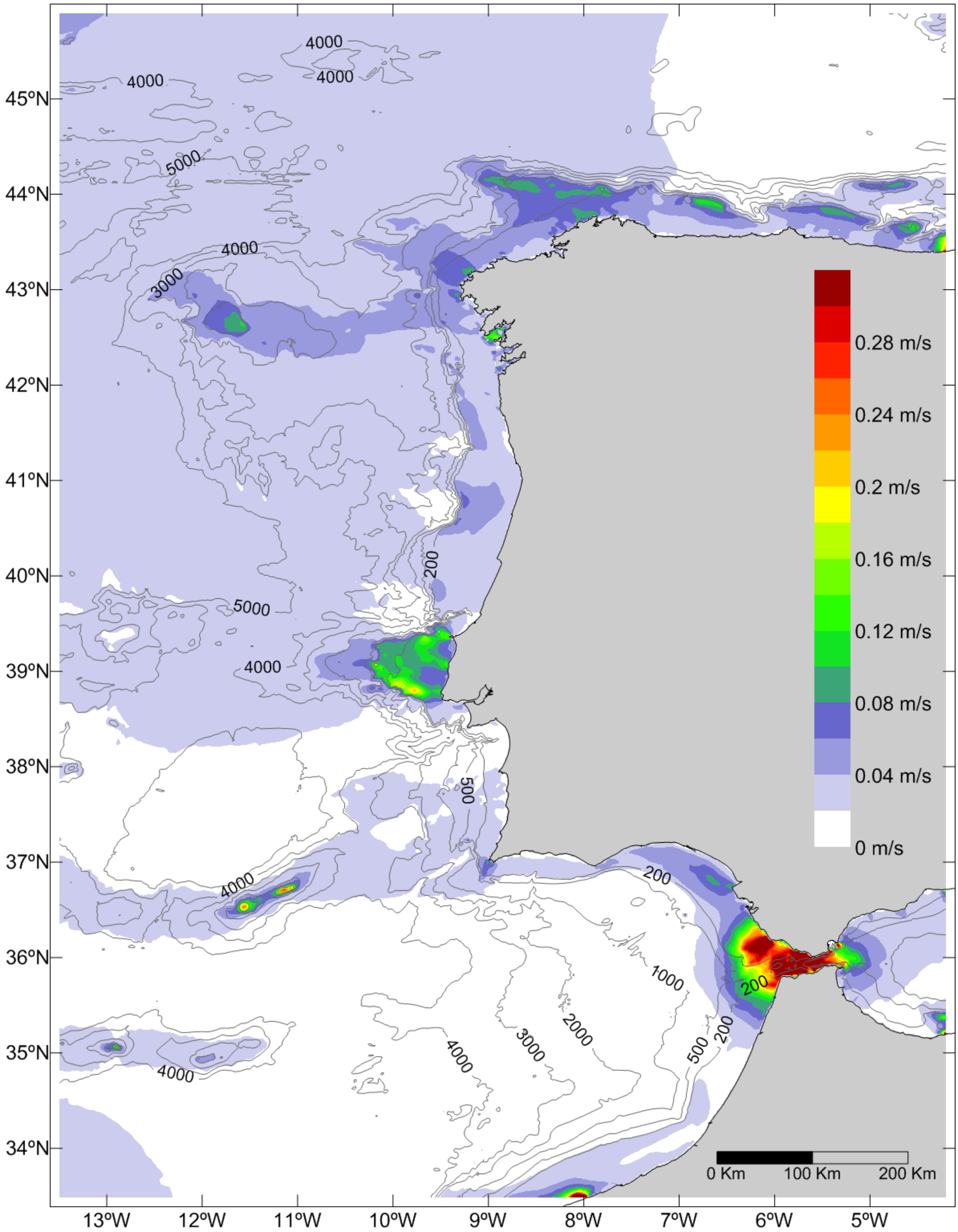

Figure 16 Residual current obtained from the barotropic tides for the year 2011. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

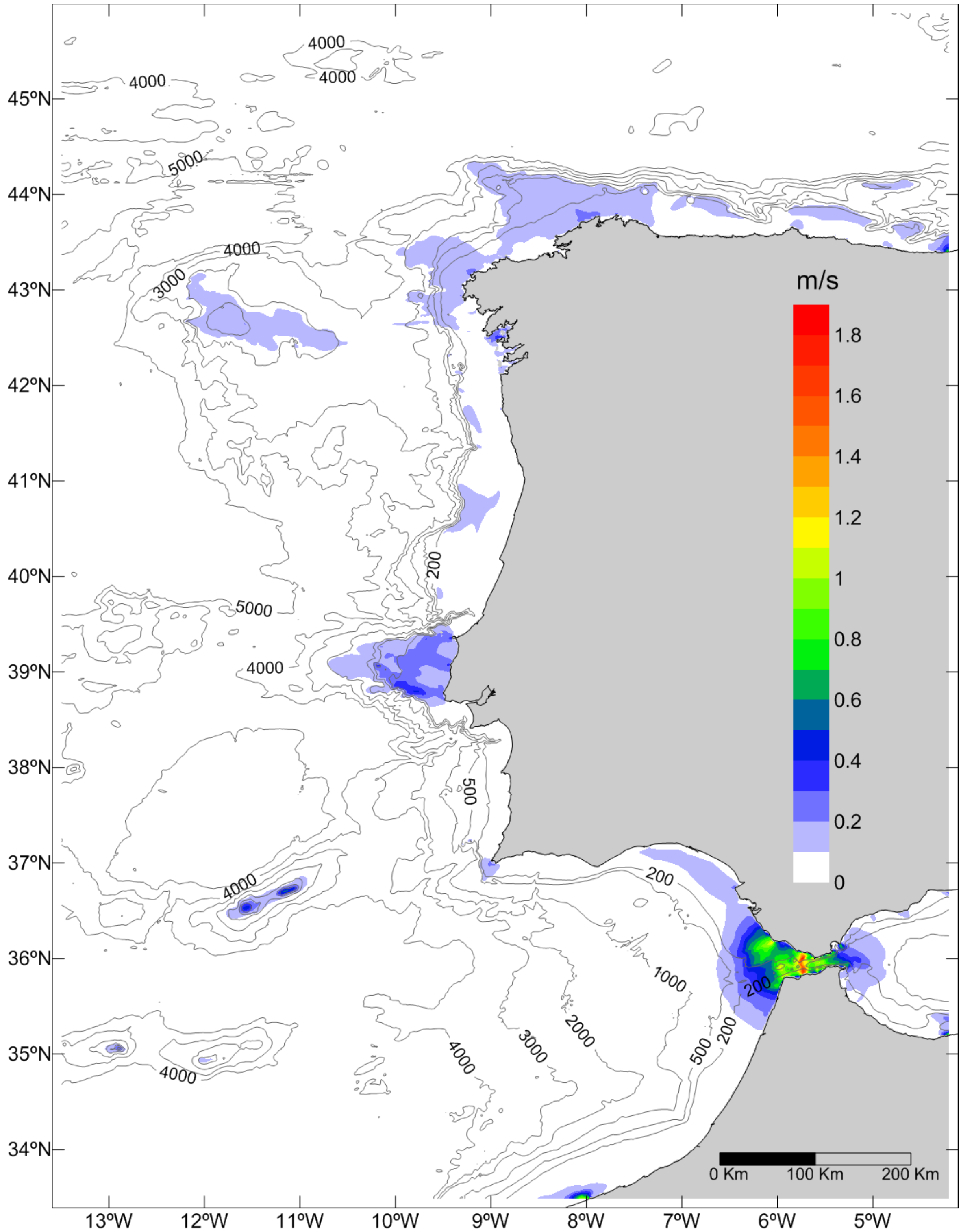

Figure 17 Mean Peak Velocity for spring tides. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

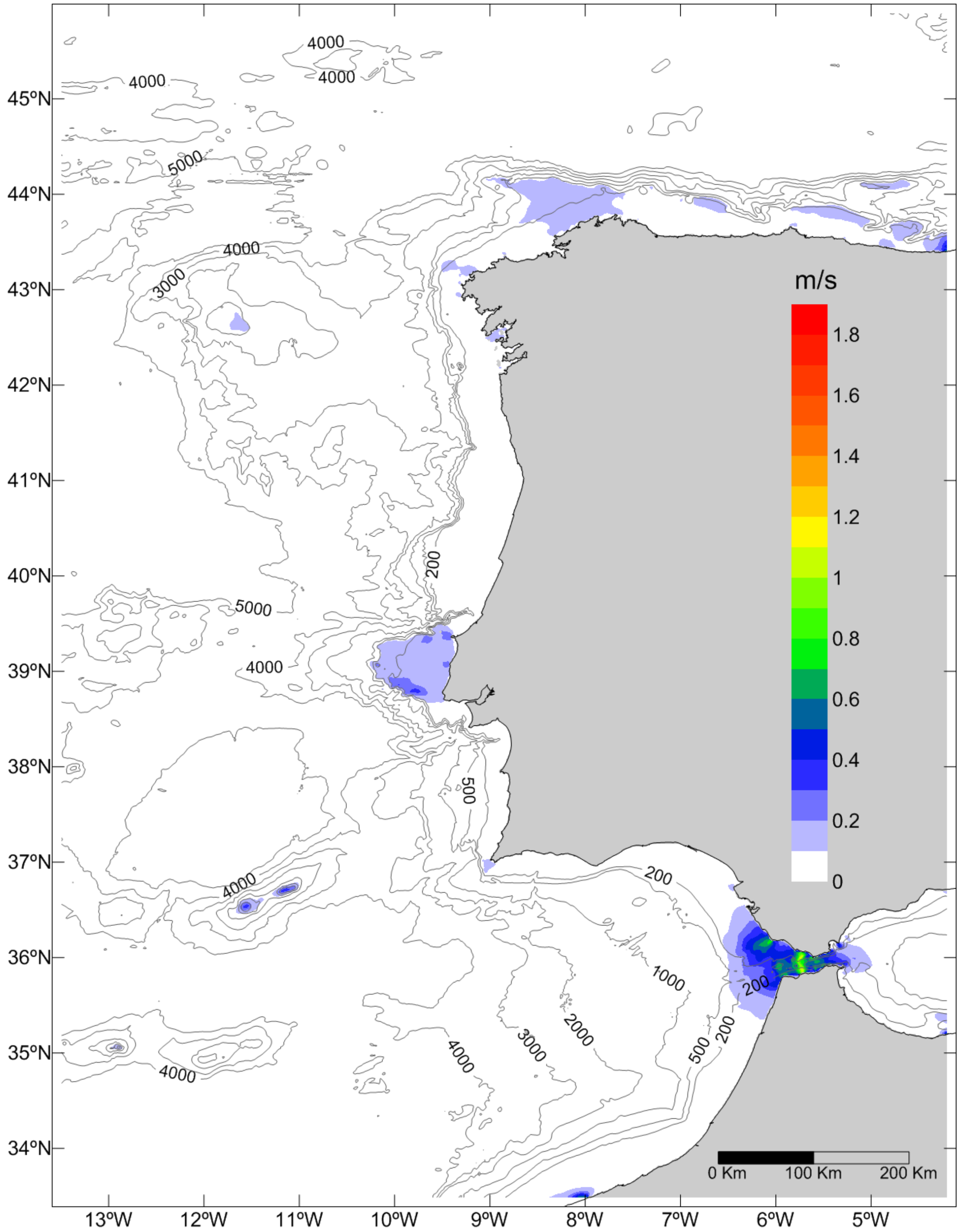

Figure 18 Mean peak velocity for neap tides. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

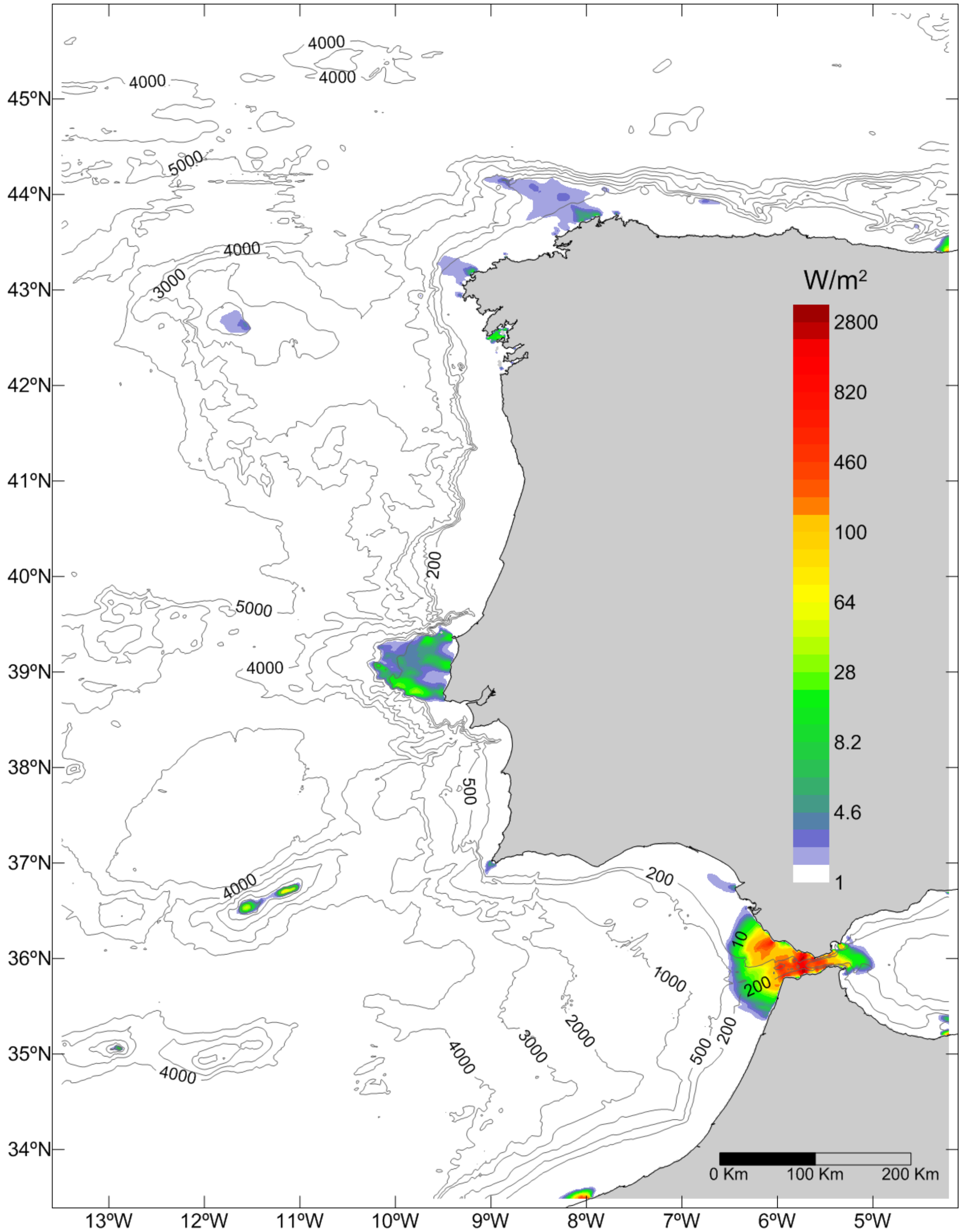

Figure 19 Spring tidal power. Values are represented in logarithmic scale. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

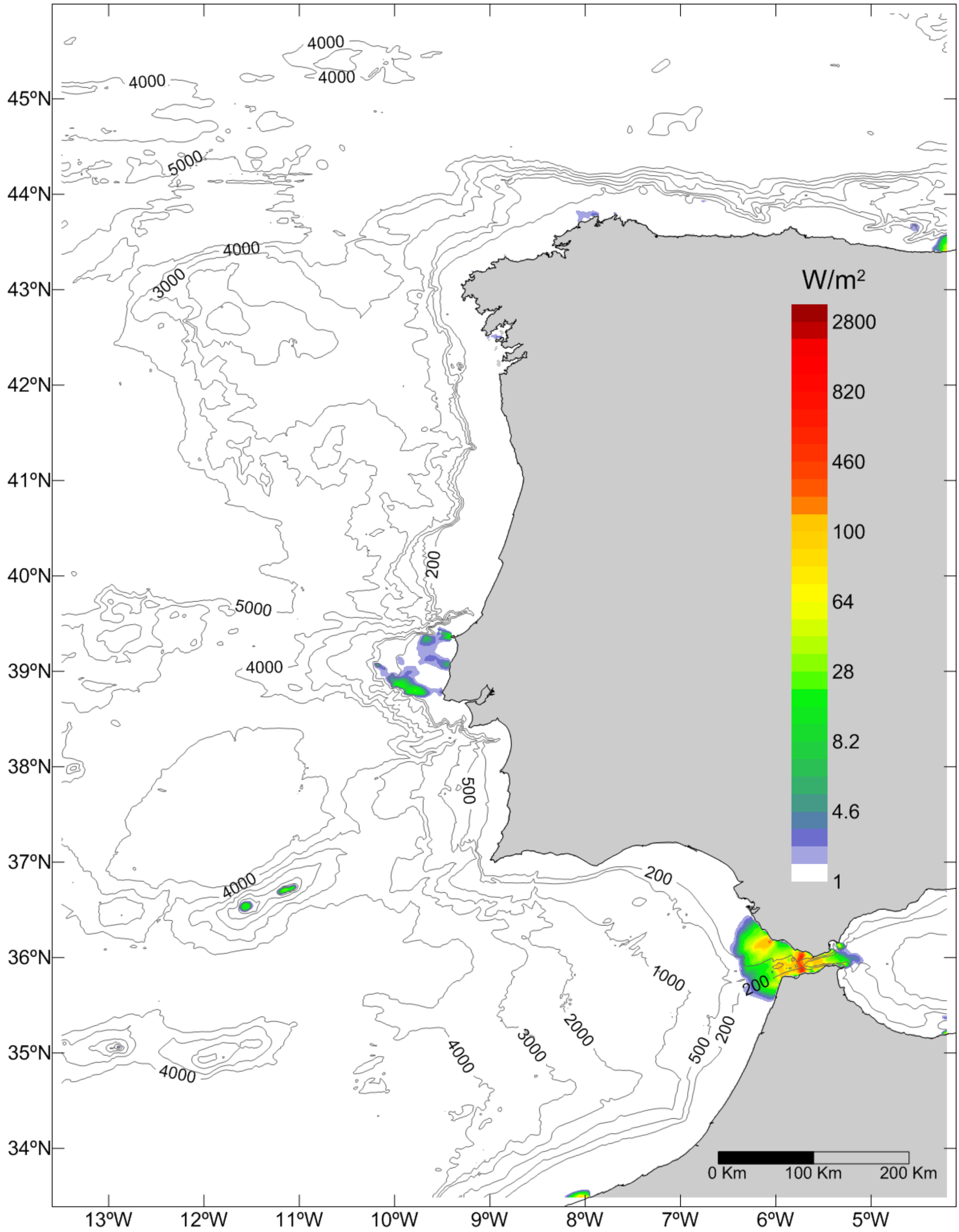

Figure 20 Neap tidal power. Values are represented in logarithmic scale. Isobaths of 200 m, 500 m, 1000 m, 2000 m, 3000 m, 4000 m and 5000 m were added.

Validation

Atmospheric model

In order to evaluate the performance of the numerical model MM5 for the Portuguese coast, the model results for the simulated period (Jun 2009-Jun 2015) were compared with the available information registered by off-shore and coastal buoys equipped with atmospheric sensors along the Western Iberia coast from the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu/).

Figure 21 shows the location of the atmospheric stations where the wind intensity and direction at 10m height was obtained and compared with the MM5 model results for the same elevation. Time coinciding values for both observed and modelled data were selected for each station statistical analysis. In order to evaluate the possible mismatch in terms of time, daily averaged statistics were also performed. In order to evaluate the direction agreement between both sources of information was evaluated by decomposing the wind data into their geographic components (U and V) to evaluate correctly the distance between each couple of data (i.e. a 1° degree direction is a very angle to the 359° while numerically they are very distant).

Table I. List of ocean and coastal buoys equipped with atmospheric stations along the Western Iberia coasts that were used for the MM5 validation. The table shows their location in terms of latitude and longitude, validation period, and coefficient of determination (R^2) for the wind velocity and its components and the number of values used for the statistical analysis for the instant and daily averaged values. The superscript next to the station name indicates the institution responsible of the data provision: [a] data provided by Puertos del Estado (Spain), [b] data provided by Instituto Hidrográfico (Portugal) and [c] data provided by Xunta de Galicia (Spain).

				Hourly Analysis				Daily Analysis			
Station Name	**Lat.**	**Long.**	**Data Period**	**U R^2**	**u R^2**	**v R^2**	**N**	**U R^2**	**u R^2**	**v R^2**	**N**
Estaca de Bares[a]	44.06 N	7.62 W	Jun2009-Jun2015	0.75	0.87	0.70	30409	0.85	0.93	0.80	1317
Cabo de Peñas[a]	43.73 N	6.19 W	Jun2009-Jun2015	0.60	0.81	0.43	47069	0.75	0.90	0.57	2045
Villano-Sisargas[a]	43.49 N	9.21W	Jun2009-Apr2015	0.77	0.83	0.75	42301	0.87	0.92	0.85	1810
Cortegada Platform[c]	42.63 N	8.78 W	Jun2009-Jun2015	0.30	0.13	0.43	42481	0.40	0.12	0.55	2032
Silleiro[a]	42.12 N	9.40 W	Jun2009-Jun2015	0.72	0.75	0.86	39283	0.80	0.85	0.92	1708
Illas Cies[c]	42.17 N	8.91 W	Jun2009-Jun2015	0.53	0.40	0.58	35337	0.66	0.53	0.71	1669
A Guarda[c]	41.90 N	8.90 W	Jun2011-Mar2015	0.45	0.53	0.71	24851	0.62	0.67	0.86	1101
Raia01[b]	41.18 N	8.70 W	Jun2010-Jun2015	0.72	0.67	0.88	19337	0.77	0.76	0.93	839
Monican01[b]	37.95 N	8.89 W	Nov2010-Feb2015	0.56	0.77	0.82	16159	0.62	0.88	0.87	718
Monican02[b]	36.90 N	7.90 W	Jun2010-Jun2015	0.56	0.67	0.79	21479	0.71	0.84	0.88	930
Cadiz[a]	36.84 N	6.98 W	Jun2009-Jun2015	0.58	0.78	0.70	45530	0.76	0.87	0.85	1950

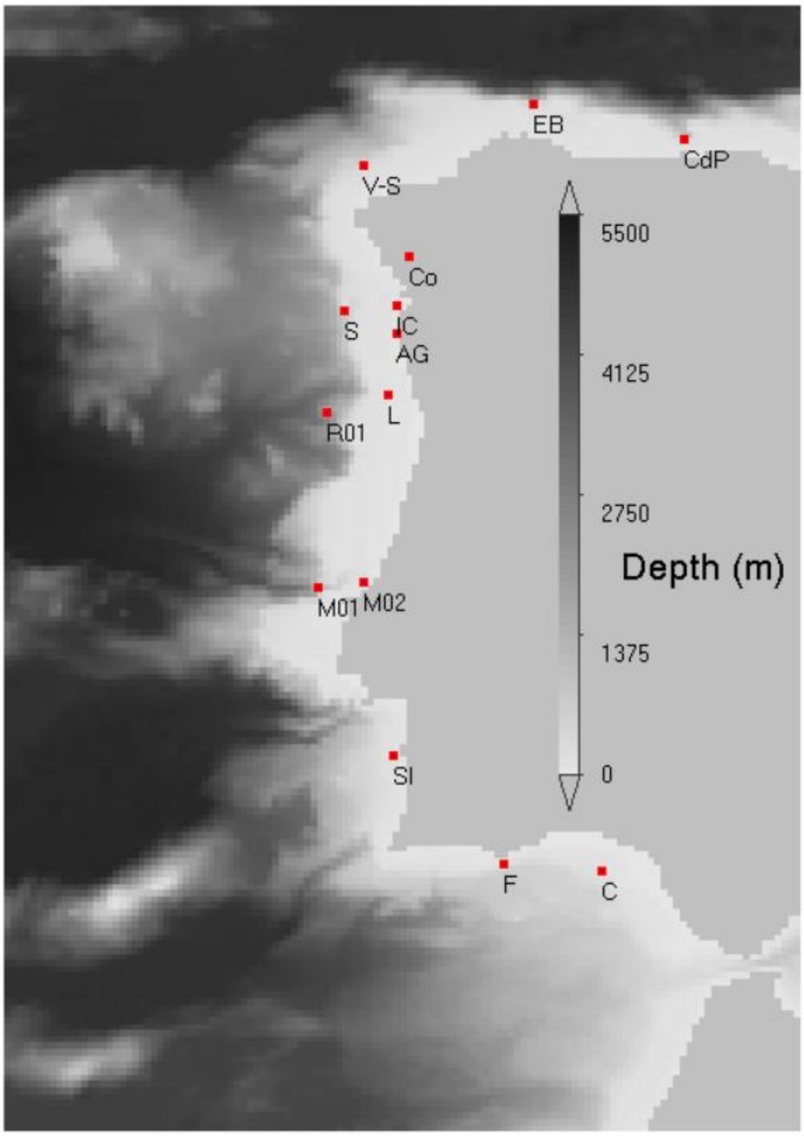

Figure 21 Location of the stations used for validating the atmospheric and wave models. The acronyms correspond to the following stations: Estaca de Bares (EB), Cabo de Peñas (CdP), Villano-Sisargas (V-S), Cortegada Platform (Co), Silleiro (S), Illas Cies (IC), A Guarda (AG), Leixões (L), Raia01 (R01), Monican01 (M01), Monican02 (M02), Sines (SI), Faro (F) and Cadiz (C).

From Table I a few conclusions can be drown, stations located in the open ocean are better represented by the model than coastal ones where the horizontal resolution of 9 km could not be enough to represent the complex topography around the observing stations. The coefficient of determination obtained for the most off-shore stations are higher than 0.70 and can reach up to 0.87 when analysing the daily average. For that reason, the evaluation of the resource by using numerical model would be considered especially interesting for off-shore developments.

Wave model

Historical wave parameters observations are scarce in the Portuguese coast. For the selected period, three stations were used from the Instituto Hidrográfico (IH) from Portugal and five stations from Puertos del Estado (PdE) in Spain covering different periods (Table II).

The observed data were compared with hourly model time series. Coefficients of determination (R^2) were obtained for each station and for significant wave height (H_s) and for wave average period (T_m) (Table II). The obtained values show a great agreement for the Hs variable for the entire area of study with R^2 values comprised between 0.79 and 0.92. On the other hand, the model, with the current version and configuration, showed a lower capacity for calculating the average period with R^2 values from 0.75 to 0.20. The capacity of the model to estimate both variables is better in open exposed coast while decreased in wave sheltered areas.

Regarding the difficulty to forecast the period and being the H_s more relevant to the wave power estimation and the area of interest for wave energy in areas exposed to the coast we consider that the current approximation is valid for characterizing the waves´ resource in the Portuguese continental coast.

Table II. List of observing stations, location in terms of latitude and longitude, validation period and coefficient of determination (R^2) for the significant wave height (H_s) and the average period (T_m). The superscript next to the station name indicates the institution responsible of the data provision: [a] data provided by Puertos del Estado (Spain) and [b] data provided by Instituto Hidrográfico (Portugal).

Station Name	Domain	Latitude	Longitude	Data Period	H_s R^2	T_m R^2
Estaca de Bares[a]	SWE	44.06 N	7.62 W	Jan2002-Dec2009	0.92	0.75
Cabo de Peñas[a]	SWE	43.73 N	6.19 W	Jan2002-Dec2009	0.89	0.71
Villano-Sisargas[a]	SWE	43.49 N	9.21 W	Jan2002-Dec2009	0.90	0.74
Silleiro[a]	PCC	42.12 N	9.40 W	Jan2002-Dec2009	0.91	0.69
Leixões[b]	PCC	41.18 N	8.70 W	Jan2008-Dec2009	0.91	0.61
Sines[b]	PCC	37.92 N	8.92 W	Jan2008-Dec2009	0.90	0.61
Faro[b]	PCC	36.90 N	7.90 W	Jan2008-Dec2009	0.80	0.20
Cadiz[a]	SWE	36.84 N	6.98 W	Dec2008-Dec2009	0.79	0.31

Tidal Model

In order to validate the tides simulated by the MOHID Modelling System (http://www.mohid.com; Neves, 2013)for the Western Iberia domain described above, tidal data available from different sources as the Instituto Geográfico (www.igeo.pt/), that maintains the tidal gauges of Cascais and Lagos, and the CMEMS (http://marine.copernicus.eu/) that provides access to several tidal stations of the Instituto Hidrográfico were collected. The observations from those stations (Table III, Figure 22) were analysed using the TASK-2000 Package (PSMSL/POL Tidal Analysis Software Kit 2000) in order to obtain their tidal components and to generate from them a time series for the period simulated by the model, the year 2011. Both comparisons, the hourly tidal observations with the corresponding values obtained from the harmonic analysis and the comparison between the MOHID model results and the generated with their tidal components for the year 2011 show a very high level of agreement with coefficient of determination above 0.97 in all the cases.

Table III. List of tidal gauges, location, analysed period and coefficient of determination (R^2) for the values observed (Obs.) and the obtained with the harmonic analysis (Harmonics) and the latter with the MOHID model results (MOHID). The superscript next to the station name indicates the institution responsible of the data provision: [a] data provided by Instituto Hidrográfico (Portugal) and [b] data provided by Instituto Geográfico (Portugal).

Tidal Gauge	Latitude	Longitude	Data Period	Obs.-Harmonics R^2	Harmonics-MOHID R^2
Leixões[a]	41.18 N	8.70 W	20/09/2014- 30/09/2015	0.99	0.98
Nazaré[a]	39.59 N	9.07 W	20/09/2014- 30/09/2015	0.99	0.98
Peniche[a]	39.35 N	9.37 W	01/10/2014-30/09/2015	0.99	0.98
Cascais[b]	38.69 N	9.42 W	01/01/2010-30/09/2015	0.98	0.99
Sines[a]	37.95 N	8.89 W	20/09/2014- 30/09/2015	0.99	0.97
Lagos[b]	37.10 N	8.67 W	01/01/2012-30/09/2015	0.99	0.99

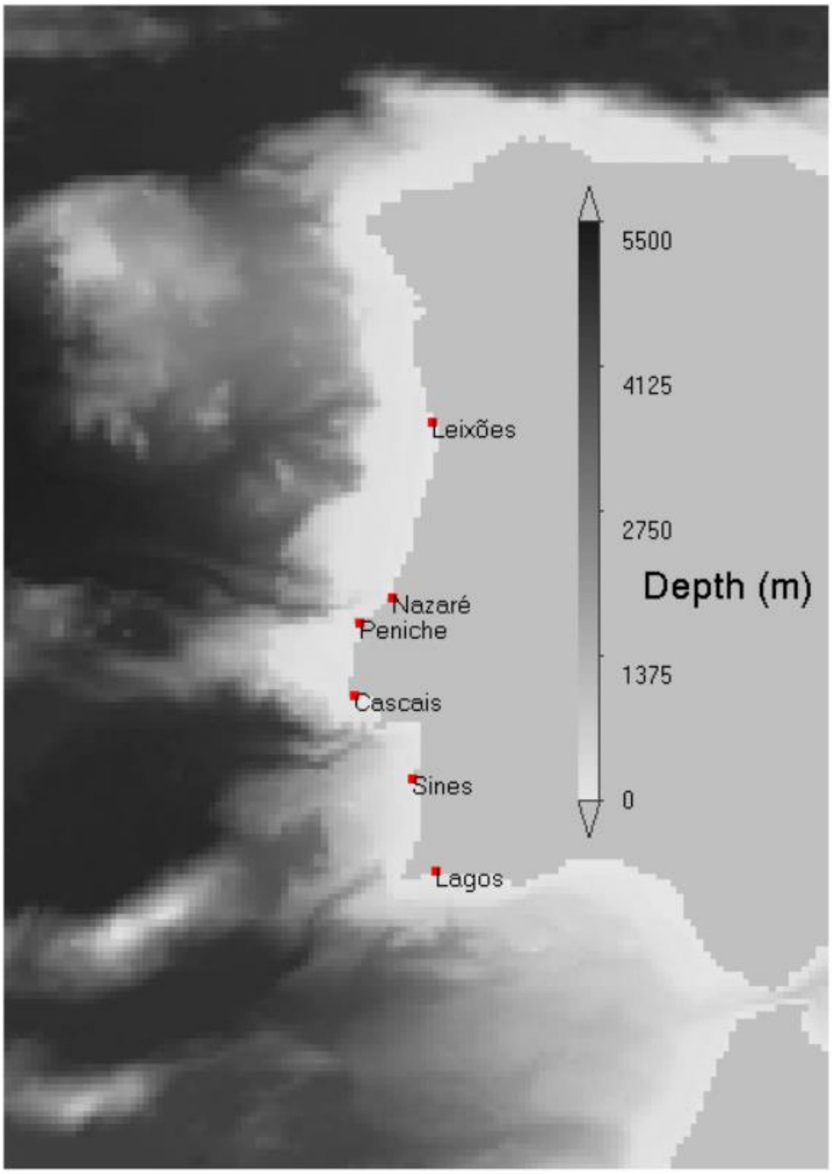

Figure 22 Location of the stations used for validating the tidal model results.

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