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# Wave energy resource at bimep (Basque coast)

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**Resumen**

La plataforma de energía marina de Bizkaia (bimep) es una infraestructura para probar convertidores de energía del oleaje en condiciones reales, situada en el litoral del sureste del golfo de Bizkaia (área de estudio). Campos de viento horarios obtenidos con dos modelos meteorológicos (MM5 y WRF) y espectros direccionales de oleaje cada tres horas proporcionados por el modelo WAVEWATCH III se utilizaron para alimentar al modelo WAM y simular el oleaje desde 2007 hasta 2010 en el área de estudio. Los modelos MM5 y WRF fueron capaces de reproducir la evolución temporal de los vientos fuera de costa con una precisión razonable. Un valor medio de $r^2 > 0,6$ fue obtenido en las comparativas realizadas entre los datos predichos y los observados. Sin embargo, los resultados sugieren que un modelo meteorológico con una mayor resolución horizontal sería más apropiado para estimar el campo de viento cerca de la costa. La altura de ola significante, $H_s$, y el periodo medio, $T_{m02}$, fueron los parámetros de oleaje obtenidos con WAM que presentaron un mejor ajuste estadístico con las observaciones en aguas profundas e intermedias, con valores medios de $r^2$ de ~0,9 y 0,7 para $H_s$ y $T_{m02}$, respectivamente. En la entrada al Puerto de Pasaia, $r^2$ para $H_s$ fue ligeramente inferior, con un valor de ~0,8. En la estación océano-meteorológica localizada en el área de bimep, las predicciones de WAM mostraron que la potencia anual del oleaje se incrementó desde 221 hasta 268 MW h m$^{-1}$ en 2007–2009, decayendo hasta 158 MW h m$^{-1}$ en 2010. Tanto el recurso de energía del oleaje como la $H_s$ obtenidos con WAM no mostraron una clara correlación con el índice NAO, mientras que los periodos de oleaje (especialmente $T_{m02}$) estuvieron positivamente correlacionados con este índice durante el invierno.

**Palabras clave:** Golfo de Bizkaia, bimep, MM5, WAM, energía del oleaje, WRF

**Abstract**

The Biscay marine energy platform (bimep) is a demonstration infrastructure to test wave energy converters in real conditions, which is located near the coast of the southeastern Bay of Biscay (study area). Hourly wind fields obtained with two meteorological models (MM5 and WRF) and three-hourly directional wave spectra provided by WAVEWATCH III were used to feed the WAM model and simulate the wave climate from 2007 to 2010 in the study area. The MM5 and WRF models were able to reproduce the time evolution of the offshore winds with a reasonable accuracy. A mean value of $r^2 > 0.6$ was obtained in the comparisons carried out between the predicted and measured data. However, the results suggest that a meteorological model with a higher horizontal resolution would be more appropriate to estimate the wind field close to the coastline. The significant wave height, $H_s$, and the mean period, $T_{m02}$, were the wave parameters obtained with WAM that showed a statistically better agreement with the observations in deep and intermediate waters. Here the mean values of $r^2$ were ~0.9 and 0.7 for $H_s$ and $T_{m02}$, respectively. At the entrance to Pasaia Harbor, $r^2$ for $H_s$ was slightly lower, with a value of ~0.8. At the metocean station located in the bimep area, the WAM predictions showed that the annual wave power increased from 221 to 268 MW h m$^{-1}$ in 2007–2009, decreasing to 158 MW h m$^{-1}$ in 2010. Both the wave energy resource and $H_s$ obtained with WAM did not show any clear correlation with the NAO index, while the wave periods (especially $T_{m02}$) were positively correlated with this index during winter.

**Keywords:** Bay of Biscay, bimep, MM5, WAM, wave energy, WRF

## Introduction

The Biscay marine energy platform (bimep) is a demonstration infrastructure for wave energy converters (WECs), owned and maintained by EVE (Basque Energy Board), which is located in the southeastern Bay of Biscay (at 1.7 km offshore of the

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Basque coast, see Fig. 1). This infrastructure responds to the need to test WECs in real conditions (Duperray *et al*., 2011). To measure these real conditions, a metocean buoy (station bimep) was installed in 2009 at a location near Armintza Harbor where the water depth is 80 m. Additionally to this information, hindcast and forecast simulations with wave prediction models, forced by meteorological model outputs, are needed over the bimep area (~5.3 km$^2$ and water depths between 50 and 100 m) in order to estimate the wave energy resource in the past, present, and near future.

Some previous works have been carried out to estimate the wave energy resource in different regions of the northern coast of Spain (e.g., Vidal, 1986; Iglesias *et al*., 2009; Iglesias and Carballo, 2010; Galparsoro *et al*., 2012), but only a small number of papers have been written on the wave energy resource and environmental parameters in the bimep area (Ferrer *et al*., 2010; Duperray *et al*., 2011). Here another issue of significance could be the relationship between the wave climate and the NAO (North Atlantic Oscillation) index. Some authors have analyzed this relationship for the northeast Atlantic, concluding that there is a partial correlation (e.g., the WASA Group, 1998; Dupuis *et al*., 2006; Wolf and Woolf, 2006).

The main objective of this contribution was the use of a wave model, forced by meteorological model outputs, to determine the information needed to estimate the wave energy resource in the southeastern Bay of Biscay from 2007 to 2010. The model results were compared with the observations of several metocean stations located in the study area in order to analyze the accuracy of the wind and wave predictions. The influence of the wind on the wave prediction during storm conditions was also investigated. Finally, the annual wave power at station bimep estimated from the wave model outputs and the relationships between the predicted wave parameters and the NAO index were obtained for the analyzed period.

## Numerical models

The meteorological forecast system considered in the present work was developed by MeteoGalicia (meteorological agency of Galicia). This system was based on the application of two numerical models: MM5 (Fifth-Generation PSU/NCAR Mesoscale Model) in the years 2007 and 2008, and WRF (Weather Research and Forecasting model) in 2009 and 2010. A description of MM5 and WRF may be found in Grell *et al*. (1994) and Skamarock *et al*. (2005), respectively. A domain with a horizontal resolution of 30 km was used in the MM5 simulations. In the WRF case, two nested domains were used: the coarser domain covered part of the North Atlantic Ocean and southwestern Europe (a larger area that the one used in the MM5 simulations), with a horizontal resolution of 36 km, while the inner domain covered the Iberian Peninsula and the Bay of Biscay, with a horizontal resolution of 12 km (see Fig. 1). The initial and boundary conditions for the coarser grids were provided by the Global Forecast System run by NCEP (National Centers for Environmental Prediction). For the inner grid used in the WRF simulations, the boundary conditions were provided by the results obtained from the coarser grid.

To obtain the wave characteristics in the southeastern Bay of Biscay, we used the WAve prediction Model (WAM). This is a third generation wind-wave model developed during the 1980s by a group of scientists from different countries around the world (the WAMDI Group, 1988; Komen *et al*., 1994; Janssen, 2008). WAM solves the spectral action balance equation and simulates the 2D wave spectral evolution, considering the following processes: energy input by the wind, energy dissipation by whitecapping, nonlinear wave-wave interactions, bottom friction, refraction, and shoaling. The model is presently used by many meteorological agencies to provide wave forecasts at different scales. The WAM version used in this research is the one obtained by Monbaliu *et al*. (2000), in which the representation of bottom friction and wave breaking was improved.

The spatial domain used in the WAM simulations extended from 43.2ºN to 48ºN and from 4.5ºW to 1ºW, with a horizontal resolution of 1.6 km (Fig. 1). WAM was forced by the wind fields obtained with MM5 and WRF. The conditions applied to the open boundary of the WAM domain were provided by the WAVEWATCH III model run by NOAA (National Oceanic and Atmospheric Administration). WAVEWATCH III (Tolman, 1997, 2009) is a third generation wave model developed at NOAA/NCEP in the spirit of the WAM model, which provides three-hourly directional wave spectra since February 2005. In our case, we used the predicted spectra at station 62001 (Gascogne buoy). This station, which is owned and maintained by UK Met Office in cooperation with Meteo France, is located at 45.2ºN-5ºW (see Fig. 1).

The WAM simulation covered the period from 2007 to 2010, in which the meteorological models were operating at high spatial and temporal resolutions. Although this period is too short for drawing far-reaching conclusions, it is long enough for obtaining a preliminary estimation of the wave energy resource in the bimep area. The WAM spectra had a resolution of 25 frequencies x 24 directions. The accuracy of the wind (eastward and northward components, $U_w$ and $V_w$, respectively) and the main wave parameters (significant wave height, $H_s$, mean direction, $\theta_m$, and mean and peak periods, $T_{m02}$ and $T_p$, respectively) obtained with the models at hourly intervals was analyzed. The wave parameters $H_s$ and $T_{m02}$ are defined as:

$$H_s = 4\sqrt{m_0}$$

and

$$T_{m02} = \sqrt{\frac{m_0}{m_2}}$$

where $m_0$ and $m_2$ are the zeroth and second spectral moments, respectively. The n-th spectral moment can be computed by the following equation:

$$m_n = \int_0^{2\pi}\int_0^{\infty} f^n S(f,\theta)\,df\,d\theta$$

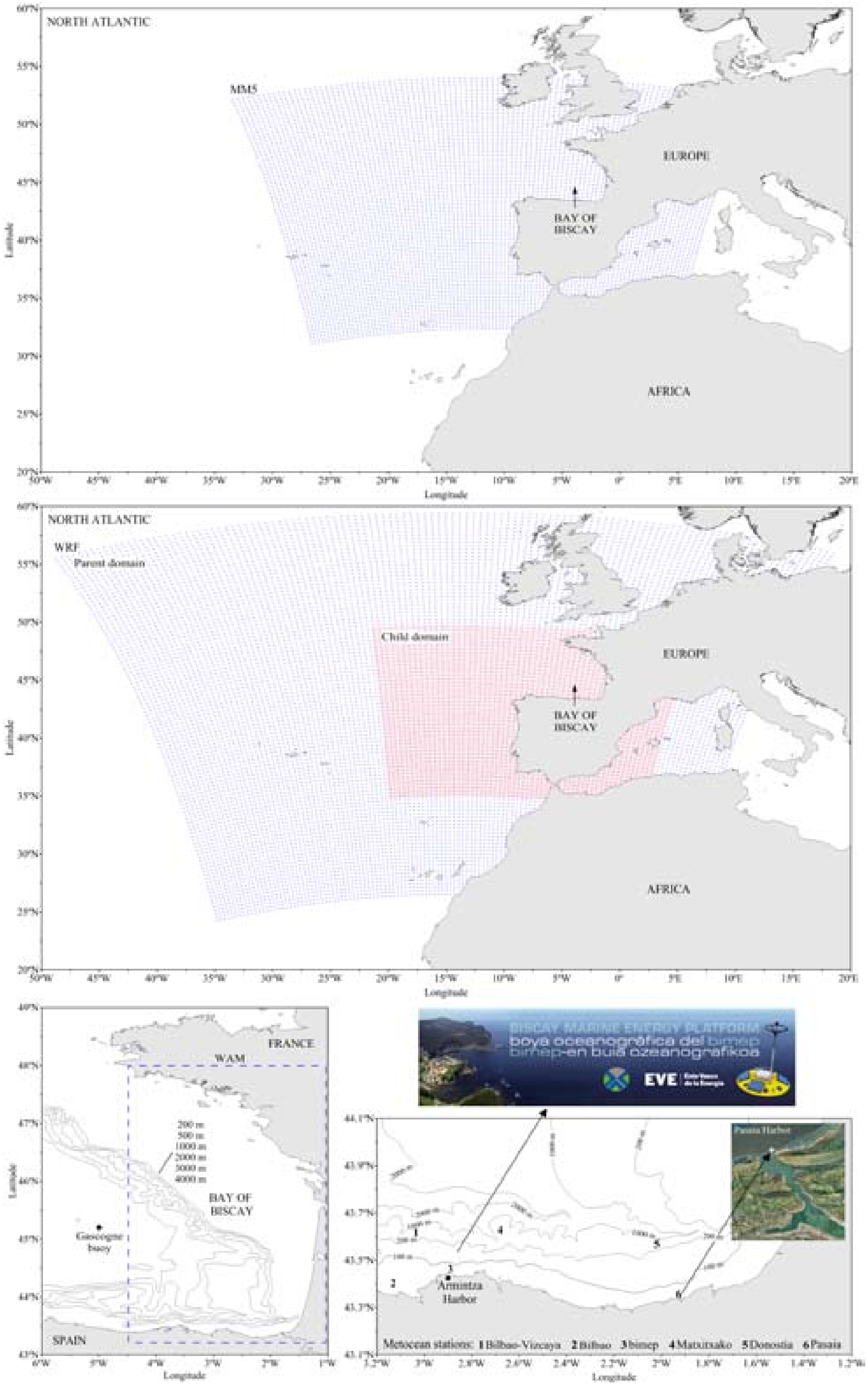


**Figure 1.** Sea grid points of the MM5 and WRF domains (top and middle), boundary of the WAM domain, bathymetry of the study area, and locations of the metocean stations listed in Table 1 (bottom).

using the wave frequency and direction, f and θ, respectively, and the spectral energy density, S(f,θ). $T_p$ (= $1/f_p$) is the wave period for which S(f,θ) attains its maximum value. The wave power, J, in a bin of the spectrum centered at a frequency $f_i$ and direction $\theta_j$ can be estimated with the following equation:

$$J_{i,j} = \rho g c_{g,i} S(f_i,\theta_j)\Delta f_i \Delta\theta_j$$

where ρ is the reference seawater density (1025 kg m$^{-3}$), g is the gravitational acceleration (9.81 m s$^{-2}$), $\Delta f_i$ and $\Delta\theta_j$ are the increments in frequency and direction, and $c_{g,i}$ is the group velocity of $f_i$ in a water depth h given by:

$$c_{g,i} = \frac{\pi f_i}{k_i}\left(1+\frac{2k_i h}{\sinh 2k_i h}\right)$$

The wave number, $k_i$, associated with $f_i$ and h is defined through the dispersion relationship:

$$(2\pi f_i)^2 = g k_i \tanh k_i h$$

The model results were compared with the observations of five metocean buoys (Bilbao-Vizcaya, Bilbao, bimep, Donostia, and Matxitxako) and a coastal station (at the entrance to Pasaia Harbor). The locations and main characteristics of these stations are shown in Fig. 1 and Table 1, respectively. Bilbao-Vizcaya and Bilbao are owned and maintained by PdE (Spanish Ports Authority), Donostia, Matxitxako, and Pasaia by DAEM (Directorate of Emergency Attention and Meteorology, Basque Government), and bimep by EVE. Bilbao-Vizcaya, Donostia, and Matxitxako are located in the open ocean (water depths between 450 and 600 m), while Bilbao and bimep are located at a distance between 2 and 4 km from the coast. The most extreme wave conditions during the analyzed period occurred on January 23–24, 2009 when the deep extra-tropical cyclone Klaus, consequence of an explosive cyclogenesis, crossed over the Bay of Biscay from west to east (González *et al*., 2009).

# Results

The meteorological and wave model outputs were extracted at each station location (Table 1) to compare them with the available observations. The scatter plots of the predicted versus measured values were drawn to obtain the linear correlations for the variables being studied and determine how well the predicted values reflect the measured data. Figure 2 shows the results at station bimep. The coefficients of determination, $r^2$, obtained following a linear regression analysis and using the available data from 2007 to 2010 are summarized in Table 2. Here the empty cells mean unavailable or wrong observations.

For the analyzed period, MM5 and WRF were able to reproduce the time evolution of the offshore winds with a reasonable accuracy. Here $r^2$ for $U_w$ and $V_w$ were between 0.57 and 0.76, indicating a moderate agreement (higher for $U_w$) between the measurements and the predicted values. At Pasaia (located at the foot of a cliff), $r^2$ for both $U_w$ and $V_w$ decreased to ~0.4. The most likely explanation for this is the low resolution (≥ 12 km) of the MM5 and WRF domains, which implies a significant loss of the small-scale details of the wind field near the coastal areas. This suggests that a meteorological model with a higher horizontal resolution (of at least 1 km, taking into account the characteristics of the study area) would be more appropriate to accurately estimate the wind field in the coastal area. This could resolve better the very rough topography of the region, responsible for the wind channelling observed at Pasaia.

Regarding the WAM outputs, similar tendencies to the ones showed by the meteorological models were obtained. In deep and intermediate waters (> 50 m depth), $r^2$ for $H_s$ was 0.9, while at Pasaia decreased to 0.8. For the wave periods, $r^2$ ranged between 0.56 and 0.69 for $T_{m02}$, and between 0.42 and 0.57 for $T_p$. For $\theta_m$, $r^2$ was between 0.32 and 0.69. The wave parameters computed by using the spectral moments ($m_0$ and $m_2$), $H_s$ and $T_{m02}$, showed a higher correlation than $T_p$ and $\theta_m$. At all the stations, both $T_p$ and $\theta_m$ presented a high variability because most of the time combined sea states occurred. The

**Table 1.** Main characteristics of the six metocean stations used in this research (for locations, see Fig. 1).

| Station | Geographical coordinates | Mean water depth (m) | Start date (month and year) | Sampling rate (min) |
|---|---|---|---|---|
| Bilbao-Vizcaya | 43º 37.8’ N<br>3º 2.4’ W | 600 | August 1990 | 60 |
| Donostia | 43º 33.8’ N<br>2º 1.4’ W | 550 | January 2007 | 60 |
| Matxitxako | 43º 37.9’ N<br>2º 41.6’ W | 450 | January 2007 | 60 |
| bimep | 43º 28.1’ N<br>2º 53.1’ W | 80 | March 2009 | 60 |
| Bilbao | 43º 23.9’ N<br>3º 7.9’ W | 53 | March 2004 | 60 |
| Pasaia | 43º 20.3’ N<br>1º 55.5’ W | 24 | August 2001 | 10 |

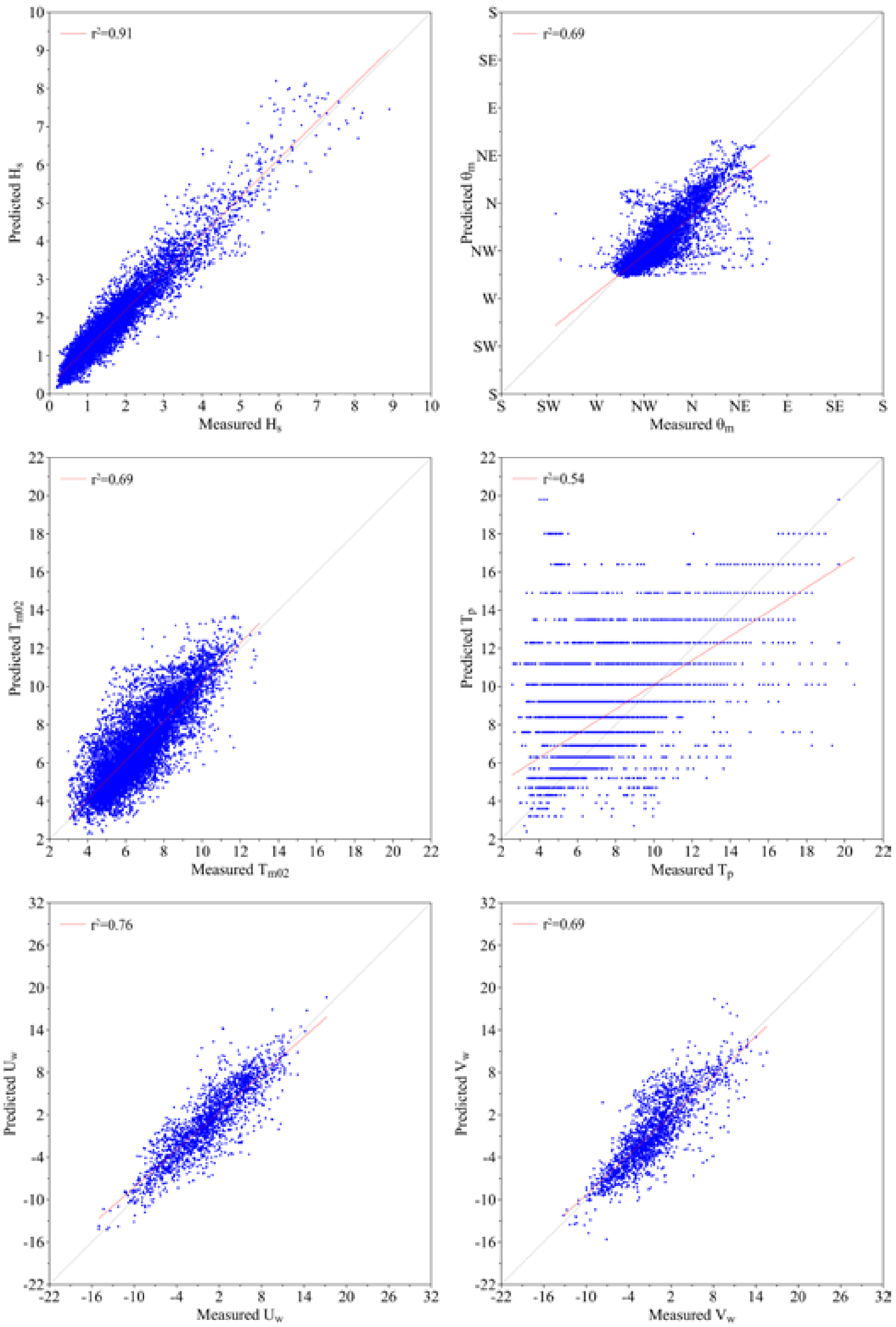


**Figure 2.** Scatter plots of the predicted versus measured variables ($H_s$, $\theta_m$, $T_{m02}$, $T_p$, $U_w$, and $V_w$) at bimep from 2009 to 2010. The fitted regression lines and coefficients of determination, $r^2$, are also shown.

**Table 2.** Coefficients of determination, $r^2$, for the linear regressions of the predicted versus measured variables ($H_s$, $\theta_m$, $T_{m02}$, $T_p$, $U_w$, and $V_w$) at the six metocean stations listed in Table 1. The number of points of each regression (in brackets), using the available data from 2007 to 2010, is also shown.

| Station | $r^2$ | | | | | |
|---|---|---|---|---|---|---|
| | $H_s$ | $\theta_m$ | $T_{m02}$ | $T_p$ | $U_w$ | $V_w$ |
| Bilbao-Vizcaya | 0.9 (31,873) | 0.53 (31,572) | 0.67 (32,174) | 0.45 (31,855) | 0.72 (28,512) | 0.61 (28,512) |
| Donostia | 0.91 (29,302) | 0.32 (29,463) | 0.56 (29,810) | 0.42 (29,810) | 0.68 (9,097) | 0.57 (9,097) |
| Matxitxako | 0.9 (24,037) | 0.55 (23,027) | 0.68 (24,123) | 0.47 (24,142) | 0.72 (6,359) | 0.62 (6,359) |
| bimep | 0.91 (13,915) | 0.69 (13,894) | 0.69 (13,915) | 0.54 (13,915) | 0.76 (2,015) | 0.69 (2,015) |
| Bilbao | 0.9 (31,313) | 0.5 (31,023) | 0.64 (31,578) | 0.57 (31,374) | - - | - - |
| Pasaia | 0.82 (29,776) | - - | 0.67 (29,774) | - - | 0.39 (33,968) | 0.42 (33,968) |

existence of a high-frequency wind sea and a low-frequency swell with similar energies and from different directions is a very common case in the study area. This fact results in jumps in the measured values of $T_p$ and $\theta_m$. $H_s$ was the parameter which showed the best agreement between the predicted and measured values, even near the coast (at Pasaia), where the meteorological models did not accurately predict the wind. This suggests that at Pasaia the local wind is of minor importance and its wave conditions are dominated by the offshore winds.

The influence of the wind on the WAM prediction was analyzed during Klaus. For this event, two simulations were carried out with WAM: (1) without winds; and (2) with hourly winds. The predicted and measured $H_s$ at Matxitxako, Donostia, and Bilbao, along with the WAVEWATCH III outputs at Gascogne, are shown in Fig. 3. This figure illustrates how a favorable wind increases $H_s$, improving the quality of the WAM predictions especially during the storm peak. In the case of no local wave generation (simulation without winds), WAM only propagated the wave field imposed on the open boundary, decreasing $H_s$ from deep to intermediate waters, as can be seen at Bilbao. The grey areas in this figure show the effect of the wind on $H_s$. The peaks of the predicted $H_s$ at Matxitxako between 6 and 10 h GMT on January 24 were 9.2 m without winds and 13.8 m using hourly winds.

When WAM used hourly winds, it was able to simulate the complicated wave field observed during Klaus, which reached $H_s$ of ~13.5 m at Matxitxako and Donostia ($T_p$ of 15 and 17 s, respectively), and 7 m at Bilbao (here $T_p$ decreased to 13 s). The maximum measured wave heights were 21.5, 20.4, and 12.4 m, respectively. The peaks of the predicted and measured $H_s$ in Fig. 3 are not properly synchronized possibly due to the effect of using in the WAM simulations wave boundary conditions every three hours. The analysis of Klaus demonstrates that for a realistic wave model simulation in the southeastern Bay of Biscay the accuracy of both wind fields and boundary conditions is a critical factor.

The annual wave power increased almost linearly from 221 to 268 MW h $m^{-1}$ in 2007–2009 and decreased to 158 MW h $m^{-1}$ in 2010 (Fig. 4). The time series of the predicted $H_s$ and $T_p$ at bimep (Fig. 5) can be used to explain the decrease in the last year of the analyzed period. In general, the tendency of both variables was to increase in autumn and winter, and decrease in spring and summer. However, this tendency was not so clear in 2010, showing annual mean values of $H_s$ and $T_p$ of ~1.6 m and 9.8 s, respectively. These mean values were lower than those predicted with WAM in 2007–2009 (≥1.8 m and 10.5 s, respectively), resulting in a decrease of the wave energy resource.

The linear correlation between the main wave parameters ($H_s$, $T_p$, and $T_{m02}$) and the NAO index were obtained for the analyzed period. The NAO index is provided by CPC (Climate Prediction Center). It is computed by means of a rotated principal component analysis of the monthly mean 500-hPa height anomalies. The seasonal variability of the NAO index did not show any clear correlation with $H_s$ or the wave energy resource ($r^2 < 0.3$). However, $T_p$ and $T_{m02}$ were positively correlated with it from December to May. The mean values of $r^2$ for these variables were ~0.4 and 0.6, respectively. This correlation disappeared in summer and autumn. This fact is probably a consequence of the dominance of the low-pressure systems over the North Atlantic Ocean in winter, which means higher swell peak periods and less local wave generation in the southeastern Bay of Biscay.

# Conclusions

Hourly wind fields obtained with two meteorological models (MM5: Fifth-Generation PSU/NCAR Mesoscale Model; and WRF: Weather Research and Forecasting model) and three-hourly boundary conditions (defined by directional wave spectra) provided by WAVEWATCH III were used to feed WAM (WAve prediction Model) and simulate the

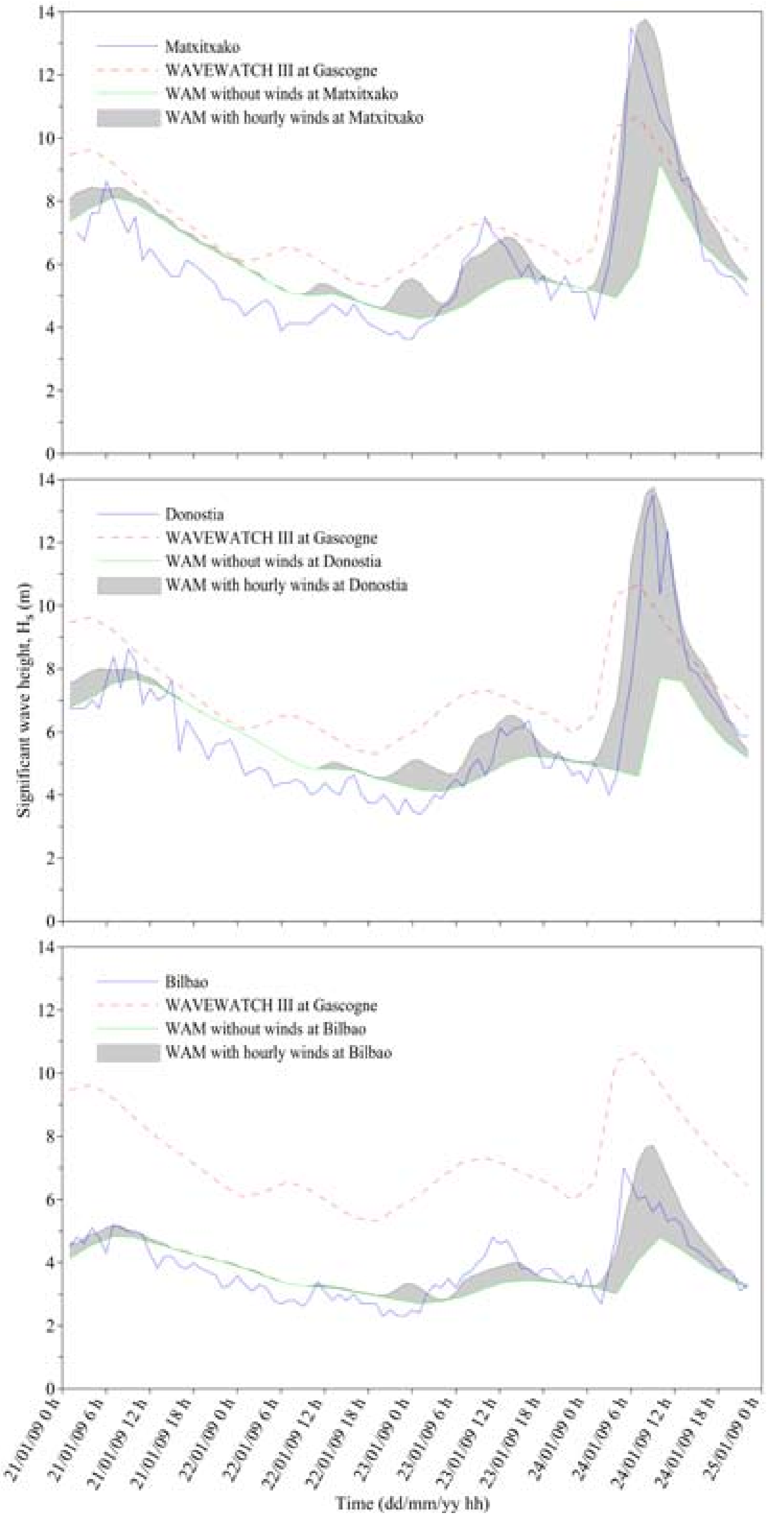


**Figure 3.** Predicted and measured $H_s$ at Matxitxako (top), Donostia (middle), and Bilbao (bottom) during Klaus. For this event, two simulations were carried out with WAM: (1) without winds; and (2) with hourly winds. The WAVEWATCH III outputs provided by NOAA at Gascogne are also shown.

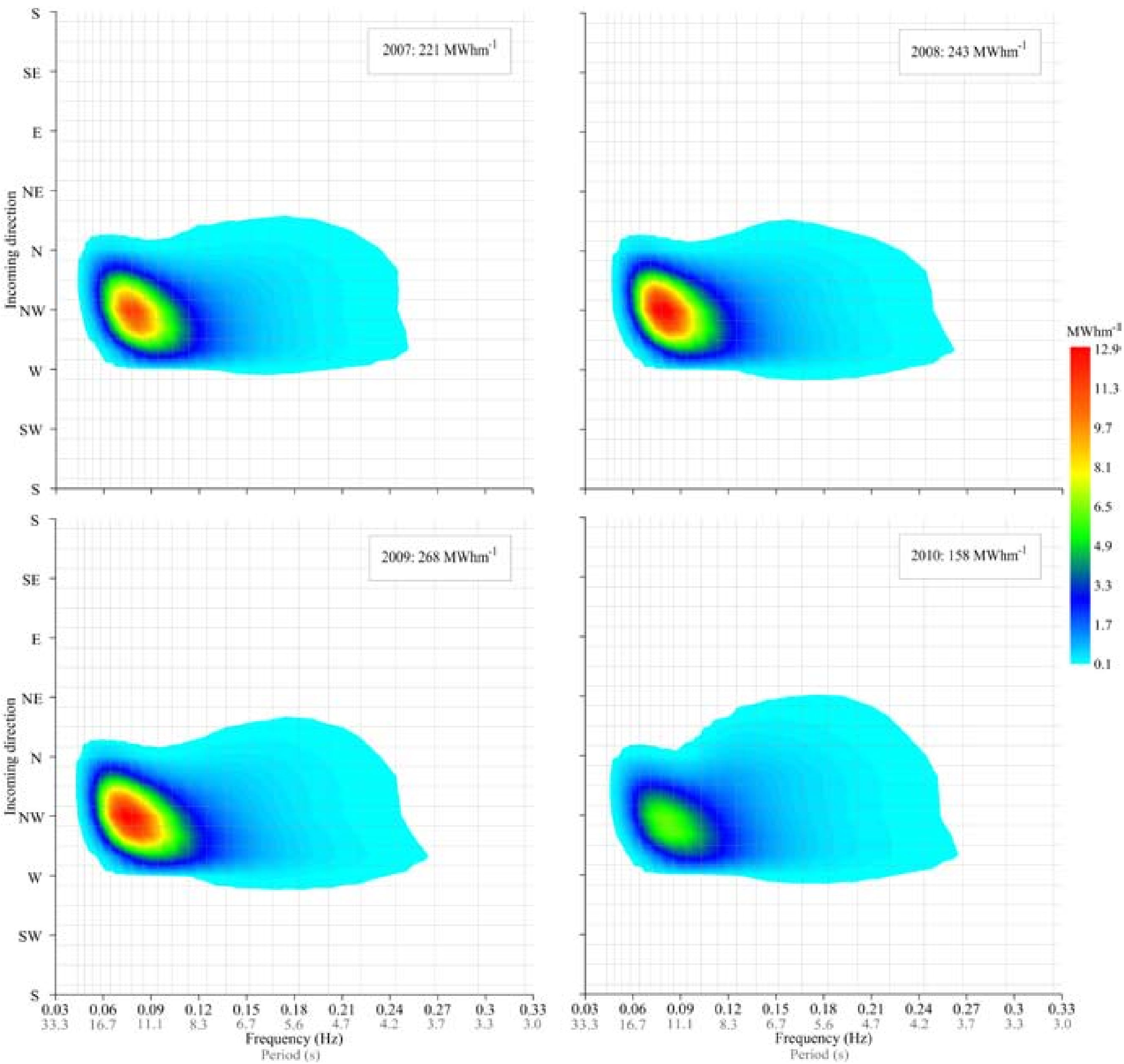


**Figure 4.** Predicted annual wave power spectra at bimep from 2007 to 2010.

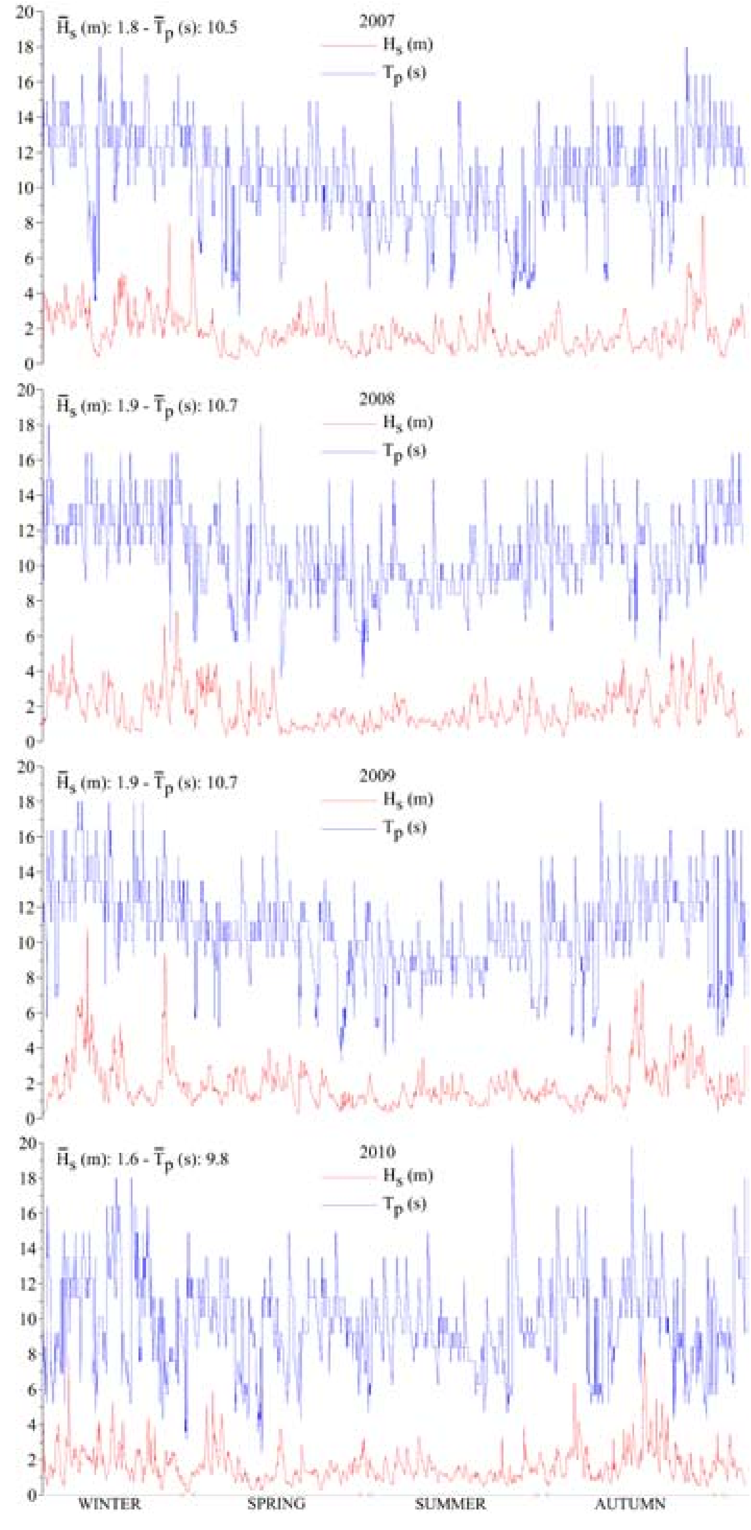


**Figure 5.** Predicted $H_s$ and $T_p$ at bimep from 2007 to 2010. The annual mean values of these variables are also shown.

wave climate in the southeastern Bay of Biscay (study area). Here it is located bimep (Biscay marine energy platform), a demonstration infrastructure to test wave energy converters in real conditions. The period from 2007 to 2010 was selected to analyze the performance of the models in determining the information needed to estimate the wave energy resource in the study area. MM5 (with a horizontal resolution of 30 km) was used for the years 2007 and 2008, and WRF (with a horizontal resolution of 12 km) for 2009 and 2010. The model results were compared with the available observations of six metocean stations located in the study area: Bilbao-Vizcaya, Bilbao, bimep, Donostia, Matxitxako, and Pasaia. MM5 and WRF were able to reproduce the time evolution of the offshore winds with a reasonable accuracy (a mean value of $r^2 > 0.6$). However, the results suggest that a meteorological model with a higher horizontal resolution (of at least 1 km) would be more appropriate to estimate the wind field in the coastal area. Regarding the WAM model (with a horizontal resolution of 1.6 km), the significant wave height, $H_s$, and the mean period, $T_{m02}$, were the wave parameters that showed a statistically better agreement with the observations in deep and intermediate waters, with mean values of $r^2$ for $H_s$ and $T_{m02}$ of ~0.9 and 0.7, respectively. The errors in $H_s$ increased at Pasaia (located at the foot of a cliff), where $r^2$ decreased to ~0.8. The annual wave power at station bimep increased almost linearly from 221 to 268 MW h m$^{-1}$ in 2007–2009 and decreased to a value of 158 MW h m$^{-1}$ in 2010. Both the wave energy resource and $H_s$ did not show any clear correlation with the NAO index, while the wave periods (especially $T_{m02}$) were positively correlated with it from December to May.

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