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## Evaluating wind datasets for wave hindcasting in the NW Iberian Peninsula coast

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### ABSTRACT

The available wind datasets can be exploited to support the setup of accurate wave models, able to reproduce and forecast extreme event scenarios. It is of utmost importance in the actual context of climate change. This study focuses on evaluating the performance of a numerical wave model, using different wind datasets, helping to create a tool to assess coastal risks, and further on to support the future implementation of reliable warning systems based on numerical models. The numerical model SWAN was implemented, configured and validated for the NW Iberian Peninsula coast, as a test case region. A period of two months, from December 2013 to January 2014, was simulated due to the winter storms that crossed the area. Six distinct wind datasets were selected to test their suitability in regional wave modelling. The results were validated against several sets of wave buoy data, considering wave parameters such as significant wave height, mean wave period and peak direction. The implemented wave model configuration allowed the representation of the wave evolution with relatively good accuracy. All the wind datasets were able to produce reasonably good wave condition estimates. The dataset that best represented the wave properties varied from one wave parameter to another, but the most reliable for the selected region was the reanalysis product generated at the European Centre for Medium-Range Weather Forecasts.

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Wave activity; SWAN; coastal processes; wind datasets comparison; NW Iberian Peninsula coast

## 1. Introduction

The wave action in coastal zones can generate strong erosion. During extreme events, the combination of wave setup and hazardous wave conditions may result in significant risks to coastal navigation, structures, ecosystems and population. To minimise the risks on a vulnerable coastline, it is necessary to anticipate the storm's impacts and increase the coastal resilience. The Intergovernmental Panel on Climate Change (IPCC) depicts a future with an increase in the frequency and strength of the extreme events and larger waves, associated with sea-level rise (IPCC 2014). Monitoring the ocean condition is needed to describe the coastal dynamics. However, they are vast, and thus, the observational data is scattered over large areas (Bastos et al. 2016). Numerical models can fill this gap, being able to represent the complex patterns of coastal dynamics and allow to set up early warning tools to predict the potential effects of storms on coastal environments.

The growing importance of accurate prediction of wave conditions and wave climate requires continuous improvements of the modelling systems. The model's performance depends both on a correct physical

formulation and on the quality of the forcing wind data. The accuracy of the wind products can change from one region to another and should be taken into account when choosing the best dataset to force a wave model. Álvarez et al. (2014) evaluated different wind products for the Bay of Biscay through comparisons with real data. Carvalho et al. (2013) tested QuikSCAT and Cross-Calibrated Multi-Platform (CCMP) project wind datasets for the Iberian Peninsula. QuikSCAT products were also validated for the Ligurian Sea by Pensieri et al. (2010), while Sharp et al. (2015) assessed the UK CFSR hourly wind speed product using onshore and offshore wind measurements.

Regarding the datasets efficiency in ocean modelling, Stopa and Cheung (2014) carried out a long-term (1980–2010) inter-comparison of wind speed and wave height from ERA-Interim and CFSR in the NE Pacific and NW Atlantic. Both products have good spatial homogeneity, with a consistent level of errors, and show that ERA-Interim generally underestimates and CFSR tends to over-predict the wind speed and wave heights. Appendini et al. (2013) assessed the wave modelling performance in the Gulf of Mexico and Western Caribbean

Sea, analysing NCEP/National Centre for Atmospheric Research (NCAR), ERA-Interim and NCEP's North American Regional Reanalysis (NARR) wind products. They found that NCEP/NCAR and ERA-Interim data sets outperform NARR. NARR is more suitable for simulating extreme cyclonic events due to its higher-resolution in time and space. However, the capabilities of different wind datasets for wave modelling forecasting in the Iberian Peninsula has so far received little attention.

For this study, the numerical wave model SWAN was selected. It has been successfully applied to several oceans and seas (Lalbeharry and Ritchie 2009; Van der Westhuysen 2012; Alari 2013; Viitak et al. 2016), and also to the Iberian Peninsula coast, assessing the performance of its numerical and physical formulations (Faria 2009; Rusu and Soares 2013; Rusu et al. 2015; Silva et al. 2015).

The goal of this work is to implement and validate SWAN v41.10 (SWAN 2016), using six wind data products and applying them to the NW Coast of the Iberian Peninsula (NWCIP). The following questions will be addressed. Which wind dataset leads to the most accurate simulation of wave propagation? How do the spatial and temporal properties of wind data influence wave modelling? How accurate is the SWAN wave model? This paper is structured as follows: in section 2, the materials and methods used are introduced. Section 3, presents the results and section 4 the discussion. Conclusions are summed up in section 5.

## 2. Materials and methods

### 2.1. Characterisation of the study area

The NWCIP is a complex region in terms of meteo-oceanic conditions (Bastos et al. 2016). It is characterised by a relatively narrow continental shelf (<40 km-wide) and a steep continental slope (>20°). The ocean becomes deeper than 1000 m in just a few tens of kilometres away from the coast (Gómez-Gesteira et al. 2011). The coastal bathymetry presents prominent capes, submarine canyons and promontories that induce hydrodynamic features such as filaments and eddies (Pinheiro et al. 1996; Peliz et al. 2003; Lavín et al. 2006; Mason et al. 2006; Relvas et al. 2007; Rossi et al. 2013).

The North Atlantic Oscillation (NAO), mainly mediates the weather conditions in the NWCIP. The Azores High induces northerly and north-westerly (NW) winds over the area that are prevalent throughout the year, with the highest magnitudes in the summer season (Ramos et al. 2011). As a result, dominant NW waves are produced with a mean  $H_s$  of 2m and a peak period

between 9 and 13s (Costa and Esteves 2008). During winter, low-pressure systems generated over the Atlantic can cross the NWCIP with associated south-westerly (SW) and south (S) winds, producing extremely high energetic conditions on the continental shelf (Vitorino et al. 2002a).  $H_s$  between 3 and 6m are not uncommon, reaching between 9 and 12m during strong storm events (Dias et al. 2002; Vitorino et al. 2002a, 2002b; Costa and Esteves 2008).

### 2.2. Case study: winter storm events

The time window between 12/2013 and 01/2014 was selected, because during this period, several storms hit the NWCIP causing extensive damage to infrastructures, such as roads and harbours (Rusu et al. 2015). Between 5-7/01/2014, the passage of the low-pressure system Hercules caused floods in coastal areas, washed away sand dunes and dragged away breakwater concrete armour units, leaving behind considerable damage in harbours, beach structures, roads, sidewalks and promenades. Deposits of sand, mud and debris were moved inland (Santos et al. 2014). During this event, strong SW winds blew over the entire region, producing long period waves with measured maximum wave heights between 7 and 12 m (Figure 1). During the entire analysis period, the mean wave direction was from the N-W sector, with mean  $H_s$  between 4 and 5 m, mean wave period from 7 to 9s.

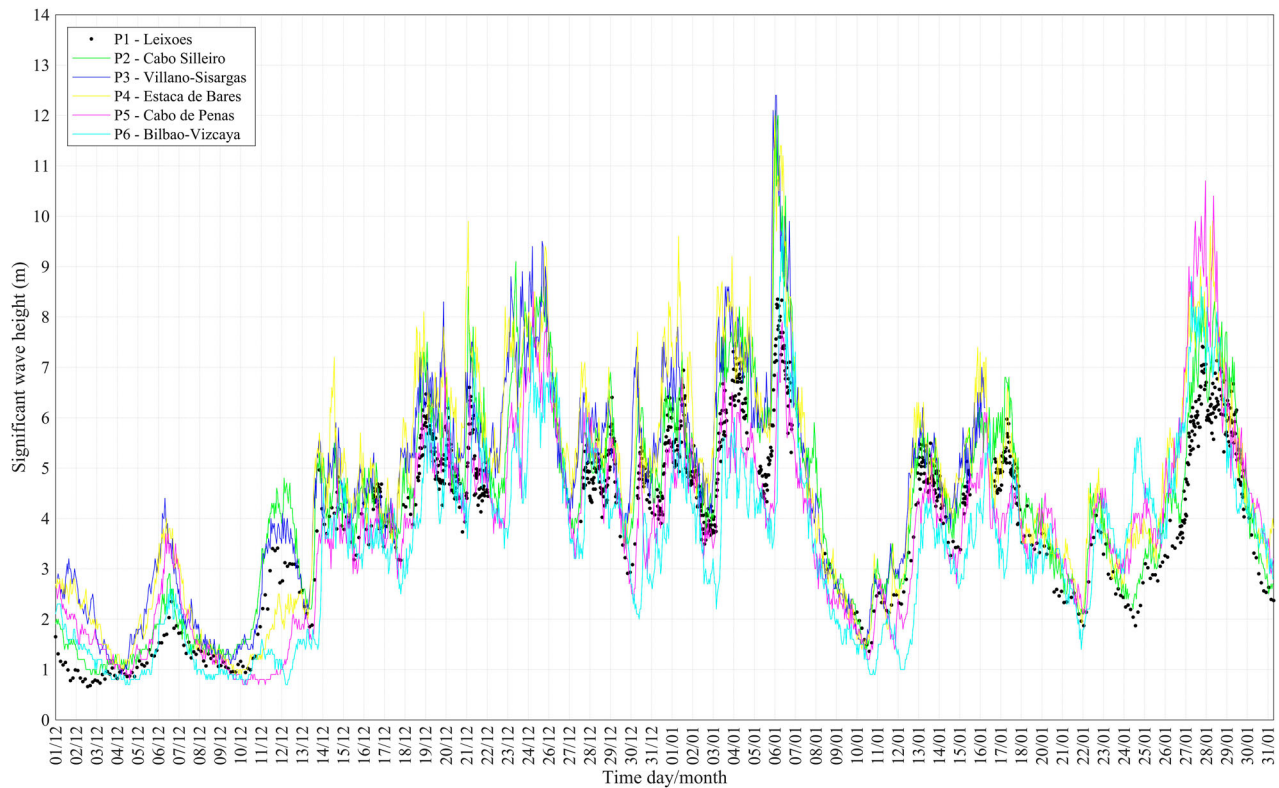
### 2.3. Wind data products

Surface wind fields were obtained from six databases (Table 1), with a reference height of 10 m above the sea level. They were applied in different stages depending on their spatial coverage.

From the ECMWF, the two most recent reanalysis were selected: ERA-Interim (Dee et al. 2011) and ERA5 (Copernicus Climate Change Service 2017). ERA-Interim is a global atmosphere reanalysis, continuously updated in real-time with data available since 1979. ERA5 is a recent reanalysis of the EU-funded Copernicus Climate Change Service (C3S) operated by ECMWF. The first segment (2010–2016) provides data at higher spatial and temporal resolution than ERA-Interim.

MERRA-2 (GMAO 2015), the second version of NASA atmospheric reanalysis was constructed using the Goddard Earth Observing System Model V5 with Atmospheric Data Assimilation System.

From the NCEP products, the 6-hourly forecast surface winds products from CFSv2 ds094.0 and the hourly time-series from CFSv2 ds094.1 were selected (Saha et al. 2011a, 2011b and 2014).



**Figure 1.** Hs evolution observed for the 6 buoys during the study period (01/12/2013–31/01/2014).

Finally, historical forecasts from the regional Weather Research and Forecasting model, implemented by Meteogalicia (<http://www.meteogalicia.gal/>) for local forecast, were considered. This model runs operationally twice a day with three available domains and spatial resolutions. The highest spatial resolution product was selected.

#### 2.4. Observational data

Model results were validated against data from six wave-buoys at various depths (Figure 2(b)). Leixões (P1) is maintained by the Instituto Hidrográfico (IH, <http://www.hidrografico.pt/boias-ondografo.php>). The directional Waverider Datawell is moored in shallow waters (83 m), and records data in a 3-hours interval, increasing the frequency during energetic events ( $H_s > 5$  m). Cabo Silleiro (P2), Villano-Sisargas (P3), Estaca de Bares

(P4), Cabo de Peñas (P5) and Bilbao-Vizcaya (P6) are maintained by Puertos del Estado (<http://www.puertos.es/>), gathering data in a 1-hour interval. They are equipped with a directional Met-Oce sensor and located in relatively deep waters close to the continental shelf border or areas of complex bathymetry and strong depth gradients.

Due to the resolution of the available bathymetric data and the discrete nature of the computational grids, there is a difference between the computed depth and the real depth at the buoy locations (Table 2), especially evident for the coarser grid.

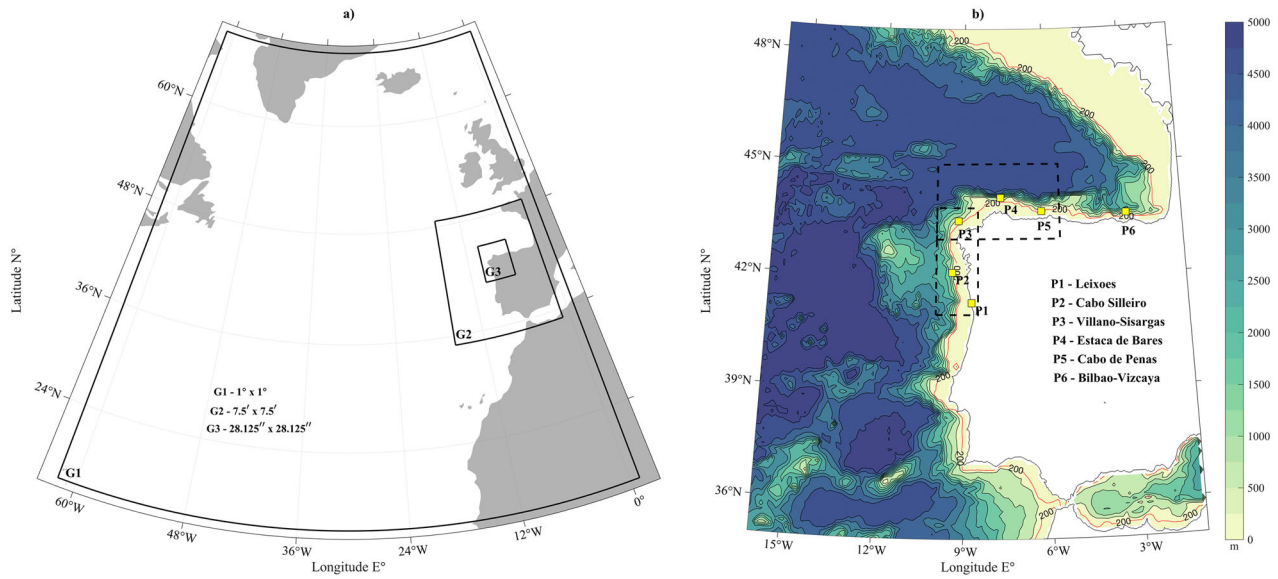
#### 2.5. Numerical model setup

SWAN is a third-generation wave model developed at the Delft University of Technology. Short-crested wind-wave generation and propagation over realistic bathymetry are described by means of a two-dimensional wave action density spectrum. A spectral wave action balance equation is solved without any *a priori* restrictions on the spectrum for wave growth evolution (Booij et al. 1999).

A grid nesting procedure was implemented to guarantee proper simulation of nearshore processes. Three computational grids with different spatial extent and

**Table 1.** Wind datasets characteristics.

| Dataset              | $\Delta x \times \Delta y$ (°) | $\Delta t$ (h) | Availability |
|----------------------|--------------------------------|----------------|--------------|
| ECMWF Era-Interim    | $0.75 \times 0.75$             | 6              | 1979–2019    |
| ECMWF ERA5           | $0.2815 \times 0.2815$         | 1              | 2010–present |
| NASA MERRA-2         | $0.5 \times 0.625$             | 1              | 1980–present |
| NCEP CFSv2 (ds094.0) | $0.5 \times 0.5$               | 1              | 2011–present |
| NCEP CFSv2 (ds094.1) | $0.5 \times 0.5$               | 1              | 2011–present |
| WRF-MeteoGalicia     | $0.1079 \times 0.1079$         | 1              | 2008–present |



**Figure 2.** a) Nesting set-up and computational grids G1, G2 and G3 placements and b) bathymetry of the G2 computational area. The two sectors of the study area are, Atlantic (West) and Cantabrian (North), marked with black intermediate lines and the red isoline indicates the border of the continental shelf. Additionally, the locations of wave buoys are shown with yellow squares.

resolution were defined (Figure 2(a)). The first and coarser grid, G1 (1°x1°), covered the whole North Atlantic to provide swell information for inner computational grids (G2, G3). It lacks detailed information on depth over the continental slope and shelf, thus significantly altering the nearshore wave processes and leading to inaccurate readings at buoys locations. Nevertheless, G1 resolution was enough to accurately represent the long-wavelength low-frequency waves travelling across the ocean. The first nested level or second grid G2 (7.5'x7.5'), covered most of the oceanic area around the Iberian Peninsula. Finally, the second nested level G3 (28.125''x28.125'') covered the NW coastal seas of the Iberian Peninsula. The increase in the resolution along with the reduction of the observed area (Figure 2(a)) allowed a better agreement between the buoys real depth and depth on the grid (Table 2).

Bathymetric information for G1 was extracted from the GEBCO 30'' global grid (Becker et al. 2009). G2 and G3, used information extracted from the West Iberian bathymetry model WIBM2009 (Quaresma and Pichon 2013), which has 1' resolution.

G1 results were compared with observational data from five wave-buoys (P1, P2, P4, P5, P6) out of six. P3 was considered as a land cell on this grid due to the low resolution, as each cell covered an area of, approximately, 112 x 112 km, causing some inaccuracies in the coastal line representation. G3 covered also five buoys out of six (P1, P2, P3, P4, P5), leaving out the most eastward wave buoy (P6) (cf. Figure 2(b)).

In the G1 level all the wind datasets except MeteoGalicia, due to its limited spatial coverage, were used for the wave hindcast. For the next nesting level G2, MeteoGalicia data plus the three G1 best performing wind datasets were applied. The boundary conditions for the simulation with MeteoGalicia winds were obtained from the G1 grid run with ERA5 wind data. In the second nesting level G3, the three best performing wind datasets in G2 were tested.

A spin-up time of 1 week was considered to avoid model inconsistencies. After several tests, spectral directional resolution of 5° and 25 spectral frequency bins logarithmically spaced between 0.0418 and 0.8 Hz were chosen. For G1 and G2 the higher-order numerical

**Table 2.** Buoys location and depth (real and interpolated at the numerical grids).

| Buoy | Name             | Location |           | Depth (m) |        |      |         |
|------|------------------|----------|-----------|-----------|--------|------|---------|
|      |                  | Latitude | Longitude | Real      | G1     | G2   | G3      |
| P1   | Leixões          | 41.32 °N | 8.98 °W   | 83        | 84     | 82   | 86      |
| P2   | Cabo Silleiro    | 42.12 °N | 9.43 °W   | 600       | 2564   | 702  | 700     |
| P3   | Villano-Sisargas | 43.50 °N | 9.21 °W   | 386       | Inland | 422  | 482     |
| P4   | Estaca de Bares  | 44.12 °N | 7.67 °W   | 1800      | 751    | 1514 | 1586    |
| P5   | Cabo de Peñas    | 43.75 °N | 6.16 °W   | 615       | 2393   | 350  | 497     |
| P6   | Bilbao-Vizcaya   | 43.64 °N | 3.09 °W   | 870       | 1789   | 894  | Outside |

S&L scheme and Janssen whitecapping formulation (Janssen 1991) were selected. At G3, the first-order upwind scheme BSBT was applied to guarantee the numerical stability (SWAN 2013) and Westhuysen whitecapping (Van der Westhuysen et al. 2007) was chosen.

## 2.6. Validation method

To assess the quality of the results, a statistical analysis was performed for three wave parameters: significant wave height (Hs) and the spectrum mean zero-up-crossing wave period (Tm02), calculated from the density spectrum as:

$$H_s = 4\sqrt{E(\omega, \theta)d\omega d\theta} \quad (1)$$

$$\begin{aligned} T_{m02} &= 2\pi \left( \frac{\omega^2 E(\omega, \theta) d\omega d\theta}{E(\omega, \theta) d\omega d\theta} \right)^{-\frac{1}{2}} \\ &= 2\pi \left( \frac{\omega^2 E(\sigma, \theta) d\sigma d\theta}{E(\sigma, \theta) d\sigma d\theta} \right)^{-\frac{1}{2}} \end{aligned} \quad (2)$$

and, the spectrum peak wave direction (Pdir), which is the peak direction in  $E(\theta) = \int E(\omega, \theta) d\omega$ , where E is the variance density spectrum,  $\omega$  the absolute circular frequency determined by the Doppler shifted dispersion and  $\theta$  the wave propagations direction. Note that Pdir, correspond to the absolute maximum bin of the corresponding discrete wave spectra  $E(\theta)$  hence might not be the real Pdir.

Four statistical parameters, the Root Mean Square Error (RMSE), the Scatter Index (SI), the mean error (BIAS), and the correlation coefficient (Cor) were considered:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (a_i - b_i)^2} \quad (3)$$

$$SI = \frac{RMSE}{\frac{1}{n} \sum_{i=1}^n b_i} \times 100 \quad (4)$$

$$BIAS = \frac{\sum_{i=1}^n (a_i - b_i)}{n} \quad (5)$$

$$Cor(a, b) = \frac{cov(a, b)}{\sigma_a \sigma_b} \quad (6)$$

where  $a$  represents the model results,  $b$  the observed measurements,  $n$  the number of observations,  $cov(a, b)$  the covariance between  $a$  and  $b$ , and  $\sigma_a$  and  $\sigma_b$  the standard deviation of  $a$  and  $b$ , respectively.

Regarding Pdir, to eliminate any discontinuity between  $0^\circ$  and  $360^\circ$ , the difference between observations

$\theta_{obs}$  and model results  $\theta_{mod}$  was obtained (Pensieri et al. 2010). The corrected values were calculated as:

$$\theta_{mod} = \theta_{mod} - 360^\circ \text{ when } \theta_{obs} - \theta_{mod} > 180^\circ \quad (7)$$

$$\theta_{mod} = \theta_{mod} + 360^\circ \text{ when } \theta_{obs} - \theta_{mod} \leq -180^\circ \quad (8)$$

However, and due to the proper definition of the statistical parameters, SI was not calculated for Pdir, and the results of this variable were validated using only RMSE.

## 3. Results

### 3.1. Wind datasets performance

#### 3.1.1. Significant wave height (Hs)

The results show a good performance for all the considered wind datasets, with a satisfactory reproduction of the Hs evolution over time. Nevertheless, some differences arise in terms of Hs magnitude. ECMWF products and MERRA-2 were underestimating the highest Hs peaks, while the NOAA-NCEP datasets were largely overestimating. Both ECMWF products gave similar results, but some improvements can be seen with ERA5 (Figure 3(a)).

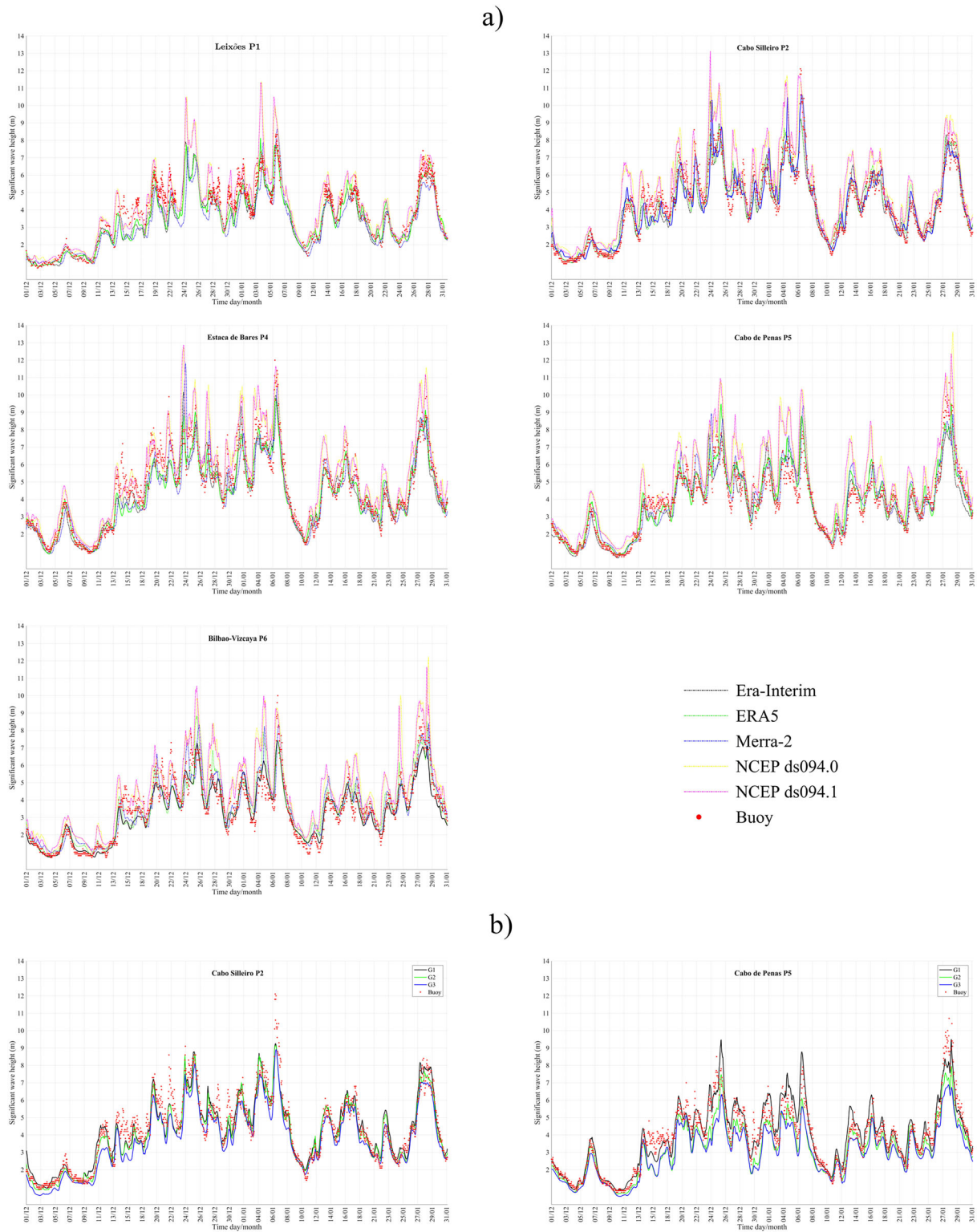
The best wind dataset for Hs at G1 was ERA5 (Table 3.a), giving the best results for three considered buoys (P1, P4, P5). In these locations, ERA5, RMSE varies from 0.43–0.71 m, SI from 9.30–17.52%, BIAS from  $-0.12$ – $0.17$  m and Cor from 0.92–0.95. For P2 and P6, the best results are obtained with MERRA-2 and ERA-Interim, respectively.

G2 was forced with MeteoGalicia WRF dataset and the three best performing wind datasets in grid G1 ERA-Interim, ERA5 and NCEP CFSv6 (ds094.0). As expected, some improvements can be seen when compared with G1 (Table 3.a). For ERA-Interim, RMSE reduced between 0.02 and 0.03 m at P1 and P4, but presents higher values, up to 0.26 m, for the rest of the buoys locations. For ERA5, Hs RMSE improves few centimetres in P1 and P2, but the error increases up to 0.17 m in rest of the buoys. NCEP CFSv6 (ds094.0) demonstrates better results compared to the G1 level. Cor coefficient maintains the same values or improves a bit for the G2 domain.

G3 did not show almost any improvement over the previous grid. Comparing the statistical metrics for the three considered domains (G1, G2, G3), G3 outputs presents the worst results, even when the MeteoGalicia highest resolution wind dataset was implemented.

Minimal differences between G1 and G2 results were depicted in the estimated values for P2 (Figure 3(b)). Furthermore, the G3 results seem to lead to a higher Hs underestimation. This is further confirmed by the P5 results, where this underestimation was even larger.

The best results for Hs at G1 and G2 were produced using ERA5, for G3 MeteoGalicia.



**Figure 3.** Measured and modelled  $H_s$  for the period between 01.12.13–31.01.14. Red dots represent buoys measurement, dotted lines are SWAN results for each wind dataset considered. The bold line indicates the best fit for each buoy. a) Comparison of measurements and G1 computational grid. b) Measured and modelled results with ERA5 wind data, representing all three computational grids in buoy locations P2 and P5.

### 3.1.2. Mean wave period ( $T_{m02}$ )

$T_{m02}$ , was reasonably well represented whatever the wind dataset used at the G1 grid. Nevertheless, ERA-Interim,

ERA5 and MERRA-2 lead to underestimation of the  $T_{m02}$  at all the buoy locations, whereas it was overestimated at some locations for both NOAA datasets.

**Table 3.** RMSE, SI, BIAS and Cor for each computational domain (G1, G2 and G3) at buoys location for a) significant wave height, b) mean wave period and c) wave peak direction. The most optimal dataset for each domain is marked in bold.

|                      | Mean (m)    |             |             | RMSE (m)    |             |             | SI (%)       |              |              | BIAS         |              |              | Cor         |             |             |
|----------------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------|-------------|-------------|
|                      | G1          | G2          | G3          | G1          | G2          | G3          | G1           | G2           | G3           | G1           | G2           | G3           | G1          | G2          | G3          |
| a) Hs                |             |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| P1                   | 4.62        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 4.17        | 4.24        | 4.04        | 0.47        | 0.44        | 4.48        | 10.12        | 9.46         | 10.47        | -1.18        | -0.15        | -0.22        | <b>0.92</b> | <b>0.92</b> | <b>0.94</b> |
| ERA5                 | <b>4.30</b> | <b>4.36</b> | <b>4.12</b> | <b>0.43</b> | <b>0.40</b> | <b>0.45</b> | <b>9.30</b>  | <b>8.74</b>  | <b>9.76</b>  | <b>-0.12</b> | -0.10        | <b>-0.19</b> | <b>0.92</b> | <b>0.92</b> | <b>0.94</b> |
| Merra-2              | 4.09        |             |             | 0.55        |             |             | 11.98        |              |              | -0.21        |              |              | 0.89        |             |             |
| NCEP CFSv2 (ds094.0) | 5.10        | 5.13        |             | 0.62        | 0.62        |             | 13.52        | 13.45        |              | 0.18         | 0.20         |              | 0.89        | 0.89        |             |
| NCEP CFSv2 (ds094.1) | 5.08        |             |             | 0.64        |             |             | 13.84        |              |              | 0.18         |              |              | 0.80        |             |             |
| MeteoGalicía WRF     |             | 4.50        | <b>4.12</b> |             | 0.44        | 0.46        |              | 9.57         | 9.98         |              | <b>-0.05</b> | -0.19        |             | 0.90        | 0.93        |
| P2                   | 4.30        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 4.21        | 4.02        | 3.71        | 0.68        | 0.71        | 0.82        | 15.84        | 16.39        | 19.16        | -0.10        | -0.29        | -0.59        | 0.94        | <b>0.95</b> | <b>0.96</b> |
| ERA5                 | 4.28        | 4.08        | 3.76        | 0.67        | <b>0.66</b> | 0.81        | 15.49        | <b>15.26</b> | 18.72        | -0.02        | -0.22        | -0.55        | 0.94        | <b>0.95</b> | <b>0.96</b> |
| Merra-2              | <b>4.29</b> |             |             | <b>0.64</b> |             |             | <b>14.85</b> |              |              | <b>-0.01</b> |              |              | <b>0.95</b> |             |             |
| NCEP CFSv2 (ds094.0) | 5.22        | 4.91        |             | 1.27        | 1.03        |             | 29.55        | 24.04        |              | 0.92         | 0.61         |              | 0.93        | 0.94        |             |
| NCEP CFSv2 (ds094.1) | 5.18        |             |             | 1.33        |             |             | 30.96        |              |              | 0.88         |              |              | 0.90        |             |             |
| MeteoGalicía WRF     |             | <b>4.21</b> | <b>3.77</b> |             | 0.72        | <b>0.78</b> |              | 16.67        | <b>18.21</b> |              | <b>-0.09</b> | <b>-0.53</b> |             | 0.94        | <b>0.96</b> |
| P3                   | 4.52        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          |             | <b>4.53</b> | 4.06        |             | 0.63        | <b>0.67</b> |              | 13.97        | 14.82        |              | <b>0.00</b>  | -0.36        |             | 0.94        | <b>0.96</b> |
| ERA5                 |             | 4.41        | 3.99        |             | <b>0.55</b> | 0.71        |              | <b>12.25</b> | 15.67        |              | -0.08        | -0.41        |             | <b>0.95</b> | <b>0.96</b> |
| NCEP CFSv2 (ds094.0) | 5.36        |             |             | 1.08        |             |             | 23.77        |              |              | 0.64         |              |              | 0.94        |             |             |
| MeteoGalicía WRF     |             | 4.66        | <b>4.07</b> |             | 0.76        | <b>0.67</b> |              | 16.73        | <b>14.77</b> |              | 0.11         | <b>-0.35</b> |             | 0.93        | <b>0.96</b> |
| P4                   | 4.57        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 4.30        | 4.32        | 3.82        | 0.77        | 0.75        | 0.99        | 16.77        | 16.43        | <b>21.65</b> | -0.27        | -0.25        | <b>-0.75</b> | 0.94        | 0.94        | <b>0.96</b> |
| ERA5                 | <b>4.31</b> | 4.31        | 3.82        | <b>0.71</b> | <b>0.72</b> | 1.01        | <b>15.57</b> | <b>15.77</b> | 22.14        | <b>-0.26</b> | -0.26        | <b>-0.75</b> | <b>0.95</b> | <b>0.95</b> | 0.95        |
| Merra-2              | <b>4.31</b> |             |             | 0.86        |             |             | 18.82        |              |              | -0.25        |              |              | 0.92        |             |             |
| NCEP CFSv2 (ds094.0) | 5.31        | 5.24        | 1.14        | 1.09        | 24.85       | 23.96       | 0.74         | 0.67         | 0.94         | 0.94         |              |              |             |             |             |
| NCEP CFSv2 (ds094.1) | 5.29        | 1.20        | 26.15       | 0.72        | 0.93        |             |              |              |              |              |              |              |             |             |             |
| MeteoGalicía WRF     |             | <b>4.60</b> | <b>3.95</b> |             | 0.90        | <b>0.91</b> |              | 19.66        | 19.82        |              | <b>0.03</b>  | -0.62        |             | 0.92        | <b>0.95</b> |
| P5                   | 3.79        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | <b>3.77</b> | 3.10        | 2.94        | 0.71        | 0.93        | 1.07        | 18.68        | 24.57        | 28.17        | -0.03        | -0.70        | -0.86        | 0.92        | <b>0.95</b> | <b>0.95</b> |
| ERA5                 | 3.96        | 3.24        | 3.02        | <b>0.66</b> | 0.83        | 1.01        | <b>17.52</b> | 22.00        | 26.60        | 0.17         | -0.56        | -0.77        | <b>0.94</b> | 0.94        | <b>0.95</b> |
| Merra-2              | 3.95        |             |             | 0.74        |             |             | 19.38        |              |              | <b>0.15</b>  |              |              | 0.93        |             |             |
| NCEP CFSv2 (ds094.0) | 4.86        | <b>3.86</b> |             | 1.43        | <b>0.64</b> |             | 37.60        | <b>16.86</b> |              | 1.07         | <b>0.06</b>  |              | 0.93        | <b>0.94</b> |             |
| NCEP CFSv2 (ds094.1) | 4.89        |             |             | 1.51        |             |             | 39.72        |              |              | 1.09         |              |              | 0.91        |             |             |
| MeteoGalicía WRF     |             | <b>3.72</b> | <b>3.22</b> |             | 0.83        | <b>0.81</b> |              | 21.88        | <b>21.40</b> |              | -0.07        | <b>-0.57</b> |             | 0.91        | <b>0.95</b> |
| P6                   | 3.46        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 3.32        | 2.83        |             | <b>0.64</b> | 0.90        |             | <b>18.39</b> | 26.04        |              | -0.14        | -0.63        |              | <b>0.94</b> | <b>0.95</b> |             |
| ERA5                 | <b>3.58</b> | 3.17        |             | 0.72        | <b>0.77</b> |             | 20.74        | <b>22.33</b> |              | <b>0.12</b>  | -0.29        |              | 0.92        | 0.92        |             |
| Merra-2              | 3.63        |             |             | 0.72        |             |             | 20.92        |              |              | 0.17         |              |              | 0.92        |             |             |
| NCEP CFSv2 (ds094.0) | 4.41        | 3.79        | 1.33        | 0.78        | 38.49       | 22.45       | 0.96         | 0.33         | 0.91         | 0.92         |              |              |             |             |             |
| NCEP CFSv2 (ds094.1) |             | 4.45        |             |             | 1.43        |             |              | 41.46        |              |              | 1.00         |              |             | 0.88        |             |
| MeteoGalicía WRF     |             | <b>3.35</b> |             |             | 0.81        |             |              | 23.38        |              |              | <b>-0.11</b> |              |             | 0.89        |             |
|                      | Mean (m)    |             |             | RMSE (m)    |             |             | SI (%)       |              |              | BIAS         |              |              | Cor         |             |             |
| b) Tm02              |             |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| P1                   | 8.94        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 7.62        | 7.86        | 7.90        | 1.24        | 1.13        | 0.85        | 13.85        | 12.56        | 9.55         | -0.51        | -0.42        | -0.40        | 0.75        | 0.76        | 0.84        |
| ERA5                 | 7.66        | 7.86        | <b>7.95</b> | 1.25        | 1.14        | <b>0.82</b> | 13.96        | 12.77        | <b>9.13</b>  | -0.49        | -0.42        | <b>-0.38</b> | 0.76        | 0.76        | <b>0.86</b> |
| Merra-2              | 8.46        |             |             | 1.14        |             |             | 12.71        |              |              | -0.19        |              |              | 0.71        |             |             |
| NCEP CFSv2 (ds094.0) | 8.87        | <b>9.16</b> |             | <b>1.02</b> | <b>0.89</b> |             | <b>11.43</b> | <b>9.96</b>  |              | <b>-0.03</b> | <b>0.09</b>  |              | <b>0.79</b> | <b>0.82</b> |             |
| NCEP CFSv2 (ds094.1) | <b>8.95</b> |             |             | 1.10        |             |             | 12.31        |              |              | 0.00         |              |              | <b>0.79</b> |             |             |
| MeteoGalicía WRF     |             | 7.61        | 7.72        |             | 1.27        | 0.95        |              | 14.24        | 10.61        |              | -0.52        | -0.47        |             | 0.72        | 0.84        |
| P2                   | 7.73        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 6.95        | 6.85        | 7.23        | 1.59        | 1.68        | 1.04        | 20.52        | 21.68        | 13.40        | -0.78        | -0.88        | -0.51        | 0.71        | 0.74        | 0.87        |
| ERA5                 | 6.94        | 6.81        | <b>7.27</b> | <b>1.43</b> | 1.65        | <b>0.94</b> | 18.47        | 21.36        | <b>12.19</b> | -0.79        | -0.93        | <b>-0.46</b> | 0.77        | 0.76        | <b>0.89</b> |
| Merra-2              | 6.94        |             |             | 1.58        |             |             | 20.45        |              |              | -0.79        |              |              | 0.72        |             |             |
| NCEP CFSv2 (ds094.0) | <b>7.86</b> | <b>7.85</b> |             | <b>1.43</b> | <b>1.53</b> |             | <b>18.46</b> | <b>19.82</b> |              | <b>0.12</b>  | <b>0.12</b>  |              | <b>0.78</b> | <b>0.79</b> |             |
| NCEP CFSv2 (ds094.1) | 7.93        |             |             | 1.50        |             |             | 19.46        |              |              | 0.20         |              |              | 0.76        |             |             |
| MeteoGalicía WRF     |             | 6.78        | 7.20        |             | 1.71        | 1.02        |              | 22.11        | 13.21        |              | -0.95        | -0.53        |             | 0.71        | 0.87        |
| P3                   | 7.65        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          |             | 6.75        | 7.11        |             | 1.2         | 0.80        |              | 15.72        | 10.48        |              | -0.68        | -0.41        |             | 0.81        | 0.90        |
| ERA5                 |             | 6.86        | <b>7.19</b> |             | <b>1.17</b> | <b>0.75</b> |              | 15.29        | <b>9.78</b>  |              | -0.6         | <b>-0.35</b> |             | 0.81        | <b>0.91</b> |
| NCEP CFSv2 (ds094.0) | <b>7.69</b> |             |             | <b>1.17</b> |             |             | <b>15.27</b> |              |              | <b>0.03</b>  |              |              | <b>0.8</b>  |             |             |
| MeteoGalicía WRF     |             | 6.78        | 7.12        |             | 1.26        | 0.81        |              | 16.48        | 10.58        |              | -0.66        | -0.40        |             | 0.77        | 0.90        |

(Continued)



**Table 3.** Continued.

|                      | Mean (m)    |             |             | RMSE (m)    |             |             | SI (%)       |              |              | BIAS         |              |              | Cor         |             |             |
|----------------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|--------------|--------------|--------------|--------------|--------------|-------------|-------------|-------------|
|                      |             |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| P4                   | 7.60        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 6.61        | 6.59        | 7.05        | 1.32        | 1.42        | 0.94        | 17.42        | 18.75        | 12.38        | -0.99        | -1.01        | -0.55        | 0.85        | 0.81        | 0.90        |
| ERA5                 | 6.67        | 6.62        | <b>7.10</b> | 1.26        | 1.36        | <b>0.87</b> | 16.55        | 17.95        | <b>11.46</b> | -0.93        | -0.97        | <b>-0.50</b> | 0.85        | 0.83        | <b>0.91</b> |
| Merra-2              | 6.76        |             |             | 1.24        |             |             | 16.30        |              |              | -0.84        |              |              | 0.83        |             |             |
| NCEP CFSv2 (ds094.0) | 7.44        | <b>7.34</b> |             | <b>0.95</b> | <b>1.14</b> |             | <b>12.53</b> | <b>14.97</b> |              | <b>-0.15</b> | <b>-0.26</b> |              | <b>0.86</b> | <b>0.84</b> |             |
| NCEP CFSv2 (ds094.1) | <b>7.42</b> |             |             | 1.03        |             |             | 13.50        |              |              | -0.18        |              |              | 0.84        |             |             |
| MeteoGalicía WRF     |             | 6.53        | 6.97        |             | 1.44        | 0.97        |              | 18.87        | 12.77        |              | -1.06        | -0.63        |             | 0.81        | 0.90        |
| P5                   | 7.56        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 6.82        | 6.46        | 7.38        | <b>1.40</b> | 1.8         | 1.12        | 18.52        | 23.81        | 14.83        | -0.73        | -1.1         | -0.17        | 0.80        | 0.69        | 0.82        |
| ERA5                 | 6.69        | 6.62        | <b>7.43</b> | 1.49        | 1.51        | <b>0.96</b> | 19.66        | 19.93        | <b>12.70</b> | -0.86        | -0.94        | <b>-0.12</b> | 0.78        | 0.8         | <b>0.87</b> |
| Merra-2              | 6.92        |             |             | 1.41        |             |             | 18.64        |              |              | -0.63        |              |              | <b>0.81</b> |             |             |
| NCEP CFSv2 (ds094.0) | <b>7.59</b> | <b>7.21</b> |             | <b>1.40</b> | <b>1.35</b> |             | <b>18.53</b> | <b>17.9</b>  |              | <b>0.03</b>  | <b>-0.34</b> |              | <b>0.81</b> | <b>0.81</b> |             |
| NCEP CFSv2 (ds094.1) | 7.61        |             |             | 1.54        |             |             | 20.32        |              |              | 0.06         |              |              | 0.78        |             |             |
| MeteoGalicía WRF     |             | 5.95        | 6.75        |             | 1.97        | 1.24        |              | 16.12        | 16.39        |              | -1.61        | -0.81        |             | 0.72        | 0.84        |
| P6                   | 8.31        |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | <b>8.31</b> | <b>7.01</b> |             | 1.98        | <b>1.9</b>  |             | 23.88        | <b>22.89</b> |              | -1.56        | <b>-1.3</b>  |              | <b>0.86</b> | <b>0.83</b> |             |
| ERA5                 | 6.50        | 6.07        |             | 2.24        | 2.69        |             | 26.99        | 32.32        |              | -1.81        | -2.25        |              | 0.82        | 0.76        |             |
| Merra-2              | 6.47        |             |             | 2.37        |             |             | 28.51        |              |              | -1.84        |              |              | 0.77        |             |             |
| NCEP CFSv2 (ds094.0) | 7.20        | 6.69        |             | 1.89        | 2.31        |             | 22.73        | 27.85        |              | <b>-1.11</b> | -1.62        |              | 0.80        | 0.73        |             |
| NCEP CFSv2 (ds094.1) | 7.20        |             |             | <b>1.81</b> |             |             | <b>21.73</b> |              |              | <b>-1.11</b> |              |              | 0.83        |             |             |
| MeteoGalicía WRF     |             |             | 5.83        |             |             | 2.93        |              |              | 35.3         |              |              | -2.48        |             |             | 0.72        |
|                      | Mean (m)    |             |             | RMSE (m)    |             |             | BIAS         |              |              | Cor          |              |              |             |             |             |
| c) Pdir              | G1          | G2          | G3          | G1          | G2          | G3          | G1           | G2           | G3           | G1           | G2           | G3           |             |             |             |
| P1                   | 322         |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | <b>322</b>  | <b>326</b>  | <b>325</b>  | 12          | <b>9</b>    | 10          | 0.21         | <b>1.43</b>  | 1.31         | 0.88         | 0.94         | 0.93         |             |             |             |
| ERA5                 | 324         | 327         | 326         | 15          | 11          | <b>9</b>    | 0.92         | 2.06         | 1.52         | 0.84         | 0.91         | <b>0.94</b>  |             |             |             |
| Merra-2              | 323         |             |             | <b>10</b>   |             |             | 0.44         |              |              | <b>0.92</b>  |              |              |             |             |             |
| NCEP CFSv2 (ds094.0) | <b>322</b>  | <b>326</b>  |             | <b>10</b>   | <b>9</b>    |             | <b>0.02</b>  | 1.79         |              | <b>0.92</b>  | <b>0.95</b>  |              |             |             |             |
| NCEP CFSv2 (ds094.1) | 322         |             |             | 11          |             |             | 0.19         |              |              | 0.90         |              |              |             |             |             |
| MeteoGalicía WRF     | 329         | <b>325</b>  |             | 17          | 10          |             | 2.81         | <b>1.08</b>  |              | 0.83         | 0.93         |              |             |             |             |
| P2                   | 297         |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | <b>302</b>  | <b>304</b>  | <b>303</b>  | 31          | <b>24</b>   | <b>20</b>   | 5.16         | <b>7.34</b>  | <b>5.68</b>  | 0.91         | <b>0.95</b>  | <b>0.97</b>  |             |             |             |
| ERA5                 | 304         | 306         | 304         | 33          | 27          | 22          | 7.51         | 9.12         | 6.68         | 0.91         | 0.94         | 0.96         |             |             |             |
| Merra-2              | 305         |             |             | <b>26</b>   |             |             | <b>7.95</b>  |              |              | <b>0.94</b>  |              |              |             |             |             |
| NCEP CFSv2 (ds094.0) | 303         | 306         |             | 27          | 27          |             | 6.46         | 9.06         |              | 0.94         | <b>0.95</b>  |              |             |             |             |
| NCEP CFSv2 (ds094.1) | <b>302</b>  |             |             | 29          |             |             | 4.88         |              |              | 0.93         |              |              |             |             |             |
| MeteoGalicía WRF     |             | 313         | 305         |             | 42          | 24          |              | 16           | 7.69         |              | 0.89         | 0.95         |             |             |             |
| P3                   | 293         |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          |             | <b>298</b>  | <b>296</b>  |             | 29          | <b>25</b>   |              | <b>3.94</b>  | <b>1.82</b>  |              | 0.94         | <b>0.95</b>  |             |             |             |
| ERA5                 |             | 301         | 298         |             | 30          | <b>25</b>   |              | 5.73         | 3.25         |              | 0.94         | 0.95         |             |             |             |
| NCEP CFSv2 (ds094.0) |             | 300         |             |             | <b>27</b>   |             |              | 4.77         |              |              | <b>0.85</b>  |              |             |             |             |
| MeteoGalicía WRF     |             | 303         | <b>296</b>  |             | 37          | 27          |              | 7.5          | 1.85         |              | 0.91         | 0.94         |             |             |             |
| P4                   | 313         |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 318         | 317         | 317         | 31          | <b>29</b>   | <b>25</b>   | 4.84         | 4.35         | 3.62         | <b>0.89</b>  | <b>0.9</b>   | <b>0.92</b>  |             |             |             |
| ERA5                 | 317         | <b>313</b>  | 315         | 33          | 37          | 27          | 3.84         | -0.59        | 2.01         | 0.88         | 0.86         | 0.91         |             |             |             |
| Merra-2              | 317         |             |             | 31          |             |             | 3.80         |              |              | <b>0.89</b>  |              |              |             |             |             |
| NCEP CFSv2 (ds094.0) | <b>316</b>  | <b>313</b>  |             | 35          | 35          |             | <b>2.45</b>  | <b>-0.26</b> |              | 0.86         | 0.86         |              |             |             |             |
| NCEP CFSv2 (ds094.1) | 317         |             |             | <b>30</b>   |             |             | 4.29         |              |              | <b>0.89</b>  |              |              |             |             |             |
| MeteoGalicía WRF     |             | 318         | <b>314</b>  |             | 40          | 34          |              | 4.82         | <b>1.09</b>  |              | 0.83         | 0.87         |             |             |             |
| P5                   | 316         |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 328         | <b>317</b>  | 320         | <b>29</b>   | <b>29</b>   | <b>25</b>   | 11.74        | <b>0.66</b>  | 3.62         | <b>0.63</b>  | <b>0.53</b>  | <b>0.61</b>  |             |             |             |
| ERA5                 | 321         | 312         | <b>317</b>  | 35          | 34          | 31          | 5.57         | -4.18        | 0.81         | 0.54         | 0.46         | 0.49         |             |             |             |
| Merra-2              | 324         |             |             | 32          |             |             | 8.13         |              |              | 0.60         |              |              |             |             |             |
| NCEP CFSv2 (ds094.0) | <b>320</b>  | 311         |             | 37          | 31          |             | <b>4.21</b>  | -4.87        |              | 0.52         | 0.5          |              |             |             |             |
| NCEP CFSv2 (ds094.1) | <b>320</b>  |             |             | 39          |             |             | 4.39         |              |              | 0.51         |              |              |             |             |             |
| MeteoGalicía WRF     |             | 315         | 315         |             | 38          | 37          |              | -1.14        | <b>-0.68</b> |              | 0.43         | 0.43         |             |             |             |
| P6                   | 320         |             |             |             |             |             |              |              |              |              |              |              |             |             |             |
| ERA-Interim          | 327         | <b>321</b>  |             | <b>19</b>   | <b>18</b>   |             | 6.87         | <b>0.92</b>  |              | <b>0.85</b>  | <b>0.83</b>  |              |             |             |             |
| ERA5                 | <b>325</b>  | <b>318</b>  |             | 29          | 30          |             | 4.91         | -2.68        |              | 0.75         | 0.71         |              |             |             |             |
| Merra-2              | 326         |             |             | 33          |             |             | 5.43         |              |              | 0.69         |              |              |             |             |             |
| NCEP CFSv2 (ds094.0) | <b>325</b>  | <b>318</b>  |             | 29          | 25          |             | <b>4.09</b>  | -2.64        |              | 0.74         | 0.75         |              |             |             |             |
| NCEP CFSv2 (ds094.1) | 326         |             |             | 31          |             |             | 5.80         |              |              | 0.71         |              |              |             |             |             |
| MeteoGalicía WRF     |             | 323         |             |             | 34          |             |              | 2.57         |              |              | 0.69         |              |             |             |             |

For the first two weeks (01/12–13/12), the mean period was largely underestimated for all the datasets with the exception for buoy P4, where SWAN results were closer to measured values than at any other considered buoy (Figure 4(a)). The correlation results reveal a better performance of the wind datasets at the Cantabrian sector, with Cor between 0.77 and 0.86. At the West Atlantic sector, Cor was lower, between 0.71 and 0.79. When compared with Hs Cor values, a decrease in the correlation of 17% in the West Atlantic sector and 11% in the Cantabrian sector was noticed (Table 3.a and b).

Nevertheless, and contrary to the Hs results, Tm02 for G2 presents a slightly poorer outcome at all buoys but P1, being quite improved for G3. G3 shows the best results from the three considered computational grids. RMSE for Tm02 was close to or over 1.50 s for most buoys and wind datasets for G1 and G2, while for G3 it remains below 1.0 s for ERA5 and close to 1.0 s for all the other wind datasets (Table 3.b).

For the two initial simulation weeks, G1 and G2 solutions do not accurately represent Tm02 evolution. Such pattern was corrected for the highest resolution simulation on grid G3. At P1, and after the first two weeks within the simulation, it seems that for G1 and G2, the wave energy was more spread along the frequency bins, nevertheless, the lower frequency bins were under-represented in G3. At P5, G3 results clearly show a much better performance, with a good capture of Tm02, which might indicate a better representation of the wave energy along the different frequency bins (Figure 4(b)). The best results for Tm02 at G1 and G2 were produced using NOAA NCEP ds094.0. For the three wind datasets selected for forcing the waves on G3, ERA5 led to the best results for Tm02.

### 3.1.3. Peak direction (Pdir)

For Pdir, the best G1 results were obtained with NCEP ds09.1, MERRA-2 and Era-Interim (Figure 5). The best statistical parameters were obtained at P1, where NCEP ds09.1 and MERRA-2 provided similar outcomes. For both datasets, RMSE was 10° and Cor was 0.92. For the other buoys, the RMSE was mostly close to 30° reaching up to 39°, with the exception of the ERA-Interim results at P6 where RMSE of 19° was obtained. All the wind datasets clearly display a bias in the peak wave direction, with a tendency for an anti-clockwise error in the estimated wave direction (Table 3.c).

Similar to Tm02, the numerical model seems to be less accurate in estimating Pdir for all the buoys locations for the initial two weeks period.

For G2, the best wind datasets were NCEP CFSv2 (ds094.0) for P1 and P3 and Era-Interim for P2, P4, P5 and P6. For G3, the best dataset was ERA-Interim,

although the Atlantic sector results present small differences (from 1° up to 4°) between the considered datasets. In the Cantabrian sector, larger differences arise, reaching up to 13° at P1.

There existed a small but consistent improvement in almost each buoy location for all the wind datasets when G1 and G3 results were compared.

## 4. Discussion

The presented results revealed minor differences in model solutions when using different wind datasets. Nevertheless, for each considered wave parameter, the best ones can be clearly distinguished. ERA5 gives the best results for Hs, Era-Interim for Pdir and NCEP CFSv2 (ds094.0) for Tm02, although the difference between NCEP CFSv2 (ds094.0) and ERA5 was relatively small and both can be considered to properly simulate mean wave period (Table 3.b).

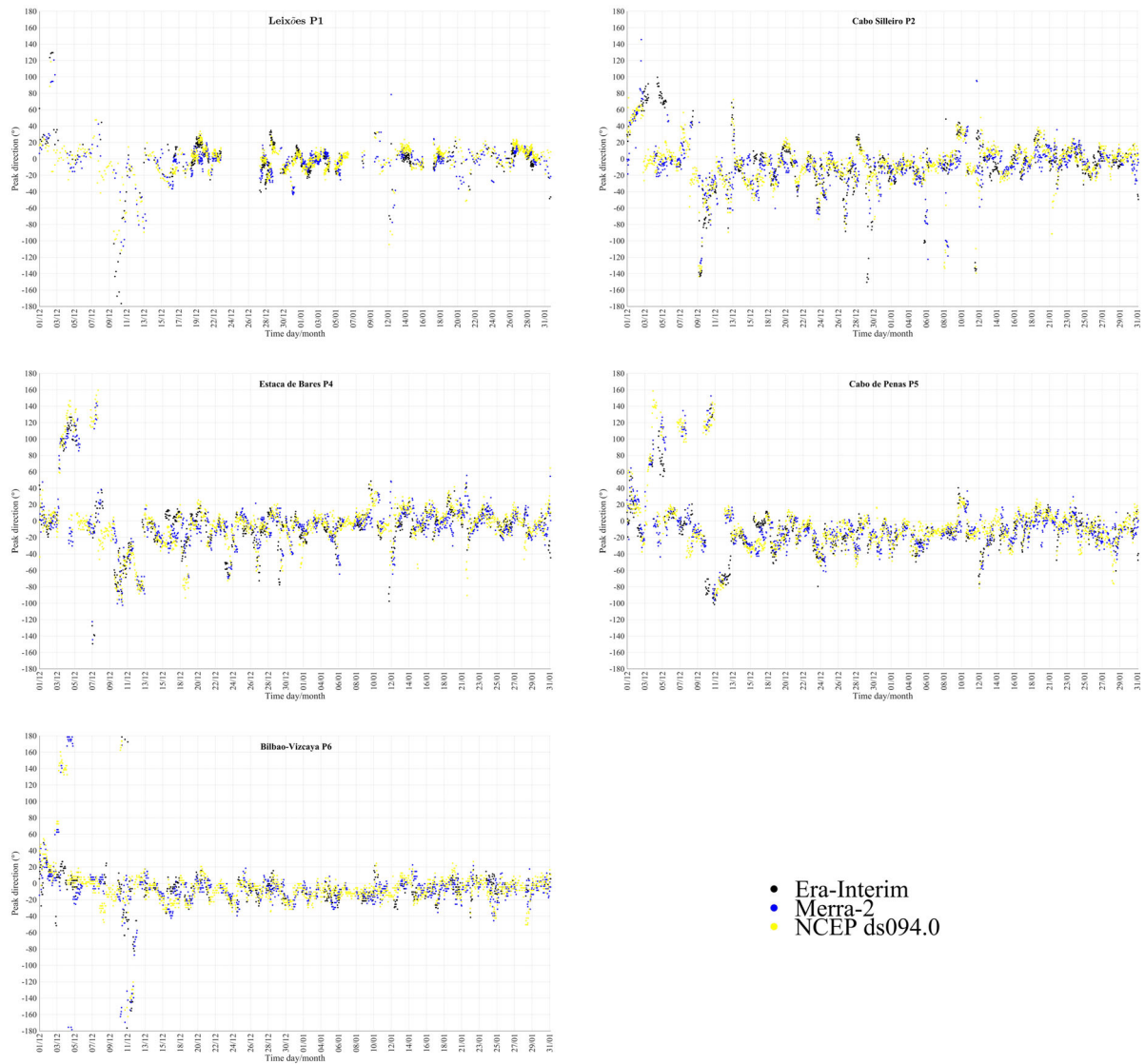
The temporal and spatial characteristics of the wind datasets did not have a big influence on the results. The best Pdir results were obtained with Era-Interim, which was the lower temporal and spatial resolution database (Table 1). Therefore, to simulate the approaching swell, coarse grids and larger time steps with a proper representation of wind speed and direction, seem to be appropriate to produce accurate solutions.

The different responses observed for the wave parameters in G3 could be related to the wave spectrum. When calculating the wave variables, different parts of the wave energy spectra are considered. Hs is calculated taking into account the total wave energy, whereas the rest of the parameters are found through circular frequency or direction. Errors in the velocity and direction fields of the wind could be transferred to the wave model and may produce inaccurate frequencies transference to the surface waters. This seems not to have such a big effect on the total energy rather affecting the individual components.

Álvarez et al. (2014) concluded that coarser databases are less reliable in near-shore areas. Additionally, they noted that the wind speed and direction are less accurate for low wind speed events (<4 m/s). In wave modelling it is not possible to determine which waves are induced with low wind speed, so another approach was considered. Calm and storm periods were analysed separately considering a 5 m wave height threshold. The results obtained at P1 and P5 with ERA5 for all the three modelling levels revealed that the more accurate Hs results were obtained mostly during calm conditions (Table 4). Tm02 and Pdir were better represented during storms. This confirms that, with lower wind speed, the wave simulations are less accurate and the total energy



**Figure 4.** Measured and modelled Tm02 for the period between 01.12.13–31.01.14. Red dots represent buoys measurement, dotted lines are SWAN results for each wind dataset considered. The bold line indicates the best fit for each buoy. a) Comparison of measurements and G1 computational grid. b) Measured and modelled results with ERA5 wind data representing all three computational grids, in buoy locations P2 and P5.



**Figure 5.** Difference between buoys and model outcome (buoy-SWAN, G1 computational domain) with three wind datasets, ERA-Interim, Merra-2 and NCEP ds094.0.

**Table 4.** RMSE, SI, BIAS and Cor for each computational domain (G1, G2 and G3) at P1 and P5 in a storm and calm situation using ERA5 wind fields.

|                | Hs    |       |       |       | Tm02  |       |       |       | Pdir  |       |       |       |
|----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                | P1    |       | P5    |       | P1    |       | P5    |       | P1    |       | P5    |       |
|                | storm | calm  | storm | calm  | storm | calm  | storm | calm  | storm | calm  | storm | calm  |
| <b>G1</b> RMSE | 0.33  | 0.28  | 0.43  | 0.51  | 0.74  | 1.01  | 0.60  | 1.36  | 7     | 13    | 12    | 33    |
| SI             | 5.50  | 7.55  | 6.99  | 16.54 | 7.48  | 12.13 | 6.81  | 18.98 |       |       |       |       |
| BIAS           | -0.07 | -0.06 | 0.04  | 0.13  | -0.16 | -0.34 | -0.08 | -0.78 | 0.04  | 0.88  | 4.62  | 0.96  |
| Cor            | 0.72  | 0.90  | 0.73  | 0.91  | 0.72  | 0.70  | 0.67  | 0.73  | 0.65  | 0.87  | 0.45  | 0.56  |
| Med. s         | 5.49  | 3.47  | 6.35  | 3.22  | 8.85  | 6.83  | 8.49  | 6.13  |       |       |       |       |
| Med. M         | 5.91  | 3.72  | 6.17  | 3.06  | 9.84  | 8.31  | 8.85  | 7.16  | 329   | 317   | 315   | 316   |
| <b>G2</b> RMSE | 0.30  | 0.27  | 0.59  | 0.59  | 0.64  | 0.94  | 0.63  | 1.37  | 5.05  | 10.17 | 7.48  | 32.86 |
| SI             | 5.11  | 7.22  | 9.52  | 19.38 | 6.52  | 11.36 | 7.09  | 19.14 |       |       |       |       |
| BIAS           | -0.06 | -0.04 | -0.24 | -0.32 | -0.12 | -0.29 | -0.17 | -0.77 | 0.58  | 1.48  | 2.25  | -6.44 |
| Cor            | 0.73  | 0.91  | 0.82  | 0.90  | 0.71  | 0.71  | 0.70  | 0.76  | 0.69  | 0.93  | 0.57  | 0.48  |
| Med. s         | 5.54  | 3.52  | 5.17  | 2.64  | 9.05  | 7.02  | 8.13  | 6.15  |       |       |       |       |
| Med. m         | 5.91  | 3.72  | 6.17  | 3.06  | 9.64  | 8.31  | 8.85  | 7.16  | 329   | 317   | 315   | 316   |
| <b>G3</b> RMSE | 0.34  | 0.30  | 0.75  | 0.67  | 0.47  | 0.67  | 0.36  | 0.89  | 2.81  | 8.49  | 8.66  | 29.51 |
| SI             | 5.74  | 7.99  | 12.21 | 21.96 | 4.73  | 8.06  | 4.03  | 12.44 |       |       |       |       |
| BIAS           | -0.11 | -0.09 | -0.33 | -0.45 | -0.15 | -0.23 | 0.04  | -0.16 | 0.42  | 1.09  | 3.13  | -2.32 |
| Cor            | 0.78  | 0.92  | 0.81  | 0.92  | 0.82  | 0.81  | 0.84  | 0.84  | 0.84  | 0.95  | 0.59  | 0.51  |
| Med. s         | 5.24  | 3.34  | 4.79  | 2.47  | 8.90  | 7.29  | 9.00  | 6.95  |       |       |       |       |
| Med. m         | 5.91  | 3.72  | 6.17  | 3.06  | 9.84  | 8.31  | 8.85  | 7.16  | 329   | 317   | 315   | 316   |

**Table 5.** Validation results of wave mode SWAN from various studies around the world.

| Author                              | Rusu et al. (2015) | Rusu and Soares (2013) | Silva et al. (2015) | Viitak et al. (2016) | This study   |
|-------------------------------------|--------------------|------------------------|---------------------|----------------------|--------------|
| Area                                | West Iber. co.     | Cont. Portugal         | Spanish co.         | Baltic Sea           | NW Iber. co. |
| Wind                                | HIPOCAS            | MM5                    | ERA-Interim         | HIRLAM               | ERA5         |
| <b>Significant wave height (Hs)</b> |                    |                        |                     |                      |              |
| RMSE                                | 0.74               | 0.40                   | 0.81                | 0.28                 | 0.45         |
| SI                                  | 0.17               | 0.19                   | 0.42                | 0.22                 | 0.10         |
| BIAS                                | 0.23               | 0.12                   | 0.36                | 0.19                 | -0.19        |
| Cor                                 | 0.9                | 0.95                   | 0.83                | 0.95                 | 0.94         |
| <b>Mean wave period (Tm02)</b>      |                    |                        |                     |                      |              |
| RMSE                                | 0.99               | 1.11                   | 1.83                | -                    | 0.82         |
| SI                                  | 0.11               | 0.15                   | 0.31                | -                    | 0.09         |
| BIAS                                | 0.25               | -0.69                  | -0.37               | -                    | -0.38        |
| Cor                                 | 0.82               | 0.86                   | 0.68                | -                    | 0.86         |

spectre of the waves is less affected by the individual parts.

Our model configuration was reliable when compared with similar studies, presenting results with the same level of accuracy, or better than previously developed works (Table 5). This comparison is not straightforward due to differences such as the geographical area, the grids resolution, the location of the buoys, the type of wind data, etc. Nevertheless, it provides an indication of the type of accuracy and credibility of the wave model set-up that was implemented in this study.

## 5. Conclusions

All the wind datasets selected for this study were able to depict quite well the evolution of the wave fields. The differences arise when analysing the wave parameters. The obtained results allow to distinguish the most optimal dataset for each wave characteristics. Hs was well represented with ERA5, Tm02 with NCEP CFSv2 (ds094.0) or ERA5, and Pdir with Era-Interim. Overall, the ECMWF datasets seem to produce the most reliable outcome for the region under study, particularly for Hs and Tm02, with a slight improvement when using ERA5. This should be taken into account for future wave modelling studies.

The spatio-temporal resolution of the wind datasets does not have a big impact on wave modelling as the accuracy of the wind speed and direction. The errors in wind datasets were most likely transferred to waves, contributing to the wave model solutions inaccuracy. It was noted that, with lower wind speed values, the results of wave modelling were not as accurate as with higher wind speed values.

The method applied to simulate NWCIP waves with SWAN was generally reliable and comparable to other similar studies. The model succeeds to predict extreme wave conditions with relatively good accuracy, depicting the wave field development during storm events. The best results were obtained for Hs, being more challenging to accurately represent Tm02 and Pdir.

The obtained results depicted the performance of a numerical wave model considering different wind datasets. Model inaccuracies were pointed out, as well as the best wind databases for each considered parameter, providing valuable information to produce the best numerical solutions and properly predict the effects of extreme events on a vulnerable seaboard, helping to mitigate the associated risks for ecosystems and populations.

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