

## Article

# Evaluation of Wind and Wave Estimates from CMEMS Reanalysis for Brazil's Offshore Energy Resource Assessment

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**Abstract:** This study aims to evaluate wind speed and significant wave height data from the Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis using buoy measurements for offshore energy application off the east coast of Brazil. Such analysis has become important, since reanalysis datasets can be fundamental tools in identifying regions with wind energy potential that are suitable for the installation of offshore farms. Two sets of reanalysis were used: wind speed (with spatial resolution of 0.25° and temporal resolution of 6 h) and significant wave height (with spatial resolution of 0.2° and temporal resolution of 3 h). For validation, seven MetOcean buoys were selected. In the statistical validation, Pearson's correlation, coefficient of determination ( $R^2$ ), slope of the straight line, root mean square error (RMSE), mean square error (MSE), probability density function (PDF), mean and standard deviation were calculated. In the evaluation of offshore wind energy resources, the calculation of energy density was performed. The results showed correlations above 0.70 for wind speed and above 0.91 for significant wave height, and additionally, the RMSE values showed maximums of 2.31 m/s for wind speed and 0.28 cm for significant wave height. In the PDF comparison of buoy data and reanalysis, similarities were observed, mainly in the PDF parameters. The energy density presented values consistent with other studies (352–461 W/m<sup>2</sup>). The results show that the reanalysis data can be applicable in studies focusing on offshore wind potential.

**Keywords:** CMEMS reanalysis; wind and significant wave height; Weibull distribution; offshore wind energy; Brazil coastal zone



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## 1. Introduction

Brazil has a large territorial extension with extensive renewable resources that have been used to meet the electricity demands of its population. Among the resources, the production of continental wind energy has grown in recent years [1].

According to data from the National System Operator, wind energy was responsible for producing approximately 4.66 GWh in 2019 [2], but this number represents only onshore generation with wind turbines installed on land. Wind exploration is expanding to the ocean (offshore) where there are areas with higher wind speeds and smaller variations in wind speed due to the absence of physical barriers, such as mountains, buildings and vegetation [3].

The use of offshore wind energy in Brazil is of paramount importance, since approximately 25% of the Brazilian population resides in coastal areas [4], and therefore the installation of offshore wind farms can be close to the places of demand. As this natural resource is abundant in several Brazilian regions, it is important to carry out studies that

identify locations for the installation of offshore wind farms and to try to take advantage of the energy capacity to meet the population's demand.

Observational data of significant wave height and wind speed are often used to define the characteristics of offshore areas [5]. These data are obtained through automatic stations installed in ocean buoys [6]. However, the main problems that still hinder studies related to offshore data is the lack of wind measurement and significant wave height data in oceanic areas, due to the technical challenges and high costs associated with conducting ocean measurement campaigns [7]. Also, compared to the amount of onshore measurements, offshore measurements tend to have fewer in situ stations: only 13 buoys operate over the vast offshore region [8].

Faced with the problem of lack of in situ data, other data sources have played a fundamental role in the characterization and monitoring of winds and waves. Currently, several efforts are being made to overcome the lack of observational data. The use of high-resolution models, satellite, and reanalysis estimations is increasing in frequency [7,9–13]. In Brazil, several studies have evaluated the performance of different datasets to calculate the offshore wind resource, and others have compared it with observations in buoys [14–17]. In this sense, the studies concluded that there are some advantages, especially in the use of reanalysis data, as these data have high spatial and temporal resolutions and no gaps. Although there are advantages in using reanalysis, they have failed data series, especially with the assimilation of different satellites data that result in inharmonious temporal series, thus it is necessary to constantly assess the quality of the data.

The Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis is the reprocessing of a long series of analyses, containing a set of several oceanographic and meteorological variables for oceanic areas. Those data were used in several applications in different regions of the world [18–21]. To exploit this large source of information for potential offshore wind energy production, it is important to determine the consistency of the CMEMS reanalysis with observational references. Thus, the main objective of this study is to validate the reanalysis with buoy measurements for periods when data were available. In addition, the energy density estimates are calculated to identify geographical distribution of potential energy resources.

## 2. Materials and Methods

### 2.1. Data

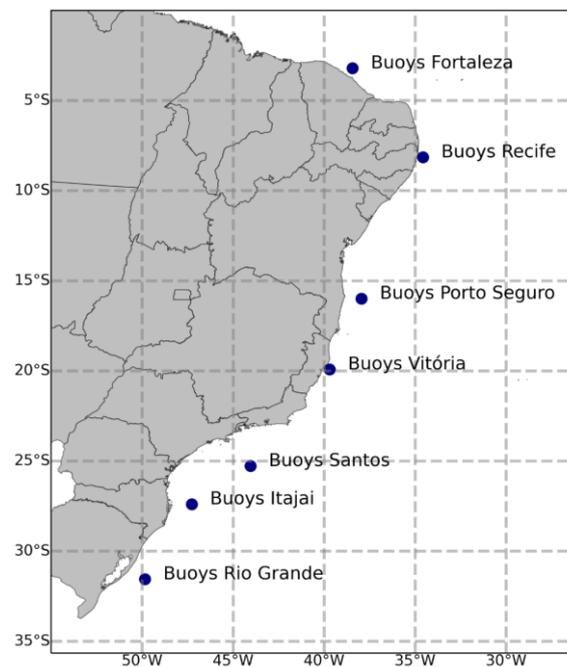
#### 2.1.1. CMEMS

The "Wind" (reference: WIND\_GLO\_WIND\_L4\_REP\_OBSERVATIONS\_012\_006) and "Height" (reference: GLOBAL\_REANALYSIS\_WAV\_001\_032) data from the global reanalysis of the Copernicus Marine Environment Monitoring Service (CMEMS) were used. The first dataset that was used is the reprocessing of a long series of global analyses of 10 m high wind speed oceans, with spatial resolutions of 0.25° latitude and longitude, and with a temporal resolution of 6 h (00, 06, 12, 18 UTC). These data are calculated based on various sources of wind observation data obtained through remote sensing (ERS-1, ERS-2, QuikSCAT, RapidScat, ASCAT-A, ASCAT-B, HY2A and OceanSat-2, SSM/I, SSMIS, WindSat) and atmospheric reanalysis (ERA-Interim), where these data are interpolated by kriging methods to build a series of wind climatology from 1992 to the present time, to describe the spatial characteristics of the wind only over oceanic areas [22,23].

The wave height dataset is also part of the CMEMS services: it is a global wave reanalysis that describes the ocean characteristics as significant wave height (Hs) or the mean wave period available from 1993 to the present time. The CMEMS wave reanalyses provide integrated data with a time interval of 3 h (00, 03, 06, 09, 12, 15, 18 and 21 UTC), with a spatial resolution of 0.2° [24]. This reanalysis takes into account the ocean currents from the physical reanalysis of the GLORYS12 ocean data, along with the wave height obtained from Sentinel 1 SAR (Synthetic Aperture Radar) to Sentinel-3A missions; a more detailed description can be obtained from Chune et al. (2020b) [25].

### 2.1.2. Buoys

The performance of the CMEMS reanalysis in the coastal region of Brazil is evaluated by comparison with seven MetOcean buoys located along the Brazilian east coast. These buoys are part of the Brazilian Navy's National Buoys Program (PNBOIA), which aims to provide near real-time meteorological and oceanographic information on points of the South Atlantic Ocean. The data is available on the Brazilian Navy database [8], where hourly values of wind speed and significant wave height ( $H_s$ ) were downloaded in two dataset: one containing wind speed information and the other containing significant wave heights. The comparison with CMEMS was carried out for January 2011 to December 2018. The buoy locations are shown in Figure 1. The buoy location names, position, and height of the anemometer are listed in Table 1.



**Figure 1.** Locations of automatic stations installed on buoys to measure wind speed and wave height.

**Table 1.** Location of the MetOcean buoys used in the assessments.

Buoys	Latitude (South)	Longitude (East)	Height of Anemometer (m)
Fortaleza	3° 12' 48.96"	38° 25' 57"	4.71
Recife	8° 09' 12.96"	34° 33' 34.2"	4.71
Porto Seguro	16° 0' 2.88"	37° 56' 25.08"	4.71
Vitória	19° 55' 33.96"	39° 41' 28.68"	4.71
Santos	25° 26' 22.2"	45° 2.0' 9.96"	4.71
Itajaí	27° 24' 15.84"	47° 15' 38.16"	4.71
Rio Grande	31° 33' 44.28"	49° 50' 14.28"	4.71

The wind speed data measured by the ocean buoys are defined at the heights of the anemometers, mentioned in Table 1. In order to make the comparison with the data from the CMEMS reanalysis, the instrument height corrections for 10 m was applied, according to [26,27], where the conversion considers a neutral and stable boundary layer. The following equation is applied when the anemometer is less than 10 m high:

$$U_{10m} = U_z \sqrt{\frac{K^2}{Cd} \frac{1}{\ln\left(\frac{z}{z_0}\right)}} \quad (1)$$

where  $U_z$  represents the wind speed measured on the anemometer;  $Z$  is the height of the anemometer;  $K$  is the constant (equal to 0.4);  $Z_0$  the roughness of the ocean surface ( $9.5 \times 10^{-5}$ ); and  $Cd$  is the drag coefficient, the value of  $Cd$  varies according to wind speed and sea conditions, thus, it was assumed that sea conditions did not interfere with wind speed, defining a constant  $Cd$  ( $1.4 \times 10^{-3}$ ).

## 2.2. Statistics

The purpose of this work will be to validate the data from the CMEMS reanalysis, followed by an application of the data in offshore resource calculations. The wind speed and variables were validated. For quantitative statistical validation, linear regressions were calculated between the buoy data and reanalysis, Pearson correlation, coefficient of determination ( $R^2$ ), slope of the straight line, root-mean-square error (RMSE), mean-square error (MSE), in addition to the mean and standard deviation of the buoys' and CMEMS data. The probability density function (PDF) of the buoy and CMEMS was compared to confirm that the reanalysis estimates are consistent with the buoy measurements across the range of variability of the wind speed and data. In addition, the distribution parameters (shape and Weibull scale) were extracted to verify the similarity between the buoy and CMEMS data across the variability series. A more detailed description of how to perform these statistical calculations can be found in [28].

## 2.3. Offshore Resource Estimates—Energy Density Estimate

When carrying out projects to install wind farms, various information related to the wind must be calculated. This information becomes important during the decision, which makes investments to explore offshore wind resources viable [29], for example, the energy density to identify areas usable for offshore energy generation that are suitable for the development of wind farms. The energy density in some areas where buoys are installed (Fortaleza and Rio Grande) was estimated, shown in Figure 1, since there are wind farms to start construction.

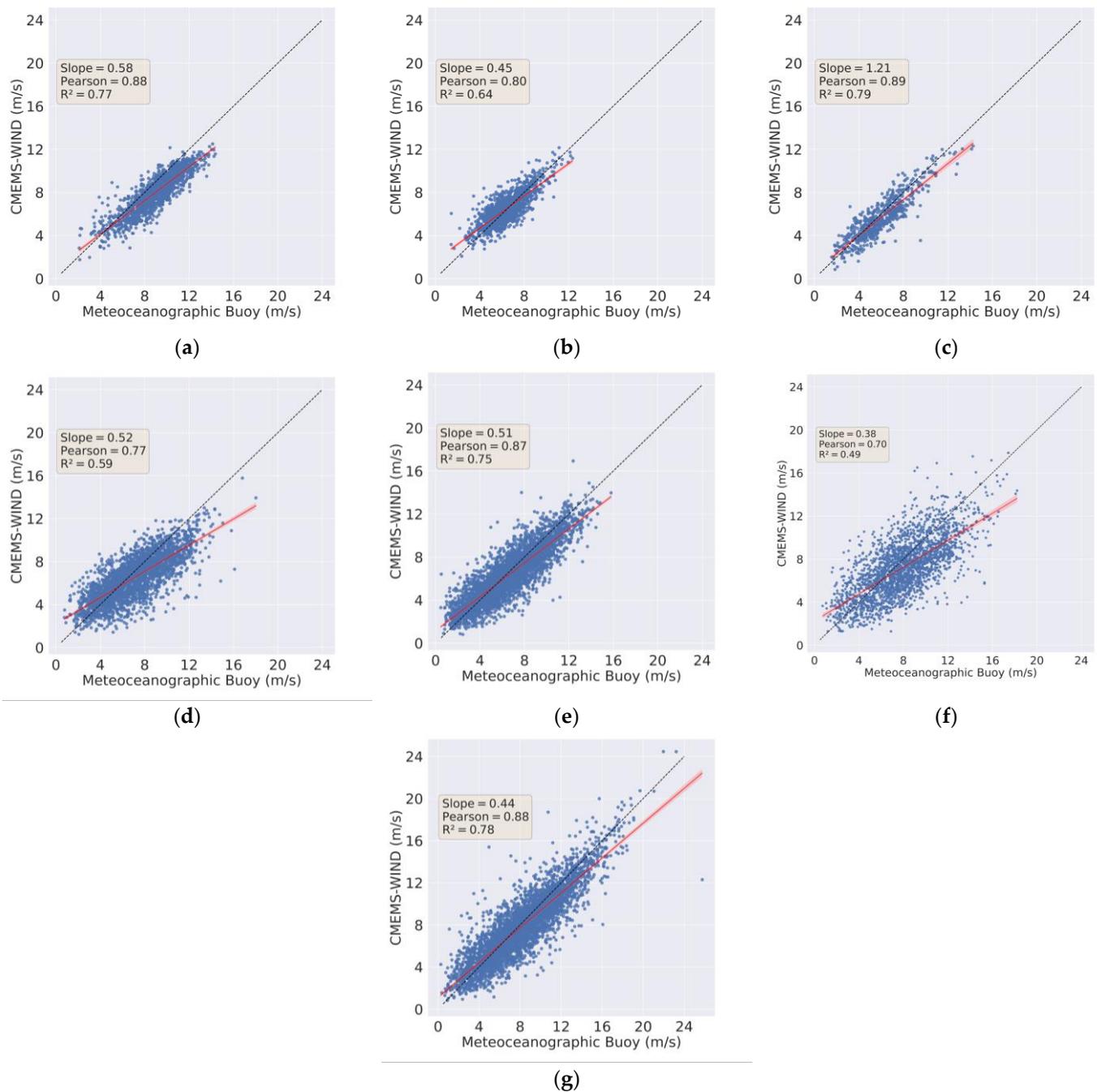
To calculate the energy density ( $E$ ), the methods suggested by Jamil et al. [30], which uses the scale ( $c$ ) and shape ( $k$ ) parameters of the distribution, the gamma function ( $\Gamma$ ), and the air density ( $\rho$ ) equal to  $1.225 \text{ kg/m}^3$ .  $E$  is expressed in  $\text{W/m}^2$ , calculated according to Equation (2) [28]:

$$E = \frac{1}{2} \rho c^3 \Gamma \left( 1 + \frac{k}{3} \right) \quad (2)$$

## 3. Results

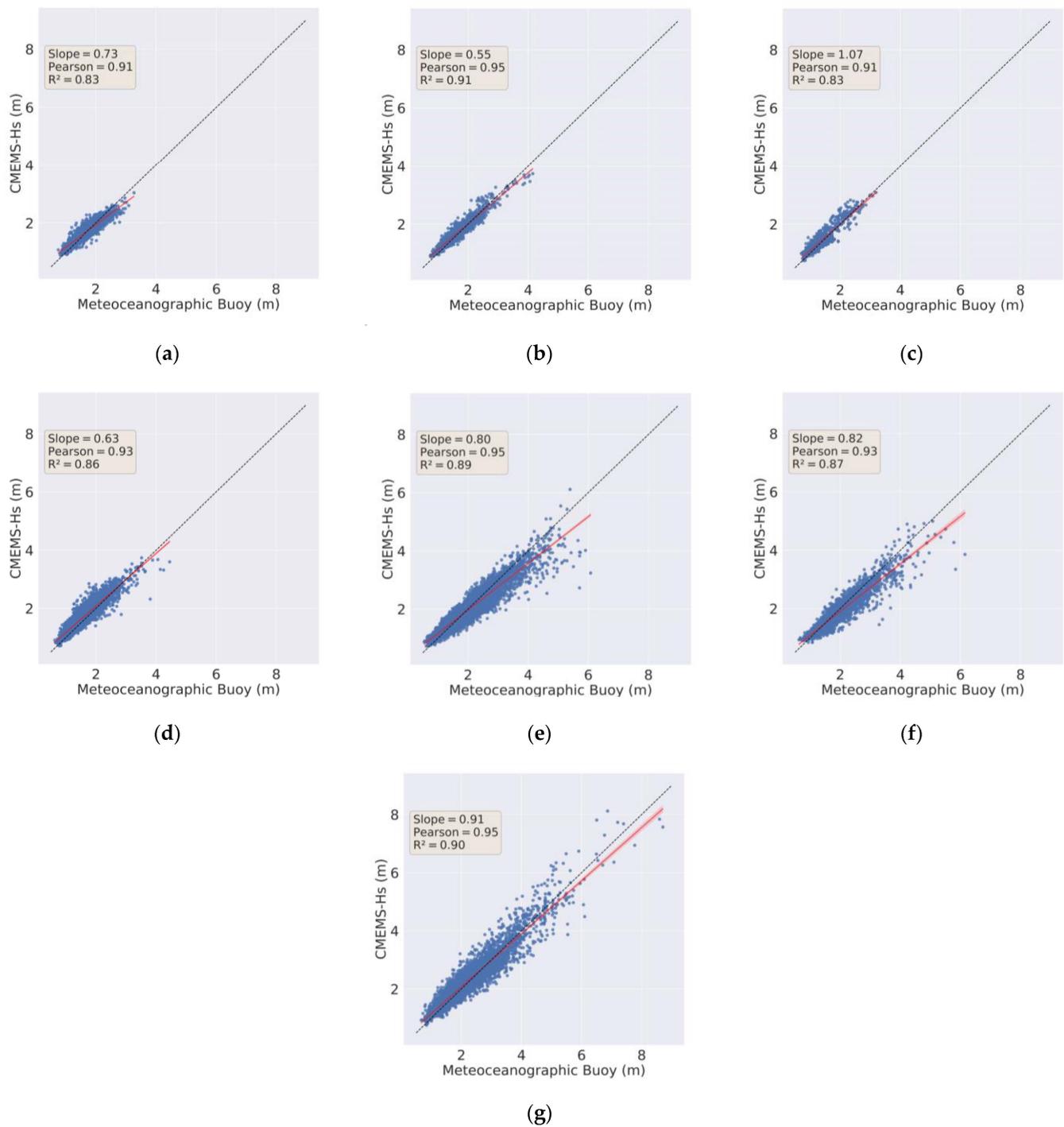
### 3.1. Statistical Validation

Figure 2 shows the scatter plot comparing the CMEMS reanalyses with data from observations of wind speed, in addition to presenting Pearson's correlation, coefficient of determination ( $R^2$ ), and slope of the straight line for the evaluated targets. Buoys missing data were not applied in this analysis. In all sites, the estimated winds were highly correlated and the  $R^2$  coefficient was between 0.49 and 0.79. As the reanalysis data is made available through grid points, the distances of the buoy locations in relation to the grid point were calculated when the information was extracted. Figure 2a,c,e,g correspond to the buoys located closer to the grid point, while Figure 2b,d,f show greater distances. In all evaluated locations, there is a tendency of the reanalysis to underestimate or overestimate the observations that present wind speed with high or low intensity, respectively. According to [31], the bias is caused by the data from the reanalysis having been obtained based on information every 6 h, thus, we assume that the bias originates due to temporal resolution in the data interpolation process that make the reanalysis available. As shown in Figure 2, the slope of the regression lines varied between 0.3 and 1.21. According to [21], this can be defined as a proportional bias to differentiate from a constant bias in which the regression line is parallel but off-diagonal.

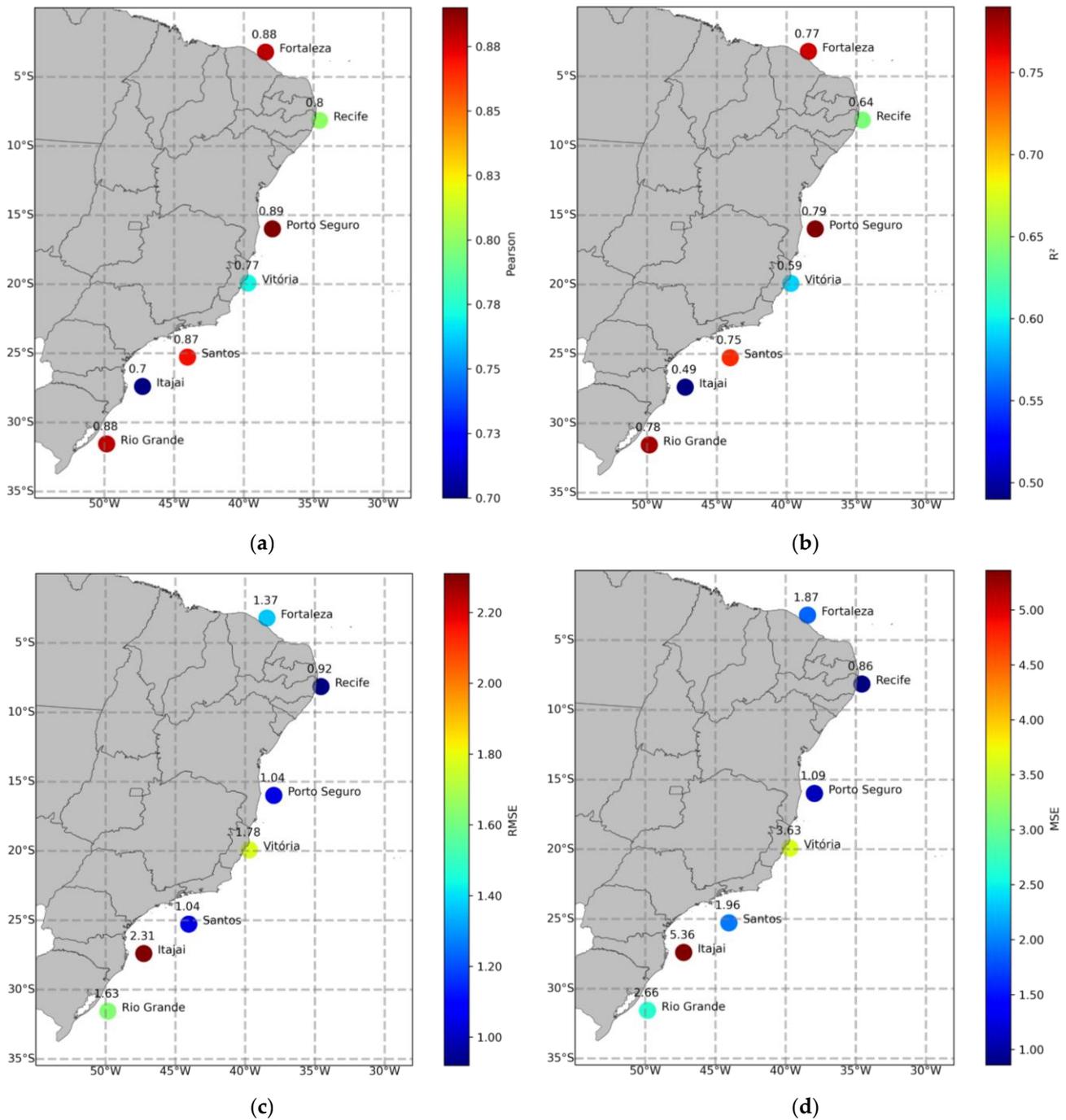


**Figure 2.** Linear regression graphs comparing wind speed data estimated by CMEMS and MetOcean buoys at the following locational targets: Fortaleza (a), Recife (b), Porto Seguro (c), Vitória (d), Santos (e), Itajaí (f), and Rio Grande (g). The red line is the best fit linear regression line, with a 99% confidence interval. The black dashed line is the reference for observed data (the closer the red line is to the black dashed line, the better the CMEMS reanalysis skill).

Figures 2 and 3 show the scatter plot comparing the Hs reanalysis and in situ observations. Compared with wind speed, the Hs data show a smaller distribution with proportional bias, with highest correlation and R<sup>2</sup> above 0.83 (Figure 4). In all evaluated locations, the regression line follows close to the main diagonal line (dashed black line), but similar to wind speed there is a tendency to overestimate small and underestimate large values of Hs. The high performance of Hs via reanalysis is also observed in other validation studies [32,33]. The CMEMS showed worst accuracy in buoys to the south Brazil, where wind speed and Hs are higher.

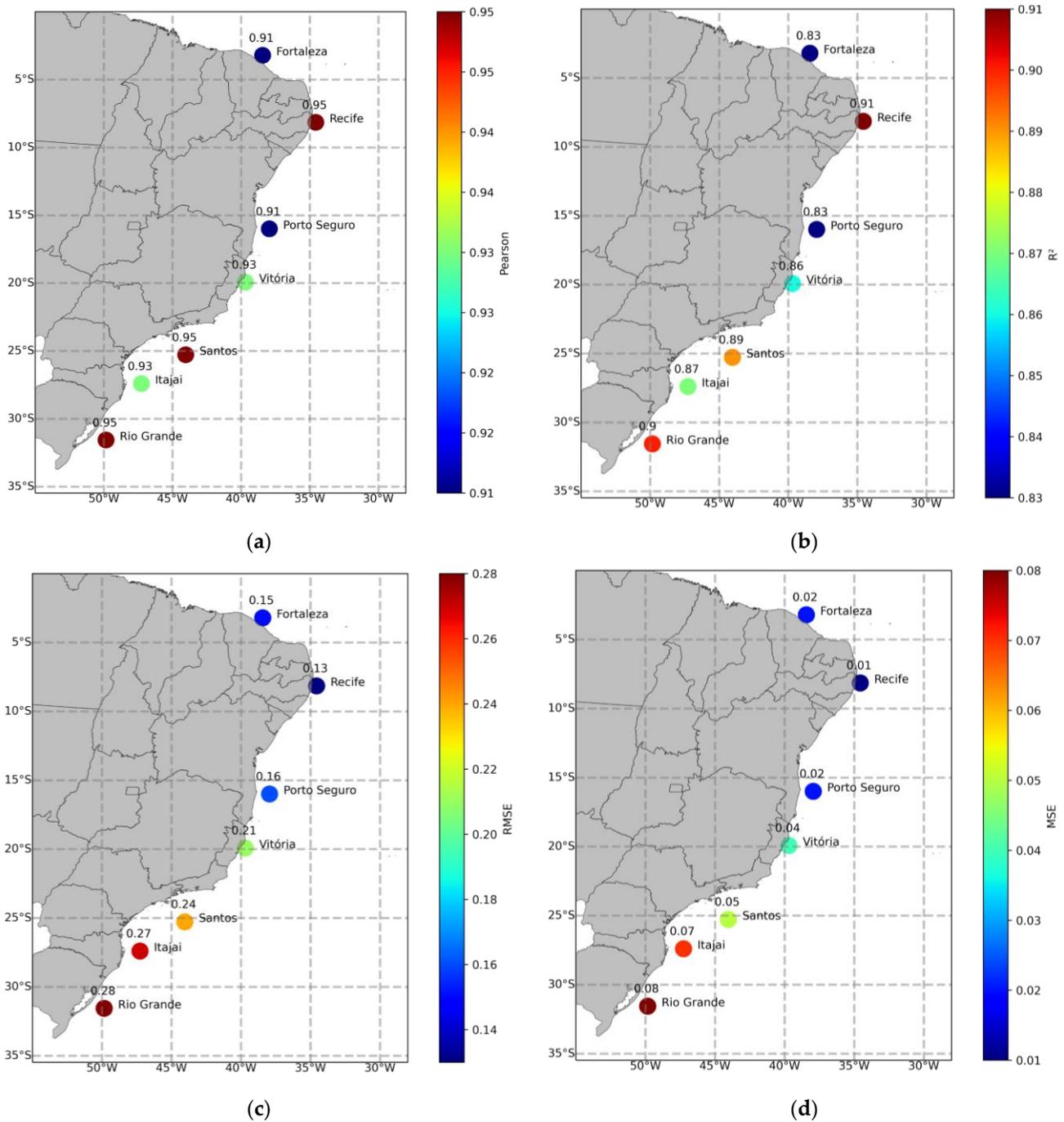


**Figure 3.** Linear regression graphs comparing Hs data estimated by CMEMS and MetOcean buoys at the following locational targets: Fortaleza (a), Recife (b), Porto Seguro (c), Vitória (d), Santos (e), Itajaí (f), and Rio Grande (g). The red line is the best fit linear regression line, with a 99% confidence interval. The black dashed line is the reference for observed data (the closer the red line is to the black dashed line, the better the CMEMS reanalysis skill).



**Figure 4.** Correlation (a), coefficient of determination (b), RMSE (c) and MSE (d) values between buoy wind speed measurements and CMEMS reanalysis.

Figures 4 and 5 present Pearson’s correlation coefficient, determination coefficient, RMSE and MSE for wind speed (m/s) and Hs (meters), respectively. It is possible to observe that Pearson’s correlations for wind speed at 10 m were greater than 0.70. The targets with the lowest correlations and the highest mean deviations (Recife, Vitória and Itajaí) are furthest from the grid points. The Itajaí buoy had the highest RMSE for wind speed (2.31 m/s). Pearson’s correlation for Hs is greater than 0.91, RMSE is less than 28 cm. Altimetry missions aboard satellites have a high degree of reliability and exert greater influence on the interpolation methods for Hs data, thus, the distance from the grid point did not result in larger errors.

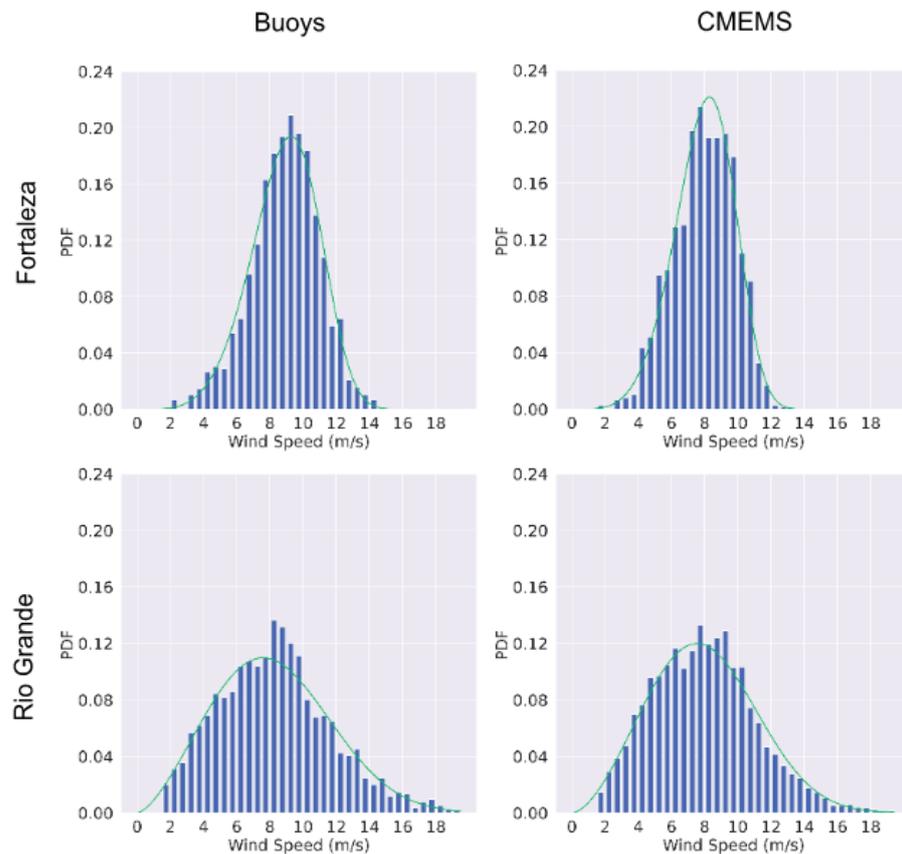


**Figure 5.** Correlation (a), coefficient of determination (b), RMSE (c) and MSE (d) values between the Hs measures of the buoys and CMEMS reanalysis.

The probability density function (PDF) of the CMEMS reanalysis was also compared with observations of the  $U_{10\text{ m}}$  and Hs for the Fortaleza and Rio Grande buoys. These buoys were selected because they present a sample size large enough to determine the PDFs and define a distribution with confidence for both variables. Figures 6 and 7 show the PDF to compare the variability of the wind speed and Hs data measured by the buoys and estimated by the CMEMS reanalysis. It is noteworthy that in all cases and data sources the distribution of  $U_{10\text{ m}}$  is broader than the distribution of Hs in Fortaleza and Rio Grande (Figures 6 and 7).

Another characteristic observed in Figure 6 is that the maximums of the wind distribution in the data from the Fortaleza buoy are shifted to lower values in the CMEMS

reanalysis. The Weibull distribution of the wind speed (calculated by the using the formula  $A/\sqrt{2}$ , where  $A$  is the scale parameter of the Weibull distribution) is 6.85 m/s for the Fortaleza buoy and 6.10 m/s for CMEMS reanalysis, which indicates that reanalysis does not estimate events with high wind speeds. No change in location of mode for  $H_s$  was observed, assuming that the comparisons between the data are matched for all parameters (Figure 7).



**Figure 6.** Frequency distribution of wind speed variation for data from buoys and CMEMS. The fitting curves for the Weibull distribution are defined in Table 2.

Tables 2 and 3 present the parameter values of the Weibull distribution (Weibull Shape- $W. s$  and Weibull Scale- $W. sc$ ), mean (med) and standard deviation (std) of the wind speeds and  $H_s$  in the buoy data and CMEMS for every site. The two tables show that  $U_{10 m}$  fits well using  $W. s$  of 5 for Fortaleza and 2 for Rio Grande. Moreover, for the  $W. sc$  parameters they are all similar, this similarity was also observed for the average and standard deviation values. For  $H_s$ , the values of the statistical parameters further enhanced the similarity. This shows that this variable is even better estimated and corroborates the previous results.

**Table 2.** Values of the Weibull distribution parameters (shape and scale), mean and standard deviation of the reanalysis and Fortaleza buoy.

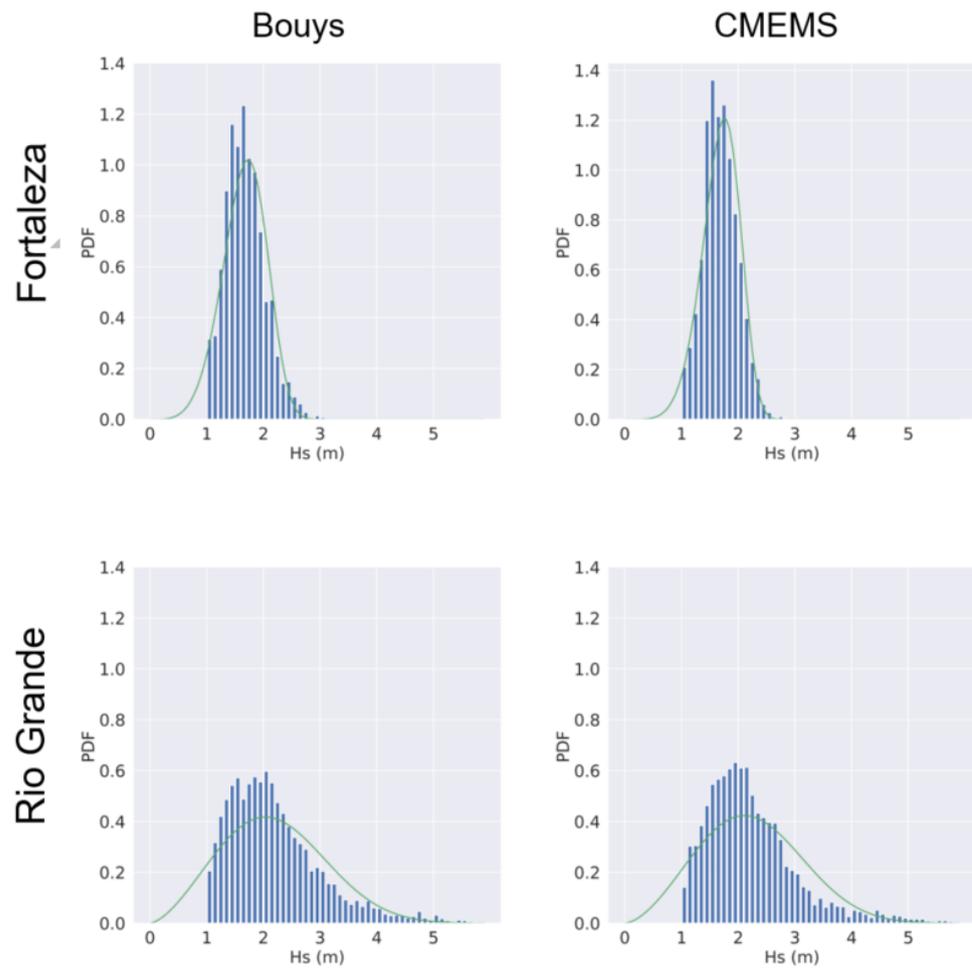
Fortaleza	Wind Speed				Hs			
	W. s	W. sc	Med	Std	W. s	W. sc	Med	Std
Buoy	5.00	9.69	8.90	2.04	5	1.81	1.66	0.35
CMEMS	5.09	8.64	7.94	1.81	5	1.81	1.68	0.30

W. s: Weibull shape; W. sc: Weibull scale; Med: mean; Std: standard deviation.

**Table 3.** Values of the Weibull distribution parameters (shape and scale), mean and standard deviation of the reanalysis and Rio Grande buoy.

Rio Grande	Wind Speed				Hs			
	W. s	W. sc	Med	Std	W. s	W. sc	Med	Std
Buoy	2	9.30	8.30	3.64	2	2.42	2.16	0.83
CMEMS	2	8.94	7.95	3.15	2	2.51	2.24	0.85

W. s: Weibull shape; W. sc: Weibull scale; Med: mean; Std: standard deviation.



**Figure 7.** Frequency distribution of Hs variation for data from buoys and CMEMS. The fitting curves for the Weibull distribution are defined in Table 3.

### 3.2. Estimate of Energy Density ( $W/m^2$ )

The results obtained so far indicate that the estimates from the CMEMS reanalysis are consistent with the reference station statistics, particularly for wind speed. The Fortaleza and Rio Grande target areas already home to offshore wind projects in the phase of environmental licensing to start construction: Caucaia Parazinho—Iparana Offshore Wind Farm and Águas Claras Marine Wind Complex, respectively [34]. Thus, the energy density without direct wind observations in the target area was calculated with CMEMS estimates and buoy data. Table 4 shows the energy density in the evaluated locations. It is possible to observe that the  $E$  is underestimated by the CMEMs, requiring a bias correction to reduce the errors. The increased values of energy density at the sites are consistent with previous work, which found values between 300–550  $W/m^2$  [14–16] based on in situ observations and reanalysis. The location with these energy density values, are considered suitable for wind energy production.

**Table 4.** Comparison of average energy density ( $E$ )  $W/m^2$  at the study sites.

Location	Buoy	CMEMS
Fortaleza	497	352
Rio Grande	526	461

#### 4. Conclusions

In this study, the potential for the characterization of wave height and wind speed of CMEMS reanalysis data was evaluated for use in offshore wind resource assessments in oceanic areas along the east coast of Brazil. The dataset from the CMEMS reanalysis was selected in this study because it presents acceptable temporal and spatial resolution to perform these analyses, especially close to coastal areas. Although reanalysis is currently performing well in several regions around the world and in different applications, its full potential for energy-related studies remains unexplored in Brazil.

Faced with the great challenge of filling large gaps in space and in time of data, especially in oceanic areas, we approached this problem by collecting data in reanalysis areas close to the reference sites, since reanalysis data are available in grid points. The results showed that for the two variables evaluated, the CMEMS data have acceptable performance.

Specifically, the results indicated a high degree of accuracy of the CMEMS data compared to the buoy observations, with the worst performance for the Itajaí buoy and the best performance for the Recife buoy, however, all locations show correlations greater than 0.70. The  $H_s$  in the CMEMS data performed very well in all locations along the east coast of Brazil.

The results indicate that the Weibull distribution fits well with the CMEMS wind speed and  $H_s$  histograms, and the parameters for the histograms of the buoy observations were very similar.

Although the CMEMS data performed well in general, there is a bias of underpredicting high speeds, possibly due to mesoscale wind gusts, which are not captured by typical reanalysis datasets. It is necessary to apply bias corrections to bring the estimates closer to the observations. The results of this study contributes to issues related to offshore engineering, logistics and monitoring.

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**Data Availability Statement:** The datasets used in this study were obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) reanalysis and National Buoys Program (PN-BOIA). The links where to download the data were provided through <https://marine.copernicus.eu/> (accessed on 2 December 2021) and <https://www.marinha.mil.br/> (accessed on 2 December 2021) to CMEMS reanalysis and Buoys, respectively.

**Conflicts of Interest:** The authors declare that there are no conflict of interest regarding the publication of this paper.

## Abbreviations

Hs	Significant Wave Height
Gw	Gigawatts
R <sup>2</sup>	Coefficient determination
RMSE	Root Mean Square Error
MSE	Mean Square Error
PDF	Probability Density Function
W. s	Weibull distribution Shape
W. sc	Weibull Scale
Med	Mean
SAR	Synthetic Aperture Radar
UTC	Coordinated Universal Time

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