ASSESSING WIND ACCURACY IN A COUPLET ATMOSPHERE-WAVE SYSTEM FOR THE NORTHEAST COAST OF BRAZIL

Nícolas de Assis Bose – nicolasbose@isi-er.com.br
Instituto SENAI de Inovação em Energias Renováveis
Institute of Geosciences, Federal University of Rio Grande do Sul, Porto Alegre, RS, 91501-970
Jean Souza dos Reis
Vanessa de Almeidas Dantas
Ana Cleide Bezerra Amorim
Maria de Fátima Alves de Matos
Samira de Azevedo Santos Emiliavaca
Leonardo de Lima Oliveira
Luciano Andre Cruz Bezerra
Instituto SENAI de Inovação em Energias Renovávei
Leandro Farina
Institute of Geosciences, Federal University of Rio Grande do Sul, Porto Alegre, RS, 91501-970

Abstract. *This paper investigates the sensitivity of offshore wind simulations, focusing on the northeast coast of Brazil. The study utilizes the Coupled Ocean-Atmosphere-Wave-Sediment Transport Modeling System (COAWST), integrating the Weather Research and Forecasting (WRF) and Simulating Waves Nearshore (SWAN) models. The research emphasizes the impact of wind-wave interaction on wind speed, considering factors such as atmospheric and ocean surface conditions. The methodology includes site selection, model overview, and validation techniques. Results indicate that the coupled atmosphere-wave model outperforms the stand-alone atmospheric model, showcasing enhanced accuracy in predicting wind speed. The paper discusses the significance of considering wave effects in offshore wind modeling and provides insights into the interplay between wind and waves, emphasizing the need for precise simulations in wind energy assessments.*

Keywords: *Atmosphere-wave Interaction, Numerical Model, Wave-induce Wind*

1. INTRODUCTION

Brazil is currently immersed in the exploration of its offshore wind resources, actively conducting comprehensive investigations to assess the potential for harnessing wind power along its coastal regions. As highlighted by Reis *et al.* (2021), four pivotal regions in Brazil—namely, the north, northeast, southeast, and south—have shown substantial potential. However, the challenge lies in obtaining precise measurements of offshore wind due to the relatively limited data available in this context. Consequently, this evaluation heavily relies on a combination of observed wind speeds and advanced numerical weather simulations. The utilization of numerical weather models proves particularly advantageous across various stages of the wind resource assessment, primarily because measured wind speeds are typically gathered at later phases of wind farm planning.

Numerical weather models are pivotal in the investigation of wind energy, given their capacity to replicate wind dynamics across a broader spatial domain. These models have been widely utilized for tasks such as forecasting production, creating future wind scenarios with climate change considerations, and constructing wind atlases (GOV-RN & ISI-ER 2022, Souza *et al.* 2022, Salvação & Soares 2018). To achieve the utmost precision in estimating wind power, numerical models provide var- ious configurations, encompassing physical parameterization, integration of ocean/land surface information, consideration of domain characteristics, and the use of forcing databases.

However, achieving precise simulation of offshore wind poses challenges on multiple fronts. The interaction between land and sea significantly affects offshore wind dynamics, with winds over land exerting a substantial influence on patterns downstream from the coast, extending over considerable distances (Svensson, Bergström, Rutgersson & Sahlée 2019, Hahmann *et al.* 2015). Moreover, variations in land-sea temperatures lead to warm-air advection over the sea surface, influencing both atmospheric stability and low-level jet velocity (Svensson, Arnqvist, Bergström, Rutgersson & Sahlée 2019, Svensson, Bergström, Rutgersson & Sahlée 2019).

Additionally, local wind and wave conditions play a crucial role in impacting the heat and momentum transfer between the atmosphere and the ocean. Offshore wind farms significantly affect these conditions by extracting momentum from the wind to generate energy, resulting in a reduction in wind speed within their wake (Fischereit & Larsén 2019). This modified wind speed subsequently influences the generation of wind-induced waves in the wake, leading to alterations in the overall wave conditions. As a result, changes in the wave field not only impact wind conditions but also adjust the air-sea momentum exchange, directly affecting the power production of wind farms.

Recent research underscores the significance of considering the interaction between atmosphere-wave-couplet systems to accurately evaluate the offshore wind energy potential in specific regions (Porchetta *et al.* 2021, Kalvig *et al.* 2014). In particular, Porchetta *et al.* (2021) has demonstrated that coupling the Weather Research and Forecasting

(WRF) model with the Simulating Waves Nearshore (SWAN) model improves the precision of wind speeds in offshore wind fields, resulting in increased energy production compared to systems that neglect wave effects.

Other studies have investigated into the influence of waves on smaller wind turbine farms. For example, AlSam *et al.* (2015), employing large eddy simulation (LES), discovered that aligning waves and winds can enhance the energy production of a single wind turbine by 3% to 8.4%. Similarly, Wu *et al.* (2020) observed that incorporating interactions among oceanic- atmospheric models led to a 2% increase in potential wind power in the North and Baltic Seas during January, but a 3% decrease in July.

Consequently, this paper aims to analyze the sensitivity of wind-wave interaction in a coupled atmosphere-wave model. The structure of this paper is organized as follows: In Section 2, we provide a comprehensive overview, including details on the site, model configuration, experiment design, and the methods used for measurements. Section 3 is dedicated to presenting and discussing the results obtained from both coupled and stand-alone simulations, with a particular emphasis on the impact of wind-wave interaction. Concluding the study, Section 4 offers the final insights and findings.

2. METHODOLOGY

2.1 Site selection

This study focuses on the northeast coast of Brazil, particularly the Ceará coastal zone, which is experiencing significant investments in future wind farms. The primary objective is to investigate the interaction between wind and wave dynamics and understand their impact on wind speed. This knowledge is essential for developing an effective management plan that can address uncertainties in wind power production before the construction of the wind farm. In summary, this study seeks to offer an overview of the challenges associated with modeling offshore wind in the coastal zone, considering the influence of wind-wave and swell systems during the months of September and October.

2.2 Model Overview

In our investigation of the sensitivity of wind power production to ocean wave conditions, we employ the Coupled Ocean- Atmosphere-Wave-Sediment Transport Modeling System (COAWST, v3.7). COAWST, an open-source code, integrates four distinct models through the Model Coupling Toolkit (MCT) (Warner *et al.* 2010). This modeling system allows for the exploration of interactions among the atmosphere, ocean, and waves. However, our focus in this study is specifically on the interaction between wind and waves. To achieve this, we couple the atmospheric model with the wave model, utilizing the Weather Research and Forecasting model (WRF) (Skamarock *et al.* 2019) for the atmospheric component and the Simulating Waves Nearshore model (SWAN) Booij *et al.* (1996), Ris *et al.* (1999) for simulating wave conditions.

The exchange of variables between the two models includes the wind speed at 10 meters from WRF, calculated based on the Monin-Obukhov similarity theory, and ocean wave parameters such as significant wave height, wavelength, and wave direction, which are transmitted from SWAN to WRF.

COAWST facilitates the use of different numerical grids for each model. The interpolation process is executed through the Spherical Coordinate Remapping Interpolation Package, employing the nearest neighbor method to calculate weights for numerical domain interpolation where both the WRF and SWAN grids overlap (Warner *et al.* 2010). Importantly, information exchange occurs only in regions with overlapping grids, while in non-overlapping regions, no information on wave conditions is exchanged. To address this limitation, additional data sources, such as reanalysis data, can be incorporated alongside simulated data, ensuring comprehensive coverage even in cases where numerical domains do not align.

2.3 Atmospheric Model Overview

The WRF model uses the non-hydrostatic compressible Euler equation with infinite difference discretization to characterize the atmosphere. It was developed at the National Center for Atmospheric Research (NCAR). Parameterization schemes are used to capture different physical processes such as radiation, microphysics, surface layer, turbulence flux, and ocean surface roughness. Since we specifically study atmospheric boundary layer processes, the surface layer scheme determines the lower boundary condition for temperature and velocity. This program computes critical variables such as friction velocity and momentum and heat exchange coefficients. These flux exchanges estimate vertical flux and serve as a lower bound for the planetary boundary layer parametrization. The surface layer scheme continues to compute friction in the context of the coupled atmospheric-wave model.

In terms of numerical domain, it includes a portion of the northeastern coast of Brazil, and the oceanographic buoy is located in the offshore region of Ceará (Fig. 1). Two-way coupled nested domains with 48 vertical resolution levels and horizontal resolutions of 5 and 1.66 km, respectively, are used in the WRF simulation. The atmospheric boundary conditions are forced and initialized using the ERA5 reanalysis dataset from the European Center for Medium-Range Weather Forecast. With 48 vertical levels available up to 10 Pa, the ERA5 dataset boasts both temporal and spatial resolutions of 0.25º x 0.25º and hourly intervals, respectively.

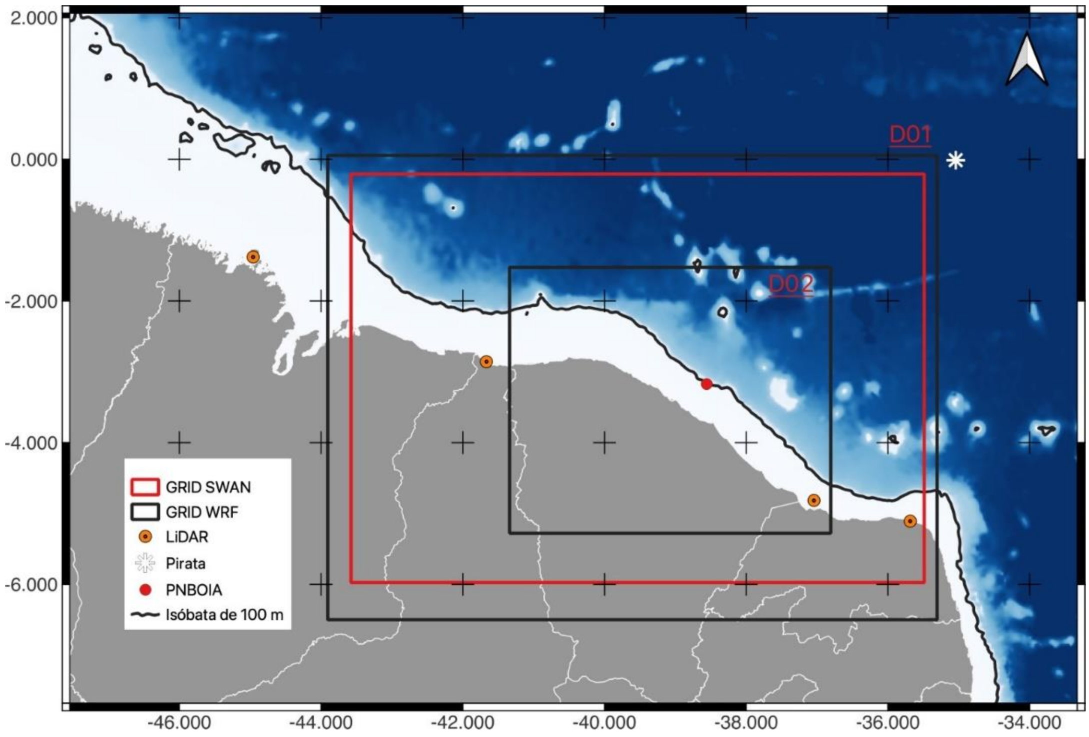

Figure 1 – COAWST domain for wind-wave interaction.

2.4 Wave model overview

The third-generation Simulating Waves Nearshore (SWAN), model version 41.31 (Booij *et al.* 1996, Ris *et al.* 1999), created by the Delft University of Technology, was used to model waves. This model uses a two-dimensional wave action density spectrum to describe the primary feature of the wind-wave system. When a wave travels from the deep ocean to shallow waters, its true nature can be ascertained using the governing equation. Actually, given the conditions of wind, wave boundary, bottom, and current, the SWAN numerical solution is so sensitive that it can characterize the wave system in small or enclosed environments, like lakes and estuaries.

The wave action balance equation provides the governing equation for SWAN. It permits wave interaction through quadruplet and triad schemes, dissipation through white-capping and breaking, and wave growth through wind. There are 25 divisions in the frequency bin of the spectrum, spanning from 0.05 to 1 Hz. In addition, there are 36 bands along the wave direction. The ocean wave condition for the area was simulated using SWAN ST6 physics. With a resolution of 0.004º in both latitude and longitude, the bathymetric data are sourced from GEBCO. There is only one numerical grid used, with 201 x 201 grid points and a resolution of about 2 km. The ERA5 database, which has a 0.5º grid spacing and is available hourly, forces SWAN wave boundary conditions. Thus, the wave boundary conditions were generated using bulk wave parameters like Significant wave height, peak wave period, and mean wave direction.

2.5 Wind-wave interaction

Investigating wind-wave interaction requires an understanding of the momentum flux transfer between the ocean's surface and the upper atmosphere. A common way to quantify this intricate relationship is with the aerodynamic roughness length parameter. In numerical models of the atmosphere-ocean surface interaction, Charnock's aerodynamic roughness length parameter (Charnock, 1955) is widely used by researchers to represent the momentum flux transfer.

$$z_0 = \alpha \frac{u_*^2}{g} \tag{1}$$

The friction velocity is denoted by u_*, the gravitational constant is denoted by g, and the Charnock coefficient is represented by α. An important quantity for characterizing the momentum flux transfer between the ocean's surface and the atmosphere is the Charnock coefficient. The Charnock coefficient for the ocean surface is typically represented by a constant value of 0.012 (Charnock, 1955), assuming that the sea state is in equilibrium with the wind, independent of the wind generation process, such as local breeze or storm. Nevertheless, based on the sea state, other studies have suggested various Charnock coefficients. For instance, Smith *et al.* (1992) determined a Charnock coefficient of $\alpha = 0.011$ for the deep ocean, contrary to Grachev *et al.* (2003) who recommended using $\alpha = 0.018$ for shallow water. In the deep ocean, Charnock coefficients close to $\alpha \approx 0.018$ indicate fully developed sea states, which may cause one to overestimate wind speed in shallow water.

There are several roughness length parameterizations available for the COAWST model, one of which was put forth by Drennan *et al.* (2003). Due to its exclusive consideration of mixed and pure wind-sea states in the algorithm development, this particular parameter performs exceptionally well in capturing the momentum exchange between the ocean surface and atmospheric boundary layer under pure wind-sea conditions. This parameter is definite as

$$z_0 = 3.35 H_s \left(\frac{u_*^2}{c_p} \right)^{3.4} \tag{2}$$

Here, the wave speed group at the peak frequency is denoted by c_p, and H_s stands for significant wave high. This roughness length equation is specifically meant to be applied to pure wind-sea conditions. The equation takes wind speed, wind duration, and fetch size into account to explain why young waves in offshore conditions cause an increase in ocean surface roughness compared to old waves.

2.6 Wind height extrapolation

When wind speed data is unavailable at the hub height, an extrapolation technique becomes useful for evaluating wind power density at a 100 m elevation. This involves employing the logarithmic wind profile derived from the Monin-Obukhov similarity theory equation:

$$u_z = \frac{u_*}{k} \left[\ln\left(\frac{z}{z_0}\right) + \psi(z, z_0, L) \right] \tag{3}$$

In this equation, κ represents the Von Kármán constant (≈0.4), z_0 signifies the surface roughness (in meters), z denotes the wind speed height, and ψ involves the stability function, with L as the Obukhov length. Simplifying under the assumption of the atmosphere being nearly neutral and in equilibrium with the underlying surface ($z/L = 0$), we eliminate ψ from the equation, resulting in:

$$u_z = \frac{u_*}{k} \left[\ln\left(\frac{z}{z_0}\right) \right] \tag{4}$$

Additionally, if the wind speed (u_1) at a given height (z_1) is known, the wind speed (u_2) at another height can be estimated, assuming constant u_*. This estimation is facilitated through the following equations:

$$u_1 = \frac{u_*}{k} \ln\left(\frac{z_1}{z_0}\right) \tag{5}$$

and

$$u_2 = \frac{u_*}{k} \ln\left(\frac{z_2}{z_0}\right) \tag{6}$$

with further simplification:

$$u_2 = u_1 \frac{\ln(z_2/z_0)}{\ln(z_1/z_0)} \tag{7}$$

The ocean surface roughness length, maintained at a constant value of $z_0 = 0.2$mm, has been determined based on insights derived from the studies conducted by Lange *et al.* (2004), Mortensen *et al.* (1993) and Wu (1980). Regardless, it is crucial to acknowledge that the accuracy of this approach could be compromised if atmospheric stability conditions deviate from neutrality or if significant alterations in surface roughness or other atmospheric conditions occur between the two heights.

2.7 Model validation

To verify the precision of the simulation, statistical metrics are employed. The model data is compared to wind information obtained from PNBOIA (do Brasil 2017). The degree of agreement between the measured and modeled data is evaluated based on five statistical analyses, namely Bias (Eq. 8), root mean squared error (RMSE, Eq. 9), Scatter index (SI, Eq. 10), Pearson's correlation coefficient (r, Eq. 11), and mean absolute error (MAE, Eq. 12). These statistical metrics can be computed using the following equations:

$$BIAS = \frac{\sum (M_i - Obs_i)}{n} \tag{8}$$

$$RMSE = \sqrt{\frac{\sum (M_i - Obs_i)}{n}} \tag{9}$$

$$SI = \frac{RMSE}{Obs'} \tag{10}$$

$$r = \sqrt{\frac{\sum (M_i - M')(Obs_i - Obs')}{(\sum (M_i - M')^2 (Obs_i - Obs')^2)^{\frac{1}{2}}}} \tag{11}$$

$$MAE = \frac{1}{n} \sum |M_i - Obs_i| \tag{12}$$

Here, M_i represents the model values for a given number of observations denoted by n, while Obs_i refers to the corresponding measured values. M′ and Obs′ signify the means of the model and measured values, respectively. All of these statistical metrics have been employed in various validation studies (Li *et al.* 2021, Souza *et al.* 2022) to ensure the reliability and accuracy of the models.

3. RESULTS AND DISCUSSIONS

Upon comparing the simulated velocity and wind directions with measurements from the PNBOIA—an offshore buoy concurrently measuring atmospheric and oceanographic variables— we observe a noteworthy concordance between the model's estimations and the actual measurements (Fig. 2). A comparable agreement is also evident when assessing the coupled atmosphere- wave model against the measurement. Despite both models showing satisfactory agreement with the measurements, a slight enhancement is evident in the coupled atmosphere-wave model.

Illustrated in Fig. 1, the coupled atmosphere-wave model demonstrates a higher relative averaged wind velocity over the simulated two-month duration when compared to the stand-alone atmospheric model. The bias values of -0.57 for the stand- alone model and 0.19 for the coupled model emphasize the contrasting performance, indicating a significant advantage for the coupled atmosphere-wave model.

Furthermore, the effectiveness of the coupled atmosphere-wave model over the stand-alone atmospheric model is evident in the comparison of performance metrics. For the coupled atmosphere-wave model, the correlation value for wind speed stands at 0.77, demonstrating a strong relationship between the simulated and observed values. Additionally, the Scatter Index (SI) is notably lower at 9%, indicating a better agreement between the model and observations. Furthermore, the Root Mean Square Error (RMSE) is low at 1.02, reflecting the model's accuracy in capturing the wind speed variability. The Mean Absolute Error (MAE) for the coupled atmosphere-wave model is 0.82, reinforcing its precision in predicting wind speed. In contrast, the stand-alone atmospheric model, while still performing well, demonstrates slightly higher correlation (0.78), SI (10%), RMSE (1.13), and MAE (0.91) values, stressing the enhanced performance of the coupled atmosphere-wave model across these metrics. Similarly, for wind direction, both models effectively capture the variability, demonstrating comparable statistical metrics. Therefore, the impact of wind and wave interaction is more evident in wind speed.

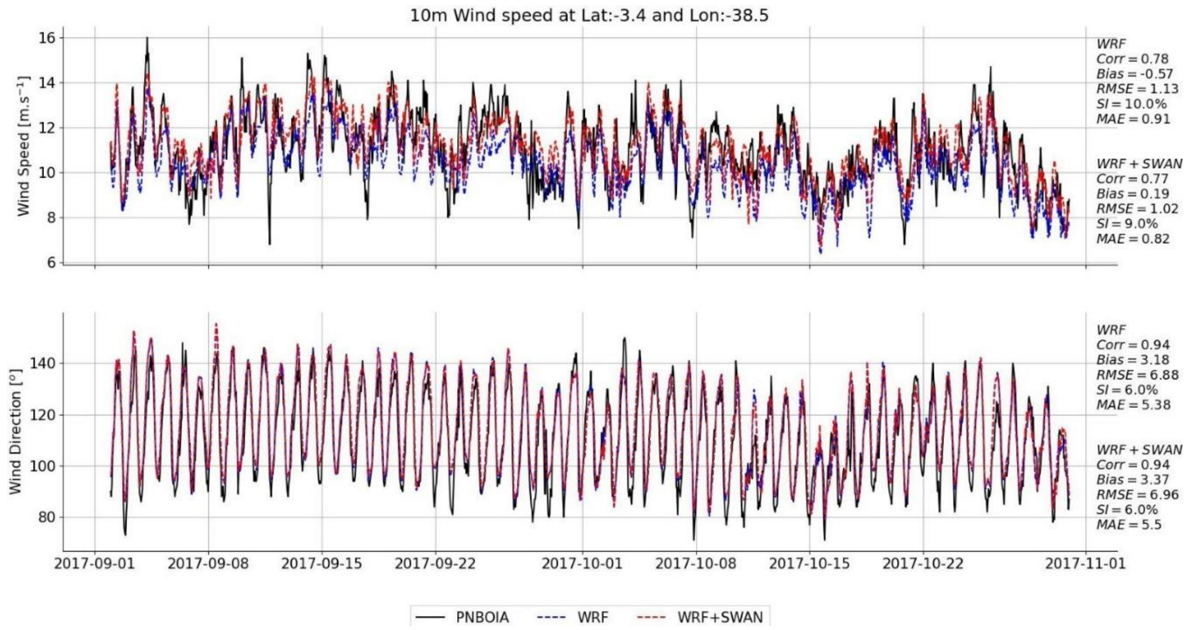

Figure 2 – A time series analysis of wind speed and direction is performed, comparing data from atmosphere-wave coupling, WRF, and PNBOIA.

The utilization of coupled atmosphere-wave models is complex, as it allows for the computation of roughness lengths based on equations that consider the sea surface conditions. This relationship reveals a significant dependence of roughness on the wave age, expressed as the ratio of phase speed to the 10-meter wind speed (cp/U10). In the scenario of young wind seas, waves actively extract momentum from the wind, therefore, during this phase, the momentum flux consistently directs downward, as noted by Semedo *et al.* (2009). Indeed, under swell conditions or in the case of older seas, the situation is reversed, and the wave-induced wind becomes positive, facilitating the transfer of momentum to the atmosphere (Drennan *et al.* 2003). In WRF model, the roughness length is a crucial parameter that influences the representation of surface processes,

especially in the atmospheric boundary layer. The roughness length characterizes the surface roughness and is an essential input for determining the surface drag, which affects the transfer of momentum, heat, and moisture between the land surface and the atmosphere (Skamarock *et al.* 2019). The WRF model typically allows users to specify the roughness length for various land use categories through parameterization schemes. These schemes consider the characteristics of the underlying surface, such as land cover, vegetation, and terrain.

The interaction with the ocean surface is not explicitly computed in stand-alone WRF models, where the roughness length is typically based on a constant value. However, the ocean surface is dynamic and subject to movement. In contrast, coupled atmosphere-wave models offer a more accurate estimation of this interaction. In this study, the parametrization proposed by Drennan *et al.* (2003) (Eq. 2) was employed in the coupled atmosphere-wave model. This allows for the consideration of all wave conditions in the computation of the roughness length, providing a more precise calculation of the momentum transfer from the ocean surface to the atmosphere.

The wind profile, a critical element in understanding offshore wind dynamics, is represented in Fig. 3. Given that wind velocity measurements and models are typically conducted at a standard height of 10 meters, the extrapolation metric for winds is employed. This approach ensures a comprehensive analysis of wind characteristics, investigating it vertical distribution of wind speed. Section 2.4 describe the methodology for the extrapolation metric. However, it is crucial to note that while the extrapolation metric addresses the vertical distribution of wind speed, it may not fully consider the atmospheric stability for offshore wind conditions.

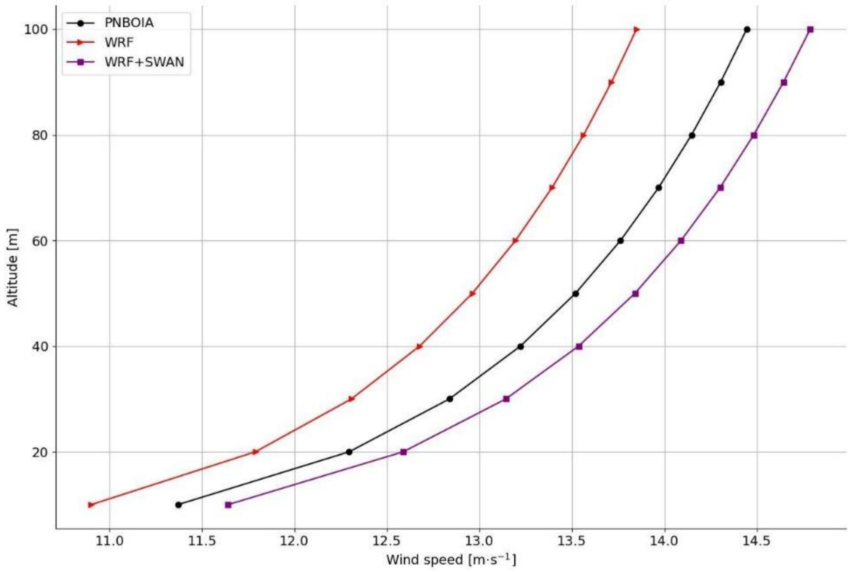

Figure 3 – A comparison between the simulated and observed average wind profiles from September to October is conducted. From Fig. 3, it is evident that the WRF stand-alone model underestimated the wind speed profile compared to PNBOIA.

In contrast, the opposite trend is observed in the coupled atmosphere-wave models, where it is notably overestimated. The ongoing underestimation observed in the WRF-simulated offshore wind is probably a result of its inheritance from ERA5, as presented in the research conducted by Kalverla *et al.* (2020). However, it is worth noting that when the same ERA5 wind is utilized in the coupled atmosphere-wave model, there is an overestimation. This phenomenon is linked to the computation of the roughness length using Equation 2, as proposed by Drennan *et al.* (2003).

We conducted an examination of variations in simulated offshore wind maps at 10 m between the WRF stand-alone and coupled models. This systematic analysis aimed to evaluate the sensitivity of simulated wind fields to different model configurations. In Fig. 4, sections of the Ceará coast display the spatial distribution of wind speeds. Notably, the wind is stronger in the WRF+SWAN coupled model and extends further into the open ocean, whereas in the WRF stand-alone model, the strongest values are concentrated near the coast. The difference map between these two models reveals a discernible trend of increasing bias from the coast to the open ocean. These results highlight the importance of considering the correct roughness length when modeling offshore wind. The smallest differences between the two models are observed onshore, while the largest disparities occur in the open ocean, where wave conditions are more turbulent.

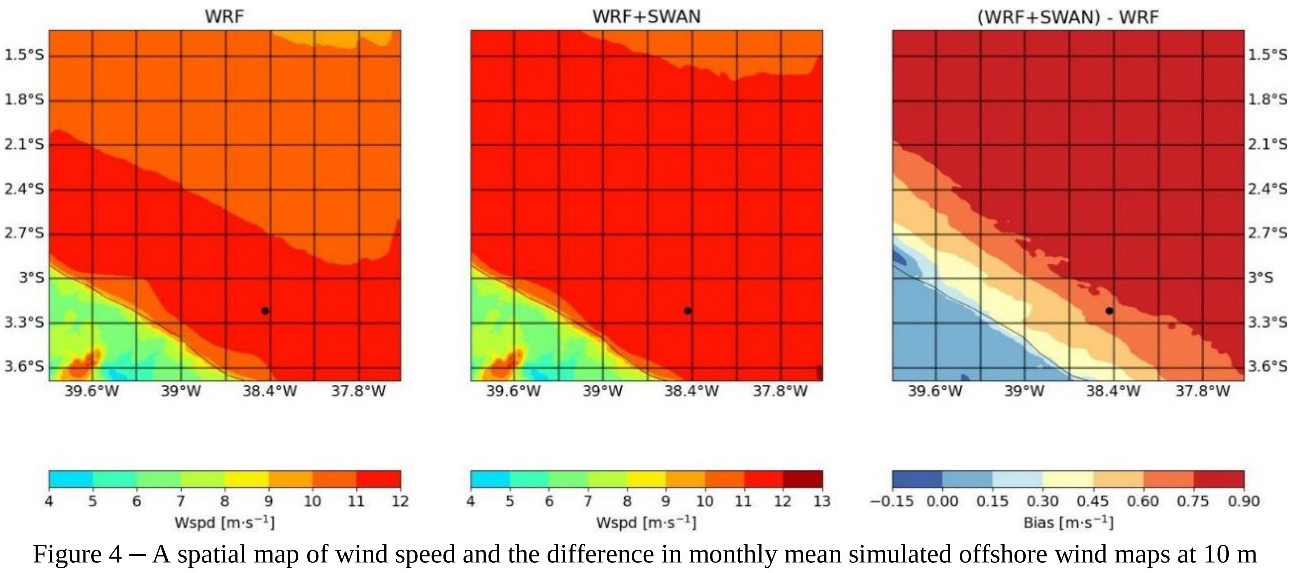

Figure 4 – A spatial map of wind speed and the difference in monthly mean simulated offshore wind maps at 10 m between atmosphere-wave coupling and WRF stand-alone. Black dot is the location of the PNBOIA. buoy

4. CONCLUSION

In summary, this study focused on analyzing the sensitivity of wind-wave interaction in a coupled atmosphere-wave model along the northeast coast of Brazil. The investigation employed the COAWST modeling system, integrating the WRF for the atmospheric component and the SWAN for simulating wave conditions. The study site, the Ceará coastal zone, is of particular interest due to significant investments in future wind farms.

The results and discussions highlighted the importance of considering wind and wave interaction in offshore wind modeling. The coupled atmosphere-wave model demonstrated improved performance in simulating wind speeds compared to the stand-alone atmospheric model. The inclusion of wave conditions in the roughness length parameterization significantly influenced the simulated wind profile, leading to better agreement with measurements from the PNBOIA offshore buoy.

The study emphasized the dynamic nature of offshore wind conditions, where the interaction between atmosphere and wave systems plays a crucial role. The coupling of atmospheric and wave models allowed for a more accurate representation of this interaction, considering factors such as sea state and wave age. The analysis of wind profiles and offshore wind maps illustrated the impact of wave conditions on the spatial distribution of wind speeds.

In conclusion, the findings of this study contribute valuable insights into the complexities of offshore wind modeling and underscore the need for accurate representations of wind-wave interaction. As the offshore wind industry continues to grow, incorporating such dynamics into modeling approaches becomes essential for reliable predictions and effective management of wind energy resources. The coupled atmosphere-wave model presented in this study serves as a promising tool for enhancing the precision of offshore wind assessments.

Acknowledgments

The authors would like to thank the team at SENAI Institute of Innovation in Renewable Energies – Rio Grande do Norte for their administrative and technical support and for providing the observed data. Additionally, gratitude is extended to the Ministry of Science, Technology, and Innovation of Brazil (MCTIC) for funding the research scholarship and current financial support under the project "Mapping the Wind Resource of the Brazilian Equatorial Margin," grant number 920008/2021.

REFERENCES

AlSam, A., Szasz, R. & Revstedt, J. (2015), 'The influence of sea waves on offshore wind turbine aerodynamics', *Journal of Energy Resources Technology* 137(5).

Booij, N., Holthuijsen, L. & Ris, R. (1996), The" swan" wave model for shallow water, in 'Coastal Engineering 1996', pp. 668– 676.

Charnock, H. (1955), 'Wind stress on a water surface', *Quarterly Journal of the Royal Meteorological Society* 81(350), 639–640. do Brasil, M. (2017), 'Programa nacional de boias—pnboia-plano nacional de trabalho', *Marinha do Brasil: Brasilia, Brazil* .

Drennan, W. M., Graber, H. C., Hauser, D. & Quentin, C. (2003), 'On the wave age dependence of wind stress over pure wind seas', *Journal of Geophysical Research: Oceans* 108(C3).

Fischereit, J. & Larsén, X. G. (2019), Interactions of oceanic surface waves and offshore wind farm wakes, in 'Annual meeting 2019: European Conference for Applied Meteorology and Climatology'.

GOV-RN, G. o. R. G. d. N. S. & ISI-ER, S. I. I. f. R. E. (2022), 'Wind and solar atlas of rio grande do norte state', Atlas 1(1), 211. Grachev, A., Fairall, C., Hare, J., Edson, J. & Miller, S. (2003), 'Wind stress vector over ocean waves', Journal of Physical

Oceanography 33(11), 2408–2429.

Hahmann, A. N., Vincent, C. L., Peña, A., Lange, J. & Hasager, C. B. (2015), 'Wind climate estimation using wrf model output: method and model sensitivities over the sea', International Journal of Climatology 35(12), 3422–3439.

Kalverla, P., Holtslag, A., Ronda, R. & Steeneveld, G. (2020), 'Quality of wind characteristics in recent wind atlases over the north sea, qj roy. meteor. soc., 146, 1498–1515'.

Kalvig, S., Manger, E., Hjertager, B. H. & Jakobsen, J. B. (2014), 'Wave influenced wind and the effect on offshore wind turbine performance', Energy Procedia 53, 202–213.

Lange, B., Larsen, S., Højstrup, J. & Barthelmie, R. (2004), 'Importance of thermal effects and sea surface roughness for offshore wind resource assessment', *Journal of wind engineering and industrial aerodynamics* 92(11), 959–988.

Li, H., Claremar, B., Wu, L., Hallgren, C., Körnich, H., Ivanell, S. & Sahlée, E. (2021), 'A sensitivity study of the wrf model in offshore wind modeling over the baltic sea', Geoscience Frontiers 12(6), 101229.

Mortensen, N. G., Landberg, L., Troen, I. & Lundtang Petersen, E. (1993), 'Wind atlas analysis and application program (wasp)'.

Porchetta, S., Muñoz-Esparza, D., Munters, W., van Beeck, J. & van Lipzig, N. (2021), 'Impact of ocean waves on offshore wind farm power production', Renewable Energy 180, 1179–1193.

Reis, M. M. L., Mazetto, B. M. & Silva, E. C. M. (2021), 'Economic analysis for implantation of an offshore wind farm in the brazilian coast', *Sustainable Energy Technologies and Assessments* 43, 100955.

Ris, R., Holthuijsen, L. & Booij, N. (1999), 'A third-generation wave model for coastal regions: 2. verification', *Journal of Geophysical Research: Oceans* 104(C4), 7667–7681.

Salvação, N. & Soares, C. G. (2018), 'Wind resource assessment offshore the atlantic iberian coast with the wrf model',

Energy
145, 276–287.
Semedo, A., Saetra, Ø., Rutgersson, A., Kahma, K. K. & Pettersson, H. (2009), 'Wave-induced wind in the marine boundary layer', *Journal of the Atmospheric Sciences* 66(8), 2256–2271.
Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., Wang, W., Powers, J. G., Duda, M. G., Barker,
D. M. *et al.* (2019), 'A description of the advanced research wrf version 4', *NCAR tech. note ncar/tn-556+ str* 145.
Smith, S. D., Anderson, R. J., Oost, W. A., Kraan, C., Maat, N., De Cosmo, J., Katsaros, K. B., Davidson, K. L., Bumke, K., Hasse, L. *et al.* (1992), 'Sea surface wind stress and drag coefficients: The hexos results', Boundary-layer meteorology 60, 109–142.
Souza, N. B. P., Nascimento, E. G. S., Santos, A. A. B. & Moreira, D. M. (2022), 'Wind mapping using the mesoscale wrf model in a tropical region of brazil', *Energy* 240, 122491.
Svensson, N., Arnqvist, J., Bergström, H., Rutgersson, A. & Sahlée, E. (2019), 'Measurements and modelling of offshore wind profiles in a semi-enclosed sea', Atmosphere 10(4), 194.
Svensson, N., Bergström, H., Rutgersson, A. & Sahlée, E. (2019), 'Modification of the baltic sea wind field by land-sea inter- action', Wind Energy 22(6), 764–779.
Warner, J. C., Armstrong, B., He, R. & Zambon, J. B. (2010), 'Development of a coupled ocean–atmosphere–wave–sediment transport (coawst) modeling system', Ocean modelling 35(3), 230–244.
Wu, J. (1980), 'Wind-stress coefficients over sea surface near neutral conditions—a revisit', *Journal of Physical Oceanography*
10(5), 727–740.
Wu, L., Shao, M. & Sahlée, E. (2020), 'Impact of air–wave–sea coupling on the simulation of offshore wind and wave energy potentials', Atmosphere 11(4), 327.