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Estimating the offshore wind resources of the State of Ceará in Brazil

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ABSTRACT

The onshore wind power is consolidated; the challenge is to reach the same level of maturity for offshore exploitation. Brazil has no offshore wind power plants and there are few studies in this direction. This paper aims to estimate the offshore wind resources in the State of Ceará, in Brazil. The investigation uses a mesoscale atmospheric computer model, the Regional Atmospheric Modeling System (RAMS), with horizontal resolution of 2 km, which estimates the offshore average wind speed, average wind direction, power density and turbulence taking into account the bathymetry data and navigation routes along the coast of Ceará. The wind potential was evaluated in three representative periods, La Niña, El Niño and Neutral year, analyzing the dry and rainy season for each period. The results indicate an average wind speed above 8 m/s and power density above 720 W/m^2 no matter the period evaluated, in the dry season. The predominant wind direction in the observed dry periods was from East to West and the turbulence intensity is smaller during dry season of El Niño. Besides, the bathymetry of the State of Ceará is shallow and the large ships route is far beyond the coast, offering no danger to future endeavors.

1. Introduction

Wind power generation has established itself over the years in the market as one of the cleanest electricity generation technologies. However, issues related to aesthetic, in special, has elicited reaction not in favor of onshore wind power plants in some parts of the world. The offshore wind facilities have then emerged as an alternative.

The distinct advantages of offshore wind power are easier transportation logistics, use of wind turbines of higher capacity, lower noise and visual impacts, better wind conditions, amongst others [1].

The lower roughness at the sea surface positively affects the Atmospheric Boundary Layer, also known as the Planetary Boundary Layer (PBL) that is the lowest part of the atmosphere, directly influenced by its contact with the surface of the planet. The PBL depth varies broadly and a tropical PBL could grow to 1 and 2 km depth [2].

The development of offshore wind power is, in many regions of the world, hindered by the lack of good quality information on the extent, characteristics and distribution of offshore wind energy resources [3].

The wind power in Brazil is growing and expected to reach 22 GW of installed capacity, 11.8% of the electricity matrix, in 2023 [4]. The South and in special the Northeast of Brazil are the regions with the greatest potential of wind power.

A study accomplished by the National Institute for Space Research (INPE) revealed that the potential for wind power generation at the Brazilian coast is about 3500 GW, ten times higher than onshore [5].

An investigation performed on the offshore wind energy resources in southeastern Brazil found that the average wind power is of 102 GW at a distance of 50 m from the coast, in the location between 28° S and 33° S [6]. Such results indicate that the offshore wind resources in Brazil, close to the coastal cities where concentrates the highest population density in the country, are promising and have great potential to complement the Brazilian electricity matrix.

Abbreviations: (RAMS), Regional Atmospheric Modeling System; (PBL), Planetary Boundary Layer; (PC), personal computer; (NCEP), National Centers for Environmental Prediction; (MBE), Mean Bias Error; (TI), turbulence intensity.

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The State of Ceará, in the Northeast of Brazil, has so far an onshore wind atlas, published in 2001. The atlas gives the wind resources at 50 m and 70 m above ground level, based on data set from 33 anemometric stations scattered over the state, at heights between 10 m and 50 m above ground, assessed by WindMAP software.

This paper aims to present the assessment results of the offshore wind resources along the seacoast of the State of Ceará with 543 km length of coastal line. The potential is estimated at 100 m above ground level, including the seacoast as well as about half of the onshore territory of the State. The assessment is based on the Regional Atmospheric Modeling System (RAMS) model to estimate the wind speed, power density, wind direction and wind turbulence. The bathymetry data and navigation routes along the coast are also taken into consideration.

The remainder of this paper is organized as follows. Section 2 gives an overview on the RAMS mesoscale model, the simulation tool applied for estimation of the offshore wind potential. Section 3 describes the methodology used in the research and the software parameter settings and Section 4 presents the validation of the results. Section 5 gives the offshore wind potential of the State of Ceará through maps of wind speed, wind direction power density, turbulence intensity and bathymetry. The conclusions are presented in Section 6, and additional results outlined in the Appendix with final remarks.

2. Regional atmospheric mesoscale model system – RAMS

RAMS is a versatile numerical code, developed at Colorado State University, often used for simulating mesoscale and large scale atmospheric systems. This model has multiple options of numerical schemes and physical parameterization that makes it possible to be useful in a broad spectrum of applications, with horizontal resolution of 2 km–2000 km [7–9].

This application tool is used by the Ceará Foundation for Meteorology and Water Resources (FUNCEME) and has proven suitable for weather forecasting, with high skill scores. It is a parallel distributed model that runs on a cluster of PC using distributed processing.

RAMS model uses prognostic and diagnostic models based on a set of hydrostatic and non-hydrostatic compressible equations of dynamics and thermodynamics of the atmosphere, plus conservation equations that includes: energy conservation, mass conservation (continuity equation), conservation of momentum (Navier–Stokes), water conservation, and the equation of state of ideal gas [8]. The microphysics is of volume, but explicit, with schemes of one or two moments, with seven distinct classes of hydrometeors: cloud water, rainwater, ice crystals, snow, aggregates, graupel and hail [10].

The application of the RAMS modelling system to predict the wind power generation in Northeastern Brazil, particularly in Ceará, has provided good results [11,12]. In this investigation, the RAMS model version 6 is used for estimation of the offshore wind resources in Ceará, Brazil.

3. Offshore wind evaluation methodology

The methodology applied for wind mapping depicted in Fig. 1 is based on RAMS model. The input data source is from the daily forecast provided by the National Centers for Environmental Prediction (NCEP). Access to NCEP grids over the Internet provides the initial and boundary conditions required to run the regional model.

The mesoscale model RAMS has the ability of grid nesting to provide high spatial resolution. For the purpose of this investigation, three nested grids were considered: the larger grid covers part of the Northeast region of Brazil; the second one encompasses most of the State of Ceará; and the higher resolution grid encompasses the entire coast of Ceará as shown in Fig. 2.

Fig. 1. Diagram of the methodology used in mesoscale.

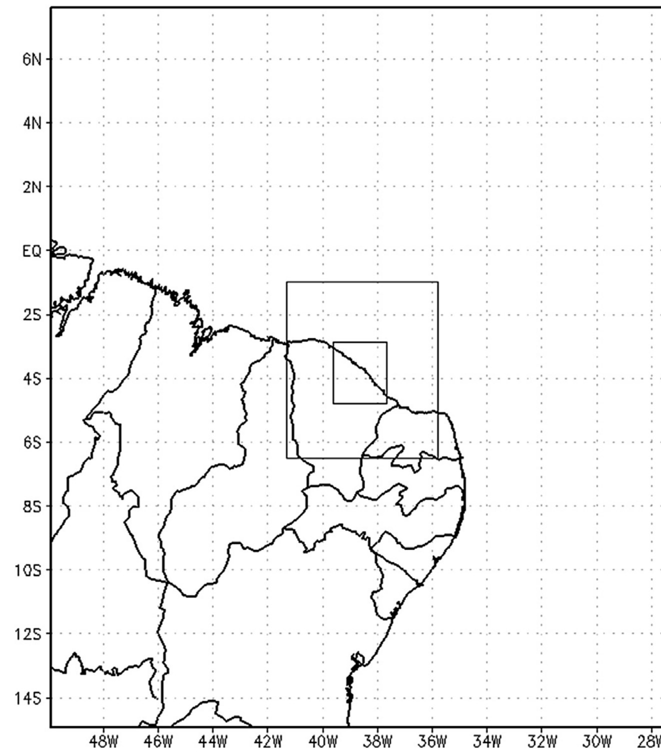

Fig. 2. Boundaries of the three nested grids.

Table 1 shows the grid configurations as horizontal resolution, grid points, initial vertical resolution, vertical levels, rate of vertical enlargement and maximum vertical spacing.

The spacing of 2 km for grid 3 was selected taking into consideration a trade-off between data storage requirements and processing time against the atmospheric events able to be viewed by the simulation rounds of interest. The grid resolution of 2 km has therefore considered the computational effort and the effects of the atmospheric forces of mesoscale where sea breeze as well as land breeze are very active.

The model parameterizations include Kain-Fritsch scheme for convection, Mellor and Yamada for turbulence, and Harrington for radiation. The Kain-Fritsch scheme is a parameterization of mass

Table 1
Grids setting adopted.

Parameter	Grid 1	Grid 2	Grid 3
Spacing x	24 km	6 km	2 km
Spacing y	24 km	6 km	2 km
Grid points x	108	122	239
Grid points y	108	122	239
Initial spacing z	20 m	20 m	20 m
Vertical levels	51	51	51

Table 2
Anomalies in sea surface temperature from the year 1996 until the year 2012.

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1996	**-0.9**	**-0.8**	**-0.6**	-0.4	-0.3	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.5
1997	-0.5	-0.4	-0.1	0.2	0.7	1.2	1.5	1.8	2.1	2.3	2.4	2.3
1998	2.2	1.8	1.4	0.9	0.4	-0.2	**-0.7**	**-1.0**	**-1.2**	**-1.3**	**-1.4**	**-1.5**
1999	**-1.5**	**-1.3**	**-1.0**	**-0.9**	**-0.9**	**-1.0**	**-1.0**	**-1.1**	**-1.1**	**-1.3**	**-1.5**	**-1.7**
2000	**-1.7**	**-1.5**	**-1.2**	**-0.9**	**-0.8**	**-0.7**	**-0.6**	**-0.5**	**-0.6**	**-0.6**	**-0.8**	**-0.8**
2001	**-0.7**	**-0.6**	**-0.5**	-0.4	-0.2	-0.1	0.0	0.0	-0.1	-0.2	-0.3	-0.3
2002	-0.2	0.0	0.1	0.3	0.5	0.7	0.8	0.8	0.9	1.2	1.3	1.3
2003	1.1	0.8	0.4	0.0	-0.2	-0.1	0.2	0.4	0.4	0.4	0.4	0.3
2004	0.3	0.2	0.1	0.1	0.2	0.3	0.5	0.7	0.8	0.7	0.7	0.7
2005	0.6	0.4	0.3	0.3	0.3	0.3	0.2	0.1	0.0	-0.2	**-0.5**	**-0.8**
2006	**-0.9**	**-0.7**	**-0.5**	-0.3	0.0	0.1	0.2	0.3	0.5	0.8	1.0	1.0
2007	0.7	0.3	-0.1	-0.2	-0.3	-0.3	-0.4	**-0.6**	**-0.8**	**-1.1**	**-1.2**	**-1.4**
2008	**-1.5**	**-1.5**	**-1.2**	**-0.9**	**-0.7**	**-0.5**	-0.3	-0.2	-0.1	-0.2	**-0.5**	**-0.7**
2009	**-0.8**	**-0.7**	**-0.5**	-0.2	0.2	0.4	0.5	0.6	0.8	1.1	1.4	1.6
2010	1.6	1.3	1.0	0.6	0.1	-0.4	**-0.9**	**-1.2**	**-1.4**	**-1.5**	**-1.5**	**-1.5**
2011	**-1.4**	**-1.2**	**-0.9**	**-0.6**	-0.3	-0.2	0.2	-0.4	**-0.6**	**-0.8**	**-1.0**	**-1.0**
2012	**-0.9**	**-0.6**	**-0.5**	-0.3	-0.2	0.0	0.1	0.4	0.5	0.6	0.2	-0.3

Legend: La Niña Neutral El Niño

Source: NOAA. 2013 (adapted) [16].

flow, which uses a simple cloud model with moist updrafts and downdrafts, including the effects of evacuation, entrainment, and relatively simple microphysics [13].

The Mellor and Yamada model uses a minimum number of universal constants, determined from laboratory experiments, and still plays well the non-dimensional observed functions of gradient in the surface layer [14].

The parameterization of Harrington takes into consideration the amount of liquid water in the cloud, the ice phase, airborne particulates, etc. [15].

For better representation of the boundaries of the wind speed in the State of Ceará, years of La Niña and years of El Niño were considered, as well as a neutral period without the influence of these extreme phenomena. La Niña is a periodic however anomalous cooling of the surface waters of the Eastern Equatorial Pacific Ocean, which favors the occurrence of rainfall above average over the semiarid of the Northeast of Brazil, reducing substantially the wind regime in the studied area. El Niño causes the opposite effects experienced during La Niña. Effects of El Niño phenomenon are like a dry period in the Northeast of Brazil and increases in local wind regime.

The El Niño period selected for analysis in this investigation was from the 2nd half of 1997 to the 1st half of 1998, considered as a period of strong El Niño, of which two months of the dry season (September and October 1997) and two months of the rainy season (March and April 1998) were analyzed. The simulated La Niña period was from the 2nd half of 2007 to the 1st half of 2008, considered also as a period of strong La Niña, of which two months of the dry season (September and October 2007) and two months of the rainy season (March and April 2008) were analyzed. The Neutral year selected was 2001/2002, from which the months from July to December 2001 and January to June 2002 were simulated. The selections were based on figures presented in Table 2.

When anomalies in sea surface temperature are positive, this characterizes the presence of El Niño and on the contrary periods of La Niña. Variations smaller than $\pm$ 0.5 are considered neutral period.

Thus, it is possible to observe how the system behaves in a Neutral year, without the influence of extreme phenomena, and evaluate the wind potential of the study area. In case of the emergence of El Niño or La Niña phenomena, it makes possible to define the influence on the wind regime on the coast of the State of Ceará.

In the Northeast of Brazil, where the State of Ceará is located, the lowest wind speed is likely to occur in the rainy season, in this region from February to May, while the most high wind speed, in the months from August to October [17].

4. Validation of the model performance

In order to validate the model estimation, the simulation results were compared to actual measurements derived from anemometric Towers supported by the State Government, located in two municipalities (Camocim and Trairi) in the State of Ceará. The data from the tower of Camocim were measurements at 60.4 m height in the year 2005 (Neutral year), selected for validation because this was the only year of full measurements available from this tower. The data from the tower in Trairi were given for 2008 (La Niña year) at 80 m height. Although 2001–2002 was selected to represent the Neutral year in the simulation, relying on the model dexterity the

Table 3
Values of the Pearson correlation criteria [18].

Correlation (r)	Performance evaluation	
>0.90	Very good	Fair correlation
0.89 a 0.70	Good	Fair correlation
0.69 a 0.40	Regular	Poor correlation
0.39 a 0.20	Bad	Poor correlation
<0.19	Terrible	Poor correlation

Table 4
Model performance values.

	r	MBE	d
2005	0.903	−1.018	0.924
2008	0.580	−1.805	0.630

Table 5
Average wind speed, average wind direction and wind power density for the three periods.

Period	El Niño, Dry season (D), Rainy season (R)	La Niña, Dry season (D), Rainy season (R)	Neutral, Dry season (D), Rainy season (R)
Average speed (m/s)	8 to 10 (D) 4 to 8 (R)	10 to 14 (D) 2 to 7 (R)	8 to 12 (D) 2 to 8 (R)
Average direction	E to W (D) NW to NE (R)	E to W (D) NW to NE (R)	E to W (D) E to W (R)
Power density (W/m^2)	under 720 (D) under 360 (R)	720 to 1080 (D) under 360 (R)	720 to 1080 (D) under 360 (R)

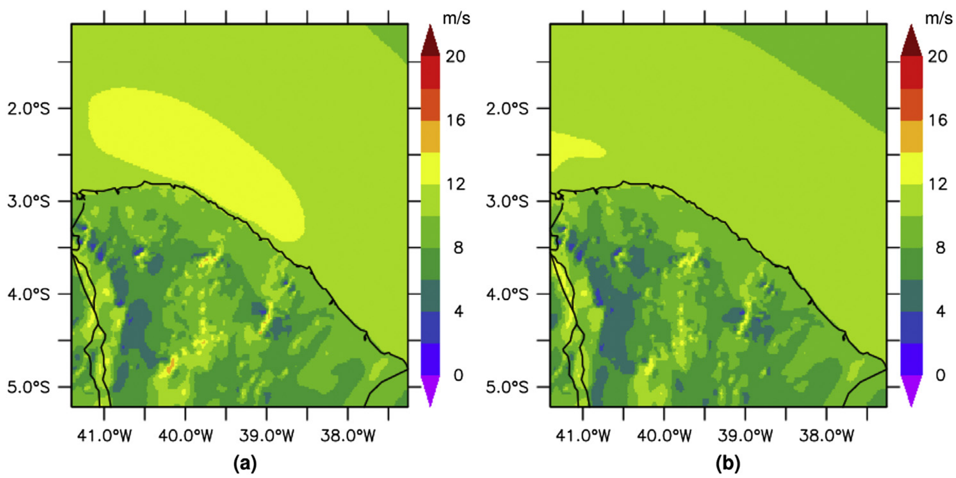

Fig. 3. Average wind speed (m/s) at 100 m in La Niña: (a) in September 2007 (b) in October 2007.

validation can be made to other period (2005) without losing its significance. Unfortunately, for the El Niño period of 1997–1998 there are no measurement data available for comparison.

Three different indices were calculated, the Pearson correlation coefficient, the Mean Bias Error (MBE) and the Index of Agreement of Willmontt, to evaluate the approach performance. All these comparing the measured (observed) and simulated (estimated) data for the years 2005 and 2008.

The Pearson correlation is a dimensionless index bounded by −1.0 and 1.0 inclusive, and reflects the strength of a linear relationship between two data sets, i.e., model estimations with pairwise-matched observations. Table 3 sets out the performance criteria adopted.

The MBE is intended to indicate average model 'bias', represented by negative values (MBE<0) or positive values (MBE>0) pointing out average over- or under-estimation [19].

Willmontt's dimensionless index of agreement describes the relative co-variability of estimation and observed values about an estimate of the 'true' mean [20]. Its values range from zero for no-correlation to one for a perfect concordance. Table 4 gives the calculated indices of Pearson (r), MBE and Willmontt's (d).

The statistical indices show a quite good performance for the year 2005 (Neutral) and a regular correlation for 2008 (La Niña).

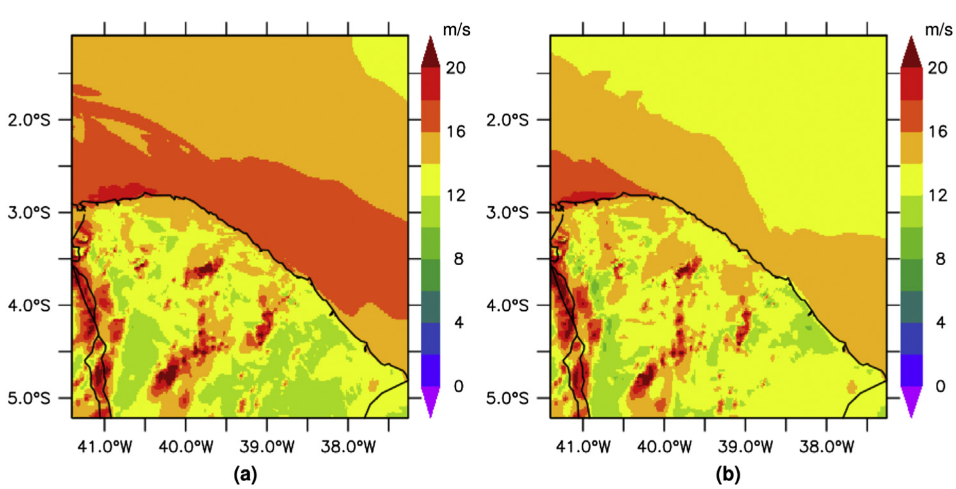

Fig. 4. Maximum wind speed (m/s) at 100 m in La Niña: (a) in September 2007 (b) in October 2007.

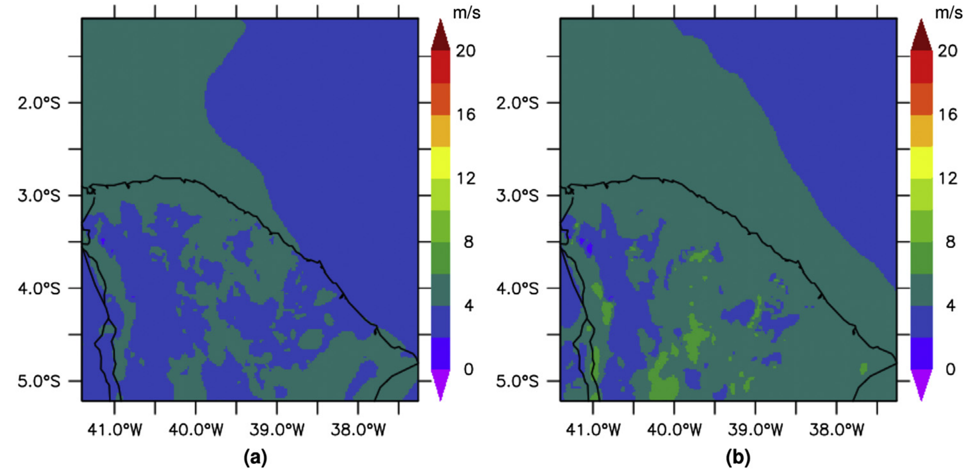

Fig. 5. Average wind speed (m/s) at 100 m in La Niña: (a) in March 2008 (b) in April 2008.

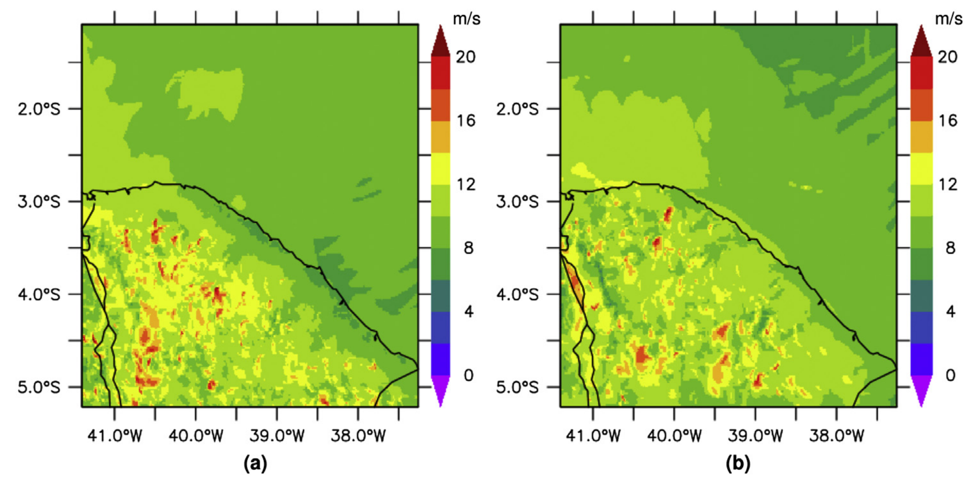

Fig. 6. Maximum wind speed (m/s) at 100 m in La Niña: (a) in March 2008 (b) in April 2008.

5. Wind resources

The wind potential is assessed by evaluating wind average speed, power density, wind average direction and turbulence. In addition to that, the bathymetry of the Ceará coast were also investigated.

Table 5 presents a summary for the three periods studied, La Niña, El Niño and Neutral. It can be observed that the wind average speed and power density are highly suitable at the dry season in all three periods. In the rainy season, the average speed is lower but still attractive for generating electricity.

The extreme conditions (maximum and minimum of estimated figures) were identified during La Niña event. For a matter of space, only the maps for La Niña period are presented next; the other two periods are shown in the Appendix.

The estimation of average wind speeds at 100 m height during La Niña, in September and October 2007, are shown in Fig. 3 (a) and (b). These months are regarded dry period in the State of Ceará. The estimated wind speeds are very satisfactory, with average values at virtually the entire coast in the range of 10 m/s to 14 m/s.

The maximum wind speeds estimated at 100 m high in the same period are on view in Fig. 4 (a) and (b); the maximum values are above of 14 m/s.

Fig. 5 (a) and (b) show the average wind speed estimated at 100 m height in March and April 2008, respectively, a likely rainy season in the State of Ceará. The estimated average wind speeds in March 2008 are in the range of 2 m/s to 6 m/s, while in April 2008 ranges from 5 m/s to 7 m/s. The maximum speed indicators for this period is between 7 m/s and 12 m/s as shown in Fig. 6.

The estimation of the average wind direction on the coast of Ceará at the height of 100 m is given in Fig. 7 for the months of September and October 2007 (dry season), and March and April 2008 (rainy season).

The average wind direction, in September and October 2007, prevails from East (E) to West (W), while in March 2008 from the sea to the mainland, with a trend from Northwest (NW) to Northeast (NE), and in April 2008 from East (E) to West (W).

Fig. 8 (a) and (b) show the estimated mean power density in September and October 2007 with values between 720 and 1800 W/m^2 in September and 720 and 1440 W/m^2 in October.

As shown in Fig. 9 (a) and (b) in some parts of the West coast the estimated maximum values of power density are above 3600 W/m^2 in the dry season in Ceará.

The estimated average power density in March and April 2008 are presented in Fig. 10 (a) and (b). These two months are rainy season in Ceará. The estimated power densities are under 360 W/m^2.

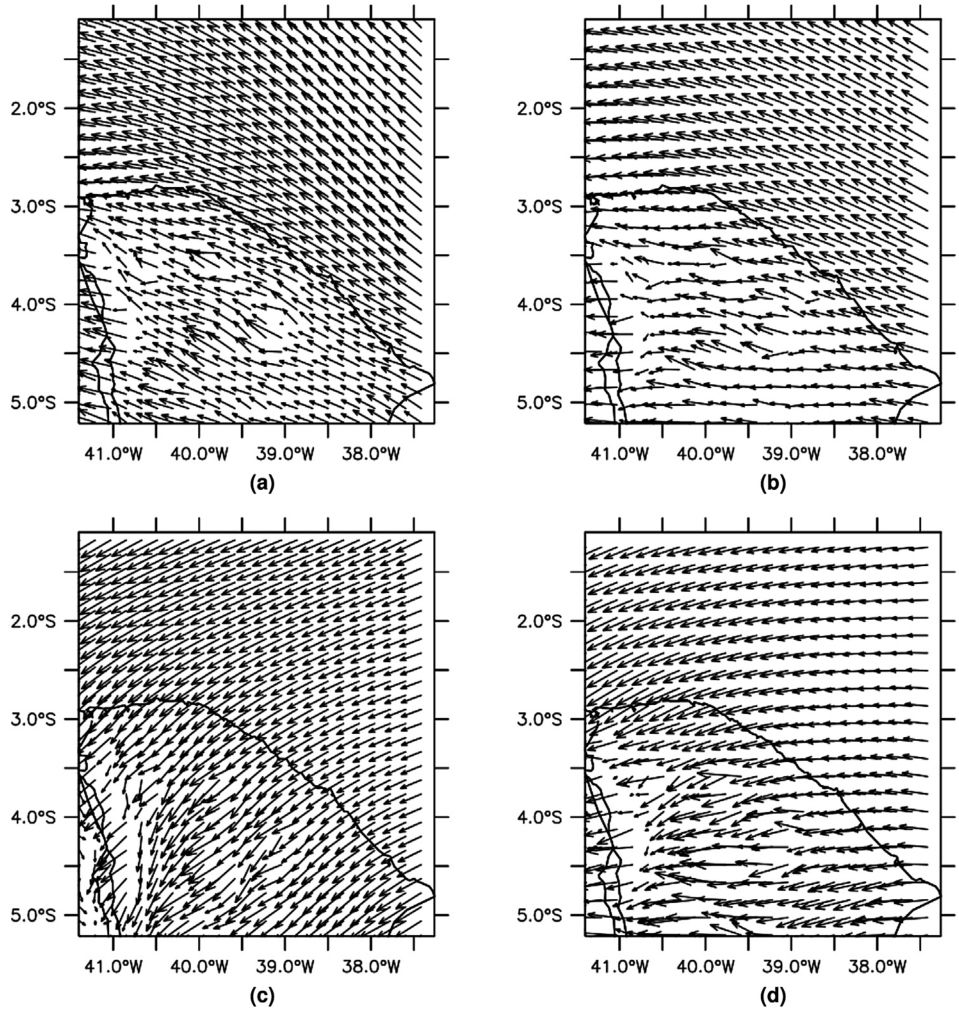

Fig. 7. Average wind direction at 100 m height in La Niña period: (a) in September 2007 (b) in October 2007 (c) in March 2008 (d) in April 2008.

The maximum values of power density were found on the West coast in March and April 2008 (rainy season) with values between 720 W/m^2 and 1080 W/m^2, as shown in Fig. 11 (a) and (b).

During the simulation rounds information about the turbulence have also been assessed. The intensity of the turbulence is calculated as the standard deviation of the longitudinal wind speed normalized to the average wind speed. The higher the value of the turbulence intensity (TI), the greater the turbulence signal. In small wind speed regimes, mostly smaller than 1 m/s and in the presence of high standard deviation, TI tends to have high values.

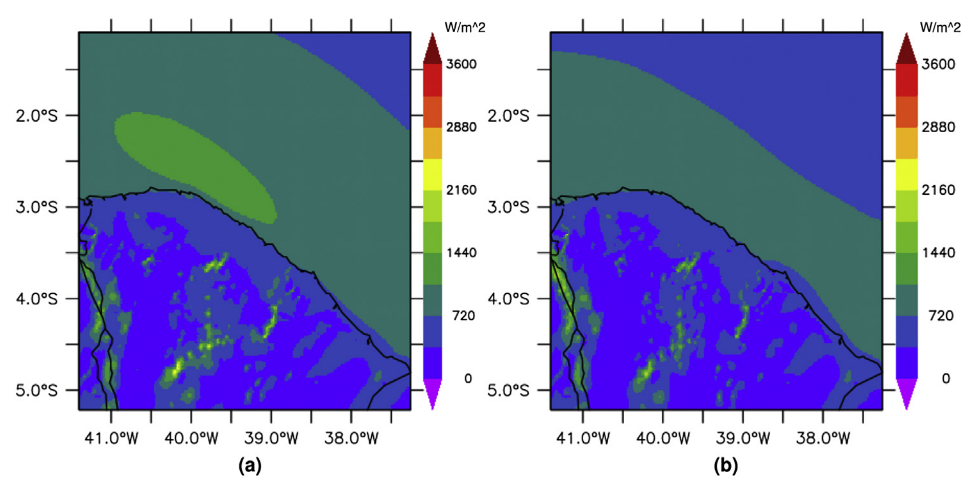

Fig. 8. Average power density of the wind (W/m^2) at 100 m in La Niña: (a) September 2007 (b) October 2007.

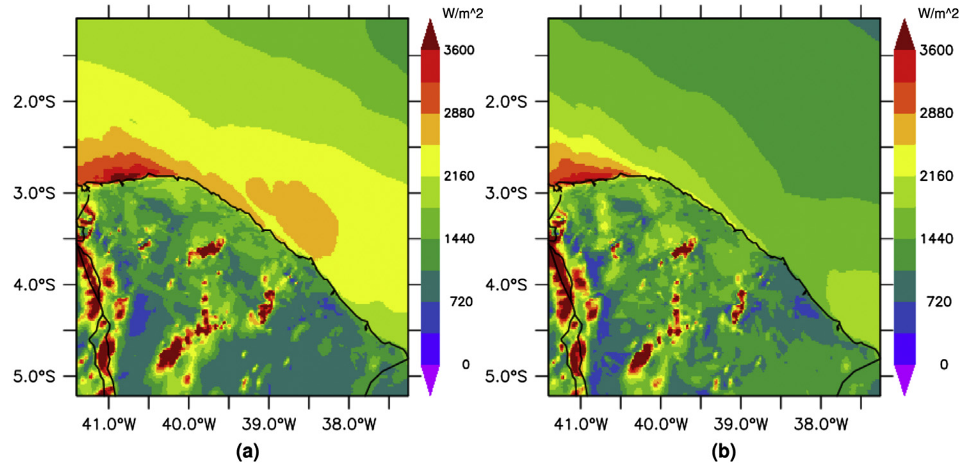

Fig. 9. Maximum power density of the wind (W/m^2) at 100 m in La Niña: (a) September 2007 (b) October 2007.

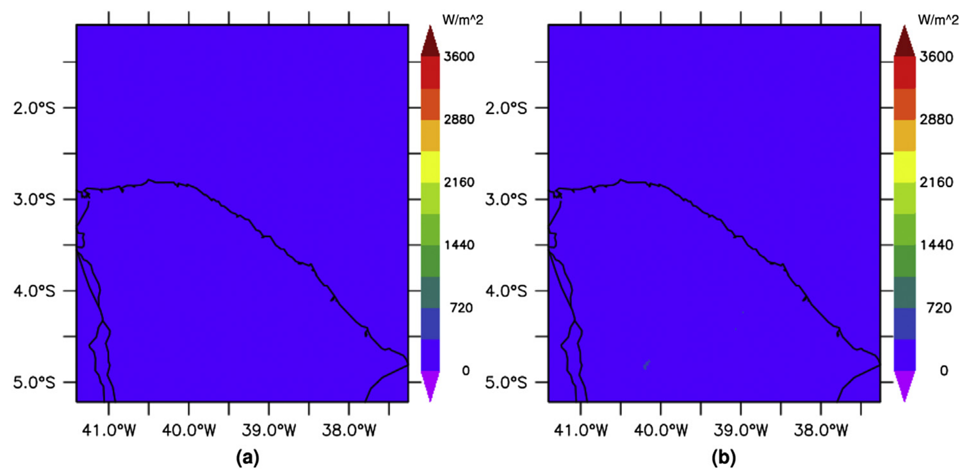

Fig. 10. Average power density of the wind (W/m^2) at 100 m in La Niña: (a) March 2008 (b) April 2008.

On the other hand, in high-value wind regimes, TI may have smaller values, since TI is a ratio of the standard deviation and average wind speed. This means that with moderate standard deviation and strong wind schemes TI tends to be smaller. Figs. 12 and 13 show the turbulence for the months of September–October (dry season) and March–April (rainy season) in La Niña period. It was estimated that in the rainy season the TI was higher than in the dry season.

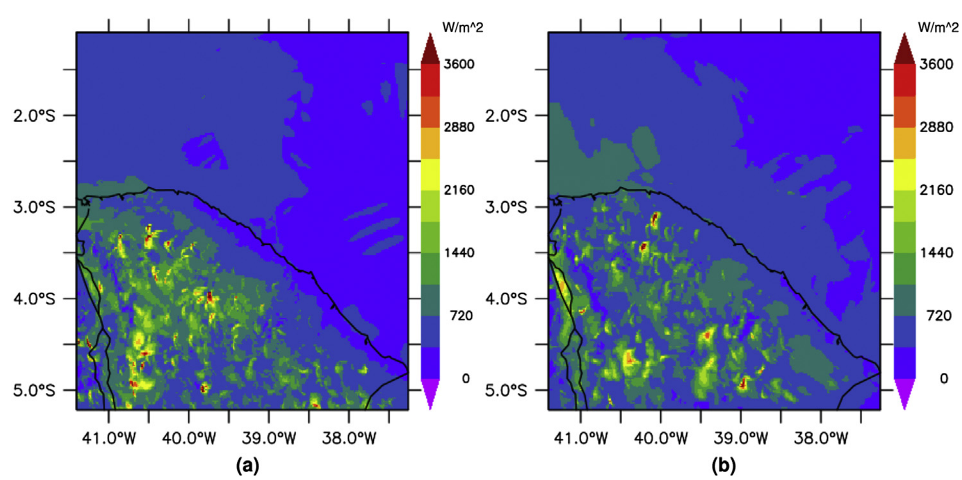

Fig. 11. Maximum power density of the wind (W/m^2) at 100 m in La Niña: (a) March 2008 (b) April 2008.

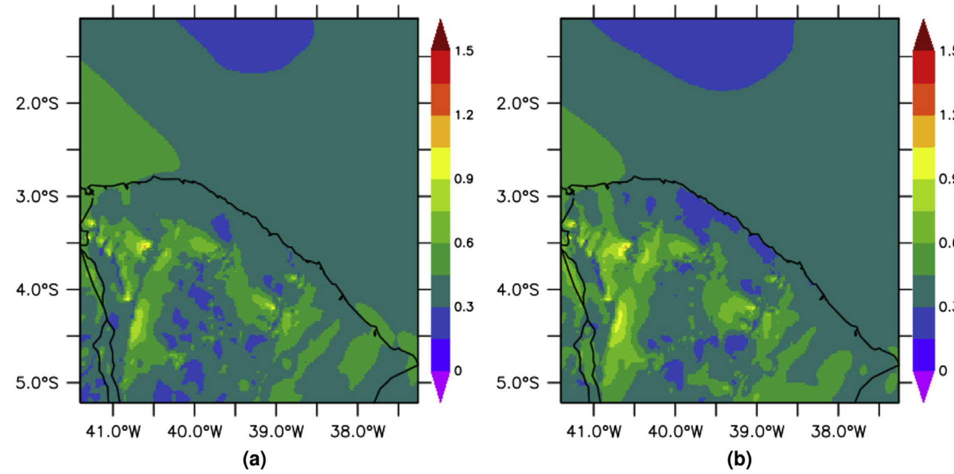

Fig. 12. Turbulence of the wind at 100 m in La Niña: (a) September 2007 (b) October 2007.

The bathymetry along the Ceará coast has gentle slope, the deep waters are found only several miles off the coast [21]. Fig. 14 shows the sea depth profile alongside the coast of Ceará; up to about 15 nm (27.78 km), a depth quite shallow.

Based on the nautical charts, provided by the Brazilian Navy, that encompass the whole coast of Ceará, it is observed that all the coast of the State has a bathymetry with low depths. Values such as 40 m depth are only located at a distance of approximately 24 km far the coast, which makes this band of the coast very suitable for offshore wind parks.

According to information from the Authorities of the Harbor of Ceará, large ships travel above 20 nm from the coast (about 37 km off the coast) because of the numerous small fishing boats (rafts) along the coast, and only when the ships reach the harbor line, they draw a perpendicular route towards the harbor to avoid accidents.

So far, there are no regulations concerning the distance to install offshore wind farms, so that they do not cause visual impact. Snyder and Kaiser [1] declared that the developments of installed offshore until 2008 have adopted distances from shore ranging from 0.03 to 27 km. Kim et al. [22] consider that the areas that are located at more than 10 km from the coast cause no visual impact. Sheridan et al. [23] consider a relevant distance of 8 nm (approximately 14.8 km) from the coast.

Fig. 15 presents the depth range with the distance to the mainland along the coast of Ceará, so that the most appropriate and least costly areas can be identified.

6. Conclusion

The mesoscale modeling has proved a suitable tool for estimation of the power available in the wind on the coast of Ceará. The approach circumvents the lack of installed anemometers, reduces the estimation cost, and provides quite reasonable results. This is the first and essential step for the development of offshore wind power plants in Brazil, the knowledge of the offshore wind potential.

The numerical simulations results achieved a satisfactory correlation with measured data, at the height of 60.4 m, showing the effectiveness of the model and configuration adopted.

Average wind speed, average power density, wind direction and turbulence intensity are amongst the indicators evaluated at both extreme episodes (La Niña and El Niño) and Neutral year. Results related to El Niño and Neutral year are shown in the Appendix.

De facto, the results indicate an average wind speed estimated between 10 m/s and 14 m/s and average power density between 720 W/m^2 and 1800 W/m^2 in La Niña dry season. In El Niño dry season, the estimated average wind speed is between 8 m/s and 10 m/s and the average power density under 720 W/m^2. In the dry

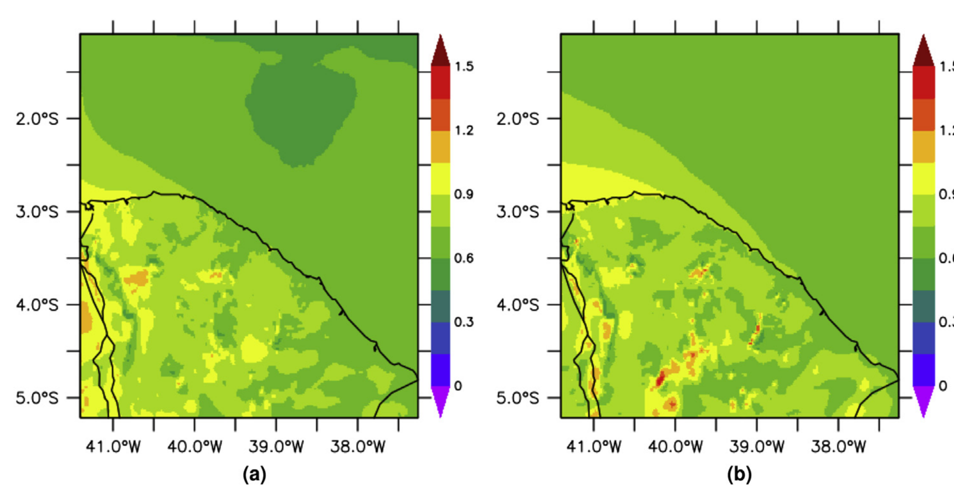

Fig. 13. Turbulence of the wind at 100 m in La Niña: (a) March 2008 (b) April 2007.

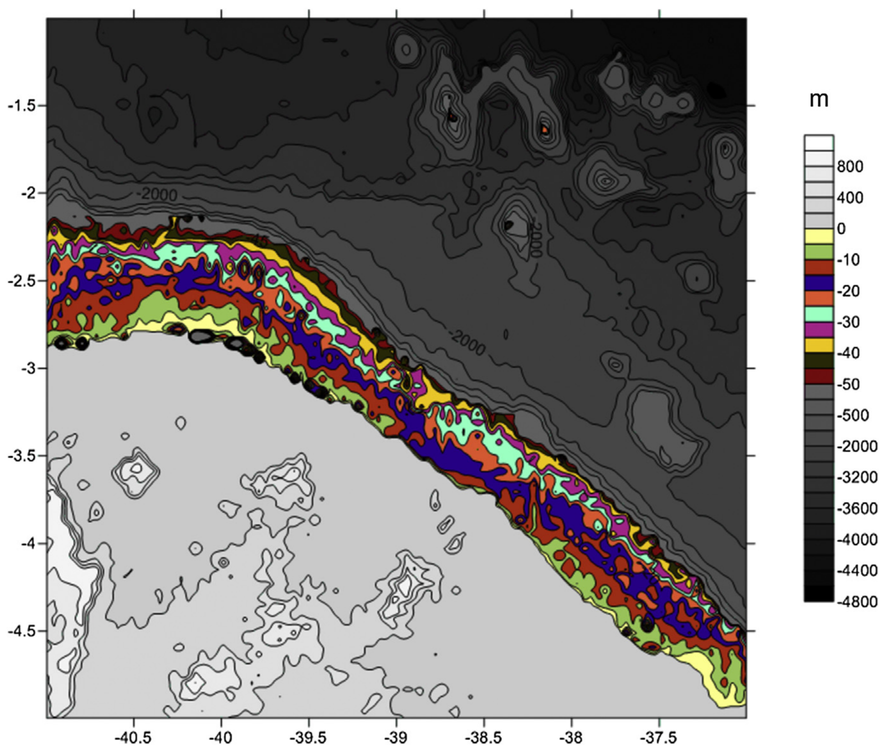

Fig. 14. Bathymetric profile of the coast of Ceará.

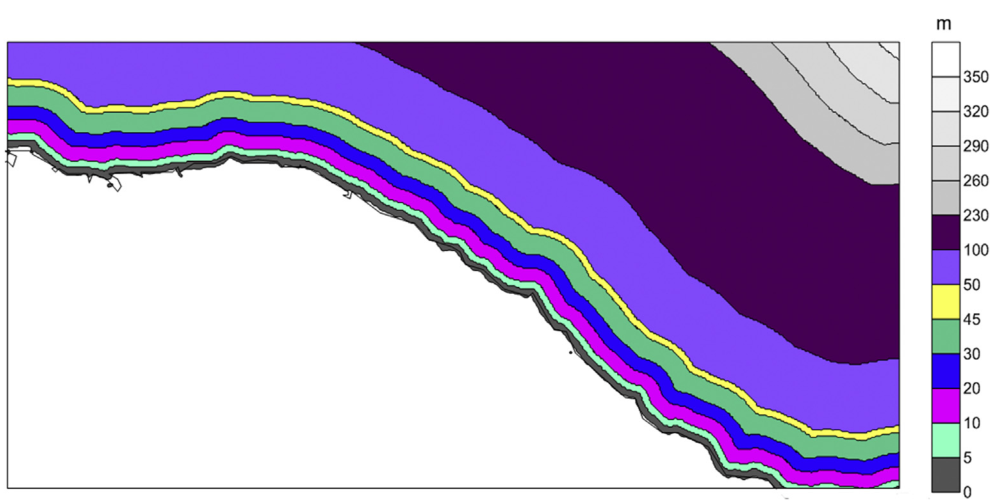

Fig. 15. Distance from the coast.

season of a Neutral year, the estimated average wind speed is above 8 m/s, and the power density between 720 W/m^2 and 1080 W/m^2. In the rainy season, the wind speed has proved lower, however, the investigation has pointed out that in the dry period there is virtually no potential difference in periods of El Niño and La Niña. The predominant wind direction in the observed dry periods was from East to West. Additionally, it was observed in the three events (El Niño, La Niña and Neutral Year) that the intensity of turbulence is higher during the rainy season. Smaller turbulence intensity was found during dry season of El Niño. Besides, the bathymetry of the State of Ceará is shallow and the large ships route is far beyond the coast, offering no danger to future endeavors.

In general, the methodology can be considered useful to the purpose of a preliminary evaluation of the offshore wind potential of the coast of Ceará, thus making it a valuable approach in the investigation of areas with potential for electricity generation from wind farms.

Acknowledgment

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Appendix

This appendix presents the average wind speed, average wind direction, power density and turbulence maps to the episode of El Niño and Neutral year. All estimations are evaluated at 100 m height.

A1. El Niño

Fig. A1(a) and (b) shows the average wind speed estimated in a deemed dry season in Ceará. The figures are very satisfying, with average speed at virtually the entire coast in the range of 8 m/s to 10 m/s.

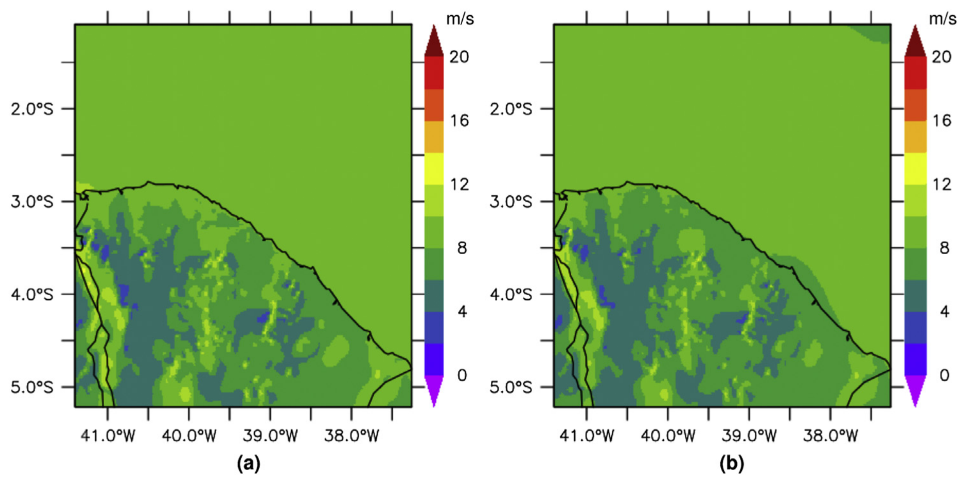

Fig. A1. Average wind speed (m/s) at 100 m in El Niño: (a) in September 1997 (b) in October 1997.

In Fig. A2(a) and (b) are observed that the maximum velocities are in the range of 12 m/s and 16 m/s.

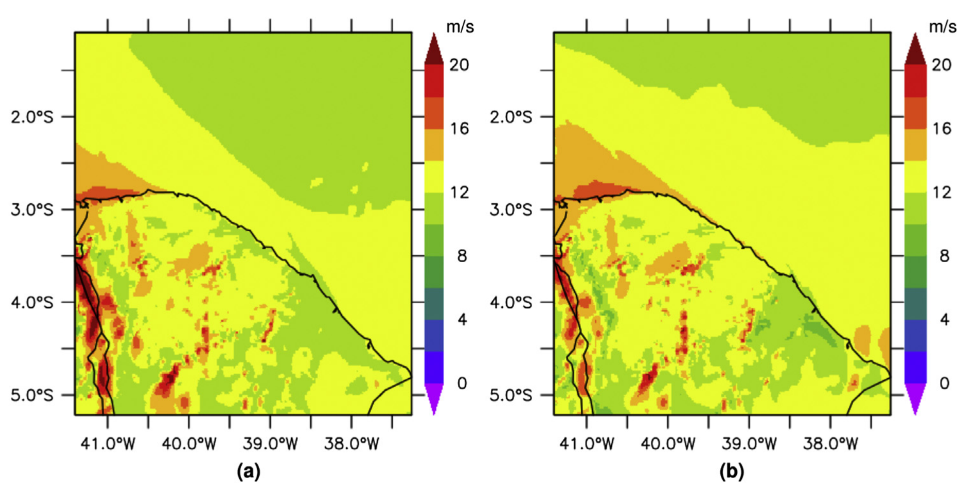

Fig. A.2. Maximum wind speed (m/s) at 100 m high in El Niño: (a) in September 1997 (b) in October 1997.

Fig. A3(a) and (b) shows the average wind speed estimated in March and April 1998, respectively. These months are regarded rainy period in Ceará. The estimated average wind speeds in March 1998 are in the range of 4 m/s to 6 m/s, while in April 1998 in between 4 m/s and 8 m/s.

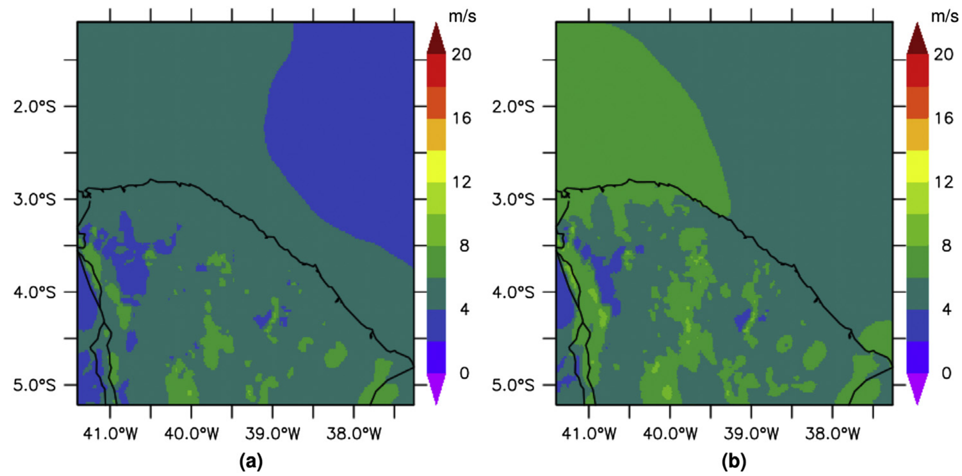

Fig. A3. Average wind speed (m/s) at 100 m in El Niño: (a) in March 1998 (b) in April 1998.

The maximum speed for this period is between 8 m/s and 12 m/s in March and 8 m/s and 16 m/s in April, as shown in Fig. A4 (a) and (b).

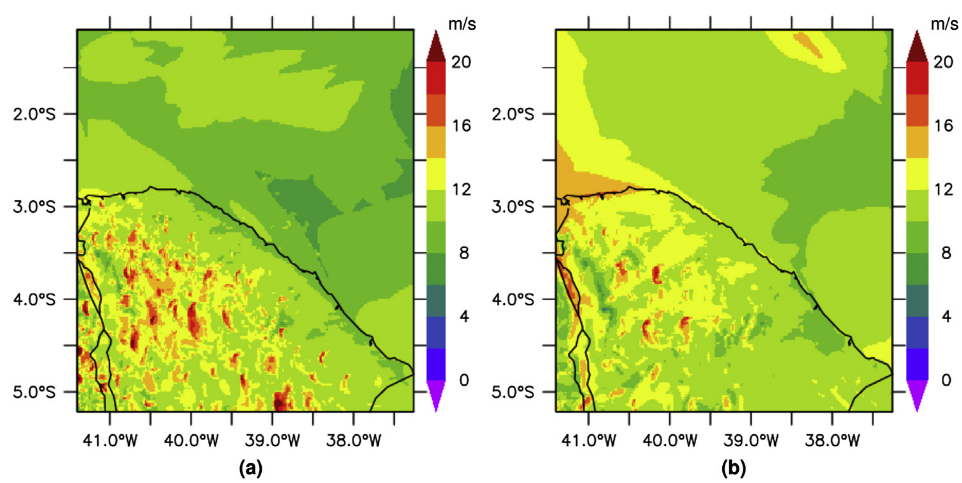

Fig. A4. Maximum wind speed (m/s) at 100 m in El Niño: (a) in March 1998 (b) in April 1998.

Fig. A5(a) and (b) indicate the estimate of the average wind direction on the coast of Ceará for the months of September and October 1997, and Fig. A5(c) and (d) for the months of March and April 1998.

The average wind direction, in September and October 1997, prevails from East to West, while in March 1998 from the sea to the mainland, with a trend from Northwest to Northeast, and in April 1998 from East to West.

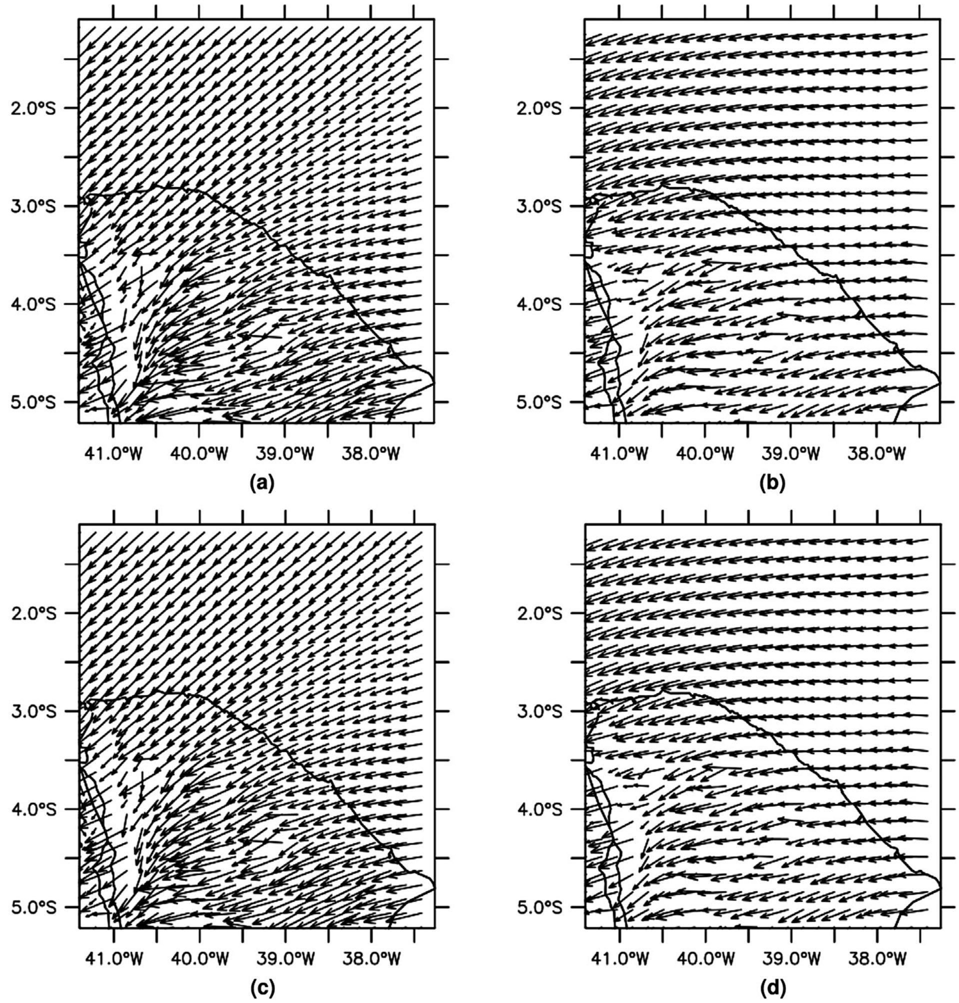

Fig. A5. Average wind direction at 100 m height in El Niño period: (a) in September 1997 (b) in October 1997 (c) in March 1998 (d) in April 1998.

Fig. A6(a) and (b) shows the estimated average power density, in September and October 1997 (dry season). The indicators are under 720 W/m^2.

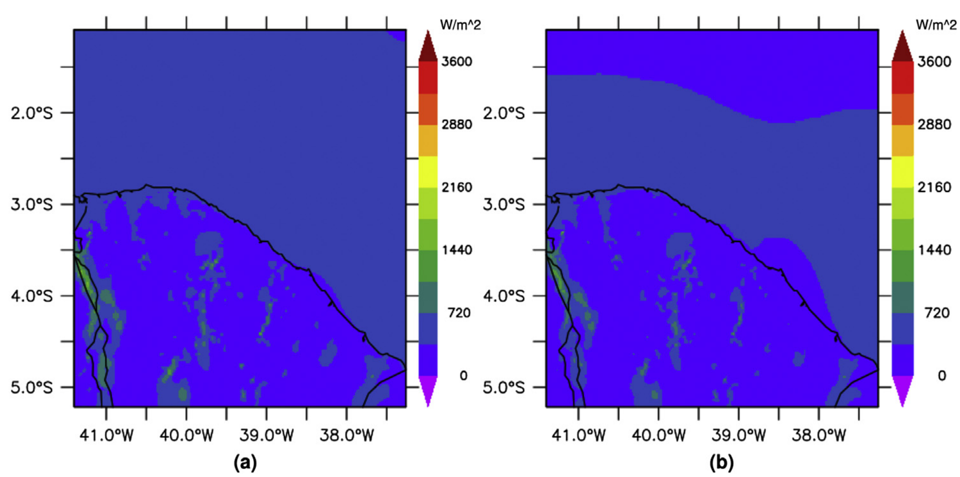

Fig. A6. Average wind power density wind (W/m^2) at 100 m in El Niño: (a) September 1997 (b) October 1997.

The maximum values of power density found in September and October 1997 (dry season) are in between 1080 W/m^2 and 2520 W/m^2, with higher values on the West coast.

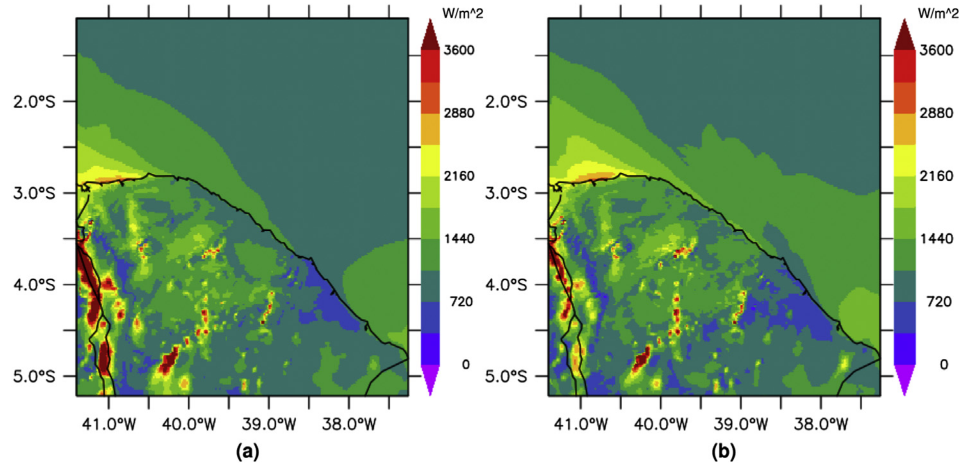

Fig. A7. Maximum wind power density (W/m^2) at 100 m in El Niño: (a) September 1997 (b) October 1997.

Similarly, Fig. A8(a) and (b) shows the estimation of the average power density, in March and April 1998 (rainy season). The figures found are under 360 W/m^2.

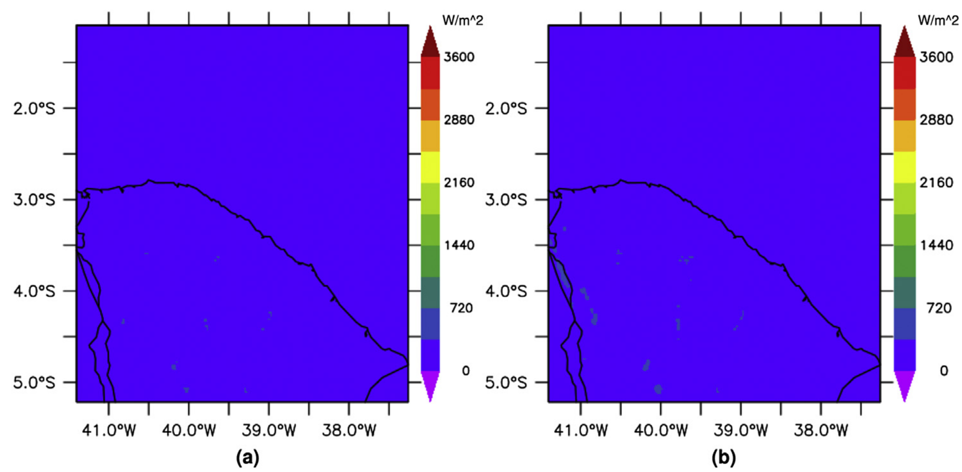

Fig. A8. Average power density of the wind (W/m^2) at 100 m in El Niño: (a) March 1998 (b) April 1998.

The maximum values of power density found in March and April 1998 are above 720 W/m^2, reaching 2160 W/m^2 in April on the West coast of the State (Fig. A9(a) and (b)).

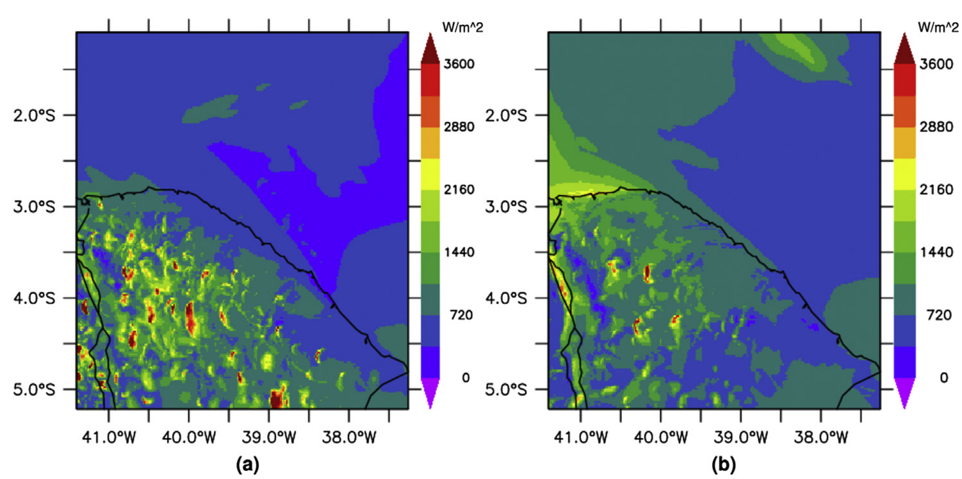

Fig. A9. Maximum power density of the wind (W/m^2) at 100 m in El Niño: (a) March 1998 (b) April 1998.

The map of turbulence intensity are shown in Figs. A10 and A11. The estimated turbulence was higher in the rainy season (March–April).

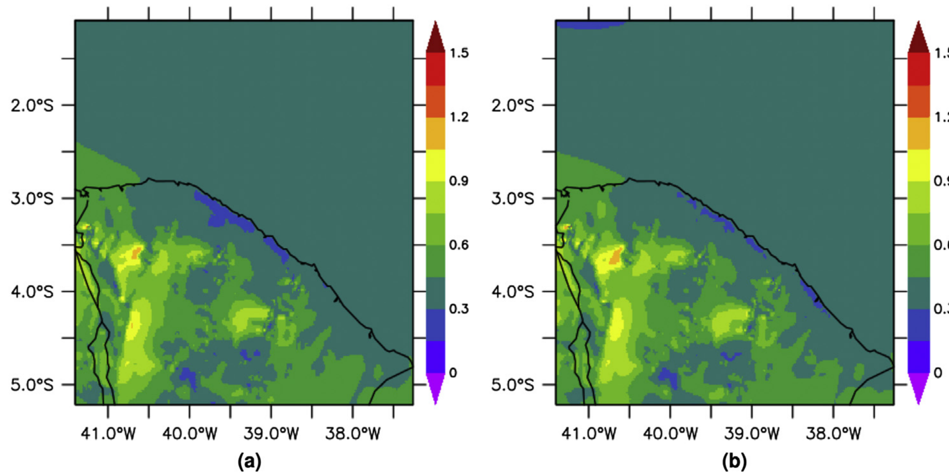

Fig. A10. Turbulence of the wind at 100 m in El Niño: (a) September 1997 (b) October 1997.

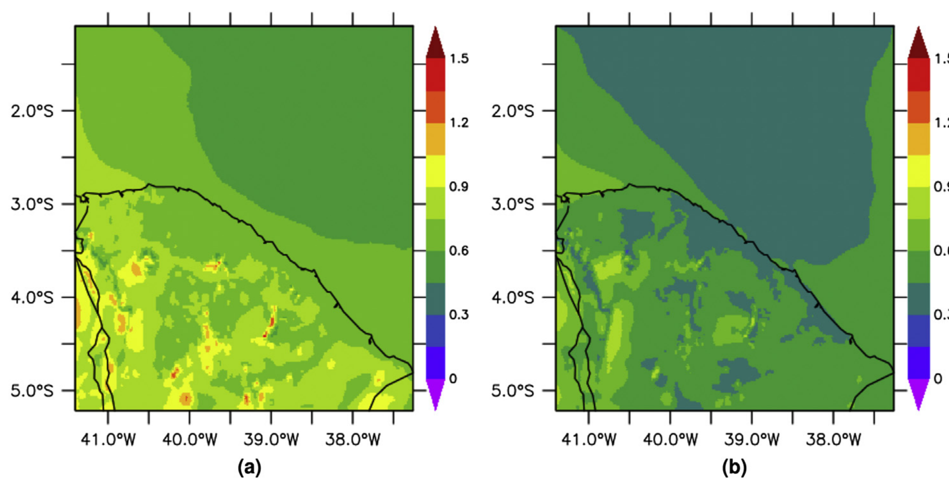

Fig. A11. Turbulence of the wind at 100 m in El Niño: (a) March 1998 (b) April 1998.

A2. Neutral year

The average wind speed are shown in Fig. A12(a)–(b). The estimated wind speed in September and October 2001 are very suitable with average values at virtually the entire coast in the range of 8 m/s to 12 m/s.

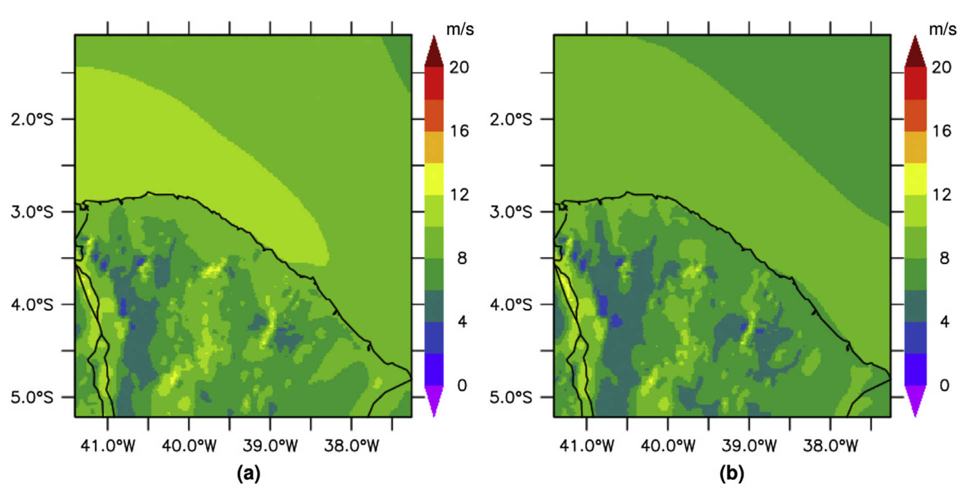

Fig. A12. Average wind speed (m/s) at 100 m in Neutral year: (a) in September 2001 (b) in October 2001.

The maximum wind speed (Fig. A13(a)–(b)) in the same period of dry season in a Neutral year are in between 12 m/s and 18 m/s with higher values on the West coast.

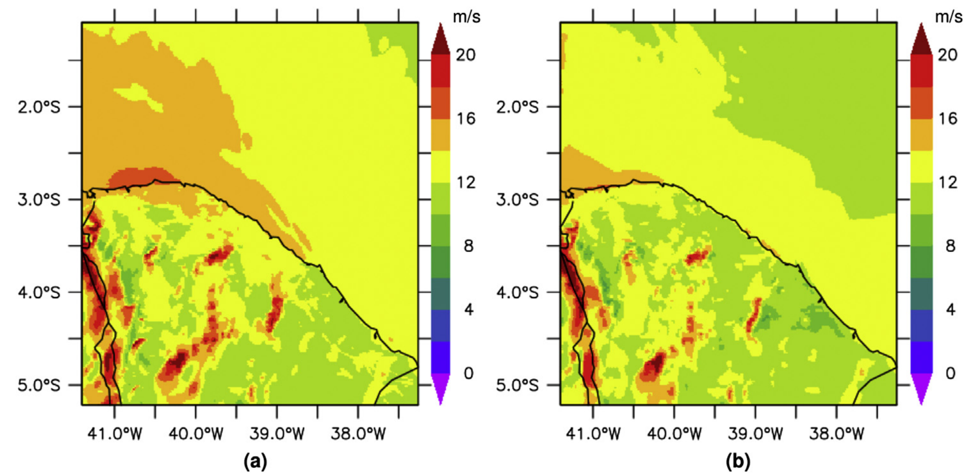

Fig. A13. Maximum wind speed (m/s) at 100 m in Neutral year: (a) in September 2001 (b) in October 2001.

Fig. A14(a) and (b) shows the average wind speeds in March and April 2002, respectively. The estimated average wind speed are in the range of 4 m/s to 8 m/s. The maximum wind speed are pictured in Fig. A15 for the same period.

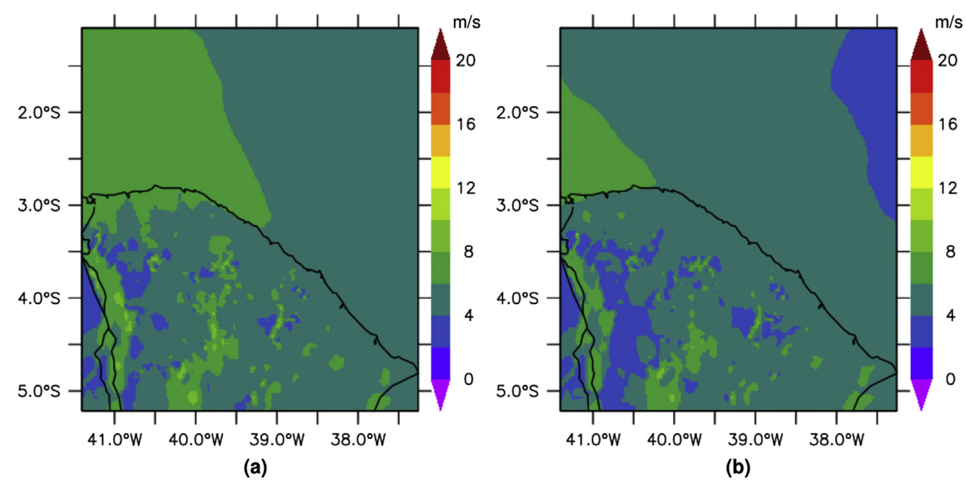

Fig. A14. Average wind speed (m/s) at 100 m in neutral year (a) in March 2002 and (b) in April 2002.

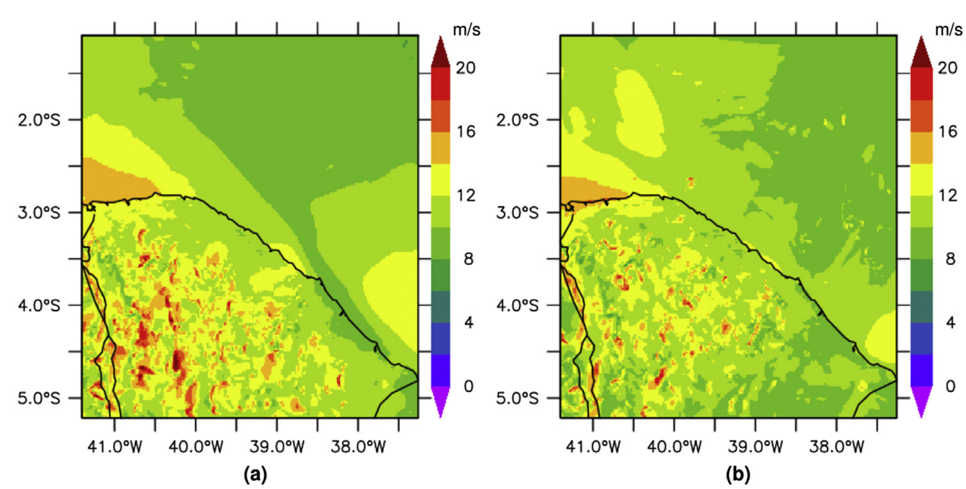

Fig. A15. Maximum wind speed (m/s) at 100 m in Neutral year (a) in March 2002 and (b) in April 2002.

The average wind direction in September and October 2001 are indicated in Fig. A16. Fig. A16(a)–(b) and Fig. A16(c)–(d) show the months of March and April 2002. The average wind direction in both two-months prevails from East to West.

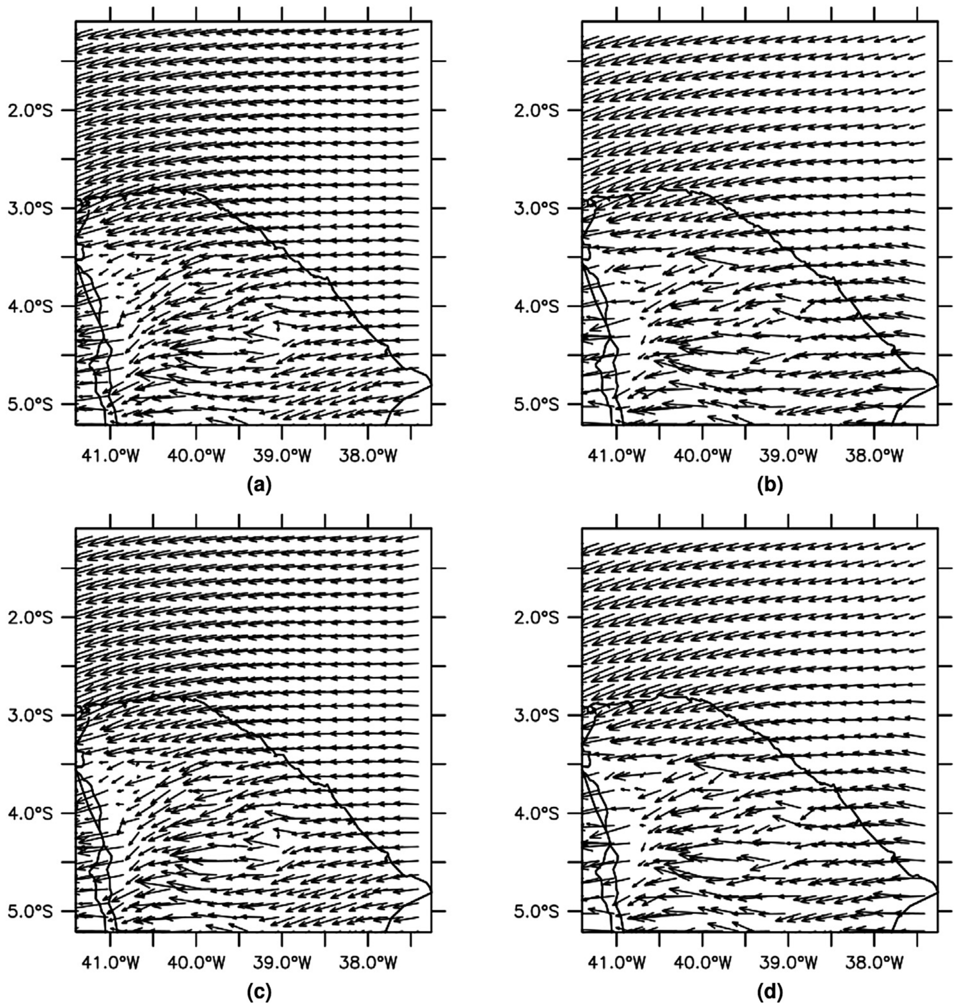

Fig. A16. Average wind direction at 100 m height in Neutral year period: (a) in September 2001 (b) in October 2001 (c) in March 2002 (d) in April 2002.

Fig. A17(a)–(b) and Fig. A18(a)–(b) show the average power density and the maximum wind speed, respectively, in September and October 2001 in the State of Ceará.

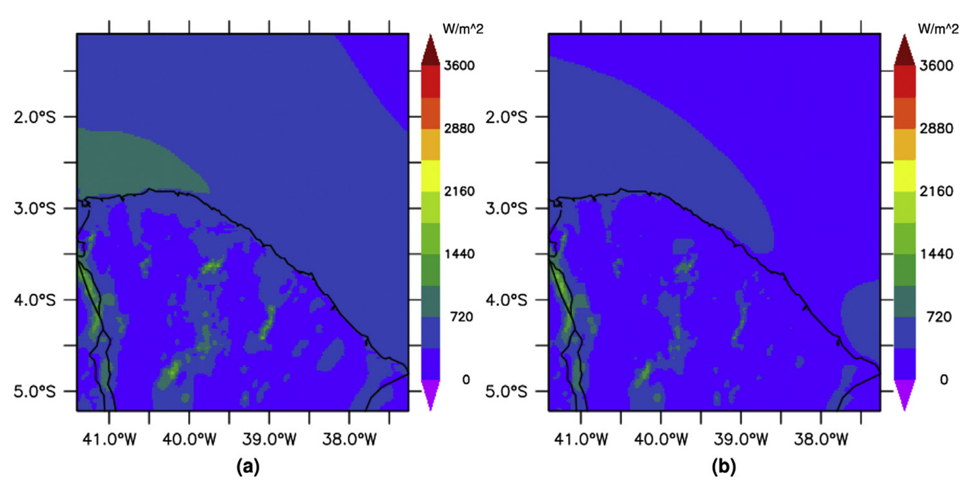

Fig. A17. Average power density of the wind (W/m^2) at 100 m in Neutral year: (a) September 2001 (b) October 2001.

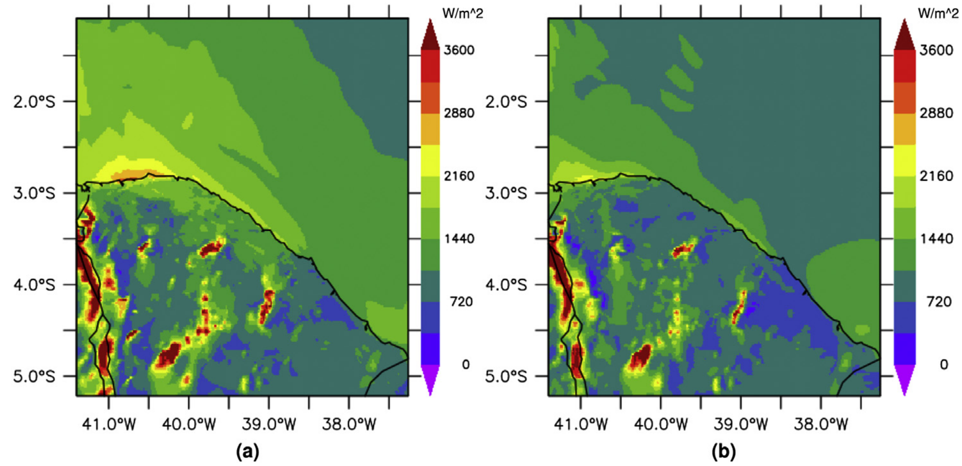

Fig. A18. Maximum power density of the wind (W/m^2) at 100 m in Neutral year: (a) September 2001; (b) October 2001.

Similarly, Fig. A19 (a) and (b) show the average power density in March and April 2002. The maximum power density is shown in Fig. A20(a)–(b). Mean values for power density found in September and October 2001 are in the range of 720–1080 W/m^2, though in March and April 2002 are below 360 W/m^2.

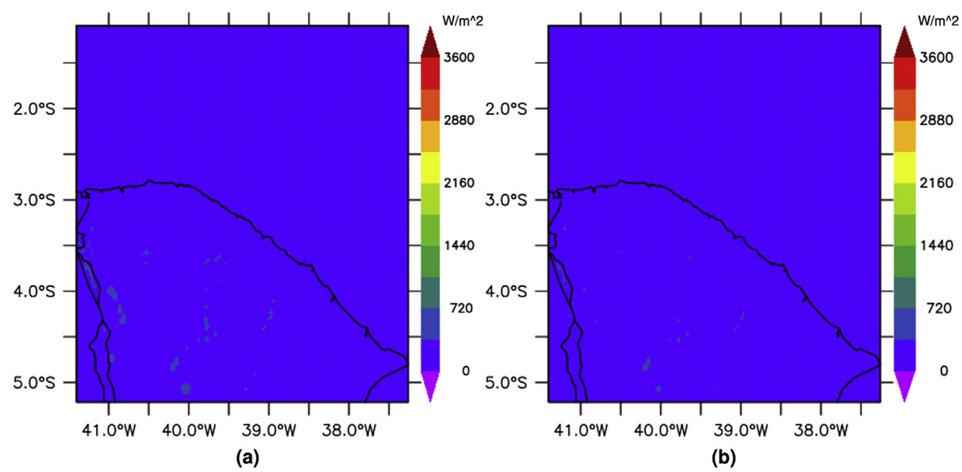

Fig. A19. Average power density of the wind (W/m^2) at 100 m in Neutral year: (a) March 2002 (b) April 2002.

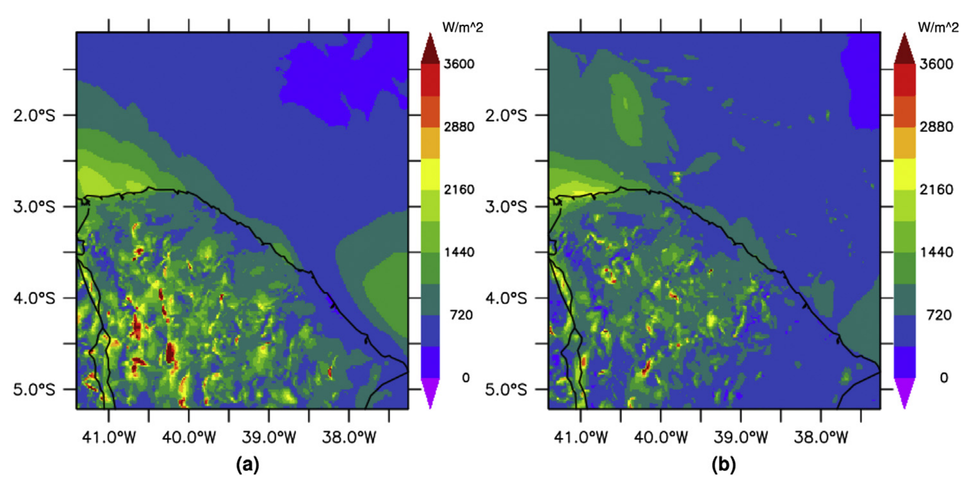

Fig. A20. Maximum power density of the wind (W/m^2) at 100 m in Neutral year: (a) March 2002 (b) April 2002.

Fig. A21 and A.22 draw the turbulence intensity in a Neutral year, higher during the rainy season and in the West coast of the State.

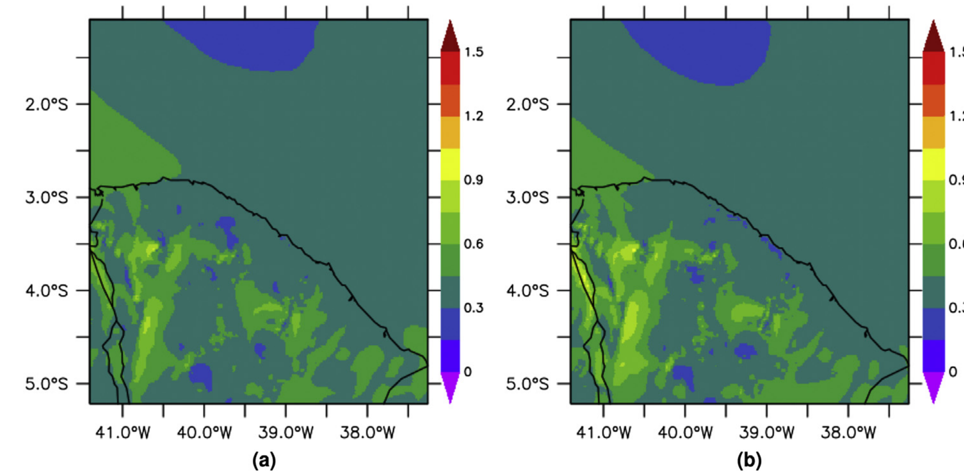

Fig. A21. Turbulence of the wind at 100 m in Neutral Year: (a) September 2001 (b) October 2001.

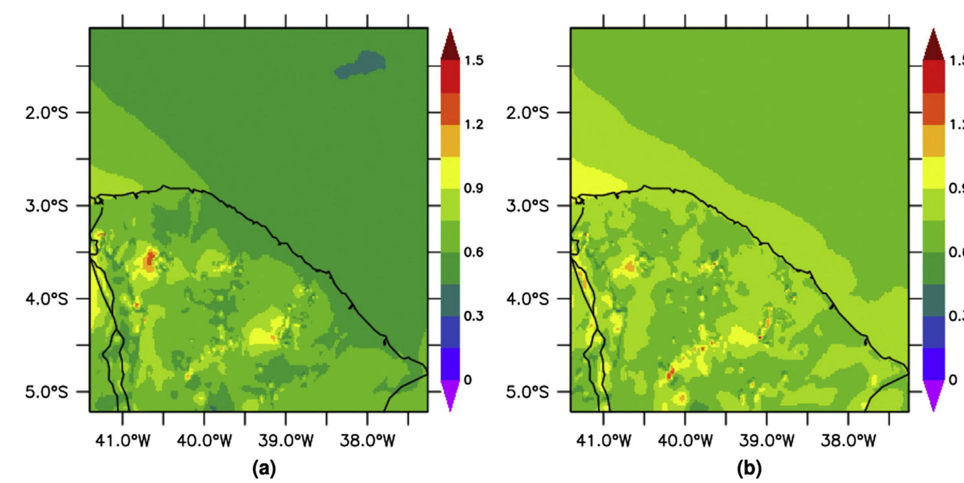

Fig. A22. Turbulence of the wind at 100 m in Neutral Year: (a) March 2002 (b) April 2002.

A3. Final remarks

The average wind speed is above 8 m/s in any of the periods evaluated (El Niño, La Niña and neutral), in the dry season. However, in the rainy season the estimated average wind speed presents best response in Neutral year, above 6 m/s.

The average power density showed similar pattern during the rainy season in all three evaluated periods. In the dry season, the average power density was a degree higher in the episode of La Niña.

As for the average direction of wind speed, one can observe a more stable direction offshore when compared to onshore. In Neutral year, however, prevails East-West wind direction in all three periods.

The intensity of turbulence proved to be greater in the rainy season (El Niño, La Niña and neutral) when minor wind speed was found.

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