Combining meteorological stations and satellite data to evaluate the offshore wind power resource of Southeastern Brazil

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Received 29 September 2007; accepted 15 January 2008

Abstract

Wind is strong and steady over the ocean, but on-site marine meteorological data are sparse for evaluation of oceanic wind power. Here, we draw on meteorological station, satellite data (QuikSCAT), and both theoretical and practical measures of wind turbine performance. The meteorological stations measure directly at high time resolution but low spacial resolution, and provide validation and adjustment of the satellite data. The satellite data provide near-complete spacial coverage at lower time resolution. For the southern coast of Brazil, we use both data sets to evaluate the location, seasonal timing, and availability of the wind power resource. Then, using bathymetry and the properties of current wind-electric technology, we develop maps of wind speed, wind power density, and practical turbine output in power units (MW). In the shallower waters of south Brazil, the most favorable conditions are along the coast between 28°S and 33°S. In just this one coastal area, we find a total resource of 102 GW average electrical production, approximately equal to the electric demand of the entire country.

Published by Elsevier Ltd.

Keywords: Wind power resources; Offshore buoys satellite; QuikSCAT; South America; Brazil

1. Introduction

Recent studies have reported the risk of anthropogenic greenhouse gases to earth’s climate, oceans and ecosystems and in response to this concern governments have been stimulating energy alternatives to fossil fuels [1]. Among renewable sources, wind power is a very large resource, with proven commercial technology and very low CO₂ emissions [2]. It is the fastest growing energy source in the world with more than 74,000 MW installed capacity; led by Germany (20,622 MW), Spain (11,615 MW), US (11,603 MW), India (6270 MW), and Denmark (3136 MW) [3]. Latin America has modest wind energy development, with less than 300 MW of installed capacity. Even in Brazil, the largest Latin American wind developer with 237 MW, wind is only 0.24% of national electrical generation [4]. The Brazilian national program ProINFRA seeks to increase the share of new renewable resources to 10% of annual electricity consumption, now predominantly from hydro- (77%) and fossil-fueled thermal electric (21%).

Brazil’s wind potential has been estimated to be between 60,000 and 143,500 MW over continental areas [4–6]. Recently, more detailed estimations have been performed in different states (see References for data resources) but to the authors' knowledge, the Brazilian offshore wind resources have been until now unknown.

Offshore wind exploration is becoming more feasible and different initiatives have succeeded in Europe [e.g. 7,8]. In comparison to a land site offshore winds are attractive because they have greater speeds and fluctuate less due to the absence of physical barriers such as mountains, buildings, and vegetation [9,10]. Resources are also presumably very large and near populated coastal centers. (These advantages must be weighted against the generally higher cost of installation in water.) In the US, it is estimated that offshore wind resources in the shallow Middle-Atlantic Bight (330 GW average output) surpass by several times the average electrical demand of the corresponding coastal states (73 GW) [11]. Two initiatives
for offshore wind development are currently in the permitting phase in the US East coast.\(^1\) In Europe, a “Super-Grid” has been recently proposed to connect the many anticipated offshore wind farms from the Baltic and North Seas to the Atlantic and Mediterranean [12].

While the methods for evaluating wind resources over land are reasonably well established [13]; there is presently a need for tools to assess offshore wind over large extensional areas. Direct measurements at sea are rare and most countries lack sustained oceanic meteorological towers or buoy observations. But even for well-established programs such as the US National Data Buoy Center (NDBC/NOAA), measurements are usually too separated to provide a proper description of wind fields.

Satellite technologies have revolutionized several areas of earth sciences and the advent of scatterometers has given researchers the capability to explore ocean winds. From scatterometer data, winds are estimated by indirect techniques that relate the ocean roughness to speed and direction through a geophysical model function [14]. Presently, two satellite technologies are being used, the Synthetic Aperture Radar (SAR) and QuikSCAT.

SAR is well designed for detailed mapping of coastal areas and, because of its high-resolution (<100 m), the technology offers a unique way to observe details of circulation such as flow separation and sheltering effects due to islands and mountains [15,16]. SAR has been applied to the estimation of wind resources over small ocean areas and the study of wake effect of wind turbines in the North Sea [17,18].

However, for evaluation of the large-scale distribution of resources, QuikSCAT may be a better alternative. Launched in late August 1999, the mission has presently 7.8 years of near global (90% of ice-free ocean) coverage and its spatial resolution (12.5–50 km) is reasonable for mapping of continental shelf wind resources, if small-scale details are not needed. Additionally, its products are continuously collected, with readings approximately daily, and are freely available to the public [14,19]. QuikSCAT information has been of critical importance for practical applications, such as weather prediction and wave forecasting [20,21] and has also helped the wind speed retrieval for SAR [15,22]. Up to now, we find no published report using QuikSCAT to estimate wind resources over large areas of the ocean. Compared with satellite data sources, meteorological stations have limited spatial coverage. Of the two satellite data resources, SAR is not available in processed form for large geographical areas, nor is it available daily over long time durations.

Here, we evaluate the distribution of offshore wind resources near one of the most populated centers of Brazil, the southern and southeastern coasts. Five state capitals, including Rio and São Paulo, are located in this sector. Populated centers from Mercosur, such as Montevideo, Buenos Aires, and Asunción are also in this region—the population density and the region’s heavy electrical load can be inferred from a sky night brightness image (Fig. 1).

Our first objective is to investigate whether QuikSCAT can be used to map wind energy properties over this large oceanic extent. Then, combining bathymetric data, satellite and offshore meteorological observations, we make a first-cut evaluation of the wind power resource for the southern Brazil area.

2. Data set and methods

2.1. Wind data

Direct measurements from meteorological stations within the study area were obtained from two offshore stations (Fig. 2). The first, located in the South Brazil Bight, measured winds at 78 m height from an oil platform from Petrobrás (hereafter station B1). The second is a meteorological buoy located in the Southern Brazilian Shelf and maintained by the Hydrographic Center of the Brazilian Navy (DHN) (station B2). Site B1 covered 6 months of data, including 90 days in the summer of 1994 and 90 days for the winter of 1998. The meteorological buoy B2 covered about 3 years of measurements. Their geographical position, time coverage and height of wind measurements are in Table 1.

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\(^1\)Cape Cod, MA by Cape Wind Associates and Delaware by BlueWater Wind.
Besides the meteorological towers and buoys within the study region, we further selected 12 North American stations from NDBC\(^2\)/NOAA and five buoys from the PIRATA\(^3\) array [23] (Figs. 4a and b and Table 4). These stations provide meteorological buoy data to compare with QuikSCAT data in Section 2.3.

The remotely sensed data is derived from the NASA QuikSCAT satellite, which estimates near-surface wind speed at 10 m height by measuring the ocean’s surface roughness with a scatterometer. The data set we use is a global database processed by the Department of Oceanography from Space (LOS/CERSAT) of the French Research Institute for Exploitation of the Sea (IFREMER).\(^4\) The QuikSCAT Mean Wind Field (MWF) from IFREMER is computed from individual scatterometer observations provided by the Jet Propulsion Laboratory (JPL/PO.DAAC)\(^5\) (Level 2B data) and is analyzed to a 0.5 × 0.5 (50 km × 50 km) global grid [19]. The database covers 7.8 years of data (August 1999 to June 2007) with daily time resolution. The true time resolution depends on orbital patterns. For most days two swaths (orbits) are available, thus two observations during a day, but on some days one and sometimes none are available. The method of Kriging is employed to interpolate the data within a grid cell; in particular, when more than one swath is present, the mean value is given. If land is detected anywhere within the grid cell, no mean wind speed is computed.

### 2.2. Methods

Meteorological wind data are taken near the surface, or at meteorological tower height (5–20 m). In wind energy studies, we are usually interested in wind at the height of the hub of a wind turbine (70–100 m), and in this article, we calculate wind speed as well as the energy content at hub height. In order to estimate speed at the hub height over water we will make use of the so-called log-law. We assume neutral stability of the atmosphere and a surface roughness of \(z_0 = 0.2\) mm, recommended as an average value for calm and open seas [24,25] (Theoretical development of a time- and location-specific value of \(z_0\) is underway [10]). The log-law states that a velocity \(V\) at a given height \(z\) is

\[
V = V_{ref} \frac{\ln(z/z_0)}{\ln(z_{ref}/z_0)} \tag{2.0}
\]

where \(z_{ref}\) is the height of our measured wind speed \(V_{ref}\). Another quantity of interest is the wind power density \(P\), the energy content of the wind given in units of watts per square meter (W m\(^{-2}\)). This quantity represents the flow of kinetic energy per unit area associated with the wind:

\[
P = \frac{1}{2} \rho V^3 \tag{2.1}
\]

For simplification, we use constant air density, \(\rho = 1.225\) kg m\(^{-3}\). Note that the actual power production expected from a wind turbine must also take into account the mechanics of the flow passing through the blades and the efficiency of the rotor/generator. However, power density is a useful measure, because it is independent of

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\(^{3}\)PIRATA. [http://www.pmel.noaa.gov/pirata/](http://www.pmel.noaa.gov/pirata/)


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Please cite this article as: Pimenta F, et al. Combining meteorological stations and satellite data to evaluate the offshore wind power resource of Southeastern Brazil. Renew Energy (2008), doi:10.1016/j.renene.2008.01.012

![Fig. 2. Distribution of wind measurements. Gray-filled circles indicate observations from offshore meteorological stations. Small, faint cross-marks indicate satellite grid points and numbered bullets (Q1–Q58) correspond to QuikSCAT points selected for analysis. Continuous lines indicate isolobaths, at 50 and 100 m.](image-url)
turbine characteristics. For instance, assuming a known swept area, $A$, we can estimate the power production $P_t$ by multiplying Eq. (2.1) by $AC_p$, given the conversion efficiency $C_p$.

In order to provide practical estimations, we will also use the power curves of two wind turbines designed for marine installations, the General Electric 3.6s Offshore (hereafter GE 3.6s) and the REpower Systems 5M (REpower 5M) (Table 2). These horizontal axis turbines are composed of three blades with diameters of 104 m (GE 3.6s) and 126 m (REpower 5M). Their swept areas are 8495 and 12469 m$^2$, respectively. To simplify calculations and exposition, we assume a hub height of 80 m above mean sea level. These turbines have a minimum speed, called the “cut-in” speed, below which they do not produce power. They also have a maximum or “cut-out” speed above which they shut down for self-protection, also not producing power. Their rated capacity is achieved for wind speeds $>14$ m s$^{-1}$ for GE3.6s and $>13$ m s$^{-1}$ for REpower 5M (Table 2). The power curves for the two turbines are plotted as solid lines in Fig. 3. These curves show how much power output is produced at each wind speed; those here were empirically derived (and provided by the manufacturers). We also plot the theoretical upper bound of $P_t$ as dotted lines, calculated as $P_t = PAC_p$ for each turbine area $A$, and $C_p$ of 59.3%. The value of 59.3% represents the Betz efficiency or maximum theoretical efficiency of a turbine rotor [26]. Compared with the theoretical maximum of 59%, about 45% of wind energy is harvested by present technology wind turbines [24, p31].

Turbines like the two illustrated here have been mounted on a tubular steel monopile driven into the ocean bottom; up to 20 m water depth is common practice. Recently, the use of a lattice structure has extended the depth limit to 50 m [27]. Either deeper lattice towers or new floating structures [e.g. 28, 29] may extend beyond the current 50 m water depth limit.

### 2.3. QuikSCAT comparison to meteorological stations

QuikSCAT has been extensively used for research and the technology was validated by prior studies. QuikSCAT swath data have been compared with meteorological buoys located over deep-waters [30] and to coastal buoys located less than 35 km from the coastline [31]. The gridded database we use has previously been compared with oceanic buoys [19]. Offshore comparisons found root mean square errors of 1 m s$^{-1}$ and a slight bias of QuikSCAT to overestimate both weak and strong winds [30, Fig. 3]. Coastal buoy comparisons indicated rms errors of 1.4 and $3.2$ m s$^{-1}$ for swath and gridded data sets, respectively. QuikSCAT winds overestimate buoy wind speeds by $0.5$ m s$^{-1}$ [31]. A similar bias ($0.35$ m s$^{-1}$) was found for QuikSCAT MWF product [19]. All these studies found Table 2 Turbine characteristics for the example wind turbines, the GE 3.6s and Repower 5M

<table>
<thead>
<tr>
<th>Operating data</th>
<th>GE 3.6s</th>
<th>RE 5M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity (kW)</td>
<td>3600</td>
<td>5000</td>
</tr>
<tr>
<td>Cut-in speed (m s$^{-1}$)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Cut-out speed (m s$^{-1}$)</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Rated speed (m s$^{-1}$)</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
<td>104</td>
<td>126</td>
</tr>
<tr>
<td>Swept area (m$^2$)</td>
<td>8495</td>
<td>12469</td>
</tr>
</tbody>
</table>

6The GE 3.6s is not in production, but data are publicly available for it and it is comparable to 3 MW marine turbines available from other companies such as Vestas and Siemens.

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errors well within QuikSCAT specifications for wind speed ($\pm 2\text{ m s}^{-1}$) [14].

The only offshore station present in our study area with simultaneous measurements to QuikSCAT mission was the buoy B2 (Fig. 2). This station wind speed data from B2 is plotted along with winds from the closest QuikSCAT grid point for a period of 180 days in Fig. 4c. The graph illustrates the high agreement between the data sets, with a correlation coefficient of $R = 0.81$. The fluctuations of buoy data (thin line) around QuikSCAT readings (thicker line) suggest that the small disagreement is due to the known time resolution difference between the data sets.

In order to provide more data points for comparison, we supplemented station B2 with other offshore stations, adding 12 NDBC buoys off North America and five PIRATA buoys [23] off northern Brazil (Fig. 4a and b). NDBC and PIRATA buoy observations, along with the offshore Brazilian buoy data (B2), were converted to 10 m height (assuming $z_o = 0.2\text{ mm}$) for comparison to QuikSCAT. The closest QuikSCAT grid point was matched to each meteorological station position (average distance was 17.5 km). Because the two have different time resolutions (hourly versus daily) they were matched by interpolating the buoy data to the time of measured QuikSCAT winds. The resulting database had 32,934 daily wind speed pairs, which are plotted as a scatter diagram in Fig. 4d. These pairs correlate at $R = 0.83$. The correlation is somewhat improved if we use temporal averages, being $R = 0.88$ for daily means and $R = 0.91$ for a 3-day average. Like earlier studies, we also observed a small tendency for QuikSCAT winds to overestimate the meteorological station observations, the mean error being $-0.45\text{ m s}^{-1}$ (overall rms error was 1.96 m s$^{-1}$).

It is sometimes stated that QuikSCAT cannot be used for near-coast estimations. We find the rms error to be near $2.2\text{ m s}^{-1}$ for all stations located up to 100 km from the coastline; rms errors were very similar for coastal stations at 14 compared with 100 km, while rms error was about $1.5\text{ m s}^{-1}$ for those much further offshore ($\sim500$ km) (from Table 3). The larger rms of coastal stations is associated with the complexity of coastal winds, which demonstrate more high-frequency energy and more spacial variability.
Nevertheless, we find that the errors are only slightly higher for the near-coastal areas (2.2 versus 1.5 m s\(^{-1}\)). In order to reduce part of the observed bias, we performed a regression between QuikSCAT velocities and meteorological station mean winds speeds were on average 3.7% or at most 9.7%. Power density error varied from 3.5 to 106 W m\(^{-2}\) being on average 8.7% of meteorological observations. For turbine power (GE 3.6s), the mean errors were typically on the order of 7.1%, with the larger differences of mean values on the order of ~200 kW (compared with ~1400 kW average power) (Table 4). Results show that QuikSCAT provides a useful measure of wind speeds and wind power derived quantities over the ocean for purposes not requiring time resolution greater than daily or spatial resolution higher than 25–50 km. In particular, since errors approximately cancel (especially after our correction), QuikSCAT appears to be a valuable tool for offshore wind resource assessments.

### Table 3

Computed difference wind speed based on buoy observations and those from QuikSCAT (prior to adjustment)

<table>
<thead>
<tr>
<th>Station</th>
<th>Dist (km)</th>
<th>Mean</th>
<th>rms</th>
<th>(\langle\text{rms}\rangle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41004</td>
<td>14</td>
<td>−0.2</td>
<td>2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>FPSN7</td>
<td>23</td>
<td>−0.9</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>CHLV2</td>
<td>25</td>
<td>−0.2</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>46082</td>
<td>26</td>
<td>−1.0</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>46028</td>
<td>30</td>
<td>−0.5</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>44009</td>
<td>33</td>
<td>−0.3</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>41009</td>
<td>49</td>
<td>−0.6</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>41008</td>
<td>58</td>
<td>−0.5</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>46029</td>
<td>85</td>
<td>−0.9</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>100</td>
<td>−0.5</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>497</td>
<td>0.1</td>
<td>1.3</td>
<td>1.5</td>
</tr>
<tr>
<td>T3</td>
<td>503</td>
<td>0.1</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>532</td>
<td>0.2</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>545</td>
<td>0.0</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>46002</td>
<td>659</td>
<td>−0.4</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>668</td>
<td>−0.7</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>46059</td>
<td>746</td>
<td>−0.4</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>46005</td>
<td>751</td>
<td>−0.2</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>

The error mean, root mean square (rms) and the distance from coastline (dist) are indicated. \(\langle\text{rms}\rangle\) represents the average rms.

### Table 4

Buoy and satellite wind speeds comparisons, after QuikSCAT adjustment (see text)

<table>
<thead>
<tr>
<th>Station</th>
<th>Coordinates</th>
<th>Mean speed (m s(^{-1}))</th>
<th>Power density (W m(^{-2}))</th>
<th>GE 3.6 (kW)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitude</td>
<td>Latitude</td>
<td>Dist</td>
<td>Met</td>
<td>Quik</td>
</tr>
<tr>
<td>41009</td>
<td>−80.17</td>
<td>28.50</td>
<td>49</td>
<td>6.21</td>
<td>6.53</td>
</tr>
<tr>
<td>46082</td>
<td>−143.42</td>
<td>59.68</td>
<td>26</td>
<td>6.91</td>
<td>7.52</td>
</tr>
<tr>
<td>41004</td>
<td>−80.87</td>
<td>31.40</td>
<td>58</td>
<td>6.21</td>
<td>6.35</td>
</tr>
<tr>
<td>44009</td>
<td>−74.70</td>
<td>38.46</td>
<td>33</td>
<td>7.07</td>
<td>7.03</td>
</tr>
<tr>
<td>FPSN7</td>
<td>−77.59</td>
<td>33.49</td>
<td>23</td>
<td>7.31</td>
<td>7.84</td>
</tr>
<tr>
<td>41004</td>
<td>−79.09</td>
<td>32.50</td>
<td>14</td>
<td>7.19</td>
<td>7.09</td>
</tr>
<tr>
<td>CHLV2</td>
<td>−75.71</td>
<td>36.91</td>
<td>25</td>
<td>6.82</td>
<td>6.74</td>
</tr>
<tr>
<td>46002</td>
<td>−130.27</td>
<td>42.60</td>
<td>659</td>
<td>7.82</td>
<td>7.89</td>
</tr>
<tr>
<td>46005</td>
<td>−131.02</td>
<td>46.05</td>
<td>751</td>
<td>8.08</td>
<td>7.91</td>
</tr>
<tr>
<td>46059</td>
<td>−130.00</td>
<td>39.78</td>
<td>746</td>
<td>7.50</td>
<td>7.52</td>
</tr>
<tr>
<td>46028</td>
<td>−121.89</td>
<td>35.74</td>
<td>30</td>
<td>7.00</td>
<td>7.14</td>
</tr>
<tr>
<td>46029</td>
<td>−124.51</td>
<td>46.14</td>
<td>85</td>
<td>6.32</td>
<td>6.93</td>
</tr>
</tbody>
</table>

Wind speed and power quantities computed from meteorological stations (Met), QuikSCAT (Quik), and their difference (Diff = Met−Quik) are indicated. Coordinates refer to meteorological station positions and “Dist” refers to the distance from the QuikSCAT grid point to the coastline. Number of observations is indicated by \(N\) and the percentages (\%) are computed as 100|Diff|/Met.
data source upon which we can base monthly or yearly wind resource estimates.

3. Wind resource

In order to characterize the wind resource, we first use the offshore meteorological stations available in the area to assess wind variability, first as a time series and second from probability distribution functions (pdfs). Then, we use QuikSCAT data to map the wind field over a large coastal ocean area. At last, given bathymetric limits of current ocean tower technologies and considering both wind speed and bathymetry, we calculate an estimate of the region’s practical electrical resource.

3.1. Meteorological station time series

We start by describing the time series from the offshore meteorological station B2, which covers both summer and winter seasons (Fig. 5). The time-series graphs make clear the fluctuating nature of the resource and how that translates into power. In the top graphs of wind speed, we observe the synoptic fluctuation of winds, within a period of 3–5 days (Fig. 5a). The lower dotted line in these figures, at 3.5 m s\(^{-1}\) is the cut-in speed of the REpower 5M turbine; below that, no electricity is generated. The upper dotted line at 13 m s\(^{-1}\) is the “rated speed” or the point the turbine achieves its maximum production. The middle graphs (Fig. 5b) give the wind power density per Eq. (2.1). Because they represent a cubic function of wind speed, the power density peaks in Fig. 5b are higher than peaks in the wind speed in Fig. 5a. The plots in Fig. 5c are the computed electrical output calculated from the machine’s power curve. Because the machine’s electrical output does not increase further above the rated “design speed,” the output fluctuates over a narrower range than might be expected from power density.

As expected, because offshore winds are stronger and less variable than terrestrial ones, the wind fluctuations resulted in relatively few periods of no electrical generation. Wnd speeds were usually above the cut-in speed of these turbines, which resulted in almost continuous power production, but not at a constant power level. Frequently wind speeds were above the rated design speed, yielding maximum power output, sometimes for more than a day running (Fig. 5c). Station B2 presented the higher wind speeds, 8.98 m s\(^{-1}\) compared with 7.49 m s\(^{-1}\) for B1 at 80 m height. The calculated power produced was also higher at B2. For example, the REpower 5M produced 2330 kW at B2 and 1598 kW for site B1 (see Table 1, height of 80 m).

3.2. Wind probability distributions

Wind speeds offshore are further analyzed via the probability distributions, based on hourly data from stations B1 and B2. The wind speed histograms for each station is graphed in Figs. 6a and b, along with the best fit...
of a Rayleigh pdf. A comparison of these graphs evidence the predominance of stronger winds for station B2 but does not display the likelihood of winds to blow above a specified speed.

In order to directly access the percentage of time that winds are found above a particular magnitude these pdf curves were integrated and then displayed as cumulative distribution functions (cdfs) in Fig. 6c. From this figure, we can observe how these sites are expected to behave within the limits of turbine operation, shown as thin dashed lines in the same panel. We found that in both stations, winds are expected to exceed turbine cut-in speeds near 85% of the time, meaning they would produce power 85% of the time. They exceed rated wind speeds (and thus produce full rated power) 12.7% of time at B1 and 19.5% at B2. Situations above cut-out turbine wind speeds (25–30 m s\(^{-1}\)) were not observed in this distribution.

In order to obtain practical estimations of turbine generation as described by the properties of each turbine’s power curve shown on Fig. 3, the cdfs of Fig. 6c can be further modified by performing a change of variables [32]. The result is a cumulative probability distribution for each turbine’s power output (Fig. 6d). These curves allow the direct inspection of the fraction of time that at least a determined production is achieved. As an example, REpower 5M turbines would achieve 4000 kW production 16% of the time if placed at station B1, but 29% of the time if placed at B2.

3.3. Mapping the wind and power fields

We demonstrated in the prior sections that offshore meteorological stations provide good point estimations of wind speeds and turbine production. In order to understand the geographical distribution of offshore wind resources along the continental shelf, QuikSCAT is a better data resource, because it has higher spatial resolution and more complete geographical coverage. Here, we use QuikSCAT data from August 1999 to June 2007. The fields shown here followed the procedure outlined on Section 2.3
to reduce the mean wind speed bias from the QuikSCAT data.

Average wind speed maps for the heights of 10 and 80 m above sea level are displayed on Fig. 7, in the top two maps. These fields demonstrate higher wind speeds (>8.6 m s\(^{-1}\) at 80 m height) in the whole southern segment between 28°S and 33°S, compared with the shelf sector along Curitiba and Rio de Janeiro, at 6.8–7.4 m s\(^{-1}\). North of Rio (>23°S) moderately high winds are also found, reaching 8.2 m s\(^{-1}\) off Vitória. (Numbers we cite from Fig. 7 refer to nearer-shore locations; values are even higher beyond the shelf.) The figure also uses white-boxed labels to illustrate that QuikSCAT compares reasonably well to the mean values obtained from the two offshore stations. Stations B1 and B2 show a difference of <0.20 m s\(^{-1}\) for mean wind speed (Fig. 7). The power density, shown in the lower left of Fig. 7, averages between 300 and 450 W m\(^{-2}\) for the northern domain and near 600 W m\(^{-2}\) for south Brazil. Satellite computed field values also compare well with meteorological stations, the differences being <25 W m\(^{-2}\).

In the lower right of Fig. 7, we plot REpower 5M turbine production, computed from the power curve. In other words, for any point on the map, the color or contour line indicates the average power that would be produced if a turbine were placed at that point. The plot identifies the southern shelf (between 28° and 33°S) and the northern coast (between 19° and 22°S) as the better areas for wind power development. Around Santa Marta, an average production of 2200 kW is expected. Station B2 yields 2330 kW, comparing well with QuikSCAT, which estimated ~2300 kW for the same location. Computations for the GE 3.6s turbine (not shown) resulted in 1691 kW for station B2, compared with 1700 kW from QuikSCAT.

Along São Paulo and Rio coasts, turbine production is lower: 1300 kW for the REpower 5M. Strong

Fig. 7. Wind properties’ geographical distribution, based on QuikSCAT winds, averaging August 1999–June 2007. Top left: wind speed at 10 m, top right: wind speed at 80 m, bottom left: wind power density at 80 m, bottom right: REpower 5M mean turbine output power. For all figures, rectangular labels with white background are average values derived from offshore meteorological stations.
cross-shore differences are observed in the south, in the order of \( \sim 500 \text{ kW} \). Although the deepest currently installed offshore turbine tower is rated up to 50 m depth, these maps show that the development of floating or deep-water fixed platforms, placed further out, would access resources on the magnitude of 2600 kW average production (RE-power 5M) in the south and 2200 kW for the northern coast of the domain. These are capacity factors of 52\% and 44\%.

Notice that in this article, we express the output of a turbine, or a field of turbines, as ‘average output’ expressed in electrical power units (kW or MW). The power industry has more typically expressed output in energy units over time (e.g. kWh per year or MWh per year). If energy units are desired, our average output figures can be multiplied by 8760 h year\(^{-1}\). Following Kempton et al. [11], we here use average power rather than yearly energy because we feel this makes it easier to compare output with rated capacity and with load. To express output as average power allows us to use the same units, and similar orders of magnitude, for load, capacity, and average output.

3.4. Along-shelf seasonal variability

To focus on the resources that are closer to the coast, shallower and thus practical to exploit with present technology, we further selected 58 QuikSCAT grid points (Q1–Q58) along the coastal extent of our study region, most of which (~90\%) were located between the coast and the 50 m isobath (Fig. 2). We used the same wind fields used on the maps of Fig. 8, but here we divide the 8 years of

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Fig. 8. Along-shelf distributions derived from QuikSCAT winds for Summer (DJF), Fall (MAM), Winter (JJA), and Spring (SON). From top to bottom: wind speed at 80 m, wind power density, GE 3.6s turbine output power, and REpower 5M turbine output power. On the top graph of velocities, the lines are QuikSCAT data and the white circles are meteorological stations. At the base of the top graph, wind classes from QuikSCAT are given by shading of squares. The x-axis here represents our QuikSCAT grid points, ranging from Q1 to Q58. This sequence traverses the study region coast from north to south per Fig. 2.

---
data into Summer (December–January–February or DJF), Fall (MAM), Winter (JJA) and Spring (SON) averages for wind speed, power density, and turbine output. The seasonal comparison is also useful for power planning. Unlike the wide-area field of Fig. 7, Fig. 8 shows only a single transect along the coast, but compares the four seasons using four lines on each graph.

Wind speed at 80 m is plotted in three ways: the two meteorological stations are plotted as open circles (B1 and B2), the wind speed from QuikSCAT is shown by the four lines, and the wind class, also computed from QuikSCAT, is displayed as colored squares along the bottom (Fig. 8, top figure). We find wind classes between 2 and 6 over the entire geographical domain. The highest wind classes, between 5 and 6, are South of 28°S (Q28 and higher), with the best location found between stations Q28–Q35. QuikSCAT reveals that besides the stronger winds, this region has small seasonal variability. In contrast, substantial variability is observed for the northern stations (Q1–Q12). Wind power density (second from top in Fig. 8) ranges from 100 to 800 W m⁻².

Graphing turbine output along-shelf gives numbers that can be related to power planning. Actual turbine power output, for the REpower 5M, ranges from 800 to 2500 kW. South Brazil stands out as the largest and most continuous resource, with expected near-shore turbine output varying from about 1800 kW during Summer and Fall to almost 2500 kW for Spring.

### 3.5. Potential power resource

In order to obtain an initial evaluation of the offshore wind resources in the practical terms of the power industry, we need to account for three major aspects: (1) the area occupied by each wind turbine, (2) shelf area at practical depths, and (3) mean turbine power production. We applied the procedure outlined by Kempton et al. [11]. Per textbook recommendation [24], we allocate spacing of 10-rotor diameters downwind and 5 crosswind, in order to minimize inter-turbine wake losses. In the occupied area of ocean, this corresponds to 0.54 km² per GE 3.6s turbine and 0.79 km² per REpower 5M.

Within the area whose wind we have analyzed, we examine bathymetric maps of the coastal waters from approximately the border with Uruguay to Florianópolis. This is the more energetic area, from stations Q27 through Q42, as seen by Figs. 2 and 8.

The bathymetric relief, computed from Brazilian nautical charts, evidences a wide (~100 km) and long (~850 km) continental shelf (Fig. 9). A total area of 77,848 km² was computed from our grid, which was partitioned into 9688 km² located between the isobaths of 0 and 20 m, 26,992 km² between 20 and 50 m, and 41,168 km² between 50 and 100 m (Table 5).

We then estimated the total power output, if this entire region were fully exploited. The calculation is very simplified. We assume an average power production relative to southern station B2, which was close to 1.5 MW per GE 3.6s and 2.2 MW per REpower 5M turbine, per Table 1 and Fig. 6. On this basis, we calculated that the wind-electric resource between the shore and the 20 m isobath is 27 GW average power output. By extending the offshore limit to 50 m, the wind power resource grows to 102 GW (Table 5).

We have not analyzed exclusion areas such as shipping lanes, marine conservation sites, commercial fishing or consistency of bottom geology with pile-driven foundations. Recent work in the highly populated US East Coast

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Table 5

<table>
<thead>
<tr>
<th>Shelf area (km²)</th>
<th>0–20 m</th>
<th>20–50 m</th>
<th>50–100 m</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE 3.6s turbines (count)</td>
<td>17941</td>
<td>49985</td>
<td>76237</td>
<td>144163</td>
</tr>
<tr>
<td>GE 3.6s average output (GW)</td>
<td>27</td>
<td>75</td>
<td>114</td>
<td>216</td>
</tr>
<tr>
<td>RE 5M turbines (count)</td>
<td>12263</td>
<td>34167</td>
<td>52111</td>
<td>98542</td>
</tr>
<tr>
<td>RE 5M average output (GW)</td>
<td>27</td>
<td>75</td>
<td>115</td>
<td>217</td>
</tr>
</tbody>
</table>

Depth ranges are selected based on current and near-term technology limitations [11].

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Fig. 9. Southern Brazilian shelf bathymetry along the coast from Florianopolis past Rio Grande to the border with Uruguay. Continuous lines are the contours of 20, 50, and 100 m.
measured the sum of these exclusions (many of which overlap) as ranging from 10% to 46% [33]. With these simplifications, our estimate of the potential in this one small section of Brazil’s coast is approximately equal to the Brazil’s national electric load expected for 2008, an average of 100 GW load. As another comparison, this offshore resource size is within the range of the wind power potential estimated over the land areas of the entire country, between 60 and 143.5 GW [4–6].

4. Discussion

Our results have shown that QuikSCAT data are complementary to meteorological station observations and can be used to usefully map wind resources in countries with large extensional areas. For Brazil, we find that the offshore winds that blow over the southern and southeastern continental shelves are a strong asset for the country. Forty-seven percent of the ~2442 km coastline has wind resources suitable for economically attractive electric generation (class ≥ 4), with two regions of higher productivity. The high productivity regions are, first, in the northern domain, between the latitudes of 19°S and 23°S, with classes 4 and 5, and second, in the southern region, between 28°S and 33°S, with classes 5 and 6 winds. This last region has two neighboring state capitals and access to three Brazilian ports (Rio Grande, Imbituba, and Itajai), which makes it a promising site for subsequent studies leading toward mobilization and development.

The distribution of resources we found is ultimately linked to the atmospheric systems of the Southeastern Atlantic, where the Subtropical Anticyclone and the Westerlies are the dominant features [34]. The Subtropical Anticyclone dominates in the summer, when prevailing winds blow from east-northeast between 15°S and 35°S. During the winter the east-northeast winds become confined to 20°S and 25°S and to the south the Westerly and Southwesterly winds prevail. The region also frequently receives the incursions of westerly waves and cold fronts, with a period of 3–5 days between passages [35].

The results indicated that Brazil’s offshore resources are promising, situated close to the densely populated coastal cities and have great potential to complement the hydroelectric system. Since most hydroelectric plants can be used for storage of energy by allowing some fluctuation of water level (as has been done with Danish wind and Scandinavian hydro), higher offshore wind power productivity can be used to expand national electrical production, save water from dams and lower the country’s air emissions.

Acknowledgments

We are deeply grateful to Prof. Richard Garvine, who passed away in early December of 2007. Prof. Garvine was the advisor of the first author, close colleague of the second author and a mentor and inspiration for both. His example, dedication to science and the ocean will always guide us. The first author acknowledges the Brazilian CAPES foundation for his support (BEX 2242/03-6). We would like to thank the Meteorology Lab of the University of Rio Grande (FURG), which kindly provided the access to B2 station. We also acknowledge Petrobras for making station B1 available. We thank Oleksiy Kalynychenko for his early suggestion on the use of QuikSCAT data and G Oliveira and KC Wong for helpful comments. Figs. 1 and 3B are reproduced with permission, as noted in the figure captions.

References


