Seasonal variability of the surface solar irradiation in Northeastern region of Brazil

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Abstract

This work aimed at investigating the surface solar irradiation variability and trends in the Northeastern Brazilian region (NEB), relating it with regional climate and environmental characteristics. The statistical analysis used ground data acquired in automated weather stations (AWS) operated by the Brazilian Institute of Meteorology. The results pointed out a remarkable variability in seasonal and annual scales. The cluster analysis provided five regional patterns presenting remarkable temporal complementary regimes for the incoming solar irradiation. The surface solar irradiation achieves the highest average in the Southeastern area of NEB and the lowest average in the Western area in the austral summer. The annual and seasonal trends of the surface solar irradiation were investigated using the Mann-Kendall method and the Sen technique. The surface solar irradiation in the Southeastern area of NEB is decreasing by 50 Wh/m^2/year since 2008. On the other hand, it is increasing around 40/m^2/year in the semi-arid area along the same timeframe.

Keywords: Incoming solar irradiation, Seasonal variability, Cluster analysis, Trend analysis, Northeastern Brazilian region,

1. Introduction

The Brazilian energy mix is based on mostly hydroelectric and thermoelectric power plants (Pereira et al., 2006). The hydropower is around 64% of the total installed power capacity in Brazil, but the climate variability is affecting the power generation due to more frequent and extreme drought events as occurred in 2001-2002 and 2013-2015. As a response to the climate variability and increasing energy demand, the thermal power generation based on fossil fuels has increased over the last years. The consumption of fossil fuels releases greenhouse gases into the atmosphere, especially carbon oxides (Goldemberg and Lucon, 2008).

The solar and wind power generation are valuable alternatives, not only because of the inherent advantages related to energy matrix diversification but also there will be great worldwide pressure to stabilize carbon emissions rate in the atmosphere through reducing the consumption of fossil fuels. Although Brazil has a vast potential for solar energy applications, some studies are pointing the technological issues related to the solar irradiation intermittency due to the weather conditions as significant barrier to the growth of solar energy share in the Brazilian electricity mix (Martins and Pereira, 2011; Ueckerdt et al., 2015; Luis et al., 2018). The solar energy resource will not replace fossil fuels or hydroelectric power in the current Brazilian scenario, but it can be gradually added to complement the existing resources through hybrid and distributed generation systems.

The required data and information on the surface solar irradiation variability to overcome such barrier is still scarce for the Brazilian territory. Several studies faced many limitations due to the small number and uneven spatial distribution of radiometric measurement sites in the Brazilian territory (Martins et al., 2007; Martins and Pereira 2011; Lima et al., 2016). Besides the reliable solar energy assessment recently published (Pereira et al., 2017), the energy sector is demanding reliable short-term forecasts of solar energy variability to support both the planning and operation of the solar generation plants and the country's electricity grid system. (Martins et al., 2008a, b, Pereira et al., 2017).

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In this context, the present work provides information and knowledge on the spatial variability of the surface solar irradiation in the Northeastern region of Brazil (NEB) using ground data acquired by the automated weather stations (AWS) operating in NEB territory from 2008 to 2015. It also aimed at investigating the climatological trends in the surface solar radiation data. The results provide information for several issues of high relevance: better understanding and knowledge on the availability and variability of solar energy resource; supporting the methodology development for solar energy forecasting, and supporting the Brazilian energy sector in planning and operating the Brazilian Electricity System.

2. Methodology

2.1. The Northeastern Brazilian region (NEB)

The Northeastern region of Brazil presents a wide variety of climate and anthropic features affecting the surface solar irradiation. The NEB has around 1.56 million km², corresponding to 18% of the Brazilian territory. The region presents three climates according to Kayano and Andreoli (2009):

- the humid coastal climate is the typical climate in the coastal area;
- the tropical climate occurs in the Western continental area; and
- the semiarid tropical climate occurs in the central area of the NEB.

This topic briefly describes the major issues, but the authors recommend the reading of Cavalcanti et al., (2009) for a more detailed description. The rainfall regime in the NEB is quite complex, and it depends on the prevailing local atmospheric systems, such as the Subtropical Anticyclones, and the South and North Atlantic Ocean Equatorial Trough (Kayano and Andreoli, 2009). The rainfall occurs from February to April in the North of the NEB linked to the Intertropical Convergence Zone (ITCZ) shift toward the south hemisphere (Kousky, 1979; Molion and Bernardo, 2002). The precipitation in the Eastern coast occurs from May to June related to the influence of the tropical air masses and easterly waves disturbances (EWD). It is important to mention that the sea breeze also has a significant contribution to precipitation rates in the coastal areas. Finally, the precipitation in the continental area occurs from November to December due to the influence of frontal systems, local convection, and cyclonic vortices.

The air temperature presents high annual averages with values between 20 °C and 28 °C. The temperature between 24 °C to 26 °C occurs in the low altitudes areas and the eastern seacoast. The surface global solar irradiation is large all year round presenting annual average around 5.5 kWh/m².day. The NEB is the area presenting the highest solar energy potential according to the Brazilian Atlas of Solar Energy (Martins et al., 2008a; Pereira et al., 2017).

2.2. Observational Data

The Brazilian Institute of Meteorology (INMET) provided the ground data acquired from January/2005 to December/2015 in 129 automated weather stations (AWS). The following meteorological parameters were available: atmospheric pressure, air temperature, relative humidity, precipitation, global solar irradiation, and wind data (speed and direction). The acquisition system records data every one-minute, but stores it with a one-hour timestep.

Fig. 1 shows the location of the AWS used for this study in NEB. A quality control procedure was applied to check all ground data. We discarded all AWS presenting less than 70% of the expected solar irradiation data records for one year-round cycle to keep representativeness of the typical seasonal variability of solar irradiation. After that, the ground measurements were checked to identify rare and suspicious data using threshold criteria established by WMO (World Meteorological Organization) for the BSRN (Baseline Surface Radiation Network) measurement sites (Roesch et al., 2011). We discarded all solar radiation data flagged as suspicious to ensure the reliability of observational data used in this study. Finally, statistical analyses were performed to describe the typical daily, monthly and annual conditions in every reliable AWS operating in NEB.

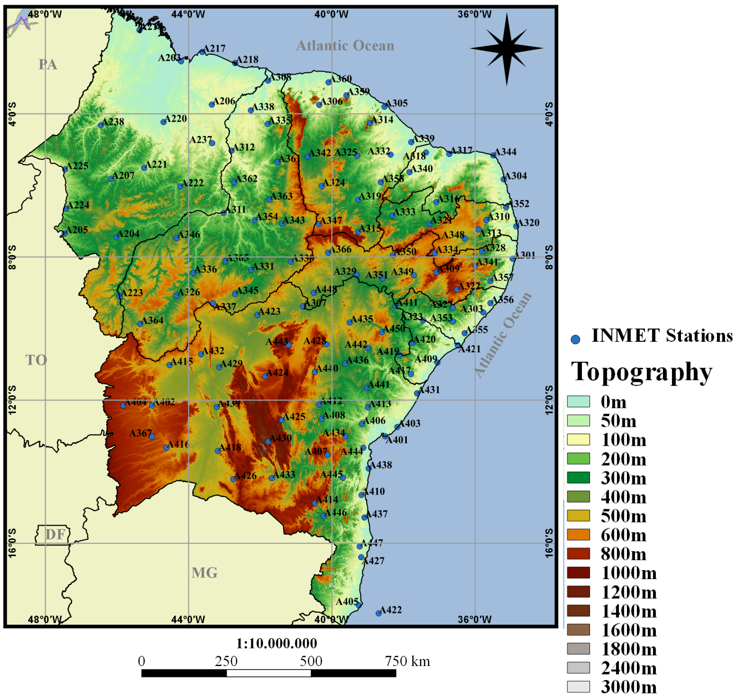

Fig. 1. The orography map shows the spatial distribution of the automatic weather stations operated by the Brazilian Institute for Meteorology (INMET) in the NEB region. Source: Modified from Lima et al. (2019)

2.3. Cluster Analysis Technique (CA)

The Cluster Analysis (CA) was the statistical approach used to identify homogenous regions based on the similarity of the surface solar irradiation's pattern. The CA techniques are commonly classified in hierarchical and non-hierarchical methods. Hierarchical or agglomerative methods merge clusters based on a similarity pattern starting from as many single-element clusters as initial objects and eventually reaching one cluster accommodating all the stations. The results are usually displayed in a dendrogram, from which a cluster solution can be found. Agglomerative hierarchical clustering methods have been fairly widely used in weather and climate applications Bednorz (2008).

For this study, the agglomerative hierarchical Ward method (1963) was the CA techniques used to identify the regions presenting similar patterns of surface solar irradiation. The CA procedure used a data array containing the monthly average values of the surface solar irradiation and the geographical coordinates of each reliable AWS data. The hierarchical cluster analysis follows three steps: calculation of the Euclidean distances between AWS data arrays, determining the AWS clusters in a dendrogram, and then identifying the best similarity threshold to establish the homogeneous regions (Tennant and Hewitson, 2002; Lima et al., 2010, 2016; Paixão et al., 2011).

2.4. Seasonal and Inter-annual Variability and Trend Analysis

The statistical boxplot technique, described by Wilks (2006), was used to evaluate the surface solar irradiation data variability on the homogeneous regions. The boxplot provides a complete statistical description: the average and/or median values, the interquartile range and the asymmetry (the distance between quartiles and median). Several studies have pointed out the Mann-Kendall method as the most appropriate method to investigate the climate trends based on historical datasets of meteorological parameters (Goossens and Beerger, 1986; Santos et al., 2017). In summary, the Mann-Kendall method is a non-parametric test to evaluate whether the null hypothesis that there is no trend in the dataset – each record data is independent and equally distributed.

We also evaluated the slope and scale of the statistical trend using the non-parametric method described by Sen according to expression (Sen 1968; Sneyers 1990). The presence of outliers does not influence the method results, so it provides a more reliable trend evaluation of the time series than the typical linear regression method (Silva and Dereczynski, 2014; Santos et al., 2016). The seasonal analyses were performed assuming the following periods: the austral summer is from December to February (DJF); the fall season is from March to May (MAM); the austral winter is between June to August (JJA), and spring occurs from September to November (SON).

3. Results

3.1. Cluster Analysis

The CA analysis was performed using the geographical coordinates and the monthly average of GHI data as input. Fig. 2 shows the geographical location of the five clustered regions. The map demonstrate a robust spatial matching between the geographical location of the homogeneous regions and the spatial patterns observed in the solar energy resource assessment provided by Pereira et al. (2017). The geographical location of the clustered regions (HR) also reflects the influence of the seasonal meteorological systems and environment features on the surface solar irradiation. The clustered regions 4 and 5 (HR4 and HR5) have a vast territorial extension over the Northeastern backlands where typical climate characteristics and topography do not sustain the development of convective clouds.

The HR4 and HR5 are the ones presenting the highest annual averages of surface solar irradiation as indicated in Fig. 3. By contrast, the lowest averages are observed in the regions HR1 and HR2. The HR2 has the lowest the surface solar irradiation due to the influence of heat and moisture from the Amazon region supporting a more convection activity than any other HR in NEB.

Fig. 3 also provides information on the distinct seasonal cycles in each HR. Three of them (HR1, HR3, and HR5) present seasonal cycles in phase with the maximum (minimum) daily solar irradiation occurring in October/November (June). The other two regions, HR2 and HR4, also get the highest values in September. However, both regions present very low variability during the first six months of the year (5 kWh/m^2) due to the deep convection systems in the Mid-Northern area of the NEB. The HR1 and HR2 have very close annual averages and very low inter-annual solar irradiation variability (Fig. 3a), but the annual cycles are different. The geographical distance between them is considerable, and they have very distinct climatic characteristics. Similar behavior can explain the differences between HR3 and HR4. The HR5 receives the largest solar irradiance all year long.

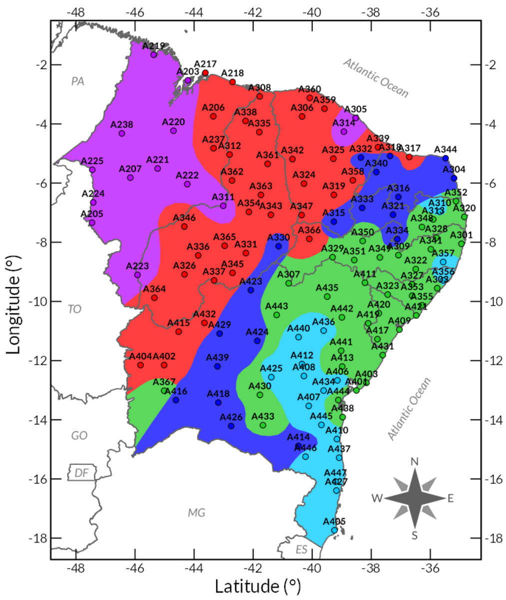

Fig. 2: The cluster areas (HR) regarding the surface solar irradiation in NEB: HR1, cyan; HR2, purple; HR3, green; HR4, Red; HR5, blue. The dots are the AWS's locations used in the cluster analysis technique. Source: Modified from Lima et al. (2019)

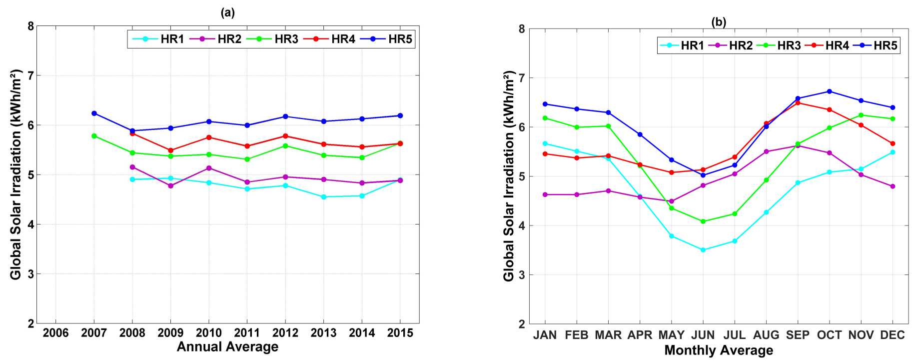

Fig. 3: The annual and monthly averages of solar irradiation in the five clustered areas in NEB obtained based on the ground data of the surface solar irradiance acquired in 129 AWS in NEB. Source: Modified from Lima et al. (2019)

Fig. 4 presents the boxplot analysis for the surface global solar irradiation in each clustered region of the NEB. The boxplot allows evaluating the inter-annual variability. The dot and line inside the rectangles represent the mean and the median values, respectively. The rectangles and vertical bars demonstrate the spreading of the annual average taking into consideration one-standard deviation and two-standard deviation interval, respectively. For the timeframe under investigation, the HR2 and HR4 showed the lowest inter-annual variability. The HR3 has the greatest variability with annual averages ranging between 3.7 and 6.7 kW/m².day, followed by the HR1 region (between 3.2 and 6.1 kWh/m².day). The highest annual mean values occurred in HR4 and HR5, up to 7.1 and 6.8 kWh/m².day, respectively. The minimum annual mean global solar irradiation was in region HR1 (around 3.2 kWh/m².day).

Figs. 4b to 4e shows the inter-annual variability on a seasonal scale. The HR1 and HR3 present the greatest inter-annual variability in the season MAM (fall) and the lowest in the austral summer (DJF). The HR2 and HR4 present the opposite behavior with the lowest variability in the fall season. The largest seasonal averages for HR4 and HR5 are in the season SON (spring). This behavior is consistent with regional climatology for the spring season – low nebulosity in most of the continental areas of the NEB.

Fig. 5 presents the results of the trend analysis for the annual and seasonal averages of the surface solar radiation using the Mann-Kendall and Sen methods. The daily surface solar irradiation in HR5 showed an increasing trend with a magnitude of +0.04 kWh/m²/year and statistical significance of 90%. On the contrary, the surface solar irradiation in HR1 showed a decreasing trend around -0.05 kWh/m²/year with the statistical significance of 90%. In seasonal scale, the surface global solar irradiation in HR1 presented a decreasing trend (around -0.05 kWh/m^2/year) with the statistical significance of 95% during the seasons MAM (fall) and JJA (austral winter). In HR5, the surface solar irradiation presented a positive trend around +0.04 kWh/m²/year in the season DJF (austral summer) and +0.07 kWh/m²/year in the season MAM (fall). Trends also occurred in the other three homogeneous regions, but none of them had statistical significance.

4. Conclusions

This work investigated the spatial and seasonal variability and trend of the surface global solar irradiation in the Northeastern region of Brazil based on statistical analysis of ground data acquired by automated weather stations (AWS) during the 2005-2015. The cluster analysis was used to identify areas presenting similar statistical patterns regarding the incoming global solar irradiation in NEB territory. Five clustered regions (HR) have a geographical location consistent with the regional climate characteristics and typical meteorological systems operating in each HR. The HR5, the driest area, has the highest daily average of global solar irradiation. The inter-annual variability is high in the mid-eastern area (HR3) due to the cloudiness associated with typical meteorological phenomena in the region.

On the other hand, the smallest inter-annual variability occurs in the western area of NEB (HR2), and HR1 presents the lowest average of the daily solar irradiation. The HR2 is the area presenting the largest nebulosity in NEB due to the influence of heat and moisture from the Amazonia region.

The austral summer, from December to February, got the smallest inter-annual variability of daily global solar irradiation, but not the largest averages in all clustered regions. It is worthy of mentioning two opposite situations: the largest seasonal average of daily solar incidence in HR1 and HR3 occurred in the austral summer DJF (summer) but, the lowest average of daily solar irradiation in HR2 happened in the same season (DJF).

Another seasonal complementarity behavior occurs between HR1 and HR4. The seasonal cycles in these areas are quite the opposite – the incoming solar irradiation reaches the lowest values in austral winter while the incoming solar irradiation in HR4 is almost in its maximum values. A similar condition is present in the SON season: low solar irradiation in HR1 and high in HR4. Both regions receive similar solar irradiation during the other six months of the year.

The Fig. 5 presents the time evolution of the annual average of surface solar irradiation. The trend analysis demonstrated that the daily surface solar irradiation in the southeastern of NEB is decreasing by 50 Wh/m^2/year since 2008. On the other hand, the daily surface solar irradiation in HR5 (the semi-arid area) is increasing around 40 Wh/m^2/year along the same timeframe.

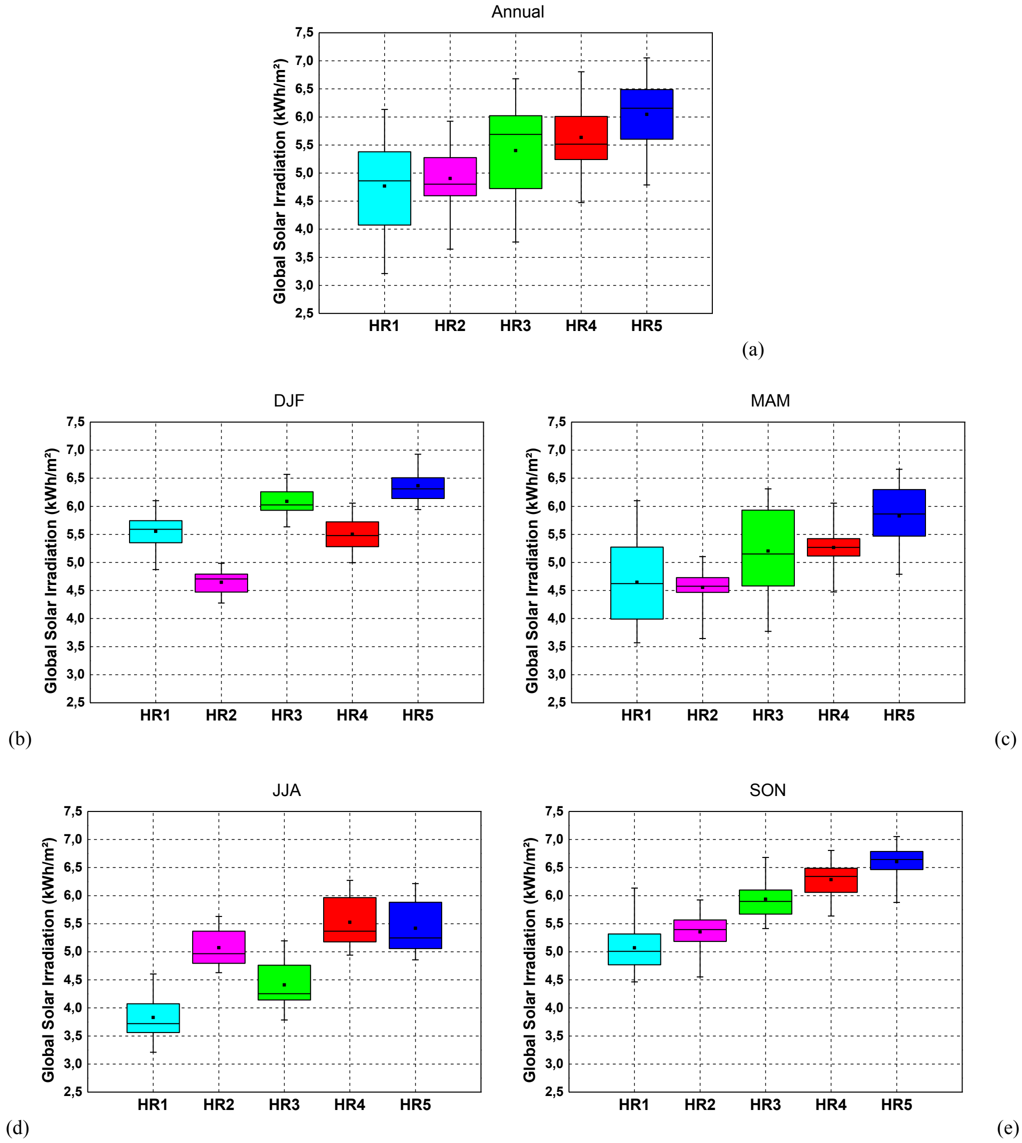

Fig. 4: (a) The boxplot analysis for the annual averages of the surface global solar irradiation (kWh/m².day) in the five clustered areas in NEB. The inter-annual variability on seasonal scale are presented in (b) DJF (austral summer), (c) MAM (fall), (d) JJA (austral winter) and (e) SON (spring). Source: Modified from Lima et al. (2019)

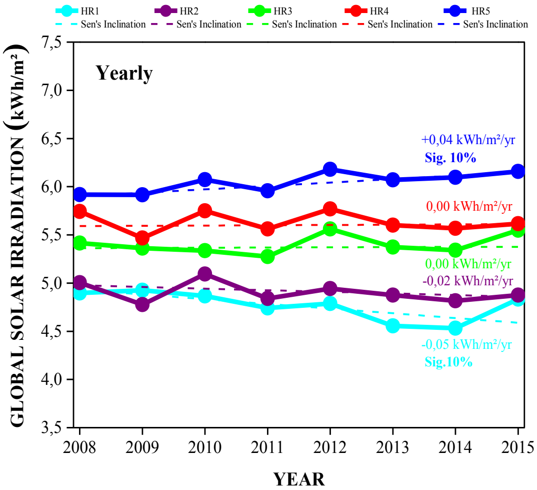

Fig. 5: The temporal evolution of the annual and seasonal averages of daily total surface global solar irradiation (kWh/m².day). The slope and magnitude of the trend obtained by using the Sen method and the Mann-Kendall test are indicated for each homogeneous region. Source: Modified from Lima et al. (2019)

The information on the spatial and seasonal patterns of the surface solar irradiation in NEB will be helpful in methodology development of forecast solar energy using satellite data, optimization/sizing of solar energy systems, and reducing the impact of the natural intermittency of the solar power resource in the Brazilian electricity grid. Besides that, the proposed methodology would be a useful tool for selecting proper sites to set-up a high-quality solar radiation measurement network. In NEB, the solar irradiance could be sufficiently monitored with five ground measuring sites: one in each homogeneous area of NEB. Finally, the results also could provide reliable and useful data for application in other areas like planning crops and land usage taking into account the solar irradiation climatology.

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