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Comparative Analysis of the Third Generation of Research Data for Evaluation of Solar Energy Potential

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Abstract**—**Renewable energy sources are dependent on climatic variability, so for adequate energy planning, observations of the meteorological variables are required, preferably representing long-period series. Despite the scientific and technological advances that meteorological measurement systems have undergone in the last decades, there is still a considerable lack of meteorological observations that form series of long periods. The reanalysis is a system of assimilation of data prepared using general atmospheric circulation models, based on the combination of data collected at surface stations, ocean buoys, satellites and radiosondes, allowing the production of long period data, for a wide gamma. The third generation of reanalysis data emerged in 2010, among them is the Climate Forecast System Reanalysis (CFSR) developed by the National Centers for Environmental Prediction (NCEP), these data have a spatial resolution of 0.50 x 0.50. In order to overcome these difficulties, it aims to evaluate the performance of solar radiation estimation through alternative data bases, such as data from Reanalysis and from meteorological satellites that satisfactorily meet the absence of observations of solar radiation at global and/or regional level. The results of the analysis of the solar radiation data indicated that the reanalysis data of the CFSR model presented a good performance in relation to the observed data, with determination coefficient around 0.90. Therefore, it is concluded that these data have the potential to be used as an alternative source in locations with no seasons or long series of solar radiation, important for the evaluation of solar energy potential.

Keywords**—**Climate, reanalysis, renewable energy, solar radiation.

I. Introduction

ONE of the greatest global challenges is to meet the rapid growth of energy needs through the development of conversion technologies and the use of natural energy resources that have less social and environmental impact as one of the ways to mitigate the effects of global warming [1]. Although still with a small share of the total energy matrix, renewable energy appears as a reinforcement in reaching the goals of reducing greenhouse gases. There are several ways of harnessing solar radiation, which can be used as a source of thermal energy, for heating environments and/or fluids and through photovoltaic conversion [2].

Renewable energy sources are directly related to climate variability, so for adequate energy planning. it is important to study the climatic conditions from a reliable database with a minimum number of missing data. Knowledge about the potential of the surface-incident solar resource is essential for the study of the use of this energy source, conventional methods of radiation measurement are punctual and therefore representative of small areas. Measurements are mainly obtained from weather stations; however, many sites still suffer from the lack of monitoring stations and the scarcity of spatial distribution.

In order to verify the possible use of these sources in the absence of data from surface meteorological stations at the extreme end of the study, the objective of this study was to evaluate the performance of the estimation of the solar radiation of the CFSR from the NCEP.

II. Materials and Methods

A. Study Area

The Rio Grande do Sul (Fig. 1) is the 9th largest state in Brazil, with a territorial extension of 281,737,888 km², occupying more than 3% of the Brazilian territory. Divided into 497 municipalities, it has 11.329 million inhabitants, according to data from the Brazilian Institute of Geography and Statistics (IBGE), which corresponds to the 5th state with the largest national population. The population density is 37.96 inhabitants/km².

The spatial definition of the climatic elements are influenced by local and regional geographic factors, according to [3], Rio Grande do Sul presents subtropical climate divided into four main climatic types (Subtropical I: Slightly Wet; Subtropical II: Slightly Wet with the longitudinal variation of the average temperatures; Subtropical III: Humid with longitudinal variation of average temperatures; and, Subtropical IV: Very Humid). The pluviometric regime of the state of Rio Grande do Sul is associated mainly to frontal systems.

According to [4], the behavior of the seasonal mean radiation for the state of Rio Grande do Sul is 6.44 kWh/m²/day for the summer months, 4.1 kWh/m²/day for In winter months, there is a fall of 1.23 kWh/m²/day relative to the previous season, and it will rise again in the spring to 5.6 kWh/m²/day.

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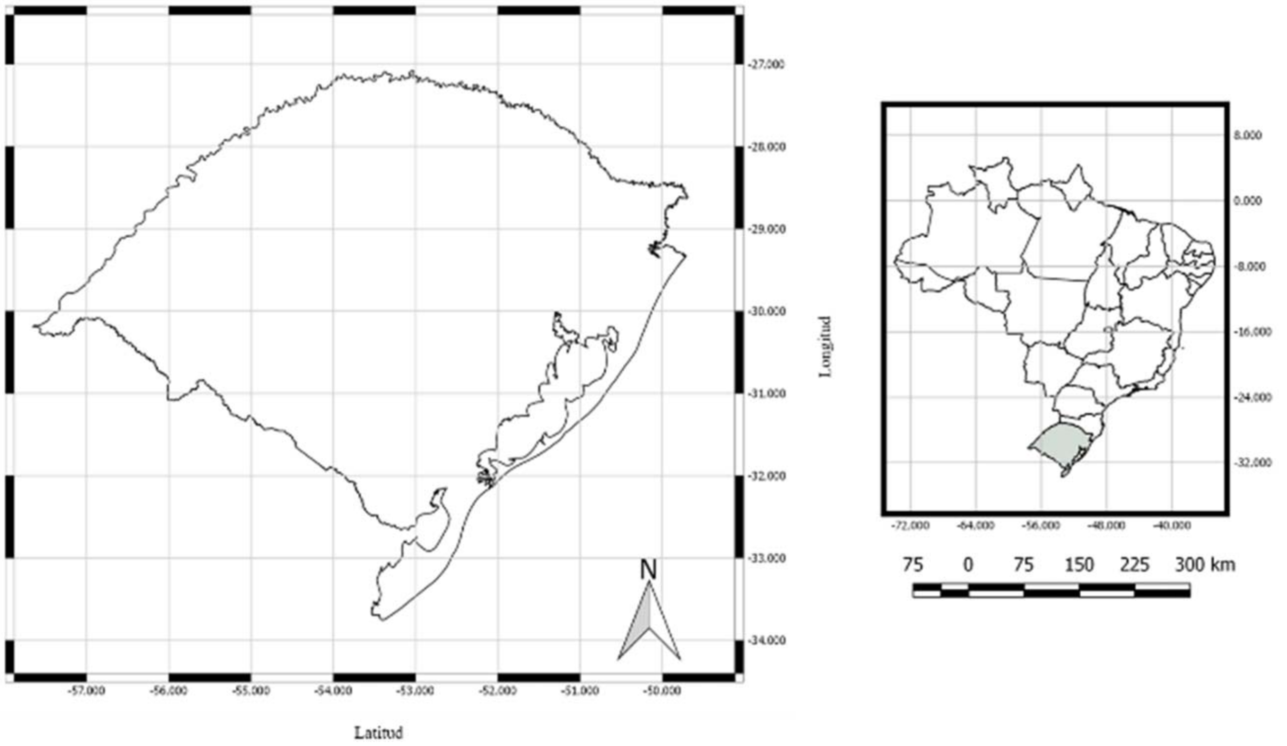

Fig. 1 Location of study area

Fig. 2 shows the distribution of the meteorological stations that were used in this research. The stations often do not present a good spatial distribution, and/or present faults, compromising the series of data, thus justifying the search for new sources of solar radiation data to the state of Rio Grande do Sul.

INMET provides a database called the Meteorological Database for Teaching and Research (BDMEP); however, solar radiation data are not available, providing only the following meteorological variables: precipitation occurred in the last 24 hours, dry bulb temperature, humid bulb, maximum temperature, minimum temperature, relative air humidity, atmospheric pressure at season level, sunshine, direction and wind speed.

The solar radiation data of approximately 45 automatic stations, distributed in the state of Rio Grande do Sul, are made available for consultation by INMET for a period of three months. The validation of the alternative databases of solar radiation were developed based on the data of the automatic stations of INMET, after being treated [4] for the preparation of the solar atlas for the State of Rio Grande do Sul.

B. Data Base

Reanalysis data are provided in binary format, the information was extracted through GRADS software (Grid Analysis and Display System) for each of the pixels, and soon after, the data were selected corresponding to the nearest surface station that composes a set of 34 surface stations, and a point-to-point comparison was made.

The CFSR provides data from 1979 to the present; this version is fully coupled and represents the interaction between the Earth's atmosphere, oceans, earth and ice. The spatial resolution is 50 km in the latitudinal and longitudinal direction, with 37 pressure levels.

C. Statistical Method

To validate the CFSR data for southern Brazil, four statistical methods were applied the bias that measures the trend of the reanalysis data to overestimate or underestimate the solar radiation in relation to the observed one. This trend, also called systematic error and is defined as:

$$BIAS = \frac{1}{N}\sum_{i=1}^{N}(Rad_{sim} - Rad_{Obs}) \quad (1)$$

The mean of the absolute errors (MAE) is considered a precise measure, since it does not take into account the outliers, presenting the ability of the numerical models to reproduce the observed conditions, being defined by:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|Rad_{sim} - Rad_{Obs}| \quad (2)$$

The mean square error (MSE), which is similar to the MAE, but more sensitive to large errors, by raising the individual differences squared. This measure is often used to verify the accuracy of numerical models. MSE is always positive. MSE = 0 indicates perfect simulation. MSE is defined by:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(Rad_{sim} - Rad_{Obs})^2 \quad (3)$$

According to [5], the concordance index (CI) has this property ($0 \leq IC \leq 1$) and can be used, for example, to compare different simulations; IC = 1 indicates perfect agreement between the simulated field and the observed one. IC is defined by:

$$IC = 1 - \frac{\sum_{i=1}^{N}(Rad_{sim} - Rad_{Obs})^2}{\sum_{i=1}^{N}(|Rad_{sim} - \overline{Rad_{Obs}}| + |Rad_{obs} - \overline{Rad_{obs}}|)^2}$$

where: Rad_{sim} is the solar radiation from the alternative data bases and Rad_{obs} is the solar atlas observed radiation for the state of Rio Grande do Sul and is $\overline{Rad_{Obs}}$ the mean of observed radiation.

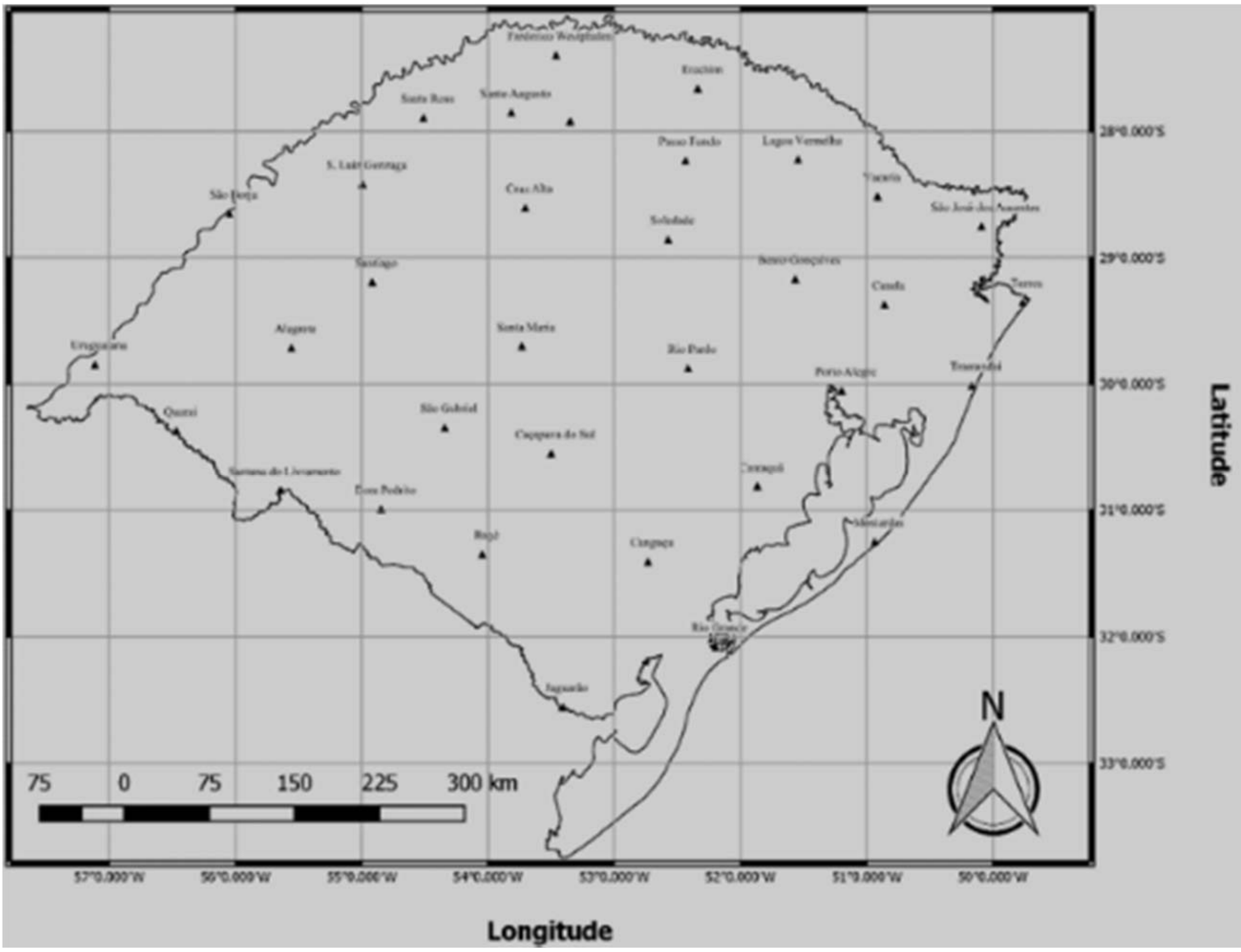

Fig. 2 Location of Weather Stations

III. Results

Next, the bias maps of each of the databases will be presented, calculated from the estimated irradiance subtracted from the observed irradiation, as described in the methodology. A positive bias indicates an overestimation of the incident solar radiation, whereas a negative bias indicates an underestimate of the alternative database in relation to the observed database.

Fig. 3 shows that the CFSR overestimates the data observed in the eastern half of the state of Rio Grande do Sul and underestimates in the region of the campaign and in a small portion of the western region of the state, but with a variation of approximately 0.20 kWh/ m²/day, both upwards and downwards. In agreement with the results obtained by [6], they find an average deviation of the CFSR of approximately 0.25 kWh/m²/day over the region of Egypt compared to the surface stations.

As described by [7], the bias does not provide information about the individual errors and therefore cannot be used as a measure of accuracy of the best analyzed database. The reason is that it is affected by the fact that individual positive and negative errors of the same magnitude are canceled in the sum. The average of the absolute errors circumvents this problem, being less affected by points with anomalously extreme values.

The mean absolute error per meteorological station can be observed in Fig. 4 and it is verified that the CFSR presents a small error in all analyzed points, with values varying from

0.10 kWh/m²/day to 0.5 kWh/m²/day.

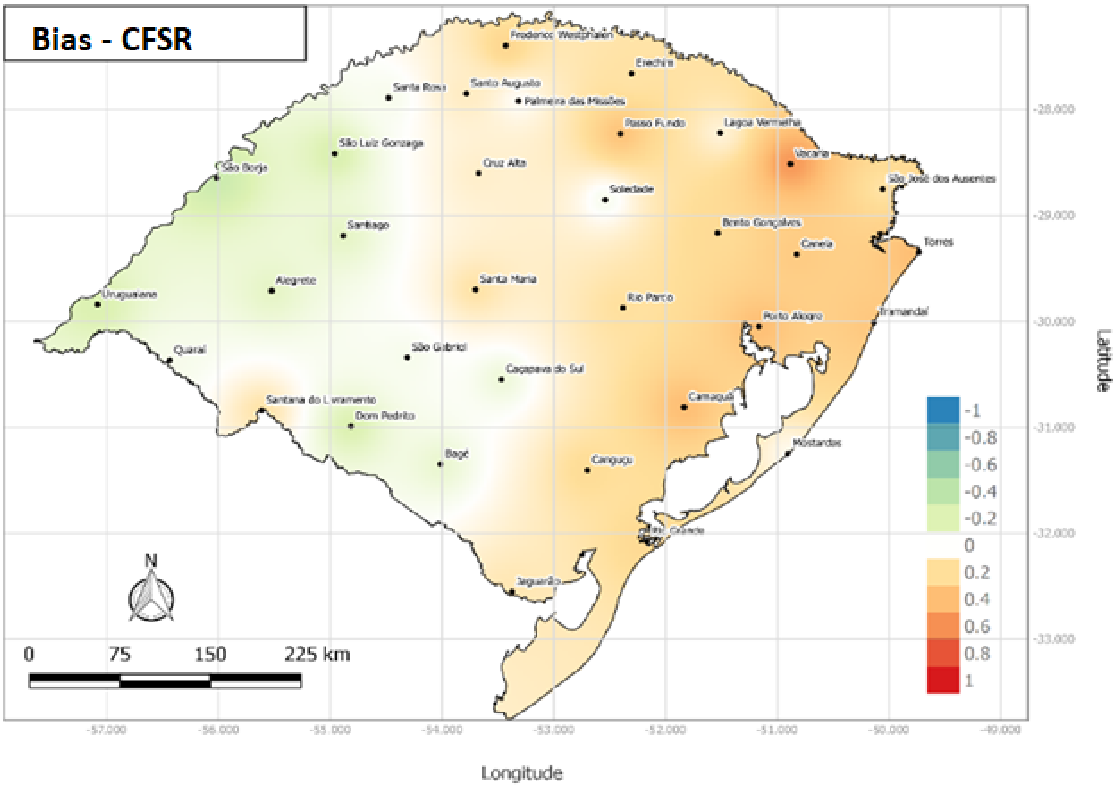

Fig. 3 Spatialization of the CFSR Bias to RS

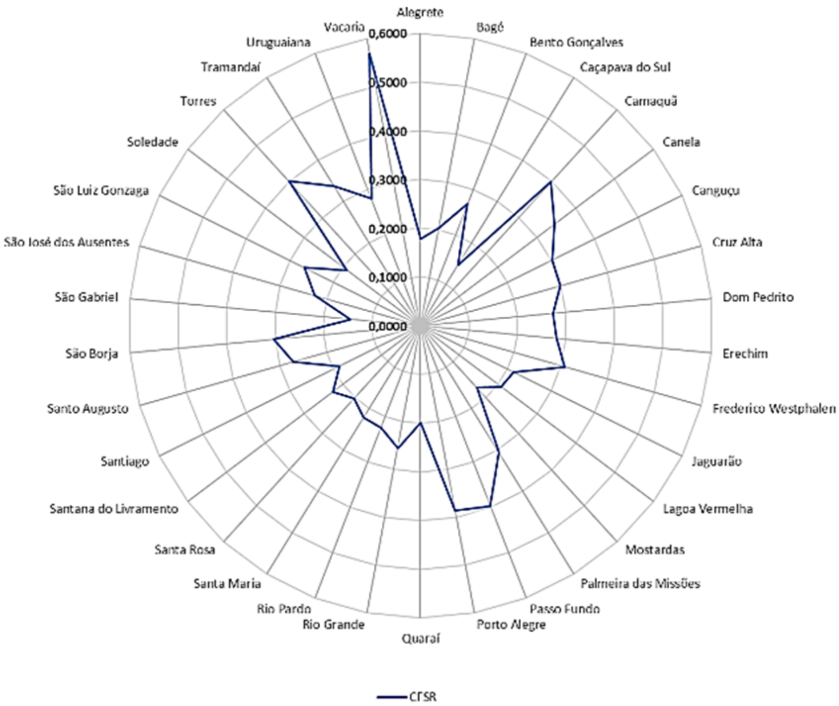

Fig. 4 Absolute average error by Meteorological Station

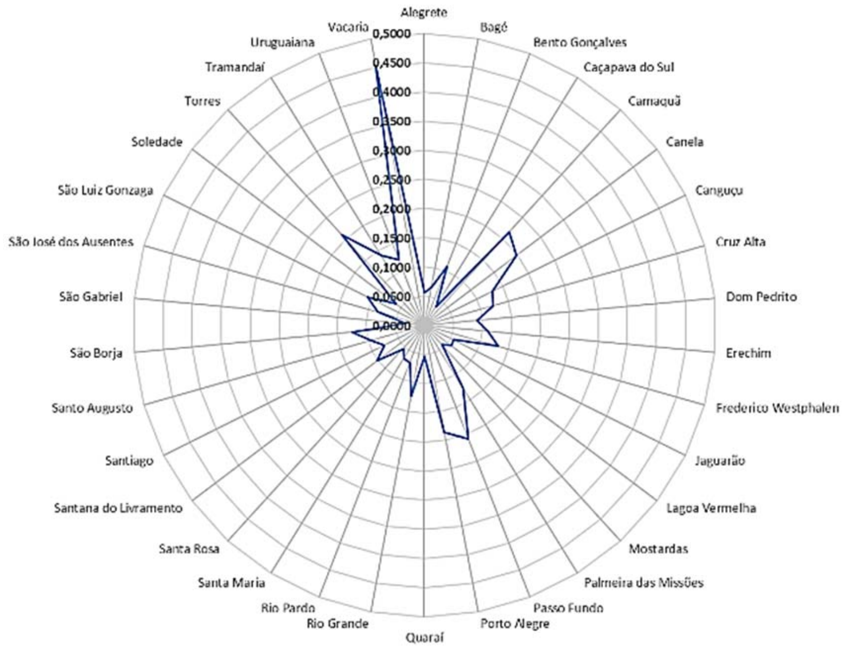

Fig. 5 Absolute average error by Meteorological Station

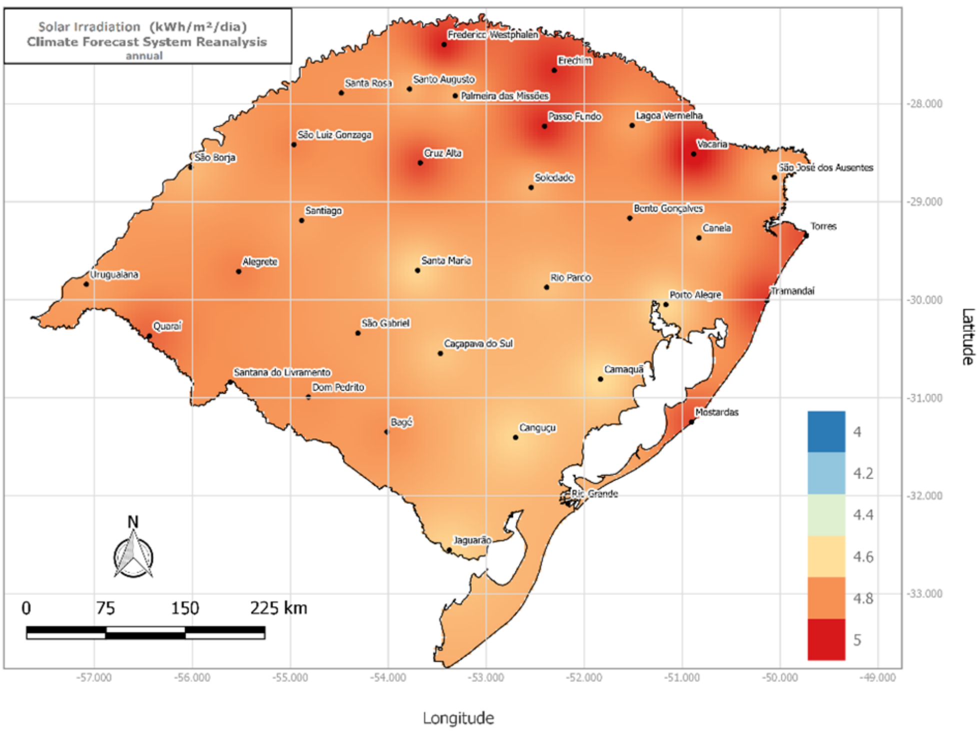

Fig. 6 Average annual global solar irradiation maps for the state of Rio Grande do Sul obtained from the CFSR

Analyzing the mean square error (Fig. 5) by meteorological station, it is verified that for all the research units evaluated the CFSR, with an error around 0.10 kWh/m² at 0.45 kWh/m².

Fig. 6 presents the mean annual index of solar irradiation in the state of Rio Grande do Sul. As it can be seen, the spatialization of the data showed that the average annual irradiation varies from values of 4.8 kWh/m^2/day to 5.0 kWh/m^2/day; this is in agreement with the data obtained through the solar atlas of the state of Rio Grande do Sul [8].

The solar irradiance maps were generated to verify the monthly variability of the availability of solar energy arriving at the surface. The following figures map the monthly mean of global solar irradiation for the months of January and February. It is observed that the state of Rio Grande do Sul has a great availability of solar energy resources throughout its territory, presenting a spatial homogeneity, with values ranging from 6.5 kWh/m²/day to 7.5 kWh/m²/day for the month of January (Fig. 7) and between 5.8 kWh/m²/day to 6.5 kWh/m²/day for the month of February (Fig. 8).

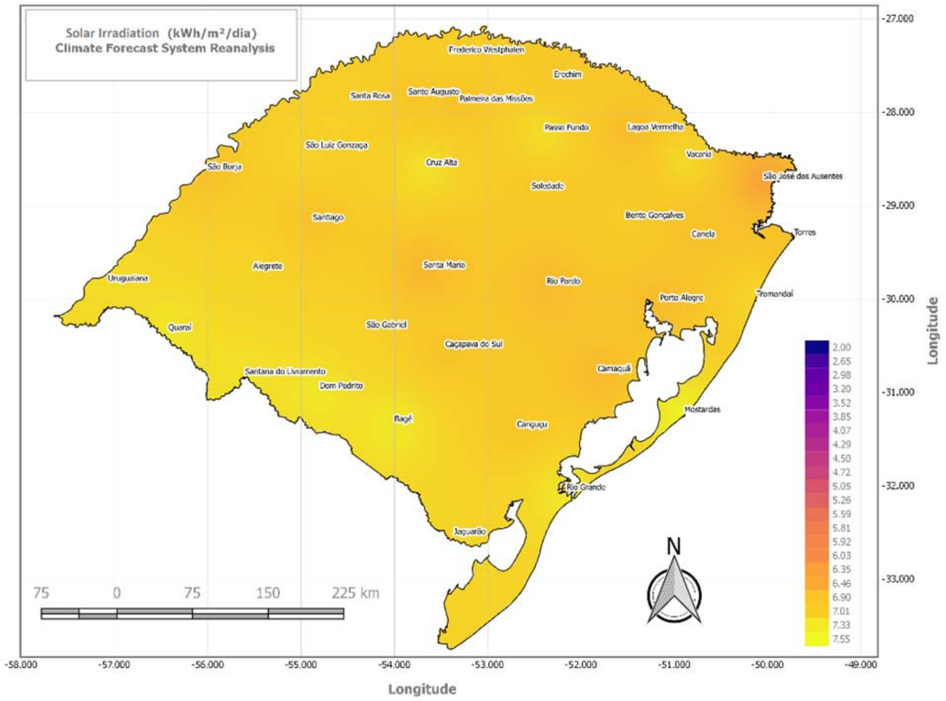

Fig. 7 Monthly average global solar irradiation maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – January

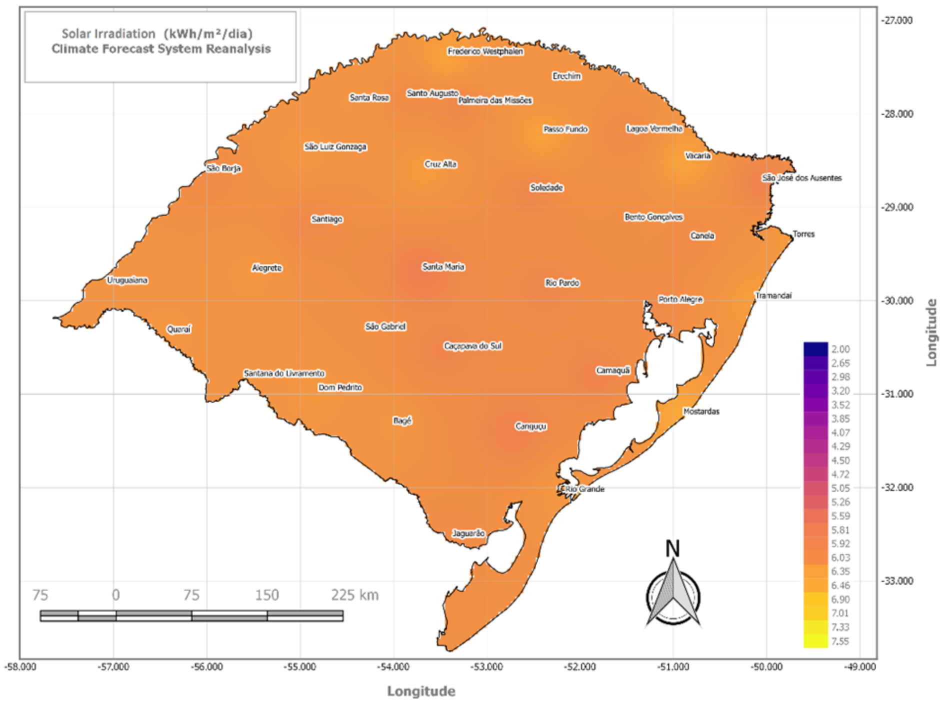

Fig. 8 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – February

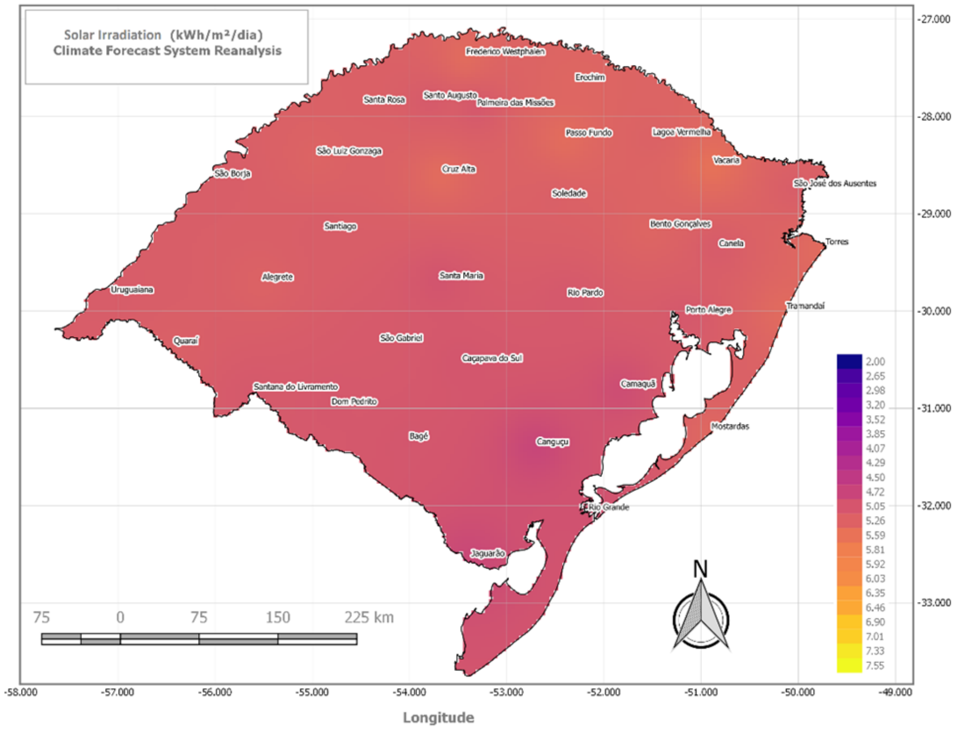

Fig. 9 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – March

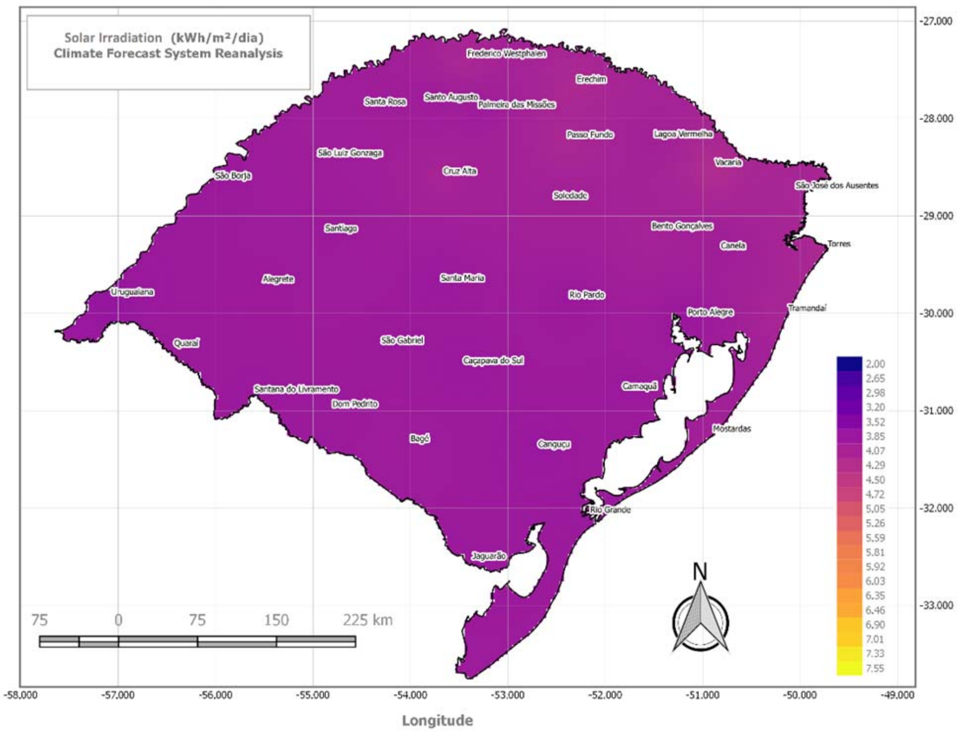

Fig. 10 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – April

In the month of March (Fig. 9) and in April (Fig. 10), the radiation showed a decrease of approximately 2.0 kWh/m²/

day, compared to the summer months, agreeing with the values obtained by [9], which found average values close to 5.12 kWh/m²/day and 4.18 kWh/m²/day for these months.

The lowest values of radiation flux are observed in the winter months, with a minimum of 2.0 kWh/m²/day in June (Fig. 11) and 3.9 kWh/m²/day in the month of August (Fig. 12).

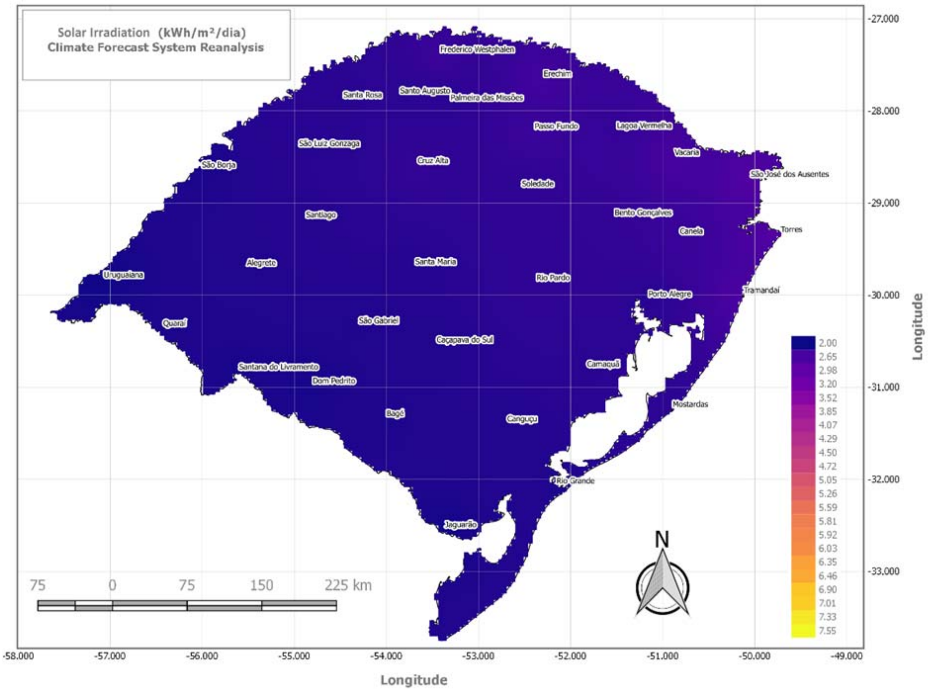

Fig. 11 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – June.

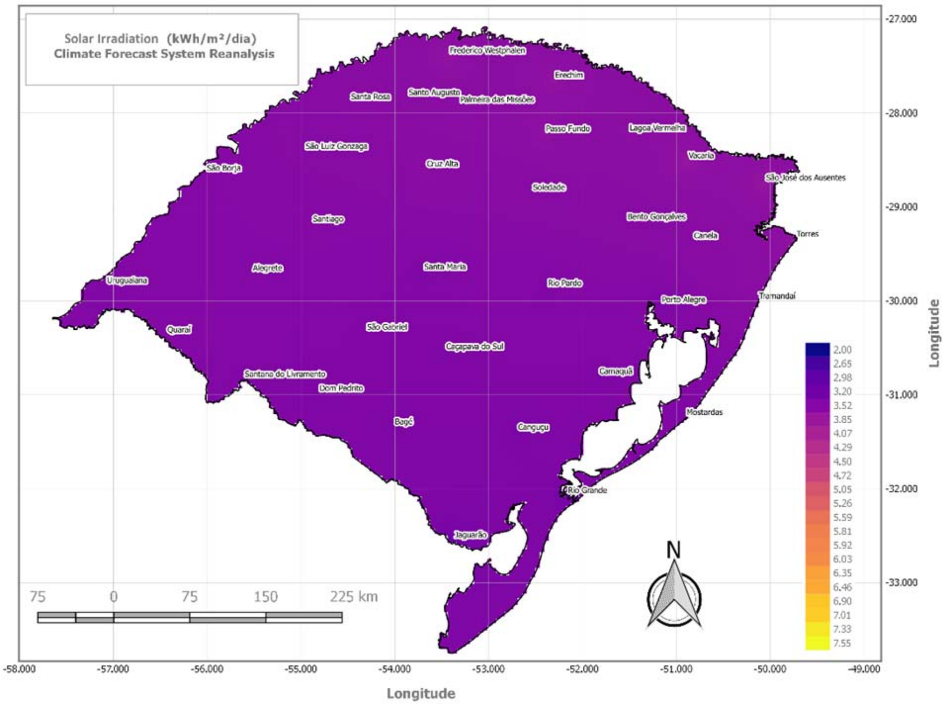

Fig. 12 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – August

It is observed that in the months of September (Fig. 13) and October (Fig. 14), the monthly average of solar irradiation rises again, with mean values varying from 5.0 kWh/m²/day to 6.0 kWh/m²/day for these months.

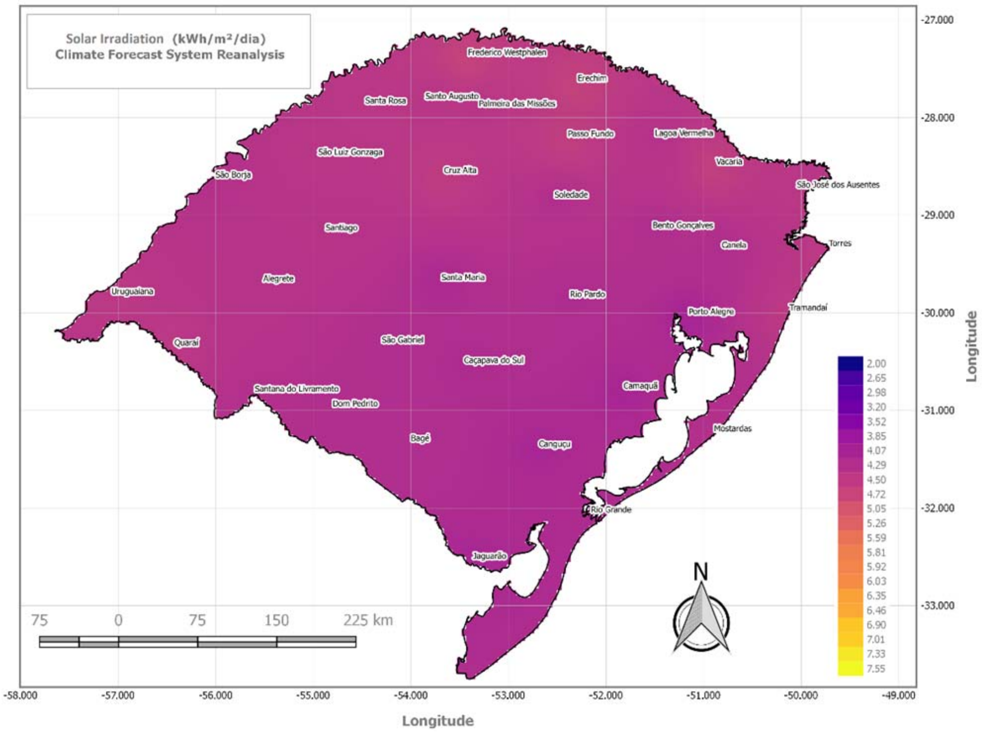

Fig. 13 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – September

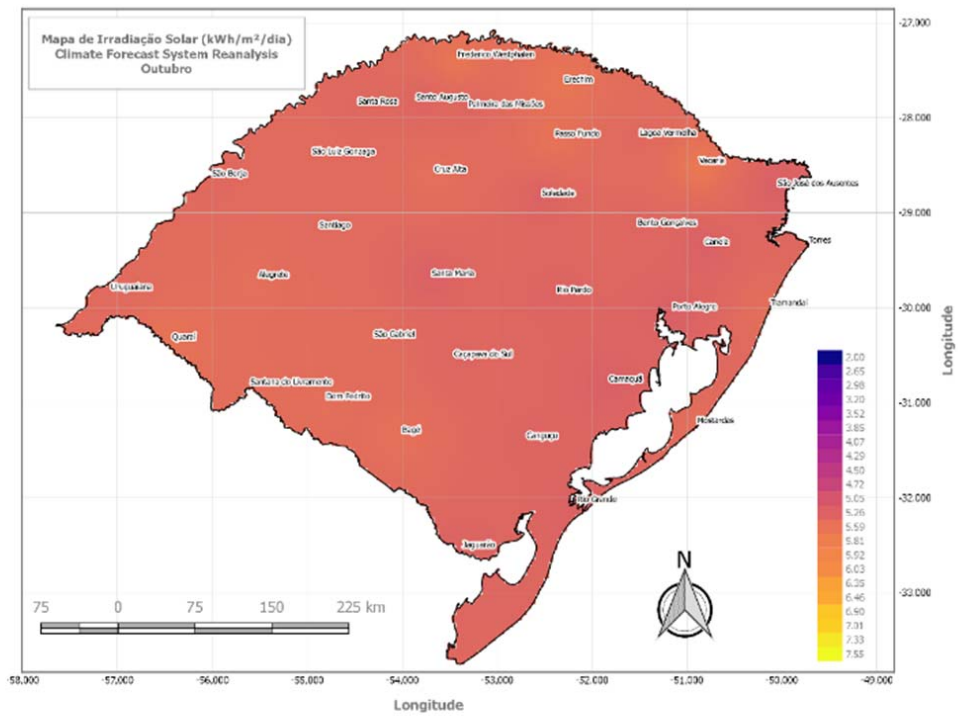

Fig. 14 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – October

The behavior of solar irradiation for November (Fig. 15) and December (Fig. 16), showing maximum values above 7.0 kW/m²/day, and according to [9], noticed that the values of solar irradiation observed in the southern region of the country are higher than the values obtained for the northern region, indicating a good potential for the generation of photovoltaic solar energy.

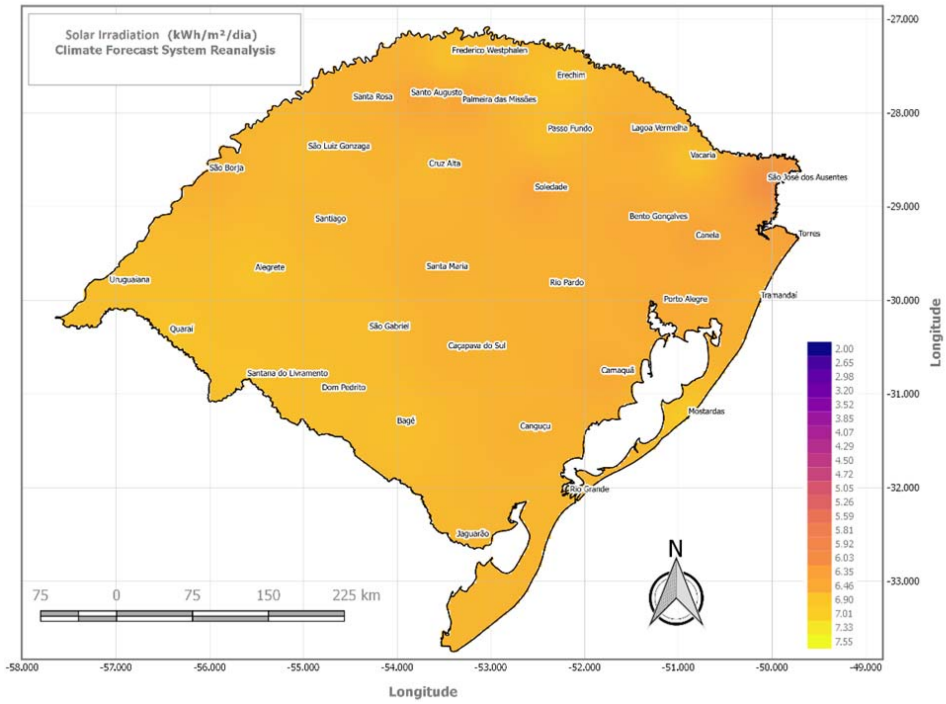

Fig. 15 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – November

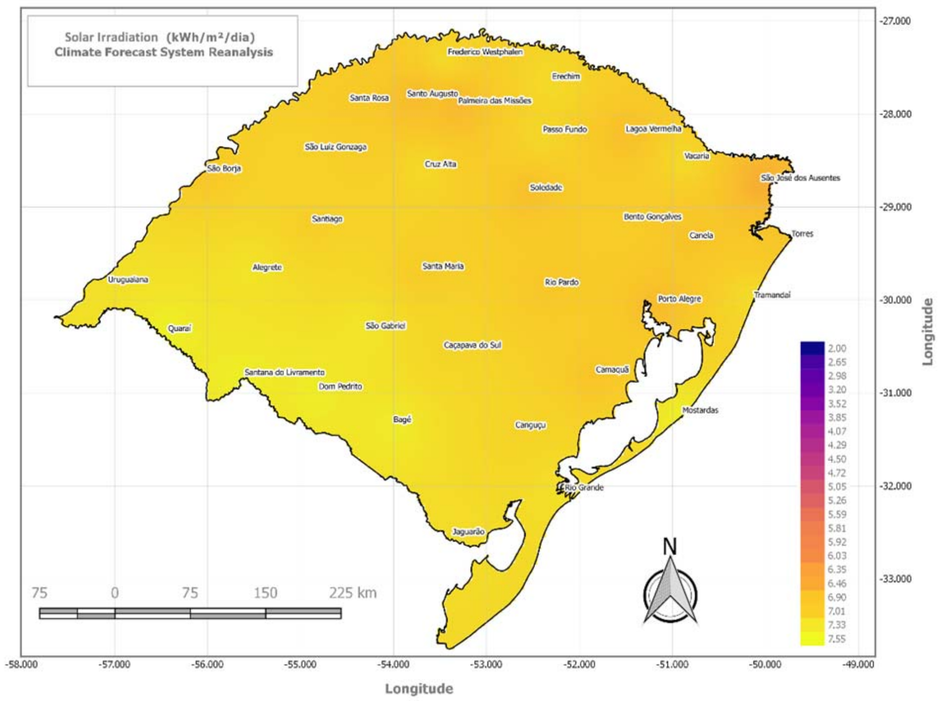

Fig. 16 Monthly average global solar irradiance maps for the state of Rio Grande do Sul obtained through the Data from Reanalysis of the Climate Forecasting System - 2001-2013 – December

IV. Conclusion

The knowledge of the spatial distribution of solar energy is essential for the development of projects that aim to use this resource as a source of energy. Although data collected at surface stations are safer sources of information, there is still a great deal of data scarcity, especially in remote and sparsely populated areas with few meteorological stations to collect this information, often without maintenance.

The historical series are generated with flaws and with inconsistent variables, so the importance of evaluating the possibility of using alternative databases, seeking to fill this lack of information. Knowing these problems, several atmospheric monitoring centers have been offering reanalysis products, which are series of meteorological data obtained through the assimilation and reanalysis of data observed all over the planet. The results showed that the CFSR Reanalysis data set was adequate for statistical analysis. Therefore, it is concluded that the CFSR database has the potential to be used as an alternative source in locations with an absence of stations or long series of solar irradiation data.

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