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On the Development of Spatial/Temporal Solar UV Irradiation Maps: A Case Study in Pernambuco State (Northeast of Brazil)

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Abstract

This work summarizes recently published information on the solar UV broadband irradiation of Pernambuco, Northeast of Brazil. We describe the spatial and temporal distribution of solar UV radiation and its relationship with climatic and geographical conditions. Statistical experimental correlation between solar total irradiation and UV broadband obtained for 03 locations was generalized by the use of Koppen-Geiger Climatic criterium, which was used for mapping the spatial/temporal distribution of broadband UV. The climatological solar radiations used in the correlations were obtained by modeling through satellite and previously verified with terrestrial data. We present one map with the location of the recording stations where the statistical correlations were measured, one annual and 12 monthly contour maps describing monthly daily solar UV radiation levels throughout the territory of Pernambuco. The solar UV irradiation ("broadband") annual-average daily value in the State of Pernambuco varied from 226 to 268 Wh/m^2. Seasonal variation of solar UV irradiation in the State of Pernambuco follows, in general and as expected, the climate, relief and seasons of the year. The highest value of monthly solar UV irradiation was observed in the central south region of the state, more precisely in Belém do São Francisco, Floresta, Ibimirim and Buíque in the month of December (summer), with 311.8 Wh/m^2. The lower value was found in the south Agreste region, in Garanhuns and Caruaru, in the month of June (winter), with 162.2 Wh/m^2.

Keywords

Solar UV Irradiation, Statistical Model, Contour Maps, Monthly and Annual UV, Pernambuco

1. Introduction

The solar ultraviolet radiation on the surface of the Earth includes a small range from 280 to 400 nm in the solar spectrum, which, in turn divides into two bands: UVB, between 280 and 315 nm; and UVA, between 315 and 400 nm. Its interaction with the biosphere is general and wide, causing many effects on both living beings (animals and plants) and also on inorganic and organic materials that are natural or developed by humans.

Usually, these exposures are related to negative effects (damaging) but it is important to highlight the beneficial effects, such as the activation of vitamin D production in the human body, the regeneration of polluted aquatic systems by organic contaminants and bacteriological and viral decontamination methods of water, food, objects and air.

The damaging effects to the human being are already widely known, whether associated to skin cancer induction, skin aging, effects on the eyes and causing a low immune system [1] [2]. On the overexposed plants, it generates size, productivity and quality decrease and the induction of early flowering.

The solar UV radiation and thermal energy absorption are the main degradation factors for many synthetic materials that are widely used in our civilization, such as plastic and paint chain materials [3] [4] [5]. Particularly in the photovoltaic solar generation technology, the theme has become significant and important, because the degradation of photovoltaic modules induced by solar UV irradiation (UVID-UV induced degradation) is one of the most prevalent. Furthermore, all the most recent and modern photovoltaic modules, which are currently dominant in the market, suffer significant degradation from UV exposure. Laboratory tests simulating 2000 hours of exposure (4.2 MJ/m^2) showed a power decrease in the average of 3.6% and a maximum of 11.6% in consequence of UVID [6], when compared to 1% of the previous technology cells (monofacial with AI back surface).

For what precedes, the knowledge of solar UV irradiation on the surface of the Earth is very important to precisely predict the effect of living being and the durability and lifespan of materials used worldwide. Particularly in human health, it is about predicting the potential erythemic dose of an individual and creating alert and prevention services to avoid the receiving of dangerous doses.

However, an extensive literature review shows that the measured information about total UV irradiation (UVA + UVB) in Brazil and the world is rarely or almost nonexistent. When it exists, its temporal and spatial distributions are very precarious [7] [8] [9]. To this day, not a single conventional meteorological station has total solar UV irradiation (UVA + UVB) or UVB measurements as standard instrument. The UV measurements that occur are sparse and driven by punctual and specific research.

The extreme shortage of experimental information of reasonable quality (terrestrial stations measurements) has directed the researchers for the creation of physical or parametric computational models, whether detailed spectral or broadband spectral. The MODTRAN (Moderate Revolution Atmospheric Radiance Transmittance Model) and the UVGAME (UV Global Atmospheric Model) are, for example, complex and sophisticated models [10] [11] that need many input data, such as type of atmosphere, aerosol, heavy molecule profile and clouds. Such characteristics make, in practice, the use of these models very difficult due to the lack of data.

An alternative for this situation is the use of simplified parametric models such as SPECTRAL-Simple Solar Spectral Model [12] and the SMARTS-Simple Model of the Atmospheric Radiative Transfer of Sunshine [13] which have simple algebraic equations and its input data can be found in conventional meteorological stations (atmospheric pressure, environmental temperature, relative humidity, among others) [14].

Finally, a third alternative, which will be used in this work, is the solar UV irradiation statistical modeling method [15] [16] [17] from the simultaneous measurements of total solar irradiation and the broadband UV irradiation (UVA + UVB). At first, a modeling performed for a local data can be applied to other regions, provided that spatial and phytogeographic homogeneity exists. The objective of this article is to create a map of solar UV irradiation map for Pernambuco based on data measured from solar UV irradiation. This is important because it will allow a better understanding of spatial and temporal (seasonal) variability of UV irradiation in the state and, in addition, made available to the general public quantitative data which allows to model public policies of UV exposition prevention, measure or model the deterioration of materials and its effects on plants and animals.

2. Background

The Empirical or Statistical Modeling that relates the information about UV and total solar irradiation is one of the most used by two reasons: 1) a quite reasonable amount of locations with total solar irradiation measurements exist and 2) it is parsimonious in the input data requirement, which facilitates its application.

According to [17], the correlations between solar UV irradiation and solar irradiation can be expressed by the following equations:

$$I_{UV} = AI_G \quad (1)$$

$$H_{UV} = AH_G + B \quad (2)$$

where:

I_{UV} and I_G are, respectively, the UV and hourly global solar radiation, H_{UV} and H_G are UV and daily global solar radiation, A is a local coefficient referred to as UV fraction (F_{UV}).

The expressions (1) and (2), or ratter the UV fractions (F_{UV}), thus obtained are only of local and seasonal validity because de UV and total solar irradiations that were used in its raw form (such as registered by the pyranometer) consist of the sum of the deterministic and stochastic component of solar irradiation. Even in the case of removing determinism using the atmospheric transparency index to express the correlation between UV and total solar irradiation, the withdrawal of determinism is still partial.

Several other works of this type were carried out abroad [8] [14] [15] [16] [18] [19], and in Brazil [9] [17] [20] and [21] which clearly demonstrated the character of local UV fraction (F_{UV}) or the linear relation between UV and global irradiation, as can be seen in **Table 1**.

The climatic Koppen classification that relates phytogeography, temperature and precipitation to categorize a given region, is admittedly the most used in Brazil and other countries around the world [22]. At its core, locations with the same Koppen classification present phytogeographic, precipitation and temperature similarities. The Koppen climate classification for Pernambuco can be seen in **Figure 1**. According to the map, Pernambuco has basically three climate categories: in a small strip on the coast, a Tropical climate with monsoons (Am), in the 1/3 region closer to the coast, a Tropical climate with dry summer (As) and finally, in the interior part of the state, a dry climate (BSh). In small regions in the north limit of the state there are region fragments classified as As. Pernambuco

Table 1. Empiric correlation (linear) between total solar irradiation and solar UV irradiation.

Authors	Location (Lat, Long, Alt)	F_{UV}	R^2
[15]	Granada, Spain 37.188N, 3.588W, 660 m	$H_{UV} = 0.040H_G$	0.97
[15]	Almeria, Spain 36.838N, 2.418W, 00 m	$H_{UV} = 0.037H_G$	0.97
[18]	Valencia, Spain 39.5˚N, SD, 15 m	$I_{UV} = 0.033I_G$ $H_{UV} = 0.030H_G$	0.96 0.96
[19]	Dead Sea, Israel 31˚09N; 35˚15E	$H_{UV} = 0.049H_G$	0.98
[19]	Beer Sheva, Israel 31˚16'N; 34˚48'E	$H_{UV} = 0.053H_G$	0.98
[16]	Cairo, Egypt	$H_{UV} = 0.034H_G$	-
[9]	Botucatu, SP, Brazil 22.85˚S, 48.45˚W, 786 m	$I_{UV} = 0.042I_G$ $I_{UV} = 0.042I_G$	0.98 0.92
[17]	Recife, PE, Brazil 8˚03'S, 34˚55'W, 7 m	$I_{UV} = 0.052I_G$ $H_{UV} = 0.0472H_G + 0.116$	0.98 0.98
[17]	Pesqueira, PE, Brazil 8˚24'S, 36˚46'W, 639 m	$I_{UV} = 0.054I_G$ $H_{UV} = 0.0441H_G + 0.2125$	0.96 0.98
[17]	Araripina, PE, Brazil 7˚34'S, 40˚29'W, 622 m	$I_{UV} = 0.048I_G$ $H_{UV} = 0.0417H_G + 0.1215$	0.97 0.96
[20]	Maceió, AL, Brazil 9.280S, 35.490W, 127 m	$H_{UV} = 0.0274H_G$	0.94

state has an area of 98,312 km^2, with 4.9 % of its territory in the Am climate region, 32.7% in the As climate region and 61.4% in the Bsh climate region.

The localities of Recife, Pesqueira and Araripina can also be seen in **Figure 1**, which are situated within the three distinct climate regions described above and where the simultaneous measurements of UV and total solar irradiation were performed to obtain the statistical correlations.

Consequently, the correlations between UV and total solar irradiation for other locations in the state of Pernambuco, where there were no such measurements, were extended in conformity to the climate similarity established by the Koppen-Geiger criteria. In the coastal region, the correlation measured for Recife; in the intermediate region known as Agreste and finally, in the extensive region to the west known as Sertão, the correlation measured for Pesqueira. The region of Araripe was modeled with the correlation obtained for Araripina.

3. Materials and Methods

3.1. Materials

Computer Programs used was QGIS 3.28. The following stages for the construction of the Spatial Database (SDB) included actions such as Survey, Analysis and Systematization of Existing Information, Analysis of Spatial Data Quality, Base Edition and Database preparation. In the Base Edition stage, the spatial data were also standardized. In it, SIRGAS2000 was used as Geodetic Reference System, Geodetic Coordinate System, Polyconic Projection, vector Data Model and Scale of 1:4,000,000.

3.2. Geodatabase

For the definition of spatial database, vectorial files archives were used related to

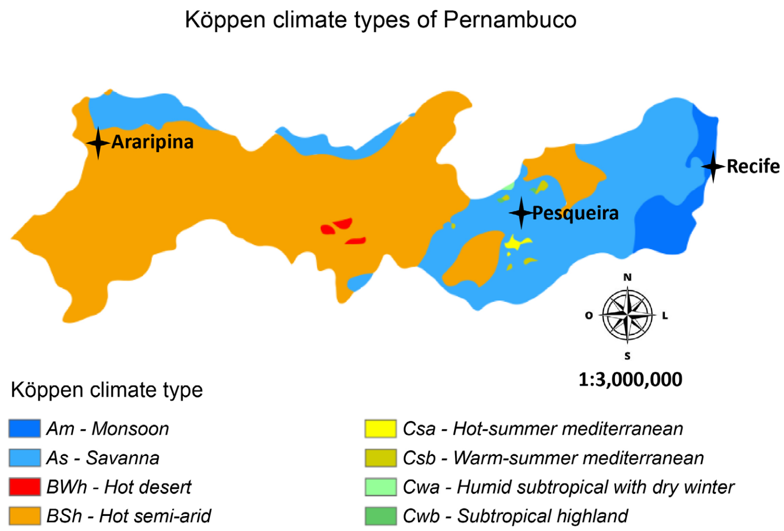

Figure 1. Koppen climate classification for the state of Pernambuco and the locations of Recife, Pesqueira and Araripina municipalities, where the statistical correlations between UV and total solar irradiation were obtained. Source: [22].

the territorial Division of Brazil, which were obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the State Agency of Planning and Research of Pernambuco (CONDEPE/FIDEM).

The database of total solar irradiation was obtained from the Atlas Brasileiro de Energia Solar O 2nd Edition [23] which allowed the data import per state in the "shapefile" format, with spatial resolution of 0.1° × 0.1° (approximately 10 km × 10 km). In **Figure 2**, the map of annual horizontal solar irradiation can be seen for the state of Pernambuco.

The referred map was elaborated with a physical model based on satellite images from the period of 1999 to 2015, by the National Institute of Space Research (INPE), by [24]. The maps of global solar irradiation obtained were validated with the use of an extensive network of surface measurements operated by the National Institute of Meteorology and Space Research Center. The database of global solar irradiation estimated by satellite imagens was validated with data measured on the surface in the period from 2005 to 2015, totaling 503 ground stations, **Figure 3**.

Table 2 summarizes the satellite modeling validation results [24]. The model showed a good performance reaching correlation coefficients (r) within the range of 0.87 to 0.98, the root of mean square error from 395 Wh/m² (8.9%) to 467 Wh/m² (9.7%) and a bias of less than 0.6%.

3.3. Study (Target) Area

The State of Pernambuco is located at the center of Northeast region of Brasil, fairly close to the Equator, **Figure 4**. Its geographic coordinates are 7˚15' and 9˚27' South latitude and 34˚00' and 48˚19' West longitude. With a territorial area of 98,149,119 km², Pernambuco borders the Atlantic Ocean and the States of

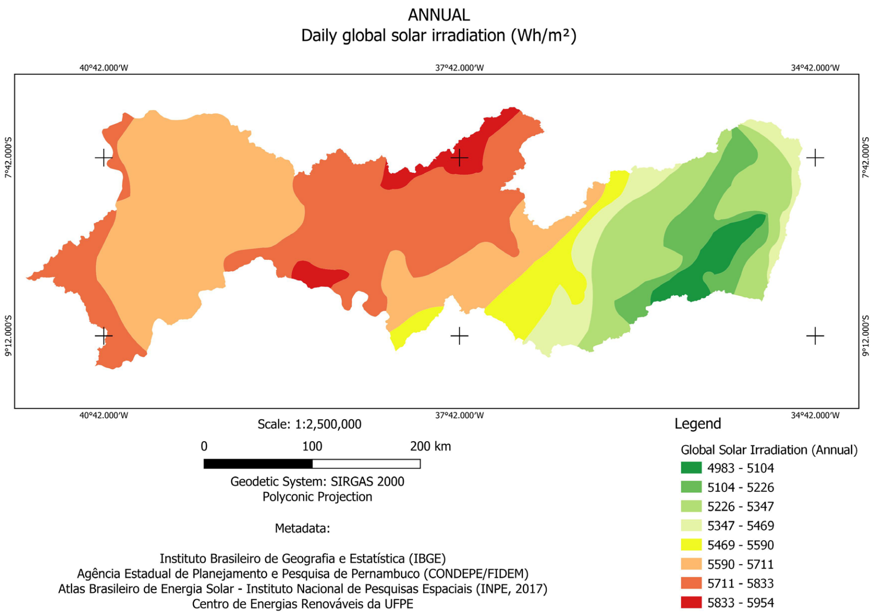

Figure 2. Annual horizontal solar irradiation for the state of Pernambuco. Source: [23].

Figure 3. Ground stations used for the validation of GHI modeling by satellite. Source: [23].

Table 2. Validation metrics for monthly averages of daily totals of global horizontal irradiation for each Brazilian region.

Region		Bias		REQM		Average Global Irradiation Measured
	r	Wh/m²	%	Wh/m²	%	Wh/m²
North	0.81	30	0.6	467	9.7	4825
Northeast	0.87	12	0.2	456	8.3	5483
Midwest	0.86	23	0.5	421	8.3	5082
Southwest	0.91	4	0.1	416	8.4	4951
South	0.98	-4	0.1	395	8.9	4444
Average	0.89	12	0.2	421	8.3	5153

Paraíba, Ceará, Piauí, Bahia and Alagoas. Fernando de Noronha Archipelago, is located 545 km from Recife (capital of Pernambuco).

3.4. Methodology

After the definition of the geospatial database according to the items 3.1 and 3.2, the necessary operations were performed in order to obtain the UV irradiation

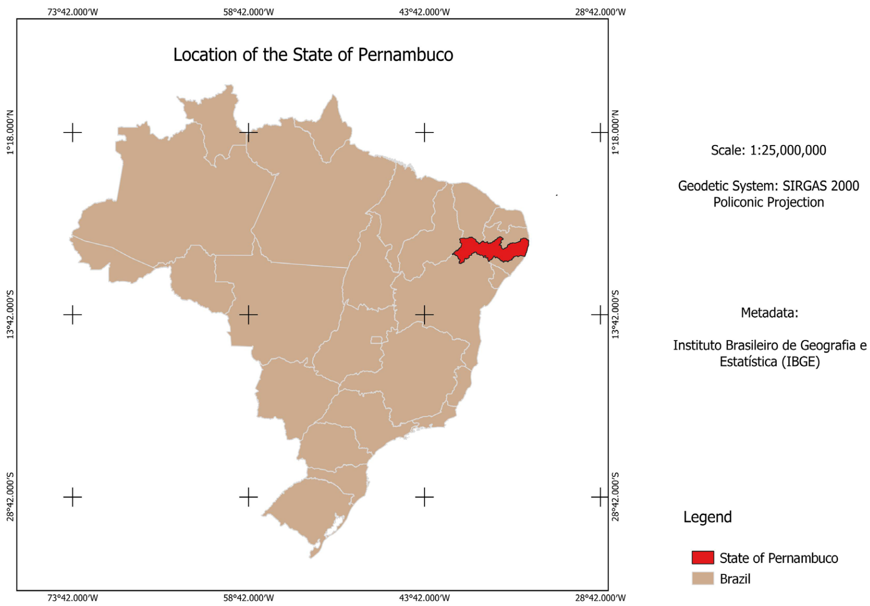

Figure 4. Location of the state of Pernambuco in Brazil.

for the state of Pernambuco in the tabular data of the shapefile, from the use of QGIS software.

Once the UV irradiation values were obtained for the studied area, the data was primarily smoothed for better viewing of the theme and, in sequence, UV irradiation themed maps were elaborated for the state of Pernambuco. In total, 13 themed maps were generated, 1 annual map and 12 monthly maps.

4. Results and Discussion

Figure 5 shows an east to northwest cross-section of the topography of Pernambuco. The east costal region and forest zone have altitudes in the range of 0 to 200 m and the climate is predominantly monsoon tropical. Next, Agreste is found 70 km from the east coast where the Borborema Plateau is located, which defines valleys with average altitude of 700 m, reaching up to 1120 m (Garanhuns) with semiarid savannah climate characteristics. Further west the so called Depressão Sertaneja is found with altitudes from 400 to 500 m and dry semiarid climate. In the north region of the Depressão Sertaneja, the localities of Triunfo, Serra Talhada have altitudes of around 1000 m and finally, in the northwest region of the state, the Chapada do Araripe is found with altitudes in the range of 800 to 900 m [23]. With increasing altitude the atmosphere is much thinner and UV levels increase, thus topographic analysis allows us to interpret and understand the spatial odd surface UV irradiance.

The monthly solar UV irradiation charts clearly show, for each month, very differentiated regions, reasonably correlated to rainfall, phytogeographic and hypsometric conditions. The annual-average daily value of solar UV irradiation ("broadband") in the state of Pernambuco can be seen in **Figure 6** and has varied from 226 to 268 Wh/m^2.

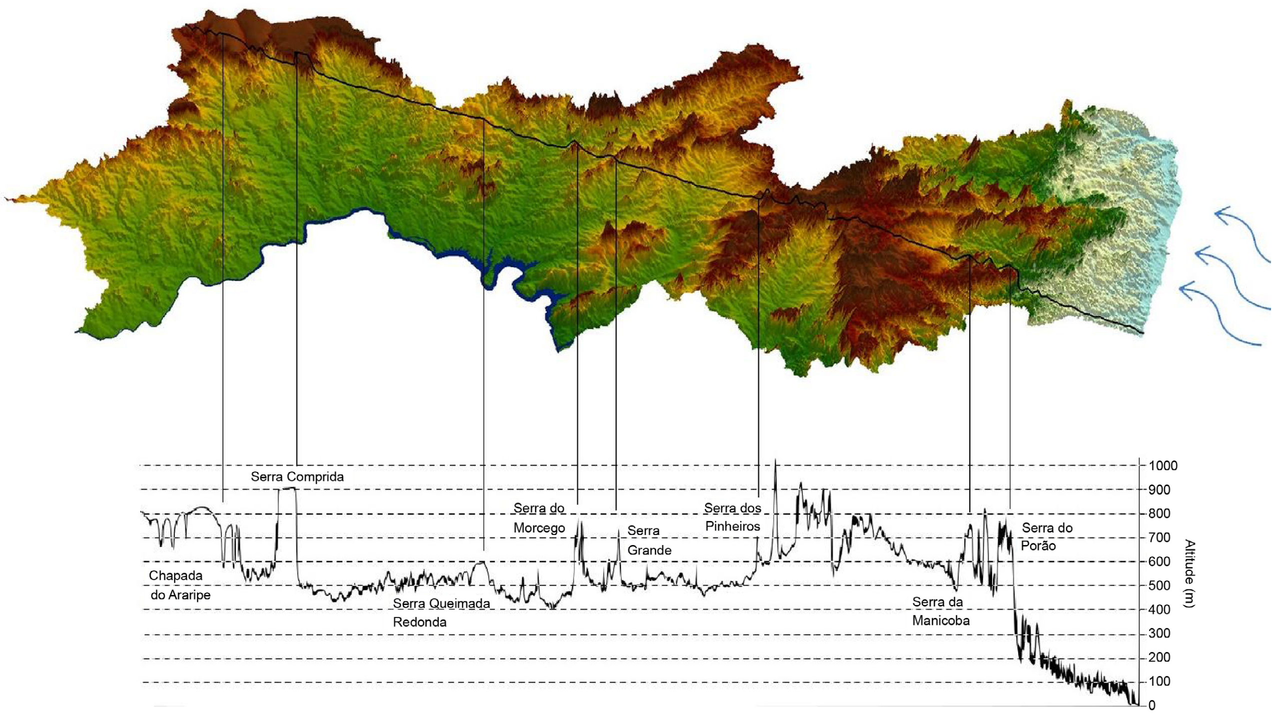

Figure 5. East to northwest cross-section of the topography of Pernambuco. Source: [23].

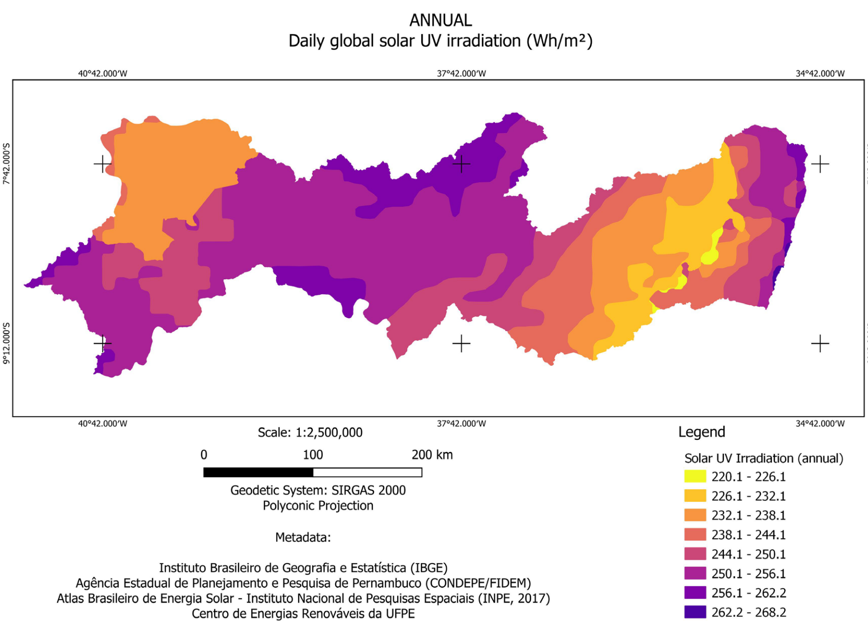

Figure 6. Annual solar UV irradiation for the state of Pernambuco. Source: Own authorship.

The highest daily UV irradiations, annual averages (268 Wh/m^2) are found north to the depressãosertaneja (Triunfo), where hight altitudes modulated high levels of solar UV irradiation. There is also another region south to the depressãosertaneja (Belém do São Francisco and Itacuruba), where high levels of UV irradiation occur. The Triunfo region has an altitude of 1010 m, which is one of the highest in the state, and each 1000 m of elevation, the atmosphere becomes more rarefied and the solar UV irradiation increases about 10%. The Belém do São Francisco and Itacuruba region has high levels of solar UV irradiation, in line with the high insolation defined as the number of hours of direct solar irradiation 120 W/m^2. In Chapada do Araripe, the solar UV irradiation was lower than the surroundings as a result of permanent emission of particles by plaster industry, either by mining itself or by combustion for the industrial process of gypsum calcination.

The seasonal variation of solar UV irradiation in the state of Pernambuco follows, in general and as expected, the climate, relief and seasons of the year. The highest monthly solar UV irradiation value was observed in the center south region of the state, more precisely in Belém do São Francisco, Floresta, Ibimirim and Buíque in the month of December (summer) with 311.8 Wh/m^2, **Figure 7**. The lowest was in the South Agreste region, in Garanhuns and Caruaru in the month of June (winter) with 162.2 Wh/m^2, **Figure 8**.

In the Northeast, no relevant changes in the temperature range nor other meteorological variables are observed when compared to other subtropical climates. As a result, only two seasons are considered in the NE: rainy and dry. The rainy season in the Sertão region of Pernambuco begins in December 21st and end in March 20th, with an average of 315 mm in the Sertão of Pernambuco and 330 mm in the Sertão of São Francisco (far west). The end of rainy season in Sertão is the beginning of rains in Agreste region, forest zone and coastline, which goes on until mid-August. The attenuation caused by rain fall (clouds) and solar geometry (tilt of the Earth's axis) markedly modulated the period of maximum UV irradiation in the various regions of the state: Sertão in September, Agreste

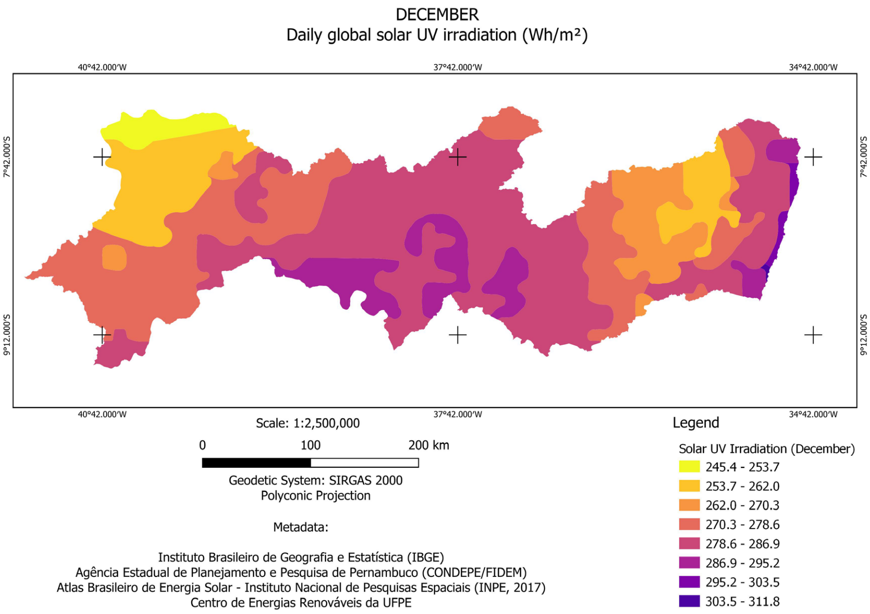

Figure 7. Seasonal variation of solar UV irradiation in the state of Pernambuco: December. Source: Own authorship.

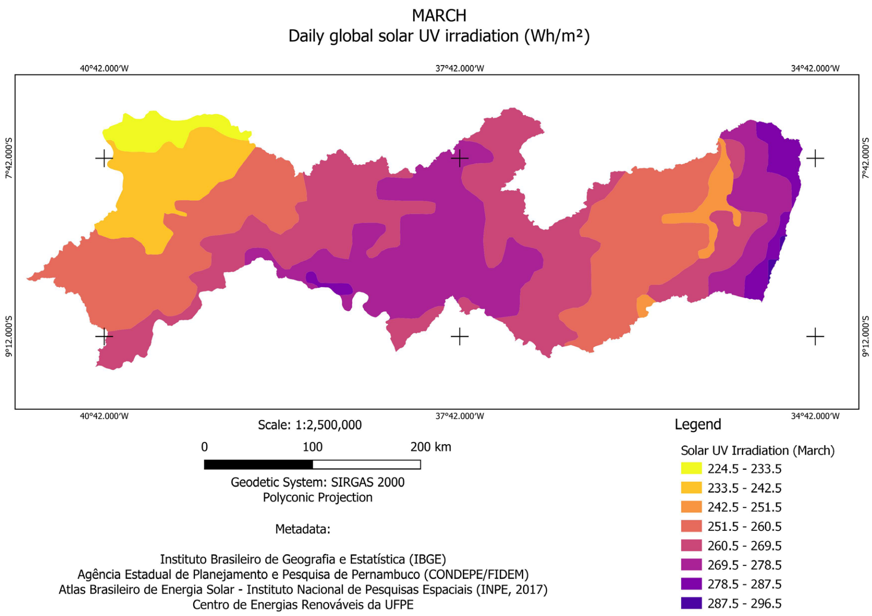

Figure 8. Seasonal variation of solar UV irradiation in the state of Pernambuco: March. Source: Own authorship.

and forest zone in March; and minimum in June, **Figure 9** and **Figure 10**. It is worth mentioning that precipitation is responsible for the decrease of solar irradiation by two means: making the atmosphere more opaque and the surface humidity also changes significantly the albedo (to less), because with more precipitation the soil vegetation covers improves.

5. Conclusions

It can be considered that the charts presented here, showing the spatial/temporal distribution of solar UV irradiation, represent adequately the data base available in Pernambuco and are also compatible with the best state of knowledge of this resource in the state.

Currently, the solar UV irradiation map for Pernambuco is the only one created and based on data measured from solar UV irradiation. This is important because it will allow a better understanding of spatial and temporal (seasonal) variability of UV irradiation in the state and, in addition, made available to the general public quantitative data which allows to model public policies of UV exposition prevention, measure or model the deterioration of materials and its effects on plants and animals. Finally, it should also be noted that the solar UV irradiation is suffering an increase as the desertification process intensifies due to anthropomorphic actions.

The continuity of this research is recommended: a) Incorporating the effects of important variables to the modeling, such as albedo, aerosol optical depth and precipitable water, b) a significant increase of locations with simultaneous measurements of UV and global solar irradiation, for at least 1 year and c) at immediate level, the extension of the map to cover the Northeast of Brazil.

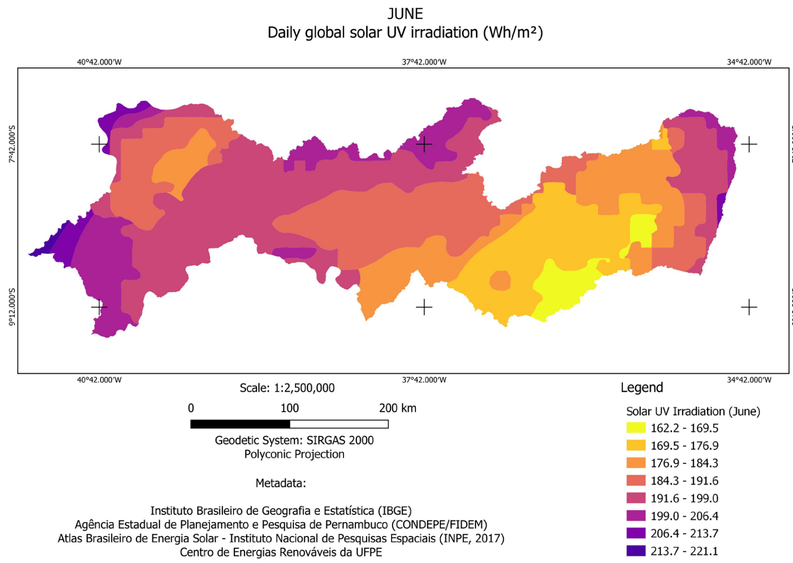

Figure 9. Seasonal variation of solar UV irradiation in the state of Pernambuco: June. Source: Own authorship.

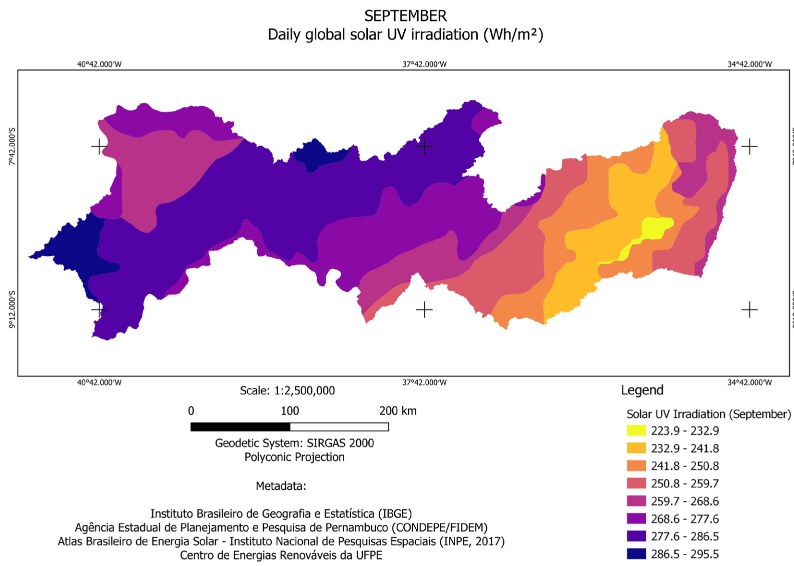

Figure 10. Seasonal variation of solar UV irradiation in the state of Pernambuco: September. Source: Own authorship.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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