

Assessing the correlation between incidence of skin neoplasm and solar irradiance: modelling of public health implications

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ABSTRACT

Background: Skin cancer is currently among the major public health concerns in Brazil due to the enormous intensity of mean annual solar radiation. This study aimed at evaluating the correlation between the incidence of skin neoplasm and solar irradiance in the São Paulo (SP) State of Brazil. **Methodology:** For this purpose, a regression analysis was performed using the mean annual number of skin neoplasm cases (melanoma and non-melanoma) as a function of the mean monthly solar irradiance reported at different Regional Health Departments (RHDs) of the São Paulo State. **Results:** According to the data collected at RHDs, the highest mean solar irradiance and skin neoplasm cases were reported in the Northwest, North and West regions of the State with a reduction in the Southeast, South and East regions. The response of the mean annual number of skin neoplasm cases was exponential at the mean monthly solar irradiance, demonstrating the high potential of solar radiation impacting the incidence of skin cancer. **Conclusion:** The higher incidence of skin neoplasms (melanoma and non-melanoma) in the Northwest, North, and West regions of the State of São Paulo is associated with greater exposure of rural workers to high solar irradiance, making legislative and public policy innovation imperative to improve population safety.

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INTRODUCTION

The rapid increase in population over the last several decades in Brazil has triggered the challenge of maintaining a sustainable regional public health administration and planning. The consistent increase in solar irradiation due to climate change, as well as weak socioeconomic conditions, is among the potential risk factors for the incidence of skin neoplasm in emerging economies (Yanagi et al., 2012; Bertemes-Filho, 2017). Several chronic-degenerative diseases such as hypertension, cardiovascular diseases,

cancer, diabetes mellitus and chronic respiratory diseases, are among the most important public health concerns in Brazil (Oliveira, 2010; Ferreira and Nascimento, 2016). Skin neoplasm needs greater attention because the risk factors, such as skin types and exposure to ultraviolet rays, are favourably assimilated in Brazil (Risi et al., 2002; Tiba and Leal, 2017). The greater exposure to ultraviolet rays is a potent factor for the incidence of skin neoplasms in tropical countries (Leiter et al., 2020), especially in the State of São Paulo, which is among the Brazilian

regions with the highest mortality rates from malignant neoplasms (Oliveira et al., 2025). In a climate with already higher intensity of ultraviolet B rays (UV B rays), the factors of high temperature and humidity are further contributing to accelerate the incidence of skin cancer (Mendonça, 1992).

UV radiation is one of the bands from the electromagnetic spectrum of solar radiation (Ilyas, 2007), so the intensity of solar radiation is directly correlated with the incidence of UV radiation. One of the ways to quantify solar radiation is to determine solar irradiance, which is defined as the total power of energy coming from the sun per unit area at a distance of one astronomical unit (AU) which is usually expressed in watts per square meter (Coariti, 2017). In addition to the studies on climate change as well as clean energy production and engineering projects, searching out information on the behaviour and intensity of solar irradiance is essential and of utmost importance for the effective management of public health services (Freitas et al. 2020). If the intensity of solar irradiance were found to be associated with the incidence of UV radiation, then it could be inferred that a relationship exists between the intensity of solar irradiance and the incidence of skin neoplasm (Urasaki et al., 2016). Therefore, establishing a mathematical correlation between these two variables for the State of São Paulo is essential to model this effect in one of the regions with the highest mortality rates in Brazil. The importance of mathematical modelling in practical and operational fields such as public health planning and administration has already been evidenced (Gomez et al. 2018; Costa, 2019). Given that, the objective of this study was to evaluate the correlation between solar irradiance and skin neoplasms (melanoma and non-melanoma) in the Regional Health Departments (RHDs) of São Paulo State, Brazil.

MATERIALS AND METHODS

The present investigation was performed at Brazil University (Universidade Brasil), Fernandópolis campus - SP, Brazil. The required data were collected from 17 Regional Health Departments (RHDs) located at different regions of the São Paulo State of Brazil (Figure 1). The correlation between the mean annual relative cases of skin

neoplasm (dependent variable) and the mean monthly solar irradiance (independent variable) was evaluated by the regression model. The mean annual relative cases of skin neoplasm (dependent variable), during the period of 2010 to 2017, were determined through the following equation 01.

$$Sc_i = \frac{\sum C_i^k}{n} \quad (\text{equation 01})$$

Where,

Sc_i - mean annual cases of skin neoplasm reported at RHDs "i" (cases/10⁵ inhabitant year),
 C_i^k - cases of skin neoplasm reported at RHDs "i" during year "k" (cases/10⁵ inhabitants),
 n - number of years from 2010 to 2017.

The relative cases of skin neoplasm, reported at RHDs "i" during year "k" of the studied period, were calculated through the following equation 02.

$$C_i^k = \frac{Ac_i^k}{P_i^k} \quad (\text{equation 02})$$

Where,

C_i^k - relative cases of skin neoplasm reported at RHDs "i" during year "k" (cases/10 inhabitants),
 Ac_i^k - absolute cases of skin neoplasm reported at RHDs "i" during year "k" (cases),
 P_i^k - number of inhabitants (inhab) registered at RHDs "i" during year "k" (inhabitants).

The absolute number of skin neoplasm cases reported at RHDs "i" during year "k" of the studied period (2010 to 2017) was obtained from the online database of the Oncocentro Foundation of São Paulo (FOSP, 2018). All cases of skin neoplasms classified under code "C44" of the Unified Health System were included in the analysis, encompassing malignant cancers (carcinomas, sarcomas, lymphomas, and melanomas), pre-malignant lesions (Bowen's disease, melanoma in situ), and non-malignant/uncertain tumours (atypical fibroxanthoma and histiocytosis), located in various parts of the body such as the external ear, eyelid, face, scalp, neck, lips, trunk, shoulder, upper limbs, hips, and lower limbs. The number of inhabitants registered at RHDs "i" during year "k" of the studied period was estimated using the

increment in mean annual population data based on the population census from 2010 to 2016 (IBGE, 2010; 2016). This procedure was done by the following equation 03.

$$P_i^k = P_i^{(k-1)} + \Delta_{(t_{2010}-t_k)} \cdot IP_i \quad (\text{equation 03})$$

where,

P_i^k - number of inhabitants at RHDs “i” in year “k” (inhabitants),

$P_i^{(k-1)}$ - number of inhabitants at RHDs “i” in the previous year “k - 1” (inhabitants),

$\Delta_{(t_{2010}-t_k)}$ - time variation between 2010 and year “k” (years),

IP_i - mean annual population increase at RHDs “i” from 2010 to 2016 (inhabitants).

The mean annual population increase at RHDs “i” between 2010 and 2016 was determined through the following equation 04.

$$IP_i = \frac{(P_i^{2016} - P_i^{2010})}{\Delta_{(t_{2010}-t_{2016})}} \quad (\text{equation 04})$$

IP_i - mean annual population increase at RHDs “i” between 2010 and 2016 (inhabitants),

P_i^{2016} - number of inhabitants at RHDs “i” during 2016 (inhabitants),

P_i^{2010} - number of inhabitants at RHDs “i” during 2010 (inhabitants),

$\Delta_{(t_{2010}-t_{2016})}$ - time interval between 2010 and 2016 (years).

The number of inhabitants at RHDs “i” during the studied period (2010 to 2016) was obtained from the census of the Brazilian Institute of Geography and Statistics (Portuguese: Instituto Brasileiro de Geografia e Estatística; IBGE). So, the number of inhabitants used in the present calculations from 2010 to 2016 was real rather than estimated.

The mean monthly solar irradiance (independent variable) at RHDs was obtained by the cross between satellite images of the monthly solar irradiance from 2010 to 2017 and the vectors of the RHDs limits. The irradiance images were produced by the CERES (Clouds and Earth's Radiant Energy System) sensor from NASA's Earth and Water satellites (NEO, 2018). The procedure was performed by geoprocessing with

the help of the ArcGIS software Educational version.

Statistical analysis

Statistical analysis was performed to compare the RHDs in terms of mean monthly solar irradiance and mean annual relative cases of skin neoplasm, and to evaluate the correlation between these two variables. To compare the mean data among RHDs, the analysis of variance was performed, followed by Scott-Knott's test at the 5% significance level. A regression analysis was performed to evaluate the correlation between the two variables (mean monthly solar irradiance as the independent variable and mean annual relative cases of skin neoplasm as the dependent variable). The linear, logarithmic, quadratic, power, and exponential models were tested. The model selection was done on the basis of significance level (p - p-value) and the coefficient of determination (r^2). The statistical analysis was performed by the SPSS (Statistical Package for Social Sciences) Educational version software, while the graphs were elaborated on the Microsoft Excel sheet.

RESULTS

The mean annual solar irradiance observed at regional health departments (RHDs) 2, 3, 5, 6, 8, 10, 11, 13, 14 and 15 (257.61 W/m²) was found significantly higher (p < 0.05) than RHDs 7, 9, 12, 16 and 17 (228.23 W/m²) (Figure 2).

It was observed that the mean annual solar irradiance at the regions with the greater exposure to the sun was 12.9% higher than those with the lower exposure to the sun. The cases of skin neoplasm were significantly higher (p < 0.05) at RHD 15 - São José do Rio Preto and 5-Barretos (mean of 124.2 cases/10⁵ inhabitants), followed by RHD 6 - Bauru (mean of 108.6 cases/10⁵ inhabitants), RHD 2 - Araçatuba and 9 - Marília (mean of 48.1 cases/10⁵ inhabitants), RHD 3 - Araraquara (mean of 29.5 cases/10⁵ inhabitants), RHD 11 - Presidente Prudente, RHD 8 - Franca, RHD 14 - São João da Boa Vista, RHD 13 - Ribeirão Preto, RHD 1 - Grande São Paulo (mean of 19.0 cases/10⁵ inhabitants), RHD 10 - Piracicaba, RHD 16 - Sorocaba, RHD 7 - Campinas, RHD 4 - Baixada Santista, RHD 12 - Registro and RHD 17 - Taubaté (mean of 6.9 cases/10⁵ inhabitants) (Figure 3).

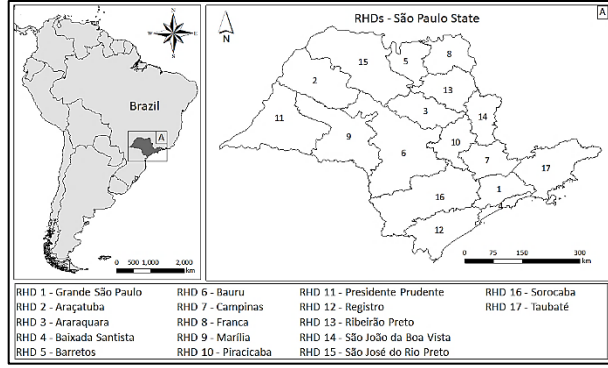


Figure 1: The map of the São Paulo State of Brazil the locations of the 17 Regional Health Departments (RHDs).

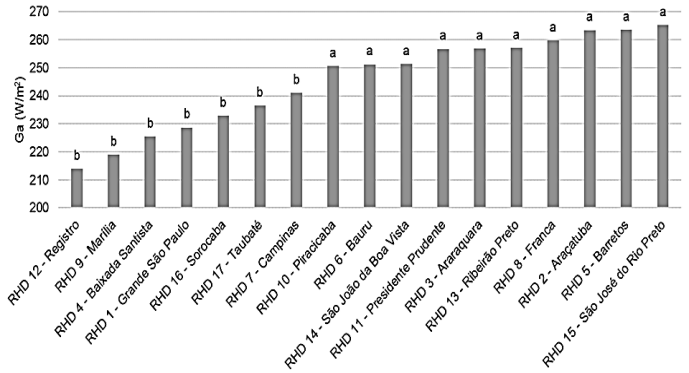


Figure 2: A comparison of the mean annual solar irradiance (Ga) among different regional health departments (RHDs) of the São Paulo State of Brazil between 2010 and 2017 ($p < 0.05$ by the Scott-Knott test and coefficient of variation equal to 1.2%).

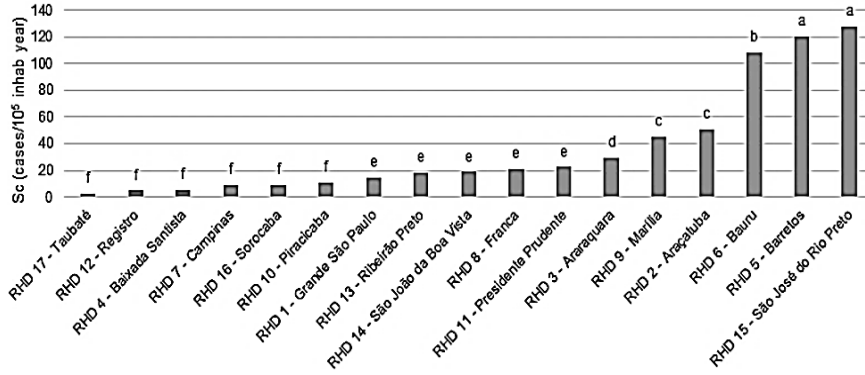


Figure 3: A comparison of the mean annual cases of skin neoplasm (Sc) at different regional health departments (RHDs) of the São Paulo State of Brazil between 2010 and 2017 ($p < 0.05$ by the Scott-Knott test and coefficient of variation equal to 33.3%).

During all months evaluated in the present study, significant ($p < 0.01$) differences were observed in the relative number of skin neoplasm cases as a function of mean solar irradiance throughout the year. The best fit, during most months, was

exponential (Table 1), with the correlation coefficients ranging from high ($r = 0.5$ to 0.7) to very high ($r = 0.7$ to 0.9).

Table 1: Statistical difference ($p < 0.05$) by the analysis of variance, with better adjusted models to the mean annual skin neoplasm cases (Sc, cases/10⁵ inhabitants) as a function of the mean monthly solar irradiance (Ga, W/m²).

Month	P – value	Fitted model	R	R²
January	< 0.01	$Sc = 7E-53 G^{21.75}$	0.741	0.549
February	< 0.01	$Sc = 4E-09 e^{0.0767Ga}$	0.732	0.536
March	< 0.01	$Sc = 1E-04 e^{0.0467Ga}$	0.755	0.570
April	< 0.01	$Sc = 2E-05 e^{0.0588Ga}$	0.758	0.575
May	< 0.01	$Sc = 0.0077 e^{0.041Ga}$	0.697	0.486
June	< 0.01	$Sc = 0.0083 e^{0.0448Ga}$	0.698	0.487
July	< 0.01	$Sc = 0.0099 e^{0.0384Ga}$	0.702	0.493
August	< 0.01	$Sc = 0.0047 e^{0.0363Ga}$	0.708	0.501
September	< 0.01	$Sc = 0.0043 e^{0.034Ga}$	0.624	0.389
October	< 0.01	$Sc = 0.0007 e^{0.0369Ga}$	0.722	0.521
November	< 0.01	$Sc = 4E-06 e^{0.0527Ga}$	0.753	0.567
December	< 0.01	$Sc = 8E-10 e^{0.0791Ga}$	0.717	0.514

The results presented in Table 1 may show that the greater exposure of the population to solar irradiance in the São Paulo State of Brazil has a significant impact on the incidence of skin neoplasms.

Figure 4 was plotted with the help of the adjusted models, in which the plotted lines represent the simulation of monthly solar irradiance required throughout the year to reach the quartile and

extreme values of the mean annual skin neoplasm cases. So, Figure 4 verifies that in order to reach the median of the mean annual skin neoplasm cases (19 cases/ 10^5 inhabitants), the mean monthly solar irradiance varied from 260 to 286 W/m^2 in summer, 173 to 234 W/m^2 in autumn, 197 to 247 W/m^2 in winter and 277 to 302 W/m^2 in spring.

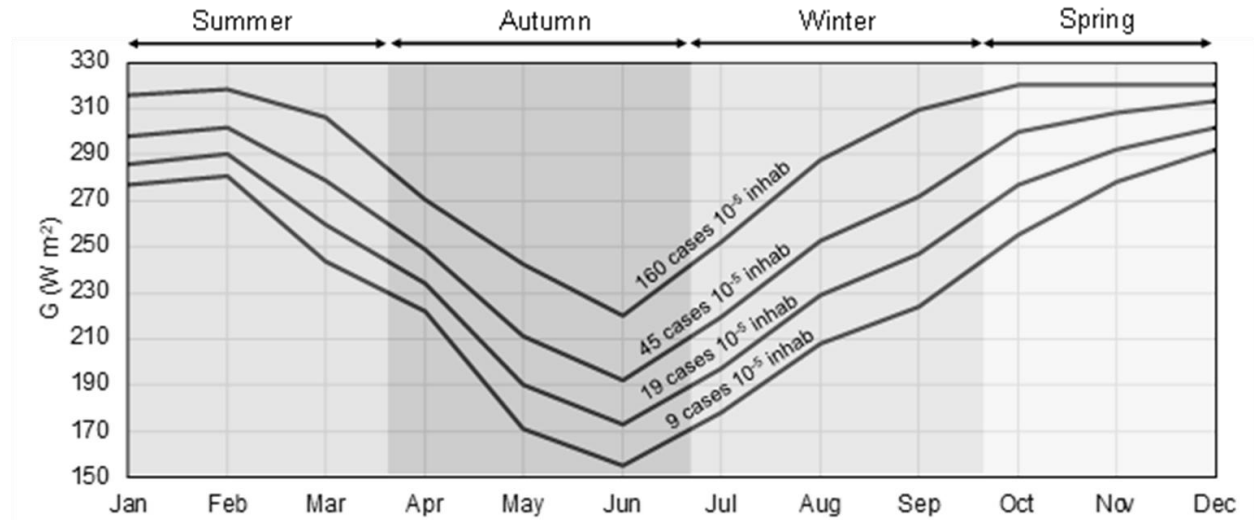


Figure 4: Variability of mean solar irradiance (Ga) required to achieve 1 quartile (9 cases/ 10^5 inhabitants), median (19 cases/ 10^5 inhabitants), 3 quartile (45 cases/ 10^5 inhabitants) and upper value (160 cases/ 10^5 inhabitants) of the mean annual relative skin neoplasm cases simulated from the models fitted to each month.

DISCUSSION

According to the results described in figure 2, the lowest mean annual solar irradiance reported at the regional health department (RHD) 12 - Registro of the São Paulo State of Brazil (213.98 W/m^2) was found higher than the mean annual global solar irradiance (170 W/m^2) (World Energy Resources, 2013). Studies on solar energy have demonstrated that the mean intensity of solar radiation within the Brazilian territory is almost equal to the maximum irradiation being observed in the European continent (Martins et al. 2005; Greinert et al., 2015). The present results agree with the distribution map of normal irradiance in Brazil (World Bank, 2017), in which the mean solar radiation intensity in the São Paulo State tends to increase from Southeast to Northwest. This fact is probably related to the climatic variation of the São Paulo State, which occurs from the Southeast (Litoral) toward the

Northwest (border with the Mato Grosso do Sul and Triângulo Mineiro). In this direction, the climate may vary from rainier to drier (Rolim et al., 2007), resulting in the attenuation of solar irradiance in the São Paulo State. Regarding the incidence of skin neoplasm (Figure 3), RHDs with the highest number of skin neoplasm cases tended to accompany RHDs with the highest solar irradiance; that is, greater exposure to UV radiation may result in a higher incidence of skin neoplasm (Trakatelli et al., 2016). Similar results regarding the spatial distribution of the cutaneous melanoma cases in the São Paulo State showed that the incidence decreased in the North, Northwest, Southwest and Southeast regions of the State, corresponding to the municipalities of São José do Rio Preto, Ribeirão Preto, Araraquara, Bauru, Marília and Sorocaba (Amancio and Nascimento, 2014). This is a

worrying fact, especially in RHDs with the higher intensity of solar radiation, because cutaneous melanomas may result in significant morbidity due to the high possibility of metastasis (Souza et al., 2009). The same author has also pointed out that this characteristic may justify the campaigns and investments which must be taken into consideration by both doctors and public health management services for the prevention of skin cancer.

The high potential of solar radiation to cause skin neoplasms may be related to the ultraviolet (UV) radiation. This is because even after the ozone layer has absorbed all UV C radiation and most of the UV B radiation, the residual UV B radiation that reaches Earth's surface is absorbed by body protein and DNA in quantities enough to kill the unprotected cells (De Gruijl, 2000). The effects and risks of solar irradiance on skin cancer incidence rates are well-known (Woodie and Fleischer Jr., 2024; Ivert et al., 2024). However, the models obtained in this study allow for the evaluation of the spatial and temporal distribution of skin cancer cases in the State of São Paulo, which is important for public health planning in this region.

During all months evaluated in the present study, significant ($p < 0.01$) differences were observed in the relative number of skin neoplasm cases as a function of mean monthly solar irradiance throughout the year. Overall, the exponential model was a best fit during most months (Table 1), with the correlation coefficients ranging from high ($r = 0.5$ to 0.7) to very high ($r = 0.7$ to 0.9) (Hopkins, 2000). The way solar irradiance increases during spring and summer (Figure 4), UV radiation also increases proportionally. In another study, it was observed that UV B radiation reached approximately 2.8%, 3.3% and 3.5% of the total UV radiation in September, March and December in São Paulo city, dropping to 2.5% in June (Correa, 2015). In the Northwest region of São Paulo State, UV indexes remain at an extreme position from October to March (UV index above 10.5), very high in April and September (UV index between 7.5 and 10.5), high in May, July and August (UV index between 5.5 and 7.5) and moderate in June (UV index between 2.5 and 5.5) (Vanzela et al., 2014). During the summer solstice in the southern hemisphere, solar declination reaches 23° South,

with the direct intensity of solar radiation on the Southeast region (Spiridonov and Ćurić, 2021), resulting in one of the highest UV indexes in Brazil. This geographical context needs greater attention since the area covered by the São Paulo State is between the latitudes 20° and 25° South, where during spring and summer population is exposed to one of the largest solar irradiance and UV index of the country (Rivas et al., 2015). On the other hand, the regions with the highest incidence of skin neoplasm are precisely the ones that have agricultural and livestock-dependent economies (SEADE, 2018), making them more exposed and vulnerable to solar radiation (Nahar et al., 2013). The high incidence of skin neoplasm cases in response to greater exposure to solar irradiance could be associated with the great demand for labour in the agricultural sector in the regions with higher solar irradiance. So, the appropriate inspection of labour sites with a special focus on the health of labour personnel, the establishment of effective public health management bodies and the execution of efficient preventive measures and strategies (with the use of individual protection and health campaigns) is imperative for the proper diagnosis (health care programs), treatment and prevention of skin neoplasm.

CONCLUSION

The months with the highest solar irradiance in the state of São Paulo, Brazil, were February, November, and December, while July had the lowest average solar irradiance. According to the spatial distribution, the Northwest and West regions of the state exhibited the highest average solar irradiance, including the Regional Health Departments (RHDs) of São José do Rio Preto, Araçatuba, and Presidente Prudente, while the South region of the state had the lowest average solar irradiance, including the RHD of Registro. The correlation between the annual average of skin neoplasia cases and average solar irradiance was significant throughout all months of the year, allowing for the development of exponential models that will serve as auxiliary information for public health management in the state of São Paulo.

The results also highlight the need for legislative innovations and public policies that improve occupational safety for agricultural workers, provide cheaper access to sunscreen and personal

protective equipment (PPE), and encourage public monitoring and awareness programs on skin cancer in high-incidence RHDs.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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