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# Global, diffuse and direct solar radiation at the surface in the city of Rio de Janeiro: Observational characterization and empirical modeling

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ABSTRACT

The city of Rio de Janeiro and others 18 cities compose the Metropolitan Area of Rio de Janeiro. The main objective of this work is to characterize observationally the diurnal and seasonal evolution of the solar radiation components in the city of Rio de Janeiro. The measurements of global and diffuse solar radiation and standard meteorological variables at the surface have been carried out regularly at the Geoscience Institute of Federal University of Rio de Janeiro since October of 2011. The microclimatic conditions show that the period 2011–2014 was warmer during most of the year and drier in summer and spring in comparison with climate normal. All solar radiation components present a well defined diurnal cycle with maximum at noon. The estimates of global and direct solar radiation indicate a great potential available for solar energy at the surface, particularly in summer. The behavior of the clearness index and diffuse solar radiation fraction is similar in summer and winter. The Angstrom formula represents properly the estimate of the monthly average daily value of global solar radiation. The sigmoid logistic function is statistically more significant in comparison with others correlation models to represent the diffuse fraction as a function clearness index.



## 1. Introduction

Solar radiation is the main source of energy in most of the surface–atmosphere interactions driving almost all physical, chemical and biological processes in earth's atmospheric and oceanic systems [1,2]. The knowledge of global ($E_G$), diffuse ($E_{DF}$) and beam ($E_{DR}$) solar radiation components at the surface is crucial to determine areas with potential for solar power generation [3–6], to assess the energy consumption in buildings [7], to subsidize ecophysiological studies [8,9], to estimate the evapotranspiration of crops [10] and to support urban planning [11].

Besides, due to environmental and economical reasons, tropical countries like Brazil will need to use their solar energy potential, estimated between 1500 and 2200 kW h m$^{-2}$ year$^{-1}$ [12], in order to diversify their energy matrix [13–15]. For instance, Brazil has an installed capacity of 134 GW of power generation, of which solar and wind energy contribute with 5% of this total [16].

Despite the importance, the knowledge of solar radiation field at the surface is still incipient in Brazil. There are small number of radiometric stations performing high quality measurements of $E_G$, $E_{DF}$ and $E_{DR}$, and only few has long-term data sets [3,17–19]. Oliveira et al. [17] were the first authors that establish the seasonal variations of the diurnal evolution of $E_G$, $E_{DF}$ and $E_{DR}$ based on measurements collected at surface of the city of São Paulo. Codato et al. [20] compared the solar radiation field at the surface in the city São Paulo with a rural site located in the city of Botucatu, where a radiometric station is measuring $E_G$, $E_{DF}$ and $E_{DR}$ with high quality since 1994. Even though these two radiometric stations are 250 km distant apart, they have similar latitude and altitude and the solar

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**Nomenclature**

| | |
|---|---|
| $a$ | Angstrom constant |
| $b$ | Angstrom constant |
| $E_G$ | global solar radiation ($Wm^{-2}$) |
| $E_G^h$ | hourly value of global solar radiation at the surface (MJ $m^{-2}$ $hour^{-1}$) |
| $E_G^d$ | daily value of global solar radiation at the surface (MJ $m^{-2}$ $day^{-1}$) |
| $E_{DF}$ | diffuse solar radiation ($Wm^{-2}$) |
| $E_{DF}^h$ | hourly value of diffuse solar radiation at the surface (MJ $m^{-2}$ $hour^{-1}$) |
| $E_{DF}^d$ | daily value of diffuse solar radiation at the surface (MJ $m^{-2}$ $day^{-1}$) |
| $E_{DR}$ | beam solar radiation ($Wm^{-2}$) |
| $E_{DR}^h$ | hourly value of beam solar radiation at the surface (MJ $m^{-2}$ $hour^{-1}$) |
| $E_{DR}^d$ | daily value of beam solar radiation at the surface (MJ $m^{-2}$ $day^{-1}$) |
| $E_T$ | extraterrestrial solar radiation ($Wm^{-2}$) |
| $E_T^h$ | hourly value of extraterrestrial solar radiation at the top of atmosphere (MJ $m^{-2}$ $hour^{-1}$) |
| $E_T^d$ | daily value of extraterrestrial solar radiation at the top of atmosphere (MJ $m^{-2}$ $day^{-1}$) |
| $F_C$ | diffuse correction factor (nondimensional) |
| $K_D$ | diffuse fraction of the solar radiation (nondimensional) |
| $K_D^h$ | hourly value of diffuse fraction of the solar radiation (nondimensional) |
| $K_D^d$ | daily value of diffuse fraction of the solar radiation (nondimensional) |
| $K_T$ | clearness index (nondimensional) |
| $K_T^h$ | hourly value of clearness index (nondimensional) |
| $K_T^d$ | daily value of clearness index (nondimensional) |
| MDD | movable detector device |
| $q$ | specific humidity (g $kg^{-1}$) |
| $r$ | ring width (cm) |
| $R$ | ring-detector distance (cm) |
| $RH$ | relative humidity (%) |
| $S$ | monthly average daily value of sunshine hours (hours) |
| $S_{max}$ | maximum monthly average daily value of sunshine hours (hours) |
| $T$ | air temperature (°C) |
| $w$ | hour angle at the sunset (degree) |
| $\alpha$ | solar elevation angle (degree) |
| $\delta$ | solar declination angle (degree) |
| $\varphi$ | latitude (degree) |
| $\theta_z$ | solar zenith angle (degree) |
| $MBE$ | mean bias error |
| $R^2$ | coefficient of determination |
| $RMSE$ | root mean square error |
| $t$ | t-test |
| $d$ | index of agreement |
| $AIC$ | Akaike's information criterion |
| $\Delta_i AIC$ | difference of Akaike's information criterion |

field at the surface in these both sites shows a similar seasonal variation. More recently, Ferreira et al. [21] characterized observationally the diurnal and seasonal variations of the radiation balance at the surface in the city of São Paulo. They concluded that, in addition to astronomical factors, the seasonal variation of $E_G$ depends more on the atmospheric broadband transmissivity and less on the surface effective albedo. Pereira et al. [3] and Martins et al. [22] used $E_G$ and $E_{DR}$ measurements collected at surface by SOLAS network to validate the satellite-derived radiative transfer model. They produced maps of $E_G$, $E_{DF}$ and $E_{DR}$ that can be used to estimate the available potential for energy production based on solar radiation for the entire Brazil considering only a set of six surface stations and a short time period of observation.

High quality measurements of $E_G$, $E_{DF}$ and $E_{DR}$ during long periods of time can be used also to develop empirical models. Given $E_G$ measurements on a horizontal surface, the $E_{DF}$ component can be obtained through an empirical function that relates diffuse fraction of the solar radiation ($K_D$) with the clearness index ($K_T$). This type of empirical model where first proposed by Liu and Jordan [23] to estimate daily values of $E_{DF}$ in terms of $E_G$ using a first order polynomial. These empirical models, also known as correlation models, have received considerable attention from the solar radiation community. They are usually expressed in terms of higher order polynomials, exponentials or logistic functions and may include multiple predictions for monthly, daily, hourly and shorter periods of time [24–26]. Erbs et al. [27] developed the correlation model for hourly value, but their results for $E_G$ were very sensitive to the presence of clouds. Reindl et al. [28] showed that in addition to $K_T$, the inclusion of other variables such as solar elevation, ambient temperature and relative humidity, improved the predict hourly $K_D$. Skartveit et al. [29] obtained a better performance for hourly values considering a variability index of $K_T$ to represent the influences of clouds in $K_D$. These works were developed to data collected in middle latitude regions located in the Northern Hemisphere, which have different characteristics from those observed in Southern Hemisphere [30].

Boland et al. [31] proposed a logistic function to represent $K_D$ as a function of $K_T$ with superior performance for an Australia location in comparison with the model of [28]. The theoretical framework for the use of the logistic function was presented in Ref. [32]. Oliveira et al. [33] showed that the overall characteristics of the $K_D$ correlation model based on $4^{th}$-order polynomials to the city of Sao Paulo represent the seasonal variations similar to other places with equivalent latitude for hourly, daily and monthly values. Soares et al. [34] used neural network technique to include implicitly the cloud effects in $K_D$ using downward atmospheric longwave measurements at the surface. Their results for hourly $K_D$ were better than those obtained by Ref. [33] for the same region.

In the search of more universal correlation model for $K_D$ including additional predictors to represent the influences of different climate conditions, Ridley et al. [30] proposed the multi predictor model BRL to estimate $E_{DF}$ and $E_{DR}$ components. The daily clearness index, solar altitude, apparent solar time and global radiation persistence are some predictions of the BRL, and the results show a better statistical performance for different regions of the world. According to [35], correlations models performance for short time variations can considerably improve when cloud effects on solar radiation field at the surface are incorporated explicitly. However, estimates of some of these predictions, with high frequency sampling, are not easily available. A review about different correlations models to estimate hourly $E_{DF}$ can be found in Refs. [24–26].

The main objective of this work is to characterize observationally the diurnal and seasonal evolution of $E_G$, $E_{DF}$ and $E_{DR}$ components in the city of Rio de Janeiro. Additionally, a new correlation model, based on fitting of logistic sigmoid function through