ASADES

Energías Renovables y Medio Ambiente
Vol. 32, pp. 45 - 51, 2013
Impreso en la Argentina. ISSN 0328-932X

PERFORMANCE OF ANISOTROPIC CORRECTIONS FOR DIFFUSE IRRADIANCE MEASURED BY THE *MEO* SHADOWRING METHOD APPLIED FOR HOURLY AND DAILY ENERGETIC TIME PARTITIONS

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Recibido:15-8-13; Aceptado:24-09-13.

ABSTRACT.- The objective of this paper is to apply and verify the performance of the anisotropic correction model developed for the MEO diffuse solar irradiance in the integrated values of the hourly and daily diffuse solar irradiations. Global, diffuse and direct irradiations from 1996 to 2005 were provided by the Laboratory of Solar Radiometry of Botucatu-UNESP. The anisotropic correction was developed for instantaneous values (5-minute-mean partition in W/m^2) and applied to the integrated values on hourly and daily energetic time partitions. The validation was performed by the MBE and RMSE statistical indicators and slope of the correlation between the shadowring and reference diffuse irradiations. It was found that only the application of the geometrical correction was not sufficient to adjust the values of the MEO shadowring diffuse irradiations. The joint application of geometric correction and the anisotropic correction as a function of atmospheric transmissivity Kt significantly reduced the difference between the hourly and daily reference and shadowring diffuse irradiations, with a difference less than 0.8% between hourly values and less than 1.3% between daily values. The use of the geometric correction and the anisotropic correction significantly improves the precision of MEO shadowring method for measurement the diffuse solar radiation, representing a viable alternative for radiometric stations with limited financial resources that monitor hourly and daily diffuse radiation.

Keywords: Diffuse solar irradiation, Measuring methods, Shadowring, Anisotropy.

RENDIMIENTO DE CORRECCIONES ANISOTROPICAS DE LA IRRADIANCIA DIFUSA MEDIDA POR ANILLO DE SOMBRA MEO APLICADAS EN PARTICIONES DE TIEMPO HORA Y DIA

RESUMEN.- El objetivo de este trabajo es aplicar y verificar el desempeño del modelo de corrección anisotrópico desarrollado para el MEO radiación solar difusa en los valores integrados de las irradiaciones em hora y día. Las irradiaciones global, difusa y directa fueron proporcionadas por el Laboratorio de Radiometría Solar de Botucatu-UNESP el período 1996-2005. La corrección anisotrópica fue desarrollada para valores instantáneos de partición y se aplica a los valores integrados en cada hora y día. La validación se realizó mediante los indicadores estadísticos MBE y RMSE entre los valores del anillo y referencia. Se encontró que sólo la aplicación de la corrección geométrica no era suficiente para ajustar los valores de irradiaciones difusas MEO. La aplicación conjunta de corrección geométrica y la corrección anisotrópica en función de la transmissividade atmosférica Kt redujo significativamente la diferencia entre las y irradiaciones difusas referencia y anillo, con una diferencia de menos de 0,8% entre los valores horarios y menos de 1,3% entre los valores diarios. El uso de la corrección geométrica y la corrección anisotrópico mejora significativamente la precisión del método de anillo de sombra MEO para la medición de la radiación solar difusa, que representa una alternativa viable para las estaciones radiométricas con recursos financieros limitados que monitorean cada hora y día la radiación difusa.

Palabras claves: irradiación solar difusa, métodos medición, anillo, sombra, anisotropía.

1. INTRODUCTION

Diffuse solar irradiance is an important meteorological parameter for many areas of knowledge, with applications in weather prediction models (Hawlader, 1984; Lalas et al, 1987; De Miguel et al, 2001), in plasticulture (Critten, 1987;Cabrera et al, 2009) and in studies of luminance environments (Muneeret al, 1998). In the area of thermal engineering, the diffuse solar irradiance is used to estimate the direct solar irradiance for financial reasons.

The direct solar irradiance, used to validate models of energy efficiency of solar collectors and photovoltaic modules, requires a high financial investment in the

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acquisition of the measuring apparatus and the solar tracking system. This fact complicates the routine monitoring of this component in many meteorological stations. As the direct irradiance is calculated by the difference between global and diffuse irradiances, a solution, then, is to measure the global and diffuse solar irradiances, which do not require large financial investments, and estimate the direct solar irradiance by difference. However, errors of 5% in the measurement of diffuse solar irradiance may lead to errors of the order of 20% in the estimate of direct solar irradiance, depending on solar elevation (Lebaron et al, 1990).

A well accepted method for monitoring the diffuse irradiance due to ease of maintenance, optimal operation and relatively low cost is the shadowring method. In this method, the ring is oriented perpendicularly to the polar axis and at an angle equal to the local latitude. It shades the bands center point from sunrise to sunset. An instrument is placed at this point and it permits the measurement of diffuse radiation for extended periods of time. Therefore, to keep the sensor in the shadow, periodical mechanical adjustments are necessary.

In this paper we use the *MEO*shadowring method (Melo& Escobedo, 1994; Oliveira et al, 2002) to measure the diffuse solar irradiance. In this method, the shadowring is fixed and the pyranometer is translated parallelly to the local horizon plan in a mobile base to compensate the solar declination. As operational advantages of this configuration, the movement of the sensor can be automated by means of motors driven by dataloggers. The Figure 1 shows the *MEO* shading setup.

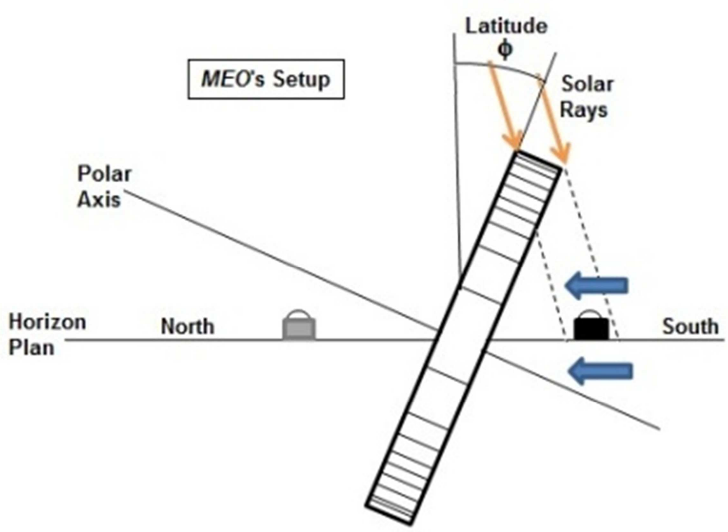

Fig. 1: MEO Shadowring setup

A drawback of the shadowring method is the use of correction factors to compensate the diffuse irradiance blocked by the shadowring (Drummond, 1956; Kastenet al, 1983; Dehne, 1984; Ineichenet al, 1984; Stanhill, 1985). The correction most commonly used is based on the isotropy of the radiation, which depends on geometrical (the ring length and width) and geographical (latitude and solar declination) factors.

However, the isotropic correction does not take in to account the circum solar radiation. This radiation is due to the scattering of direct radiation through small angles by the atmospheric particles (aerosols, water vapor, sky coverage) and is a result of the anisotropy of the radiation. Several works in the literature propose additional corrections that take in to account the anisotropic effects of radiation (Painter, 1981; Pollard&Langevine, 1988; Vartiainen, 1999). These additional corrections may present temporal (Stanhill, 1985) and spatial (Dehne, 1984) dependence due to the different sizes and concentrations of particulate matter in the atmosphere, with the atmospheric transmissivity Kt (ratio of global to extraterrestrial radiation) being the best representative parameter of anisotropic sky conditions (Lebaronet al, 1990; Battles et al, 1995).

As the anisotropic corrections are related to the concentration and distribution of atmospheric constituents, usually are developed for instantaneous time partition that responds more rapidly to atmospheric dynamics (Suehrcke& McCormick, 1988; Dal Pai et al, 2011). However, in many weather stations, the database is available on greater time partitions, as the case of the hourly and daily time partitions. Therefore, the objective of this paper is to apply and verify the performance of the anisotropic correction model developed for the *MEO* diffuse solar irradiance in the integrated values of the hourly and daily diffuse solar irradiations.

2. METHODOLOGY

The present study is based upon measurements recorded by the Solar Radiometric Station during the years 1996 to 2005. The Solar Radiometric Station is located on the Botucatu Campus of the Sao Paulo State University (22 54'S, 48 27'W, 716 m). Botucatu (Fig. 2) is a semi-rural town surrounded by sugar cane and eucalyptus crops with 127,328 inhabitants, few industries and the economy based upon services.

According to Köppen climate classification the local climate is classified as Cwa (humid subtropical climate - mesothermal) with hot and humid summers and dry winter. The air temperature and relative humid values follow the solar astronomical variations and the maximum and minimum values are 23,12 °C (February) and 17,10 °C (July) for air temperature and 78,25% (February) and 63,97% (August) for relative humid, respectively. The rainy season occurs in the summer and spring, with high cloudiness, when there are more than80% of the total annual rain falls with maximum value in January (246,2 mm). In the dry season (winter and autumn), the monthly-mean precipitation is less than 100 mm with minimum value in August (36.10 mm). With regard to aerosols emitted into the atmosphere, industries and motor vehicles are the main emitters of particulate matter. However, the study area is surrounded by70cities that release large amounts of particulate matter as a result of burning of sugar cane, especially in the winter. The highest aerosol concentration occurs in this period due to lack of rainy days, thus preventing the deposition of particulate matter (Codato et al, 2008).

The global solar irradiance I_G was measured by an Eppley -PSP pyranometer (K = 7,45 V/Wm^{-2}); the direct normal solar irradiance I_b by an Eppley-NIP pyrheliometer (K = 7,59 V/Wm^{-2}) fitted to a ST-3 sun tracking device; and the diffuse solar irradiance I_{dM} by an Eppley-PSP pyranometer (K = 7,47 V/Wm^{-2}) fitted to a MEO Shadowring (radius of 0,40m and width of 0,10m). Figure 3 shows the measuring devices while Table 1 shows their operating features.

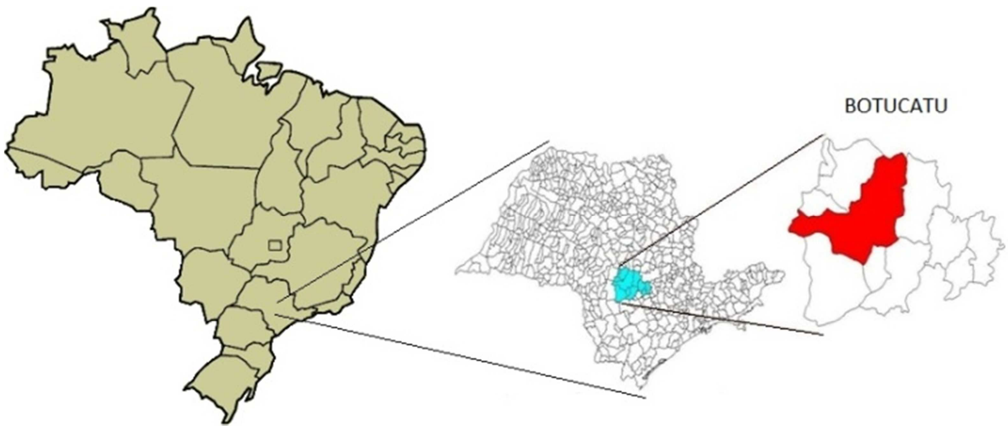

Fig. 2: Map of Brazil with divisions of states showing the sampling site (Botucatu in the State of São Paulo).

Fig.3: Global, diffuse and direct solar measuring devices.

Table 1:. Operating features of the global, direct and diffuse solar irradiances measuring devices (Source: The Eppley Laboratory (http://www.eppleylab.com))

Irradiance	**Global**	**Direct**	**Diffuse**
Sensor-marca	EppleyPrecisionSpectralPyranometer	Eppley Normal IncidencePyrheliometer	EppleyPrecisionSpectralPyranometer
Sensivity	±7,45 µV/Wm²	7,59 µV/Wm²	±7,47 µV/Wm²
SpectralRange	295 – 2800 nm	295 – 2800 nm	295 – 2800 nm
Response Time	1 s	1 s	1 s
Linearity	±0,5% (from 0 to 2800 W/m²)	±0,5% (from 0 to 1400 W/m²)	±0,5% (from 0 to 2800 W/m²)
Cosine	±1% (0º<Z<70º) ±3% (70º≤Z<80º)	–	±1% (0º<Z<70º) ±3% (70º≤Z<80º)
TemperatureDependence	±1% (from -20ºC to +40ºC)	±1% (from -20ºC to +40ºC)	±1% (from -20ºC to +40ºC)

The solar irradiance data were submitted to a quality control to ensure the reliability of the measures. The measured values that did not fit the boundary conditions were discarded. The cut values are due to misalignment, damaged wires, lack of electricity and shadowring internal reflections due to low solar altitude. Table 2 shows the boundary conditions (Kudish&Evseev, 2008).

Table 2: Quality control filters. I_{SC} is the solar constant (1367 Wm^{-2}) and I_O is the extraterrestrial solar irradiance ($I_O=I_{SC}.cosZ$)

Solar IrradianceType	Filter
Global	$I_G< I_O$
Normal IncidentBeam	$I_b \leq I_{SC}$
Shadowring Diffuse	$0{,}1\ I_G \leq I_{dM}< I_G$
Reference Diffuse	$0 \leq I_{dREFF} \leq I_{SC}$

The *MEO*Shadowring diffuse irradiance was corrected using the geometric factors proposed by Oliveira et al (2002) (eq. 1 and eq.2).

$$C_{GEOM} = \frac{1}{1-F_{LOSS}} \tag{1}$$

$$F_{LOSS} = \left(\frac{2b}{\pi R}\right).\cos(\delta).\left[\frac{\cos(\phi+\delta)}{\cos(\phi)}\right]^2.\int_0^{w_S}\cos(\theta_Z)dw \tag{2}$$

where b is the ring width, R the radius of the ring, δ the solar declination, ϕ the latitude, ω the hourly angle and θ_Z the zenital angle. Additional corrections were also applied that took into account the anisotropic behavior of the scattering caused by the interaction of radiation with the atmosphere. These anisotropic corrections were proposed by Dal Pai et al (2011) and depend on the atmospheric transmissivity (K_T). The atmospheric transmissivity (ratio of global to extraterrestrial irradiance) expresses the total irradiance that reaches the surface from the total available on the top of the atmosphere and is used to classify the sky coverage (Escobedo et al, 2009). Table 3 shows the anisotropic corrections for specific K_T intervals.

Table 3: Anisotropic correction factors for the MEO Shadowring diffuse irradiance

K_T Interval	Sky Coverage	Correction Factors
$0 \leq K_T< 0{,}35$	overcastsky	0.975
$0{,}35 \leq K_T< 0{,}55$	partiallycloudysky	1.034
$0{,}55 \leq K_T< 0{,}65$	partiallyclearsky	1.083
$0{,}65 \leq K_T< 1$	clearsky	1.108

These anisotropic corrections were developed for instantaneous values (W/m^2). However, in this paper, they will be applied in the energy values (MJ/m^2) of the hourly and daily partitions, obtained from integrating the instantaneous values (Chaves & Escobedo, 2000).

The true diffuse irradiation henceforth called reference diffuse irradiation H_{dREFF} was calculated by the difference between the global and horizontal direct irradiations given by (eq. 3):

$$H^i{}_{dREFF} = H^i{}_G - H^i{}_D \quad i = h, d \tag{3}$$

where H_{dREFF} is the integrated value of the reference diffuse irradiation, H_G is the integrated value of the global irradiation and H_D is the integrated value of the direct irradiation. The i index represents the hourly and daily partitions.

A Campbell Scientific datalogger model Cr23X was used to monitor and to store the solar irradiance data. The values were scanned at 5 s intervals and average values at 5 min intervals were calculated and stored. Every morning values were transmitted to a computer via a storage module model SM-192.

The evaluation of the numerical corrections was based on mean bias error MBE, root mean square error RMSE and t test statistical indicators (Stone, 1993) given by the (eq. 4) and (eq. 5) respectively.

$$MBE = \left(\sum_i^N (y_i - x_i)\Big/N\right) \tag{4}$$

$$RMSE = \left(\sum_i^N (y_i - x_i)^2\Big/N\right)^{1/2} \tag{5}$$

Where y_i is the estimated values, x_i the measured values and N the number of observations. The MBE provide information on the long-term performance of a model. A positive value means an over estimation where as a negative one means an under estimation. A drawback of this indicator is that over estimation of an individual observation will cancel underestimation in a separate observation. The RMSE provide information on the short-term performance of a model by allowing a term by term comparison of the actual difference between the estimated value and the measured value. While a high value means a large scattering, a low one means small scattering. A drawback of this indicator is that a few large errors in the sum can produce a significant increase in RMSE.

3. RESULTS AND DISCUSSIONS

In this section is presented the flowchart of operation of a typical solar radiometric station (in case the Solar Radiometric Station of Botucatu) in relation to the measurement of *MEO* diffuse solar irradiance. Knowledge of the operation flow will better understand how and at what time the geometric and the anisotropic corrections should be applied. So once understood the routine monitoring, it will be presented and tested an alternative routine to correct the diffuse solar radiation for stations that use greater time partitions, as the case of hourly and daily partitions.

The Solar Radiometry Station of Botucatu operates since 1996 performing measures of many solar components, such as global and diffuse irradiances on horizontal surfaces, direct incidence, global and diffuse on inclined surfaces, spectral components as ultra-violet, photo synthetically active and near infra-red, as well as measures of long wave irradiances, such as atmospheric and terrestrial ones. Specifically for the diffuse solar irradiance, the Solar Radiometry Station of Botucatu employs three different methods for monitoring: *MEO* shadowring method; disc shadowring method; and difference method (difference between global and direct solar irradiances). The difference method is considered the reference method by not requiring additional corrections (Battles et al, 1995). Figure 4 shows the flowchart representing the routine for measuring, processing and storage of *MEO* diffuse solar radiation for the Solar Radiometry Station of Botucatu.

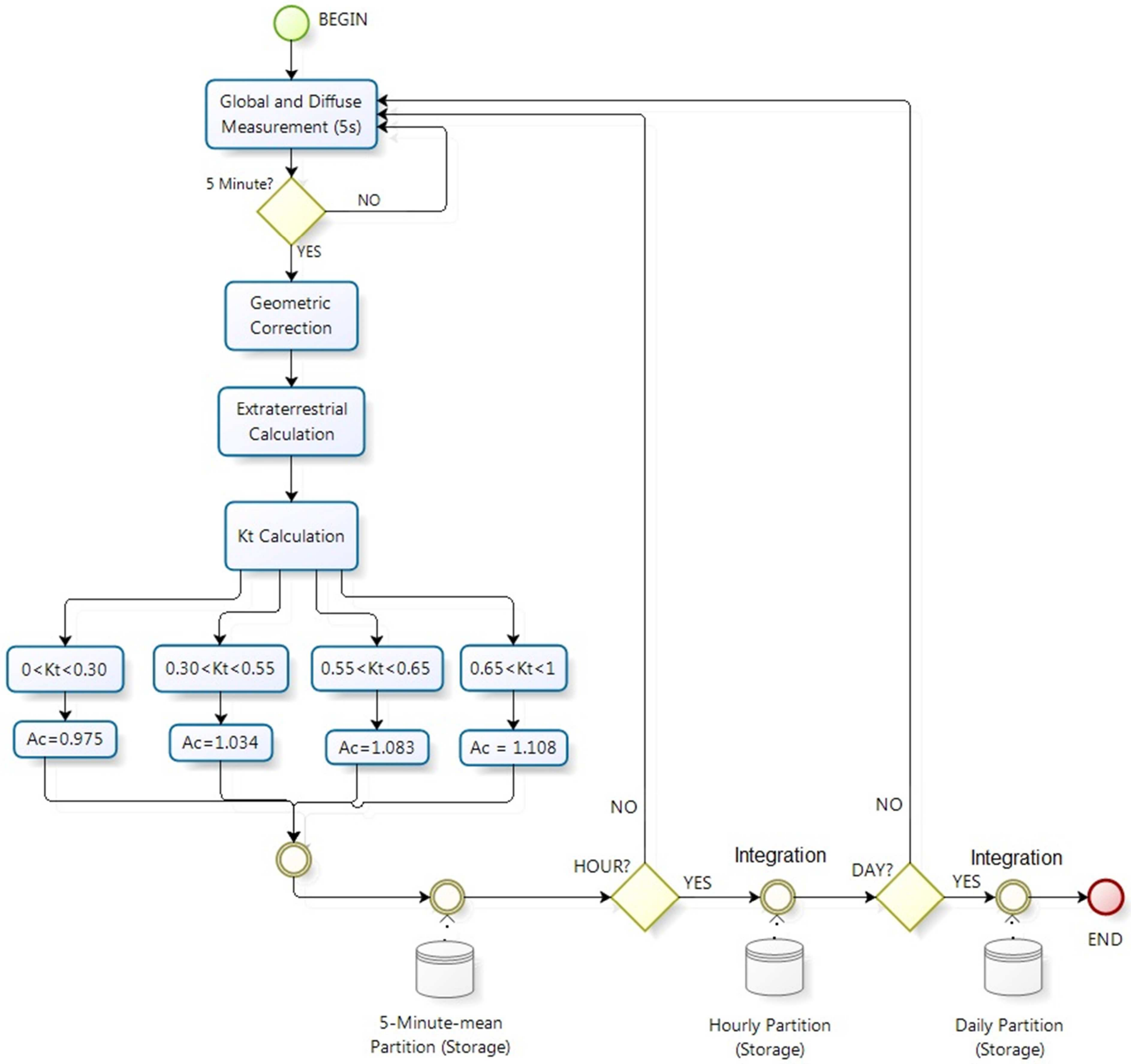

Fig. 4: Flowchart of measurement, processing and storage of diffuse solar irradiance monitored by the MEO shadowring method.

Global and diffuse measuring sensors are coupled to an automatic data acquisition (Campbell Datalogger model 23X) that makes all the measurement, processing and storage routine. The scanning sensor takes place every 5 sec (frequency of 0.2 Hz) and at the end of 5 minutes is extracted an average value (5-minute-mean partition). Then we calculate the geometric correction due to shading by the ring and it is applied on the values of diffuse irradiance. Geometric correction is calculated for daily partition, however, as its variation is minimal throughout the day, it can be used in smaller partitions of time (Drummond, 1956; Robinson & Stoch, 1964; Melo & Escobedo, 1994; Oliveira et al, 2002).

Continuing the flowchart, we calculate the cosine of the zenith angle, the extraterrestrial solar irradiance and atmospheric transmissivity Kt. Known the value of Kt, we apply a second correction to the values of diffuse solar irradiance (anisotropic correction due to Kt (Table 3), and the values are then stored in the 5-minute-mean partition database. Thus, at the end of this process, we have available in the database the global irradiance and diffuse irradiance an isotropically and geometrically corrected in W/m^2. By completing one hour, the values of the irradiances are integrated in time (summed), generating values of irradiation, in MJ/m^2, which are stored in the hourly partition database. Later, at the end of the day, the hourly irradiations are summed and the values are stored in the daily partition database. The hourly and daily partitions are said energetic partitions because of their values are stored in MJ/m^2.

This is the operating procedure of an automated radiometric station. However, at many stations, the measurements are stored in hourly and daily partitions. Diffuse radiation is corrected only with the geometric correction since anisotropic corrections were developed for 5-minute-mean partition (Dal Pai et al, 2011). In that sense, to ensure the quality of the values of diffuse radiation in hourly and daily partitions, the anisotropic correction model was applied in these time partitions and the results were compared with those obtained by the reference method. Table 4 and Figure 5 show the results of the comparison between the hourly and daily *MEO* diffuse irradiation and reference diffuse irradiation, respectively.

Table 4: Statistical indicators from the comparisonbetween thehourly and daily reference and MEOshadowring diffuse irradiations.

CORRECTION MODELS		STATISTICAL INDICATORS				
		MBE (MJ/m^2)	**MBE (%)**	**RMSE (MJ/m^2)**	**RMSE (%)**	**Slope**
Hourly	Geometric Correction	-0,028	-5,27	0,078	14,94	0,945
	Geometric Correction + Anisotropic Correction	-0,004	-0,79	0,063	12,06	0,990
Daily	Geometric Correction	-0,382	-5,59	0,680	9,96	0,951
	Geometric Correction + Anisotropic Correction	-0,086	-1,26	0,527	7,72	0,989

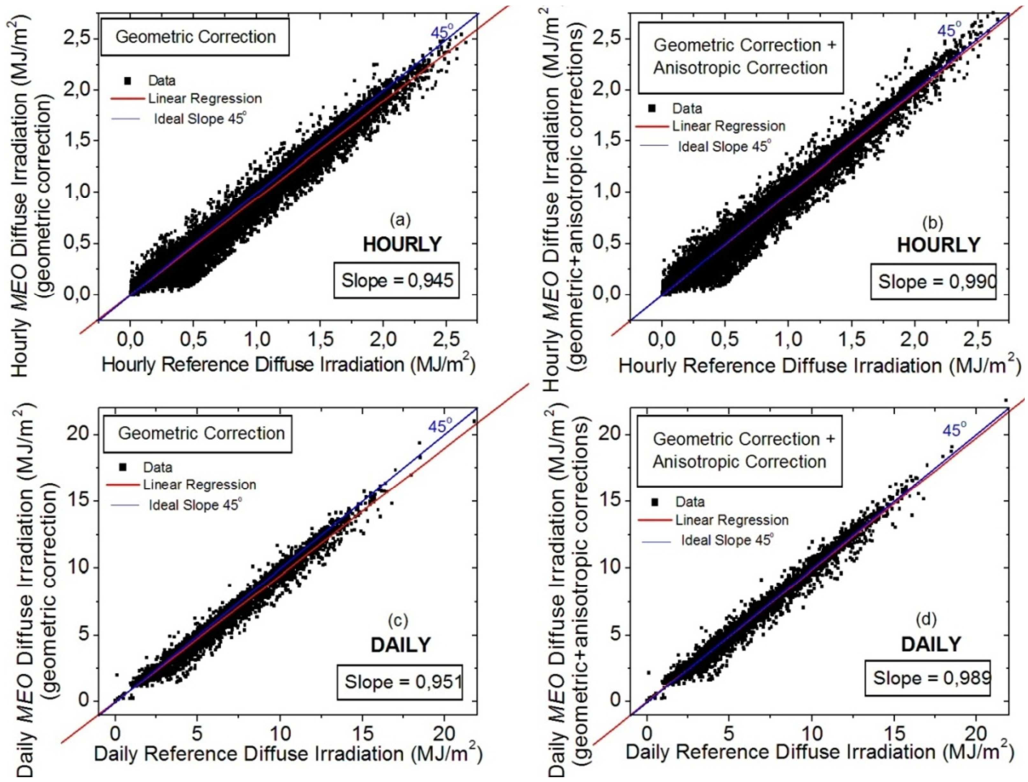

Fig. 5: Thediffuseirradiation validations for the correction methods. a) Isotropic Correction (Hourly partition). b) Isotropic + Anisotropic corrections (Hourly partition). c) Isotropic Correction (Daily partition). d) Isotropic + Anisotropic corrections (Daily partition).

For hourly partition, the MBE statistical indicator showed that the use of geometric correction in measurements of *MEO* diffuse radiation provided an underestimation of 5.27% compared with the reference values. With the integrated use of geometric and anisotropic corrections, this underestimation was reduced to 0.79%. Regarding the RMSE indicator, the scattering was reduced approximately 15% to 12%. For daily partition, the MBE and RMSE statistical indicators showed the same trend of reduction by introducing the anisotropic correction in the process of correction of *MEO* diffuse solar radiation. For MBE, reduction of -5.59% to -1.26% and for RMSE, reduction of 9.96% to 7.72%. As for the slope obtained from the comparison between the two methods of measurement, for both hourly and daily partitions, the introduction of anisotropic correction in the measurement of *MEO* diffuse irradiation generated slope values closer to the ideal line (slope=1).

Therefore, based on the results presented by statistical indicators, the anisotropic model of correction due to the atmospheric transmissivity Kt, developed for instantaneous values of irradiance (5-minute-mean partition), is recommended to correct the diffuse solar irradiation measured by the *MEO*shadowring method in the hourly and daily energetic time partitions.

4. CONCLUSION

The joint application of the geometric correction and the anisotropic correction due to the atmospheric transmissivity Kt in the hourly and daily partitions significantly reduce the difference between diffuse irradiation obtained by the reference method and diffuse irradiation measured by the *MEO*shadowring method. Therefore, the anisotropic model of correction due to the atmospheric transmissivity Kt, developed for diffuse irradiance values (5-minute-mean partition), is recommended for correction of hourly and daily values of diffuse solar irradiation measured by the *MEO*shadowring method.

The integrated use of the geometric correction and the anisotropic correction due to the atmospheric transmissivity Kt significantly improves the precision of *MEO*shadowring method for measurement the diffuse solar radiation, representing a viable alternative for radiometric stations with limited financial resources that monitor hourly and daily diffuse radiation.

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