# Estimates of Hourly Diffuse Radiation on Tilted Surfaces in Southeast of Brazil

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**Abstract-** The global radiation incident on a tilted surfaces consists of components direct, diffuse and reflected from the ground. On a hourly database, the direct radiation can be calculated by geometric projections (ratio of the incidence angle to the solar zenith angle). The reflected radiation has a small effect on calculations and may be calculated with an isotropic model. Both components presents dependence of measures in incidence or horizontal surface. The great difficulty is to evaluate the diffuse radiation by variations of circumsolar, brightness horizontal, isotropic and anisotropic subcomponents. This study evaluated twenty models to estimate hourly diffuse radiation incident on tilted surfaces at 12.85° (latitude - 10°), 22.85° (latitude) and 32.85° (latitude + 10°) facing to North, under different cloudiness sky conditions, in Botucatu, São Paulo State, Brazil (22°53′ S, 48°26′ W and 786 m above the mean sea level). In contrast, models for estimating the diffuse component show major differences, which justify the validation for local calibrations. There is a decrease of the maximum total radiation scattered with increasing atmospheric transmissivity and inclination angle. The best results are obtained by anisotropic models: Ma and Iqbal, Hay, Reindl et al. and Willmott; isotropic: Badescu and Koronakis, and the Circumsolar model. The increase of the inclination angle allows for a reduction in the performance of statistical parametric models for estimating the hourly diffuse radiation.

**Keywords-** atmospheric transmissivity, indicate statistical, solar energy, parametrized models.

## 1. Introduction

The temporal variation of the quantity of solar radiation incident on the surface depends basically of the astronomical, geographic and climatic factors, with greatest influences on atmospheric transmissivity given water vapor concentrations, aerosols and clouds [1-4]. Considering the local variables, the topography is essential for determine the quantity of energy to effect the solar flux (mainly the geometry incidence of direct radiation) by variations in the altitude, inclination, orientation (azimuth) and shading.

The knowledge levels of diffuse radiation incident on tilted surfaces is important in estimating the radiation absorbed by surfaces with natural inclination and vegetated, providing support for applications in hydrological, architectural (thermal comfort), urban planning, agronomic and micrometeorological studies, also in projects of energy conversion including engineering designs for solar collectors [5-8; 43-47]. Therefore, the definition of the levels of diffuse radiation, indirectly defines the direct energy incident on surfaces with inclinations and orientations forced (case of photovoltaic and solar water heaters).

The total of solar radiation incident in the horizontal planes is composed by the direct and diffuse components. According Iqbal [9], the hourly global radiation [ $H^h_{G\beta}$ ] incident on tilted surface with an angle of inclination (β), is given by the sum of the direct [ $H^h_{B\beta}$ ], diffuse [ $H^h_{D\beta}$ ] and reflected [ $H^h_{R\beta}$ ] hourly radiations.

$$H^h_{G\beta} = H^h_{B\beta} + H^h_{D\beta} + H^h_{R\beta} \tag{1}$$

In Brazilian meteorological stations, due to the cost of acquisition and maintenance, normally are measurements of only two components (global, diffuse or direct) and other is obtained by difference. For tilted surfaces, the direct and reflected components may be obtained with good accuracy using simple algorithms, but the diffuse component requires isotropic and anisotropic corrections [10-12], dependent on atmospheric change. Those corrections include the astronomical, geographical, climatic and geometric ring variations [13].

In routine measures, for estimates of diffuse or direct radiation applied statistical or parametric models estimation [14]. Recently several studies were developed order at present and evaluate models to estimate diffuse radiation on tilted surfaces for different climatic regions. However, the Brazilian's conditions doesn't studies it since most meteorological stations measure only global radiation on horizontal planes routinely. According Evseev and Kudish [15] there is a relatively large number of estimation models that correlate the diffuse radiation tilted based on measured surface horizontal, indicating the possibility to evaluate of the seasonal variation of that diffuse component of solar radiation and the assessments of the estimates in different atmospheric conditions and tilt angles, minimizing the difficulties of obtaining reliable values for the Brazilian stations.

This article discusses a statistical performance of twenty parametrized models for estimation hourly diffuse radiation incident on tilted surfaces to 12.85, 22.85 and 32.85° facing to North, in different sky conditions (cloudiness).

## 2. Methods of Investigation

### *2.1. Site and Measurements*

The data of global, direct and diffuse radiation used in this work was measured at the radiometric station, at 22°53′S of latitude and 48°26′W of longitude, located in the rural area of Botucatu city, in the country side of State of São Paulo, Brazil (Fig. 1a). Botucatu, a city with 119.3 thousand habitants, is located in the countryside of Brazil, at 786 m above the mean sea level, and approximately 221 km far from the Atlantic Ocean (Fig. 1b).

Evaluations were conducted on three inclinations, with slopes of 12.85° (latitude - 10°), 22.85° (latitude) and 32.85° (latitude + 10°) and occurred in different periods: between 09/2001 and 02/2003 to 12.85°; 04/1998 and 08/2001 to 22.85°; 03/2004 and 12/2007 to 32.85°. Independently of the period measurements were concomitant with measures horizontal surface. Analysis was performed consistency of databases and outliers (derived from reading errors or malfunction of the sensors and system data acquisition) were removed from the databases.

Measurements were considered instant values when obtained by average in five minutes (300 readings). Employed the acquisition system Micrologger CR23X, operating at a frequency of 1Hz and a memory module SM192 interface with SC532 microcomputer operated by software PC 208W, both of Campbell Scientific, Inc. the instant global horizontal irradiation ($I_{GH}$) was measured by an Eppley pyranometer - PSP with calibration factor of 7.45 µV $W^{-1}$ $m^{-2}$ and linearity of ± 0.5% (0-2800 W $m^{-2}$). For instant global tilted radiation ($I_{G\beta}$) was used CM3 pyranometer from Kipp & Zonen, who owns response sensitivity of ± 10-35 µV $W^{-1}$ $m^{-2}$, a response time of 18s, the temperature response of ± 1.0% for the range of -40° C to 80° C and deviations for the cosine effect of ± 2% ($0 < z < 80°$). The direct radiation instantaneous incidence ($I_{BN}$) was obtained by a pireliômetro Eppley NIP-coupled to solar tracker ST3 Eppley with calibration factor of 7.59 µV $W^{-1}$ $m^{-2}$ and linearity of ±0.5% (0-1400 W $m^{-2}$).

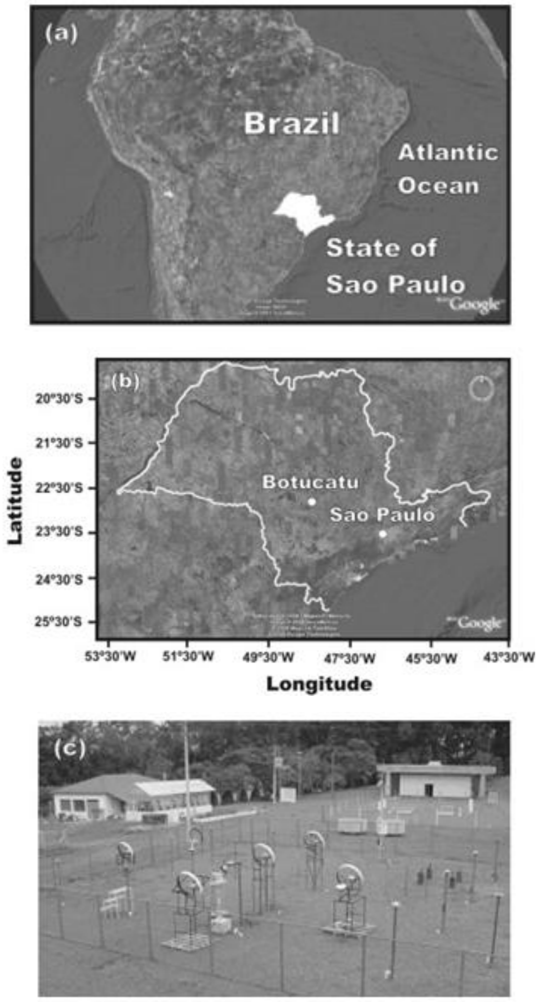


**Fig. 1.** Geographic position of the (a) State of São Paulo; (b) Botucatu and (c) view of the NW quadrant of the Radiometric Station in Botucatu, State of São Paulo, Brazil [2].

### *2.2. Data Processing*

The hourly diffuse radiation on horizontal [ $H_{DH}^{h}$ ] and tilted surfaces [ $H_{D\beta}^{h}$ ] were obtained by the difference method (Eq. 2,3). Assessments were given the seasonality by obtaining the average annual and monthly schedules of energy levels.

$$H_{DH}^{h} = H_{GH}^{h} - H_{BH}^{h} \quad (2)$$

$$H_{D\beta}^{h} = H_{G\beta}^{h} - H_{B\beta}^{h} - H_{R\beta}^{h} \quad (3)$$

Therefore, the hourly global radiation was obtained by integrating the instantaneous values. The projection of hourly direct radiation – also obtained by integrating the instantaneous values - on the horizontal surface [ $H_{D\beta}^{h}$ ] was given by the product between the direct radiation measure on incidence and zenital angle by horizontal surface.

$$H_{BH}^{h} = H_{BN}^{h} \cos Z_H \quad (4)$$

The projection of radiation directly to hourly inclined planes [ $H_{D\beta}^{h}$ ] is given by the geometrical relationship between the extraterrestrial radiation to an inclined surface and a horizontal surface or the ratio of the cosine of the zenith angles inclined ($Z_\beta$) and horizontal ($Z_H$) [9, 16].

$$R_B = H_{0\beta}^{h} / H_{0H}^{h} \quad (5)$$

where: $H_{0H}^{h}$ and $H_{0\beta}^{h}$ are extraterrestrial radiation to horizontal and the inclined surfaces respectively, obtained by Eq. 6 and 6 described Iqbal [9].

$$H_{0H}^{h} = H_{SC}\, E_0\, [(\sin\delta \sin\varphi) + (\cos\delta \cos\varphi \sin \omega_s)] \quad (6)$$

$$H_{0\beta}^{h} = H_{SC}\, E_0\, [\sin\delta \sin(\varphi\pm\beta) + \cos\delta \cos(\varphi\pm\beta) \sin \omega'_s] \quad (7)$$

where: $H_{SC}$ is the solar constant (4921 KJ $m^{-2}$ $h^{-1}$); φ is location latitude; δ is hourly solar declination solar (Eq. 8), dependent on season (DJ – Julian day); $E_0$ is the factor correction of the eccentricity of Earth's orbit (Eq. 9); $\omega_s$ and $\omega'_s$ are the hourly angle by horizontal and tilted surfaces, respectively (Eq. 11, 12).

$$\delta = 23.45 \sin [ (360/365)*(DJ+284)] \quad (8)$$

$$E_0 = 1.00011 + 0.034221\cos\Gamma + 0.00128\sin\Gamma + 0.000719\cos 2\Gamma + 0.000077\sin 2\Gamma \quad (9)$$

$$\Gamma = 2\pi [(DJ – 1)/365] \quad (10)$$

$$\omega_s = \cos^{-1} (– \tan\delta \tan\varphi) \quad (11)$$

$$\omega'_s = \min \{\cos^{-1} (– \tan\delta \tan\varphi) ; \cos^{-1} [–\tan\delta \tan(\varphi\pm\beta)] \quad (12)$$

The hourly reflected component [ $H_{R\beta}^{h}$ ]incident on tilted surfaces may have isotropic and anisotropic behavior, however, the anisotropy should be applied only for days with clear skies and clean. Due to the variability of sky cover conditions in Botucatu, considered only the isotropic behavior given by Eq. 13 [2, 4, 14], which in turn is dependent on surface albedo (α) considered as 0.23 for reference crop.

$$H_{R\beta}^{h} = 0.50\ H_{GH}^{h}\ \alpha\,(1 – \cos\beta) \quad (13)$$

### 2.3. Models of Estimatives Diffuse Hourly Radiation

Evalueted of twenty models for estimating the hourly diffuse radiation incident on tilted surfaces, distributed in theory circumsolar (1), isotropic or pseudo-isotropic (4) and anisotropic (15), described below:

#### 2.3.1. Circumsolar (geometric) – CIR model:

$$H_{R\beta}^{h} = H_{DH}^{h}\ (\cos Z_\beta / \cos Z_H) \quad (14)$$

where: $H_{D\beta}^{h}$ - hourly diffuse radiation on tilted surface (MJ $m^{-2}$ $h^{-1}$); β - angle of inclination; $H_{DH}^{h}$ - hourly diffuse radiation on horizontal surface (MJ $m^{-2}$ $h^{-1}$); $Z_H$ - zenith angle horizontal; $Z_\beta$ - zenith angle tilted.

#### 2.3.2. Liu and Jordan [17] – LJ model (isotropic):

$$H_{R\beta}^{h} = 0.50\ H_{DH}^{h}\ (1 + \cos\beta) \quad (15)$$

#### 2.3.3. Koronakis [18] – KO model (isotropic):

$$H_{R\beta}^{h} = H_{DH}^{h}\ [1/3 + (2 + \cos\beta)] \quad (16)$$

#### 2.3.4. Tian et al. [19] – TI model (isotropic):

$$H_{R\beta}^{h} = H_{DH}^{h}\ (1 – \beta/180) \quad (17)$$

#### 2.3.5. Badescu [20] – BA model (isotropic):

$$H_{R\beta}^{h} = H_{DH}^{h}\ [(3 + \cos 2\beta)/4] \quad (18)$$

#### 2.3.6. Temps and Coulson [21] – TC model (anisotropic): *introduced two factors on Liu and Jordan model (Eq. 15) by consider the anisotrophy of the clear sky conditions. The factors take into account the diffuse irradiance from the circumsolar area and the brightness of the sky near the horizon plane.*

$$H_{R\beta}^{h} = H_{DH}^{h}\ [\cos^2 (\beta/2)]\ [1+\sin^3 (\beta/2)]\ [1 + \cos^2 Z_\beta \sin^3 (\beta/2)] \quad (19)$$

#### 2.3.7. Bugler [22] – BU model (anisotropic): *allows correct depending on the component circumsolar and solar elevation.*

$$H_{R\beta}^{h} = [\ H_{DH}^{h} – (0.05\, H_{B\beta}^{h} / \cos Z_H)\ ((1+\cos\beta)/2)]+M_3 \quad (20a)$$

$$M_3 = 0.05\ H_{B\beta}^{h}\ \cos Z_\beta \quad (20b)$$

*2.3.8. Klucher [23] – KU model (anisotropic): modification of Temps and Coulson model (Eq. 19) by including horizontal brightness and circumsolar component.*

$$H^h_{R\beta} = H^h_{DH}\,[\cos^2(\beta/2)]\,[1+F'\sin^3(\beta/2)]\,[1+F'\cos^2 Z_\beta \sin^3 Z_H] \quad (21a)$$

where: $F'$ - clearness modified index, if cloudy conditions F' tends to zero ant the model reduces for isotropic model.

$$F' = 1 - (H^h_{DH} / H^h_{GH})^2 \quad (21b)$$

*2.3.9. Hay [24] – HA model (anisotropic): considered to be the addition of the circumsolar component coming from the direction near the solar disk and a diffuse component isotropically distributed from the rest of the sky. These two components are weighted according to an index of anisotropy, which represents transmittance through the atmosphere of direct irradiance:*

$$H^h_{R\beta} = H^h_{DH}\,[F(\cos Z_\beta/\cos Z_H) + (1-F_H)\,((1+\cos\beta)/2)] \quad (22a)$$

$$F_H = H^h_{BH} / H^h_{0H} \quad (22b)$$

where: $H^h_{BH}$ - hourly direct (beam) radiation projected horizontal (MJ m$^{-2}$ h$^{-1}$); $H^h_{DH}$ - hourly extraterrestrial radiation on horizontal (MJ m$^{-2}$ h$^{-1}$);

On cloudy days, the global radiation be composed only by the diffuse component, while the anisotropic factor ($F_{HAY}$) tends to nullity and HA model introduces only isotropic characteristics.

*2.3.10. Hay and Davies [25] – HD model (anisotropic): considers the contribution of horizontal brightness and weighting by atmospheric transmissivity in incidence of direct radiation.*

$$H^h_{R\beta} = H^h_{DH}\,(1-A)\,((1+\cos\beta)/2)] \quad (23a)$$

$$A = H^h_{BN} / H^h_{0H} \quad (23b)$$

where: $H^h_{BN}$ - hourly direct radiation obtained on incidence (MJ m$^{-2}$ h$^{-1}$).

*2.3.11. Steven and Unsworth [26] – SU model (anisotropic):*

$$H^h_{R\beta} = H^h_{DH}\,[0.51R_B + (1+\cos\beta)/2 - 1.74/(1.26\pi)\,S_1] \quad (24a)$$

$$S_1 = [\sin\beta - (\pi\beta/180)\cos\beta - \pi\sin^2(\beta/2)] \quad (24b)$$

*2.3.12. Willmott [27] – WI model (anisotropic): adapted the proposed Hay (Eq. 9) and defined a new index anisotropy.*

$$K_i = (H^h_{BN} / H_{SC})\cos Z_H \quad (25a)$$

$$H^h_{R\beta} = H^h_{DH}\,[(K_\beta/\mathrm{coz}\,Z_H) + C_\beta\,(1-K_H/\cos Z_H)] \quad (25b)$$

where: $K_H$ and $K_\beta$ – anisotropy indexes by horizontal and tilted surfaces, respectively (considering the zenith angle). The term $C_\beta$ represents a factor of radiation isotropically reduction incident in tilted surfaces, defined by geometrical integration and according Revfeim [28] varies between 0.5 e 1.0, considering the inclination angle (β) in radian.

$$C_\beta = 1.0115 - 0.2029\beta - 0.7081\beta^2 \quad (25c)$$

*2.3.13. Ma and Iqbal [29] – MA model (anisotropic): consider the coefficient of atmospheric transmissivity horizontal (KTH) obtained by the ratio between the global and extraterrestrial radiation.*

$$H^h_{R\beta} = H^h_{DH}\,[(K^h_{TH} R_B) + (1-K^h_{TH})\cos^2(\beta/2)] \quad (26)$$

*2.3.14. Gueymard [30, 31] – GU model (anisotropic): consider that radiation for partly cloudy skies conditions is a linear combination between cloudy (Rd1) and clear sky (Rd0), which in turn is the addition of the circumsolar component and a hemispheric factor.*

$$H^h_{R\beta} = H^h_{DH}\,[(1-N_G)Rd_0 + N_G\,Rd_1] \quad (27a)$$

The $N_G$ index is a term that weighs the cloudiness. The cloudiness hourly observations were not routinely measures and estimates using an approximate function originally proposed for absence cloudiness information.

$$N_G = \max[\min(Y, 1); 0] \quad (27b)$$

With Y index depends by diffuse fraction (transmittance of the diffused radiation) of global radiation in horizontal surface.

$$Y = 6.6667\,K^h_{DH} - 1.1467\,K^h_{DH} \text{ if } K^h_{DH} \le 0.227 \quad (27c)$$

$$Y = 1.212\,K^h_{DH} - 0.17587\,K^h_{DH} \text{ if } K^h_{DH} > 0.227 \quad (27d)$$

Irradiance for clear sky conditions ($Rd_0$) was calculated as the addition of circumsolar component and the hemispheric factor, with dependence on inclination angle (β) and solar elevation (h). According Gueymard [30] where:

h' = 0.01 h (h in degrees).

$$Rd_0 = \exp[a0 + a1\cos Z_H + a2\cos^2 Z_H + a3\cos^3 Z_H] + F(\beta)\,G(h) \quad (27e)$$

$$a_0 = -0.897 - 3.64h' + 3.960h'^2 - 1.909h'^3 \quad (27f)$$

$$a_1 = 4.448 - 12.962h' + 34.601h'^2 - 48.784h'^3 + 27.511h'^4 \quad (27g)$$

$a_2 = -2.77 + 9.164h' - 18.876h'^2 + 23.776h'^3 - 13.014h'^4$ (27h)

$a_3 = 0.312 - 0.217h' - 0.805h'^2 + 0.318h'^3$ (27i)

$F(\beta) = [1 - (0.2249 \sin^2\beta) + (0.123 \sin 2\beta) - (0.034 \sin 4\beta)] / (1 - 0.2249)$ (27j)

$G(h) = 0.408 - 0.323h' + 0.384h'^2 + 0.17h'^3$ (27k)

The term $Rd_1$ (cloudy sky conditions) depends just the inclination angle (in radian) and a correction factor (b), where varies between 1.0 and 2.0 – being adopted in this paper, b = 1.5 [10, 32].

$Rd_1 = [(1 + \cos\beta)/2] - [((\beta\cos\beta - \sin\beta)/\pi) + (1 - \cos\beta)/2] / [1 + (3/2b)]$ (27l)

2.3.15. *Skartveit and Olseth [33] – SO model (anisotropic): consider that in conditions of cloudy sky, a significant part diffuse radiation come from the zenith and introduces a correction factor as a linear function of the anisotropy index of Hay (1979).*

$H^h_{R\beta} = H^h_{DH} [(H^h_{BH} / H^h_{GH})R_B + \Omega\cos\beta + (1-(H^h_{BH} / H^h_{GH}) - \Omega)(1+\cos\beta)/2]$ (28a)

$\Omega = \max [\, 0.3 - 2\,(H^h_{BH} / H^h_{GH});\, 0\,]$ (28b)

2.3.16. *Muneer [34] – MU1 model (anisotropic): allows different estimates depending on sky cloudiness, while for cloudy days or hours will apply:*

$H^h_{R\beta} = H^h_{DH} [\, \cos^2(\beta/2) + 2b/\,(\pi(3+2b))\,(\sin\beta - \beta\cos\beta - \pi\sin^2(\beta/)2]$ (29a)

For the other sky conditions, will apply:

$H^h_{R\beta} = H^h_{DH} [T\,(1 - F_H) + F_H(\cos Z_\beta/\cos Z_H)$ (29b)

where: T - function of terms in brackets in equation 29a; b - distribution index of radiation (dimensionless). Munner [34], based on evaluations in 14 locations recommended for cloudy days *b*=2.5 and for other sky conditions the following equation:

$[\,2b / \pi(3+2b)] = 0.04 - 0.82F_H - 2.026F_H^2$ (29c)

2.3.17. *Perez et al. [35, 36] – PE model (anisotropic): The model of Perez et al. [36] is probably the most widely used models and among its various versions, there is the composition of three distinct elements: geometric representation of the horizon and sky, parametric representation of the solar insolation (cloudiness) and a statistical component that connects the two representations. This model incorporates the three subcomponents of diffuse radiation; circumsolar, horizon brightness and isotropic/anisotropic is determined by two empirical coefficients (F1 and F2, called coefficients of brightness reduction).*

$H^h_{R\beta} = H^h_{DH} [(1 - F_1)(1+\cos\beta)/2 + F_1(a_1/a_2) + F2\sin\beta]$ (30a)

where: $F_1$ and $F_2$ - functions of three variables that describe the cloudiness conditions: solar zenith angle (in radians), atmospheric turbidity index (ε) and atmospheric brightness (Δ), whose coefficients are obtained experimentally. In this paper, we adopted the experimental values of the coefficients $f_{ij}$ obtained by Perez et al. [35].

$F_1 = \max [\, 0; (f_{11}(\varepsilon) + f_{12}(\varepsilon)\Delta + f_{13}(\varepsilon)Z_H)]$ (30b)

$F_2 = f_{21}(\varepsilon) + f_{22}(\varepsilon)\Delta + f_{23}(\varepsilon)Z_H)]$ (30c)

$(\varepsilon) = [((H^h_{DH} + H^h_{BN}) / H^h_{DH}) + 1.041Z_H^3] / (1+1.041Z_H^3)$ (30d)

$\Delta = (m\ H^h_{DH}) / H_{(0)}$ (30e)

where: $H^h_{BN}$ - hourly direct normal incidence radiation (MJ $m^{-2}$ $h^{-1}$); $Z_H$ - zenith angle for horizontal surface (in radians); m - relative optical mass of air (dimensionless); H(O) - correction of extraterrestrial radiation by virtue of eccentricity of Earth's orbit.

$m = [\cos Z_H + 0.15(93.885 - Z_H)^{-1.253}]^{-1}$ (30f)

$H_{(0)} = H^h_{0H} [1 + 0.033\cos((360/365)\ DJ)]$ (30g)

2.3.18. *Muneer [37] – MU2 model (anisotropic): proposed mainly for cloudy conditions.*

$H^h_{R\beta} = H^h_{DH} [(1+\cos\beta)/2 + N1\ N2]$ (31a)

$N1 = 0.00263 - 0.7129F_M - 0.6883\ F_M^2$ (31b)

$N2 = \sin\beta - \beta\cos\beta - \pi\sin^2(\beta/2)$ (31c)

$F_M = (H^h_{BH} \cos Z_H) / H^h_{0H}$ (31d)

2.3.19. *Reindl et al. [38] – RE model (anisotropic): added a factor (FR) which indicates the contribution of the diffuse horizon brightness in Hay model, controlled by modulation function defined by:*

$F_R = (H^h_{BH} / H^h_{0H})^{0.5}$ (32a)

This factor is multiplied by brightness horizontal term f correction developed by Temps and Colson model.

$H^h_{R\beta} = H^h_{DH} [(F_H R_B) + (1 - F_H)((1+\cos\beta)/2)(1 + F_R\sin^3(\beta/2))]$ (32b)

2.3.20. *Olmo et al. [39] – OL model (anisotropic): defined for estimating global radiation in all cloudiness conditions and that also allows the evaluation of direct and diffuse components based on their procedures to horizontal.*

$H^h_{R\beta} = H^h_{DH} [\exp(-K^h_{TH}\, Z_\beta^2 - Z_H^2)]\, F_C$ (33a)

$FC = 1 + \rho[\sin^2(Z_\beta/2)]$ (33b) where: $Z_\beta$ and $Z_H$ - the zenith angles for tilted and horizontal surfaces, respectively, in radians; ρ - surface reflection coefficient (adopted 0.23).

*2.4. Sky Conditions Classification*

The evaluation of cloudiness classification (sky conditions) was performed considering the methodology proposed by Escobedo et al. [2, 4] for Botucatu, São Paulo, which ranked the sky conditions into 4 types according to coefficient of atmospheric transmissivity of global radiation [$K_T^h$] (ratio between global radiation and extraterrestrial radiation). This methodology avoids the use of data from direct and diffuse radiation, which are measured routinely in Brazilian few meteorological stations and consider the following sky condition:

*Interval i*: [$K_T^h$] ≤ 0.35 and direct component of the global solar radiation at the surface is practically zero. Therefore, global and diffuse solar radiations are equal and the sky condition is defined as totally covered cloud or cloudy sky

*Interval ii*: 0.35 < [$K_T^h$] ≤ 0.55. The global solar radiation at the surface is composed by a fraction of diffuse component that is larger than the fraction of direct component, and the diffuse fraction is decreasing with [$K_T^h$]. The upper limit of this interval is set where diffuse equals direct component of the solar radiation (approximately at 200 W $m^{-2}$ and at [$K_T^h$] = 0.55). In this case, the sky condition is defined as partially cloudy with predominance of diffuse component of the solar radiation because the radiation field is predominantly composed by diffuse radiation (partially cloudy sky - PCYS);

*Interval iii*: 0:55 < [$K_T^h$] ≤ 0:65. The global solar radiation at the surface is composed by a fraction of diffuse component that is smaller than the fraction of direct component and the diffuse fraction is decreasing with [$K_T^h$] until 0.65, considered as the end of the partially cloudy interval [9]. In this case, the sky condition is partially cloudy with predominance of direct component of the solar radiation because the direct beam predominantly composes the radiation field (partially clear sky – PCRS);

*Interval iv*: [$K_T^h$] > 0.65. The global solar radiation at the surface is composite by direct component of solar radiation and the diffuse contribution is very small, indicating that there is no significant cloud cover. In this case the sky condition is clear sky (CRS).

*2.5. Statistical Indicatives*

To evaluate the performance of hourly estimation by tilted and horizontal surfaces were applied the statistical indicative mean bias error (MBE), root mean square error (RMSE) and adjustment index (d) of Willmott [40], described by:

$$MBE = \frac{\sum_{i=1}^{N}(Pi - Oi)}{N} \quad (31)$$

$$RMSE = \left[\frac{\sum_{i=1}^{N}(Pi - Oi)^2}{N}\right]^{\frac{1}{2}} \quad (32)$$

$$d = 1 - \frac{\sum_{i=1}^{N}(Pi - Oi)^2}{\sum_{i=1}^{N}(|P'i| + |O'i|)^2} \quad (33)$$

where: $P_i$ – estimated values; Oi- measured values; N – number of observations; $|P'i|$ - absolute values of difference $Pi - \overline{Oi}$; $|O'i|$ - absolute values of difference $\mathrm{Oi} - \overline{\mathrm{Oi}}$.

The MBE indicative represents the deviation of averages and negative or positive values indicates underestimation and overestimation, respectively. The RMSE indicative informs about the actual value of error produced by model, however, some errors large proportion can sums significant increases in RMSE and not differentiate overestimate or underestimate. The adjustment index “d” ranges from 0 to 1, representing how the estimated values fit with the measured values. The smaller absolute value of MBE and RMSE and higher values of “d” index best performance of model tested [14, 40].

## 3. Results and Discussions

The high levels of hourly diffuse radiation occurred in lower values of zenith angle and are dependents of the atmospheric transmissivity of solar radiation (Fig. 1). In isotropic conditions (cloudy sky) observed that 97.88, 99.26 and 99.88% of values [$H_{D\beta}^h$] are less than 1.00 MJ $m^{-2}$ $h^{-1}$ to 12.85, 22.85 and 32.85°, respectively. In partly cloudy sky increased frequency of values [$H_{D\beta}^h$] for the energy level, however with reduction in mean energy for larger angles of inclination.

The averages of hourly diffuse radiation were 1.69; 2.64; 1.97 and 1.49 MJ $m^{-2}$ $h^{-1}$ for cloudy sky (CYS), partly cloudy sky (PCYS), partly clear sky (PCRS) and clear sky (CRS), respectively. Observed the following percentages of 75.07; 83.93 and 88.47% by levels less than 1.50 MJ $m^{-2}$ $h^{-1}$ to 12.85, 22.85 and 32.85°, however, in partly cloudy sky, the diffuse radiation reached 2.64; 2.56 and 2.44 MJ $m^{-2}$ $h^{-1}$ for the same inclinations.

When values of diffuse radiation coefficient transmitted by atmosphere [$K_{T\beta}^h$] were superior to 0.65 (clear sky) occurred 11.24; 5.74 and 3.41% of values [$H_{D\beta}^h$] above 1.00

MJ $m^{-2}$ $h^{-1}$, indicating low variation of diffuse radiation in this sky coverage, however, this behavior provides an increase in database dispersion of estimates generated by anisotropic models for low energy levels. This tendency depends of diurnal evolution of diffuse radiation, because at sunrise to passage in meridian plane (noon solar) usually the atmosphere of the region can be considered clean (except by of moist cold or hot masses air at winter), while in the afternoon, increases the concentration of water vapor generated by evapotranspiration process and consequently occurs higher percentages of cloudy sky for hourly partition.

The correlations between the reference diffuse radiation (obtained by difference method) and the diffuse radiation estimated by the circunsolar model (CIR) at different cloudiness conditions are shown in Fig. 2.

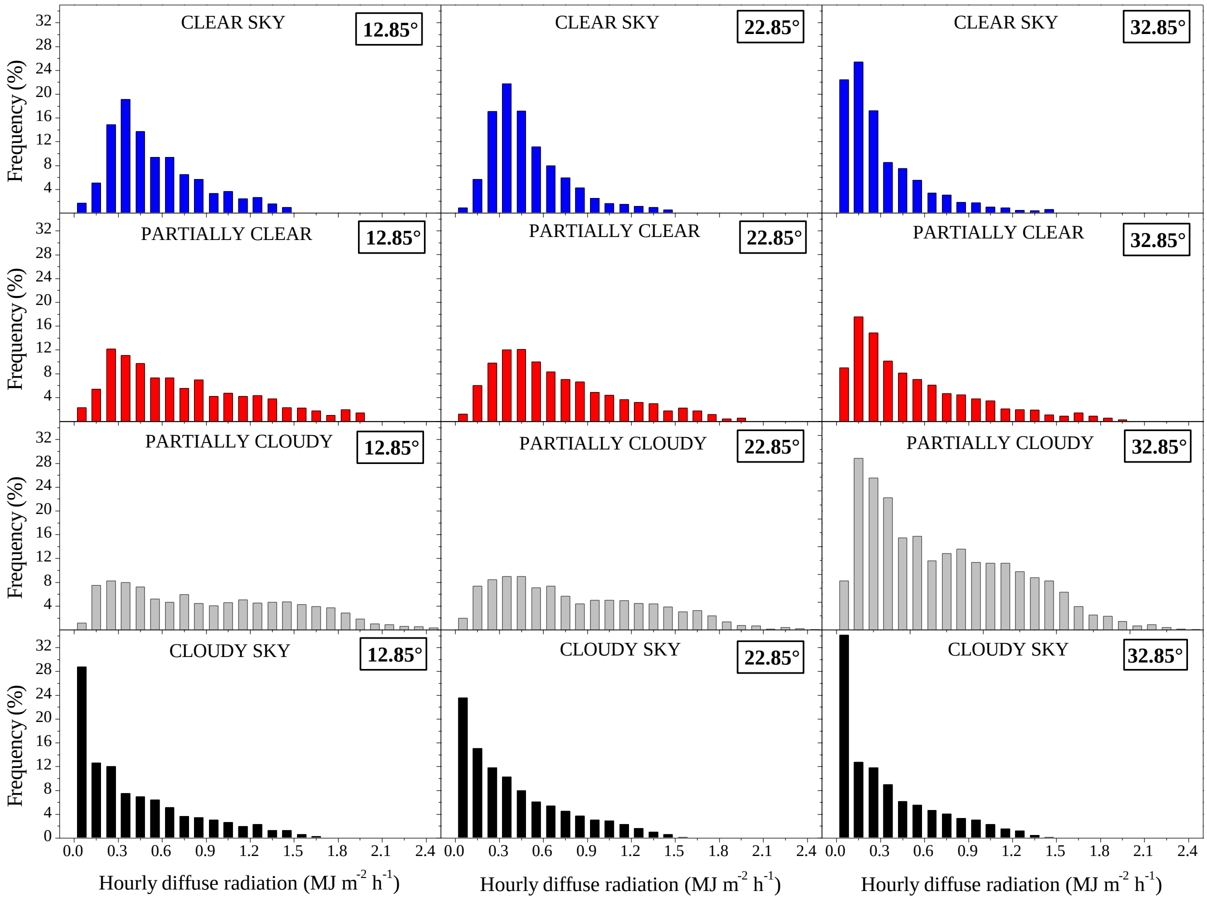


**Fig. 1.** Frequency of the hourly diffuse radiation [ ] (obtained by difference method - HDRD) in different sky conditions and inclination angles to North.

The decrease of atmospheric transmissivity together with increased angle of inclination tends to overestimate the quantity of diffuse radiation hourly (Fig. 3). In these conditions occurs increase in the percentage of diffuse radiation from the sun disc (circumsolar component), indicating that Circunsolar Model shows less scatter and greater accuracy on periods with high insolation [10]. The other models isotropic presented dispersions similar to those observed in correlation with the estimates by Liu and Jordan Model.

The largest scatterings verified with increasing inclination are due to increased levels of reflected radiation incident on inclined surfaces with high angles [14, 41]. The inclination of 32.85° receives higher (winter) and lower (summer) levels of extraterrestrial radiation, which provide high coefficient of variations of atmospheric transmissivity in addition to interactions with water vapor [4]. Connotes this fact by high dispersions observed in correlations for data on cloudy skies for the twenty models evaluated. According Dal Pai [42], smaller time partitions responds more sensitively and rapidly to instantaneous changes occurring in the atmosphere, allowing a more detailed exact distribution of the radiation and consequently generates greater variability, whereas, for higher partitions of time (daily, monthly and annual) occurs a mitigation of integration of atmospheric dynamics.

For most models, the increase of coefficient atmospheric transmissivity to the inclined surfaces ($K_{T\beta}$) resulted in higher scattering between diffuse reference and the estimates of the models parameterized. For Scolar et al. [43], in hourlies with clear sky, the anisotropy factor correction tends to 1.0 and circumsolar component. Already in cloudy sky, the anisotropic index tended to zero and practically all energetic fluxes are isotropic. Therefore the isotropic models showed low dispersion of estimated values for conditions of low light intensity (cloudy) [14]. Under these conditions, the radiation levels were low direct and diffuse radiation had uniform distribution (isotropic) after interaction with water vapor, and the correction factor *[0,5 (1+cos β)]* depends only on geometric equal to 0.9875, 0.9608 and 0.9201 to 12.85, 22.85 and 32.85°.

The lower coefficients of determination ($R^2$) were obtained for correlation with the Gueymard model (GU) regardless of cloudiness conditions and tilt angle (Tables 1 to 3). Gueymard [32] noted that in cloudy sky, the performance statistics indicate this model need to more sophisticated parameterizations that consider the characteristics optical and spatial distribution of radiation. For hourly data, this behavior corroborates with observations in other climatic regions, with spreads greater 250 W m$^{-2}$ [3,16,43]

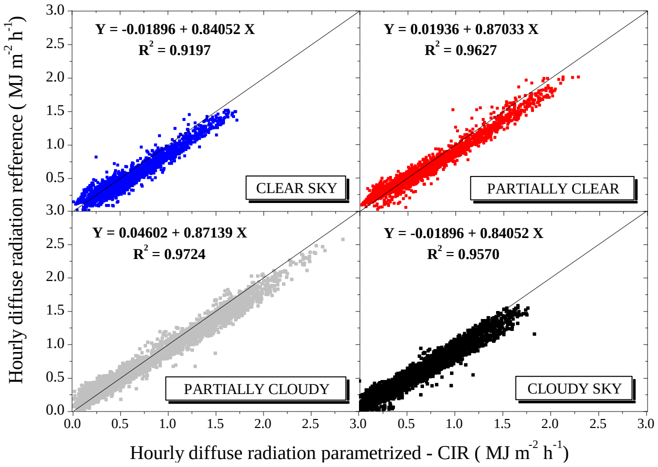


**Fig. 2.** Correlation between of the hourly diffuse radiation [ $H_{D\beta}^{h}$ ](difference method) and estimates by Circunsolar Model (CIR), grouped in different sky conditions, for the slope of 22.85° to North.

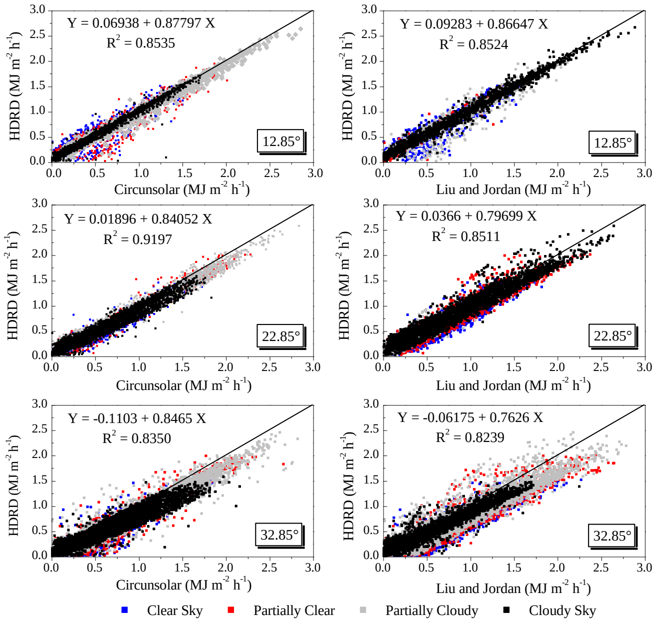


**Fig. 3.** Correlation between hourly diffuse radiation difference (HDRD) and estimates by models Circunsolar (CIR) and Liu & Jordan (LJ), in total group data and three tilted surfaces to North.

**Table 1.** Linear, angular and determination ($R^2$) coefficients of linear regression in different cloudy conditions, for inclination of 12.85° to North.

| Models | Total Group | | | Clear Sky | | | Partially Clear Sky | | | Partially Cloudy Sky | | | Cloudy Sky | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ |
| CIR | 0.024 | 0.949 | 0.9761 | 0.029 | 0.959 | 0.9696 | 0.017 | 0.929 | 0.9552 | 0.047 | 0.938 | 0.9849 | 0.015 | 0.961 | 0.9822 |
| LJ | 0.032 | 0.955 | 0.9732 | 0.045 | 0.970 | 0.9615 | 0.041 | 0.929 | 0.9478 | 0.061 | 0.933 | 0.982 | 0.015 | 0.970 | 0.9916 |
| KO | 0.032 | 0.976 | 0.9732 | 0.045 | 0.977 | 0.9615 | 0.041 | 0.936 | 0.9478 | 0.061 | 0.940 | 0.982 | 0.152 | 0.977 | 0.9916 |
| BA | 0.032 | 0.962 | 0.9732 | 0.045 | 0.992 | 0.9615 | 0.041 | 0.949 | 0.9478 | 0.061 | 0.954 | 0.982 | 0.152 | 0.992 | 0.9916 |
| TI | 0.032 | 1.029 | 0.9732 | 0.045 | 1.045 | 0.9615 | 0.041 | 1.000 | 0.9478 | 0.061 | 1.005 | 0.982 | 0.152 | 0.977 | 0.9916 |
| TC | 0.324 | 0.958 | 0.973 | 0.045 | 0.970 | 0.9615 | 0.041 | 0.939 | 0.9478 | 0.061 | 0.933 | 0.982 | 0.016 | 0.970 | 0.9914 |
| BU | - | 0.855 | 0.8598 | - | 0.983 | 0.8266 | - | 0.881 | 0.8266 | 0.011 | 0.907 | 0.9451 | 0.016 | 0.968 | 0.9844 |
| KL | 0.033 | 0.955 | 0.9728 | 0.045 | 0.970 | 0.9615 | 0.041 | 0.929 | 0.9478 | 0.061 | 0.933 | 0.982 | 0.015 | 0.970 | 0.9914 |
| HA | 0.025 | 0.967 | 0.9742 | 0.027 | 0.987 | 0.9622 | 0.024 | 0.945 | 0.9492 | 0.052 | 0.948 | 0.9833 | 0.014 | 0.982 | 0.9922 |
| HD | 0.213 | 0.948 | 0.8954 | 0.381 | 0.949 | 0.9369 | 0.378 | 0.910 | 0.9263 | 0.294 | 0.890 | 0.9464 | 0.044 | 0.974 | 0.9692 |
| SU | 0.028 | 0.633 | 0.9762 | 0.039 | 0.642 | 0.9659 | 0.031 | 0.617 | 0.9522 | 0.054 | 0.621 | 0.9856 | 0.014 | 0.643 | 0.992 |
| WI | 0.026 | 0.962 | 0.9743 | 0.029 | 0.981 | 0.9624 | 0.026 | 0.939 | 0.9494 | 0.053 | 0.942 | 0.9834 | 0.015 | 0.975 | 0.9921 |
| MI | 0.026 | 0.953 | 0.9778 | 0.032 | 0.964 | 0.9688 | 0.024 | 0.930 | 0.9542 | 0.049 | 0.939 | 0.9866 | 0.014 | 0.970 | 0.9924 |
| GU | 0.278 | 0.922 | 0.6995 | 0.407 | 0.902 | 0.7584 | 0.516 | 0.826 | 0.6294 | 0.420 | 0.869 | 0.7083 | 0.060 | 0.977 | 0.8852 |
| SO | 0.032 | 0.959 | 0.973 | 0.043 | 0.975 | 0.9612 | 0.039 | 0.933 | 0.9474 | 0.030 | 0.936 | 0.9818 | 0.015 | 0.975 | 0.9916 |
| MU1 | 0.088 | 0.909 | 0.9197 | - | 0.953 | 0.9564 | - | 0.922 | 0.9373 | 0.030 | 0.928 | 0.9737 | 0.010 | 1.060 | 0.9991 |
| PE | 0.092 | 0.963 | 0.9559 | 0.124 | 0.979 | 0.9435 | 0.141 | 0.914 | 0.9271 | 0.164 | 0.909 | 0.9719 | 0.047 | 0.985 | 0.9811 |
| MU2 | 0.014 | 0.904 | 0.9287 | - | 0.931 | 0.8981 | - | 0.878 | 0.8826 | 0.034 | 0.917 | 0.9543 | 0.014 | 1.001 | 0.9904 |
| RE | 0.025 | 0.967 | 0.9742 | 0.027 | 0.987 | 0.9622 | 0.024 | 0.945 | 0.9492 | 0.052 | 0.948 | 0.9833 | 0.014 | 0.981 | 0.9922 |
| OL | 0.033 | 0.954 | 0.9727 | 0.046 | 0.970 | 0.9615 | 0.041 | 0.928 | 0.9478 | 0.061 | 0.932 | 0.9819 | 0.016 | 0.969 | 0.9914 |

CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

**Table 2.** Linear, angular and determination ($R^2$) coefficients of linear regression in different cloudy conditions, for inclination of 22.85° to North.

| **Models** | **Total Group** | | | **Clear Sky** | | | **Partially Clear Sky** | | | **Partially Cloudy Sky** | | | **Cloudy Sky** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **$a_0$** | **$a_1$** | **$R^2$** | **$a_0$** | **$a_1$** | **$R^2$** | **$a_0$** | **$a_1$** | **$R^2$** | **$a_0$** | **$a_1$** | **$R^2$** | **$a_0$** | **$a_1$** | **$R^2$** |
| CIR | - | 0.909 | 0.9717 | - | 0.695 | 0.9806 | - | 0.911 | 0.977 | 0.046 | 0.871 | 0.9724 | 0.021 | 0.855 | 0.957 |
| LJ | 0.123 | 0.942 | 0.9402 | - | 1.036 | 0.926 | 0.050 | 0.906 | 0.9227 | 0.093 | 0.875 | 0.9453 | 0.027 | 0.908 | 0.9756 |
| KO | 0.012 | 0.965 | 0.9402 | - | 1.062 | 0.926 | 0.050 | 0.928 | 0.9227 | 0.093 | 0.896 | 0.9453 | 0.027 | 0.931 | 0.9756 |
| BA | 0.012 | 1.013 | 0.9402 | - | 0.992 | 0.926 | 0.050 | 0.949 | 0.9227 | 0.093 | 0.954 | 0.9453 | 0.027 | 1.079 | 0.9756 |
| TI | 0.012 | 0.942 | 0.9402 | - | 1.187 | 0.926 | 0.050 | 1.038 | 0.9227 | 0.093 | 1.002 | 0.9453 | 0.027 | 1.040 | 0.9756 |
| TC | 0.012 | 0.942 | 0.9402 | - | 1.036 | 0.926 | 0.050 | 0.906 | 0.9227 | 0.093 | 0.875 | 0.9453 | 0.027 | 0.908 | 0.9756 |
| BU | - | 0.805 | 0.7677 | - | 1.051 | 0.7462 | - | 0.873 | 0.8115 | 0.005 | 0.887 | 0.9105 | 0.021 | 0.930 | 0.9778 |
| KL | 0.012 | 0.942 | 0.9402 | - | 1.036 | 0.926 | 0.050 | 0.906 | 0.9226 | 0.093 | 0.875 | 0.9453 | 0.027 | 0.908 | 0.9756 |
| HÁ | - | 0.981 | 0.9474 | - | 1.094 | 0.9388 | 0.008 | 0.957 | 0.9364 | 0.068 | 0.919 | 0.9548 | 0.025 | 0.943 | 0.9778 |
| HD | 0.206 | 0.967 | 0.8655 | 0.312 | 1.056 | 0.9278 | 0.342 | 0.968 | 0.907 | 0.289 | 0.874 | 0.914 | 0.056 | 0.934 | 0.9486 |
| SU | - | 0.635 | 0.9622 | - | 0.691 | 0.9561 | 0.022 | 0.621 | 0.9518 | 0.066 | 0.599 | 0.9684 | 0.020 | 0.608 | 0.9813 |
| WI | - | 0.948 | 0.9504 | - | 1.054 | 0.9417 | 0.012 | 0.927 | 0.9394 | 0.068 | 0.887 | 0.9568 | 0.025 | 0.908 | 0.9788 |
| MI | - | 0.929 | 0.9718 | - | 0.997 | 0.9747 | 0.005 | 0.921 | 0.9651 | 0.059 | 0.885 | 0.9728 | 0.022 | 0.899 | 0.9808 |
| GU | 0.284 | 0.768 | 0.6805 | 0.327 | 0.838 | 0.7644 | 0.503 | 0.767 | 0.6101 | 0.435 | 0.703 | 0.7483 | 0.086 | 0.750 | 0.8854 |
| SO | 0.011 | 0.950 | 0.9382 | - | 1.050 | 0.9232 | 0.047 | 0.912 | 0.9197 | 0.091 | 0.881 | 0.944 | 0.027 | 0.922 | 0.9761 |
| MU1 | 0.027 | 0.928 | 0.9216 | - | 1.050 | 0.9305 | 0.003 | 0.902 | 0.9262 | 0.059 | 0.880 | 0.9498 | 0.024 | 1.186 | 0.9786 |
| PE | 0.089 | 0.975 | 0.9096 | 0.048 | 1.065 | 0.8872 | 0.183 | 0.898 | 0.8918 | 0.201 | 0.873 | 0.9268 | 0.049 | 0.959 | 0.9612 |
| MU2 | 0.028 | 0.803 | 0.8023 | - | 0.881 | 0.7256 | 0.034 | 0.756 | 0.7951 | 0.078 | 0.847 | 0.8935 | 0.028 | 0.097 | 0.974 |
| RE | - | 0.981 | 0.9474 | - | 1.094 | 0.9387 | 0.008 | 0.957 | 0.9364 | 0.068 | 0.919 | 0.9548 | 0.025 | 0.943 | 0.9778 |
| OL | 0.012 | 0.942 | 0.9398 | - | 1.036 | 0.9254 | 0.051 | 0.906 | 0.9222 | 0.093 | 0.875 | 0.9449 | 0.027 | 0.908 | 0.9756 |

CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

**Table 3.** Linear, angular and determination ($R^2$) coefficients of linear regression in different cloudy conditions, for inclination of 32.85° to North.

| Models | Total Group | | | Clear Sky | | | Partially Clear Sky | | | Partially Cloudy Sky | | | Cloudy Sky | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ | $a_0$ | $a_1$ | $R^2$ |
| CIR | - | 0.867 | 0.9423 | - | 0.962 | 0.9666 | - | 0.924 | 0.951 | 0.005 | 0.840 | 0.9351 | 0.027 | 0.771 | 0.9303 |
| LJ | - | 0.853 | 0.9139 | - | 0.952 | 0.9177 | - | 0.875 | 0.8972 | 0.058 | 0.792 | 0.8984 | 0.025 | 0.810 | 0.9526 |
| KO | - | 0.992 | 0.9139 | - | 1.003 | 0.9177 | - | 0.922 | 0.8972 | 0.058 | 0.834 | 0.8984 | 0.025 | 0.853 | 0.9526 |
| BA | - | 0.899 | 0.9139 | - | 1.165 | 0.9177 | - | 1.070 | 0.8972 | 0.058 | 0.969 | 0.8984 | 0.025 | 0.991 | 0.9526 |
| TI | - | 1.044 | 0.9139 | - | 1.108 | 0.9177 | - | 1.018 | 0.8972 | 0.058 | 0.922 | 0.8984 | 0.025 | 0.942 | 0.9526 |
| TC | - | 0.854 | 0.9128 | - | 0.952 | 0.9177 | - | 0.875 | 0.8972 | 0.058 | 0.792 | 0.8984 | 0.025 | 0.810 | 0.9509 |
| BU | - | 0.786 | 0.7216 | - | 1.098 | 0.7726 | - | 0.944 | 0.7638 | - | 0.848 | 0.8363 | 0.019 | 0.867 | 0.9553 |
| KL | - | 0.855 | 0.9126 | - | 0.982 | 0.9177 | - | 0.875 | 0.8971 | 0.058 | 0.792 | 0.8984 | 0.025 | 0.810 | 0.9506 |
| HÁ | - | 0.931 | 0.9177 | - | 1.050 | 0.927 | - | 0.974 | 0.9096 | 0.030 | 0.873 | 0.9094 | 0.023 | 0.877 | 0.9546 |
| HD | 0.119 | 0.934 | 0.8882 | 0.151 | 1.019 | 0.9132 | 0.210 | 0.942 | 0.8961 | 0.223 | 0.838 | 0.8969 | 0.046 | 0.876 | 0.9303 |
| SU | - | 0.612 | 0.9411 | - | 0.680 | 0.949 | - | 0.638 | 0.9351 | 0.022 | 0.581 | 0.9348 | 0.019 | 0.569 | 0.9644 |
| WI | - | 0.862 | 0.9239 | - | 0.968 | 0.9364 | - | 0.901 | 0.9141 | 0.034 | 0.808 | 0.9135 | 0.023 | 0.808 | 0.9571 |
| MI | - | 0.878 | 0.9492 | - | 0.975 | 0.9668 | - | 0.923 | 0.9506 | 0.013 | 0.834 | 0.9798 | 0.020 | 0.810 | 0.9624 |
| GU | 0.190 | 0.736 | 0.7669 | 0.203 | 0.798 | 0.8138 | 0.340 | 0.738 | 0.7461 | 0.346 | 0.663 | 0.7952 | 0.064 | 0.701 | 0.8928 |
| SO | - | 0.872 | 0.9076 | - | 0.983 | 0.913 | - | 0.894 | 0.8909 | 0.054 | 0.805 | 0.8932 | 0.025 | 0.835 | 0.9512 |
| MU1 | - | 0.863 | 0.9036 | - | 0.973 | 0.9254 | - | 0.897 | 0.9059 | 0.028 | 0.805 | 0.905 | 0.022 | 0.987 | 0.955 |
| PE | 0.041 | 0.875 | 0.8909 | 0.000 | 0.996 | 0.8939 | 0.039 | 0.860 | 0.8606 | 0.132 | 0.780 | 0.8774 | 0.038 | 0.835 | 0.9385 |
| MU2 | 0.002 | 0.743 | 0.7342 | - | 0.842 | 0.705 | - | 0.753 | 0.7069 | 0.054 | 0.761 | 0.7845 | 0.026 | 0.914 | 0.9453 |
| RE | - | 0.931 | 0.9177 | - | 1.050 | 0.927 | - | 0.974 | 0.9096 | 0.030 | 0.873 | 0.9094 | 0.028 | 0.877 | 0.9546 |
| OL | - | 0.854 | 0.9123 | - | 0.952 | 0.9169 | - | 0.874 | 0.8965 | 0.059 | 0.792 | 0.8979 | 0.025 | 0.810 | 0.9508 |

CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

Through evaluation of the linear and angular coefficients to analyze the behavior of the model parameterized as compared to the hourly diffuse radiation reference (*HDRD*) observed a decrease of the total radiation scattered by increases of atmospheric transmissivity and inclination angle. When hourly diffuse radiation estimated tends to 1.0 MJ $m^{-2}$ $h^{-1}$ by Gueymard model was obtained values of *HDRD*: i) all cloudiness: 1.20, 1.05 and 0.92, ii) clear sky: 1.31, 1.16 and 1.00, iii) partially clear sky : 1.34, 1.27 and 1.08, iv) partially cloudy sky: 1.29, 1.14 and 1.01, v) cloudy sky: 1.04, 0.84

and 0.76 for 12.85, 22.85 and 32.85°, respectively. These values indicated that the model did not produce good results for estimates of diffuse radiation on tilted surfaces in climatic conditions of Botucatu.

At inclination of 12.85° were found linears coefficients negative only clear sky and partially clear sky by Bugler model (BU) and two Munner models (MU1 and MU2). The increase of the inclination angle led to an increase in the number of models that allow generate hourly diffuse radiation (*HDRD*) negative when the estimated values by models parametrized were null. At 22.85°, with the exception of the Hay and Davies (DH), Gueymard (GU) and Perez (PE) models, the linear coefficients were negative in estimates for clear sky, with influence the same behavior in the database total grouping. According to Souza et al [14] this process can't occur physically, however it was worth noting that the coefficients were adjusted statistically (less than 0.09 in most models) and include correlations with models that employ measures on horizontal surface [45].

Analyzing the models of Temps and Coulson (TC), Klucher (KU), Hay (HA) and Reindl et al (RE) was observed dispersions and regression coefficients similars. This facts indicates that the Klucher (KU) and Reindl et al (RE) not provide significant improvements in the original models of Temps and Coulson (TC) and Hay (HA) by adding effects of brightness horizontal.

However, the simple display of scatter plots not allow notice if significant improvements were obtained with the models. Between Tables 4 to 6 indicate the statistical performance of the statistical models in different cloudiness sky for the three tilted surfaces, with values of *MBE* and *RMSE* presented only in energy levels. The performance of the models rely on parameterizations generated and validated for the local climatic conditions origin model and climatic conditions of Botucatu (Brazil) influenced on changes in performance this models when compared in scientific literature.

To tilted surface at 12.85°, the models of Tian et al (TI), Hay and Davies (HD), Perez et al (PE) and Gueymard (GU) underestimated levels of hourly diffuse radiation (HDRD) in all cloudiness sky. The better results of Gueymard model occurs with decreasing atmospheric transmissivity, with underestimates of 0.37, 0.44, 0.34 and 0.05 MJ $m^{-2}$ $h^{-1}$ to clear sky (CRS), partially clear sky (PCRS), partly cloudy sky (PCYS) and cloudy sky (CYS). The models Liu and Jordan (LJ), Temps and Coulson (TC), Klucher (KL), Willmott (WI), Ma and Iqbal (MI) and Olmo (OL) underestimated only on CRS and CYS (maximum -0.0244 MJ $m^{-2}$ $h^{-1}$) for that same tilted surface. To 12.85°, only Circumsolar (CIR) and Steven and Unsworth (SU) models overestimated in all cloudiness conditions with larger deviations for PCYS and PCRS (lower to 0.49 MJ $m^{-2}$ $h^{-1}$). The percentage of adjustment index (d) was superior to 80.81% found in PCRS" by Gueymard (GU) model.

**Table 4.** Statistical indicative performance estimation hourly diffuse radiation by models circunsolar, isotropic and anisotropic in different cloudy conditions, for tilted of 12.85° to North.

| Models | Total Group | | | Clear Sky | | | Partially Clear Sky | | | Partially Cloudy Sky | | | Cloudy Sky | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d |
| CIR | 0.01 | 0.10 | 0.9935 | 0.01 | 0.08 | 0.9953 | 0.05 | 0.16 | 0.9867 | 0.01 | 0.08 | 0.9953 | 0.00 | 0.05 | 0.9953 |
| LJ | 0.00 | 0.10 | 0.9929 | -0.02 | 0.14 | 0.9899 | 0.02 | 0.16 | 0.9858 | 0.00 | 0.09 | 0.9945 | 0.00 | 0.04 | 0.9977 |
| KO | -0.01 | 0.10 | 0.9930 | -0.03 | 0.14 | 0.9898 | 0.02 | 0.16 | 0.9861 | -0.01 | 0.09 | 0.9947 | -0.01 | 0.04 | 0.9977 |
| BA | -0.02 | 0.10 | 0.9930 | -0.04 | 0.14 | 0.9894 | 0.00 | 0.16 | 0.9865 | -0.02 | 0.09 | 0.9948 | -0.01 | 0.04 | 0.9977 |
| TI | -0.05 | 0.11 | 0.9910 | -0.07 | 0.16 | 0.9861 | -0.04 | 0.16 | 0.9855 | -0.07 | 0.10 | 0.9923 | -0.03 | 0.05 | 0.9956 |
| TC | 0.00 | 0.10 | 0.9929 | -0.02 | 0.14 | 0.9899 | 0.01 | 0.16 | 0.9862 | 0.00 | 0.09 | 0.9945 | 0.00 | 0.04 | 0.9977 |
| BU | 0.14 | 0.28 | 0.9499 | 0.38 | 0.48 | 0.8843 | 0.26 | 0.39 | 0.9204 | 0.08 | 0.17 | 0.9801 | 0.00 | 0.04 | 0.9974 |
| KL | 0.00 | 0.10 | 0.9928 | -0.02 | 0.14 | 0.9899 | 0.02 | 0.16 | 0.9858 | 0.00 | 0.09 | 0.9945 | 0.00 | 0.04 | 0.9977 |
| HÁ | 0.00 | 0.10 | 0.9934 | -0.02 | 0.14 | 0.9902 | 0.03 | 0.16 | 0.9864 | 0.00 | 0.08 | 0.9953 | -0.01 | 0.04 | 0.9979 |
| HD | -0.19 | 0.27 | 0.9490 | -0.36 | 0.40 | 0.9226 | -0.33 | 0.38 | 0.9274 | -0.21 | 0.26 | 0.9551 | -0.03 | 0.08 | 0.9903 |
| SU | 0.34 | 0.49 | 0.9025 | 0.35 | 0.53 | 0.9118 | 0.49 | 0.65 | 0.8687 | 0.48 | 0.60 | 0.859 | 0.20 | 0.30 | 0.9143 |
| WI | 0.00 | 0.10 | 0.9933 | -0.02 | 0.14 | 0.9903 | 0.03 | 0.16 | 0.9862 | 0.00 | 0.08 | 0.9952 | 0.00 | 0.04 | 0.9979 |
| MI | 0.01 | 0.09 | 0.9940 | -0.01 | 0.13 | 0.9920 | 0.04 | 0.16 | 0.9869 | 0.01 | 0.08 | 0.9958 | 0.00 | 0.04 | 0.9979 |
| GU | -0.25 | 0.41 | 0.8760 | -0.37 | 0.51 | 0.8729 | -0.44 | 0.61 | 0.8081 | -0.34 | 0.47 | 0.8454 | -0.05 | 0.14 | 0.9651 |
| SO | 0.00 | 0.10 | 0.9929 | -0.03 | 0.14 | 0.9898 | 0.02 | 0.16 | 0.9858 | 0.00 | 0.09 | 0.9946 | -0.01 | 0.04 | 0.9978 |
| MU1 | -0.03 | 0.18 | 0.9779 | 0.05 | 0.16 | 0.9872 | 0.09 | 0.20 | 0.9793 | 0.04 | 0.11 | 0.9913 | -0.16 | 0.22 | 0.8897 |
| PE | -0.07 | 0.15 | 0.9854 | -0.11 | 0.20 | 0.9791 | -0.12 | 0.22 | 0.9596 | -0.11 | 0.19 | 0.9682 | -0.03 | 0.08 | 0.9878 |
| MU2 | 0.06 | 0.18 | 0.9786 | 0.13 | 0.26 | 0.9652 | 0.15 | 0.29 | 0.9558 | 0.05 | 0.14 | 0.9859 | -0.01 | 0.04 | 0.9972 |
| RE | 0.00 | 0.10 | 0.9934 | -0.02 | 0.14 | 0.9902 | 0.03 | 0.16 | 0.9864 | 0.00 | 0.08 | 0.9953 | -0.01 | 0.04 | 0.9979 |
| OL | 0.00 | 0.10 | 0.9928 | -0.02 | 0.14 | 0.9899 | 0.02 | 0.16 | 0.9858 | 0.00 | 0.09 | 0.9945 | 0.00 | 0.04 | 0.9976 |

CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

**Table 5.** Statistical indicative performance estimation hourly diffuse radiation by models circunsolar, isotropic and anisotropic in different cloudy conditions, for tilted of 22.85° to North.

| Models | Total Group | | | Clear Sky | | | Partially Clear Sky | | | Partially Cloudy Sky | | | Cloudy Sky | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d |
| CIR | 0.07 | 0.13 | 0.9869 | 0.12 | 0.15 | 0.9867 | 0.08 | 0.13 | 0.9862 | 0.07 | 0.13 | 0.9855 | 0.04 | 0.10 | 0.9813 |
| LJ | 0.02 | 0.13 | 0.9839 | 0.06 | 0.18 | 0.9771 | 0.02 | 0.16 | 0.9786 | 0.01 | 0.14 | 0.9831 | 0.01 | 0.07 | 0.9919 |
| KO | 0.01 | 0.13 | 0.9845 | 0.04 | 0.18 | 0.9772 | 0.00 | 0.15 | 0.9796 | -0.01 | 0.13 | 0.9842 | 0.00 | 0.06 | 0.9930 |
| BA | -0.02 | 0.13 | 0.9838 | 0.01 | 0.18 | 0.9754 | -0.03 | 0.15 | 0.9790 | -0.05 | 0.13 | 0.9837 | -0.02 | 0.06 | 0.9932 |
| TI | -0.06 | 0.14 | 0.9787 | -0.03 | 0.20 | 0.9692 | -0.08 | 0.17 | 0.9731 | -0.09 | 0.15 | 0.9773 | -0.04 | 0.07 | 0.9896 |
| TC | 0.02 | 0.13 | 0.9839 | 0.06 | 0.18 | 0.9771 | 0.02 | 0.16 | 0.9786 | 0.01 | 0.14 | 0.9831 | 0.01 | 0.07 | 0.9919 |
| BU | 0.18 | 0.33 | 0.9091 | 0.47 | 0.57 | 0.7981 | 0.26 | 0.36 | 0.8955 | 0.10 | 0.19 | 0.9672 | 0.01 | 0.06 | 0.9934 |
| KL | 0.02 | 0.13 | 0.9839 | 0.06 | 0.18 | 0.9771 | 0.02 | 0.16 | 0.9786 | 0.01 | 0.14 | 0.9831 | 0.01 | 0.07 | 0.9919 |
| HÁ | 0.02 | 0.12 | 0.9862 | 0.07 | 0.18 | 0.9775 | 0.03 | 0.14 | 0.9830 | 0.00 | 0.12 | 0.9875 | 0.00 | 0.06 | 0.9938 |
| HD | 0.35 | 0.47 | 0.8840 | 0.42 | 0.52 | 0.8899 | 0.43 | 0.55 | 0.8555 | 0.43 | 0.56 | 0.8478 | 0.22 | 0.32 | 0.8871 |
| SU | 0.04 | 0.13 | 0.9858 | 0.42 | 0.52 | 0.8899 | 0.05 | 0.15 | 0.9820 | 0.03 | 0.13 | 0.9860 | 0.01 | 0.06 | 0.9925 |
| WI | 0.05 | 0.11 | 0.9899 | 0.10 | 0.14 | 0.9872 | 0.06 | 0.12 | 0.9872 | 0.04 | 0.11 | 0.9889 | 0.02 | 0.07 | 0.9921 |
| MI | -0.19 | 0.37 | 0.8827 | -0.27 | 0.42 | 0.8975 | -0.42 | 0.55 | 0.7765 | -0.28 | 0.42 | 0.8699 | 0.02 | 0.16 | 0.9566 |
| GU | 0.02 | 0.14 | 0.9836 | 0.06 | 0.18 | 0.9759 | 0.02 | 0.16 | 0.9781 | 0.01 | 0.14 | 0.9831 | 0.00 | 0.06 | 0.9927 |
| SO | 0.02 | 0.15 | 0.9791 | 0.11 | 0.20 | 0.9725 | 0.08 | 0.17 | 0.9748 | 0.04 | 0.14 | 0.9829 | -0.08 | 0.11 | 0.9707 |
| MU1 | -0.08 | 0.18 | 0.9709 | -0.08 | 0.23 | 0.9614 | -0.12 | 0.22 | 0.9596 | -0.11 | 0.19 | 0.9682 | -0.03 | 0.08 | 0.9878 |
| PE | 0.11 | 0.28 | 0.9325 | 0.31 | 0.46 | 0.8645 | 0.20 | 0.35 | 0.9091 | 0.05 | 0.20 | 0.9665 | -0.02 | 0.06 | 0.9928 |
| MU2 | 0.02 | 0.12 | 0.9862 | 0.07 | 0.18 | 0.9775 | 0.03 | 0.14 | 0.9830 | 0.00 | 0.12 | 0.9875 | 0.00 | 0.06 | 0.9938 |
| RE | 0.02 | 0.13 | 0.9838 | 0.06 | 0.18 | 0.9770 | 0.02 | 0.16 | 0.9785 | 0.01 | 0.14 | 0.9830 | 0.01 | 0.07 | 0.9919 |
| OL | 0.07 | 0.13 | 0.9869 | 0.12 | 0.15 | 0.9867 | 0.08 | 0.13 | 0.9862 | 0.07 | 0.13 | 0.9855 | 0.04 | 0.10 | 0.9813 |

CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

**Table 6.** Statistical indicative performance estimation hourly diffuse radiation by models circunsolar, isotropic and anisotropic in different cloudy conditions, for tilted of 32.85° to North.

| Models | Total Group | | | Clear Sky | | | Partially Clear Sky | | | Partially Cloudy Sky | | | Cloudy Sky | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d | MBE | RMSE | d |
| CIR | 0.12 | 0.19 | 0.9702 | 0.19 | 0.22 | 0.9731 | 0.18 | 0.23 | 0.9652 | 0.13 | 0.20 | 0.9638 | 0.06 | 0.14 | 0.9624 |
| LJ | 0.10 | 0.20 | 0.9659 | 0.17 | 0.26 | 0.9636 | 0.15 | 0.25 | 0.9566 | 0.11 | 0.23 | 0.9548 | 0.05 | 0.11 | 0.9751 |
| KO | 0.02 | 0.15 | 0.9769 | 0.13 | 0.24 | 0.9678 | 0.11 | 0.22 | 0.9641 | 0.07 | 0.20 | 0.9647 | 0.03 | 0.10 | 0.9818 |
| BA | 0.07 | 0.18 | 0.9722 | 0.08 | 0.22 | 0.9696 | 0.04 | 0.19 | 0.9702 | 0.00 | 0.16 | 0.9731 | -0.01 | 0.08 | 0.9875 |
| TI | -0.01 | 0.15 | 0.9756 | 0.05 | 0.22 | 0.9675 | 0.01 | 0.19 | 0.9691 | -0.04 | 0.16 | 0.9718 | -0.02 | 0.08 | 0.9867 |
| TC | 0.10 | 0.20 | 0.9654 | 0.17 | 0.26 | 0.9636 | 0.15 | 0.25 | 0.9566 | 0.11 | 0.23 | 0.9547 | 0.05 | 0.12 | 0.9743 |
| BU | 0.23 | 0.38 | 0.8845 | 0.56 | 0.65 | 0.7861 | 0.38 | 0.48 | 0.8426 | 0.18 | 0.28 | 0.9263 | 0.03 | 0.09 | 0.9831 |
| KL | 0.10 | 0.20 | 0.9654 | 0.17 | 0.26 | 0.9636 | 0.15 | 0.25 | 0.9566 | 0.11 | 0.23 | 0.9547 | 0.05 | 0.12 | 0.9743 |
| HÁ | -0.03 | 0.07 | 0.9865 | 0.15 | 0.24 | 0.9664 | 0.13 | 0.22 | 0.9648 | 0.07 | 0.18 | 0.9699 | 0.02 | 0.09 | 0.9845 |
| HD | -0.09 | 0.20 | 0.9628 | -0.16 | 0.25 | 0.9622 | -0.19 | 0.27 | 0.9488 | -0.13 | 0.22 | 0.9554 | 0.00 | 0.10 | 0.9797 |
| SU | 0.37 | 0.50 | 0.8693 | 0.45 | 0.57 | 0.8889 | 0.49 | 0.60 | 0.8483 | 0.48 | 0.61 | 0.8170 | 0.22 | 0.33 | 0.8694 |
| WI | 0.01 | 0.04 | 0.9890 | 0.18 | 0.25 | 0.9645 | 0.17 | 0.25 | 0.9575 | 0.13 | 0.23 | 0.9570 | 0.05 | 0.11 | 0.9753 |
| MI | 0.12 | 0.18 | 0.9733 | 0.18 | 0.22 | 0.9737 | 0.17 | 0.22 | 0.9670 | 0.13 | 0.20 | 0.9657 | 0.06 | 0.12 | 0.9755 |
| GU | -0.08 | 0.31 | 0.9235 | -0.13 | 0.35 | 0.9378 | -0.24 | 0.42 | 0.8909 | -0.16 | 0.36 | 0.9059 | 0.05 | 0.18 | 0.9457 |
| SO | 0.10 | 0.20 | 0.9664 | 0.16 | 0.26 | 0.9629 | 0.14 | 0.25 | 0.9565 | 0.11 | 0.23 | 0.9562 | 0.04 | 0.10 | 0.9787 |
| MU1 | 0.09 | 0.20 | 0.9653 | 0.19 | 0.27 | 0.9603 | 0.19 | 0.27 | 0.9510 | 0.14 | 0.24 | 0.9526 | -0.02 | 0.07 | 0.9878 |
| PE | 0.03 | 0.19 | 0.9693 | 0.00 | 0.22 | 0.9714 | 0.05 | 0.24 | 0.9594 | 0.03 | 0.22 | 0.9585 | 0.02 | 0.11 | 0.9778 |
| MU2 | 0.17 | 0.35 | 0.8982 | 0.41 | 0.56 | 0.8362 | 0.34 | 0.49 | 0.8488 | 0.15 | 0.31 | 0.9157 | 0.00 | 0.08 | 0.9851 |
| RE | 0.07 | 0.17 | 0.9735 | 0.15 | 0.24 | 0.9664 | 0.13 | 0.22 | 0.9648 | 0.07 | 0.18 | 0.9699 | 0.02 | 0.09 | 0.9845 |
| OL | 0.10 | 0.20 | 0.9653 | 0.17 | 0.26 | 0.9634 | 0.15 | 0.25 | 0.9564 | 0.11 | 0.23 | 0.9546 | 0.05 | 0.12 | 0.9743 |

CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

The increase in tilt angle allows a significant decrease in the indices of adjustment (d), with increases scattering and changes in trends of underestimation. Except Gueymard (GU) model, which showed statistics indicative lower in the three tilted surfaces, however, with improvement in results with increasing tilt angle. Under CRS, PCRS, PCYS and CYS conditions this Gueymard model showed *RMSE* of 0.51, 0.61, 0.47 and 0.14 MJ $m^{-2}$ $h^{-1}$ to 12.85°; 0.42, 0.56, 0.42 and 0.16 MJ $m^{-2}$ $h^{-1}$ to 22.85°; 0.36, 0.42, 0.35 and 0.18 MJ $m^{-2}$ $h^{-1}$, respectively.

According Scolar et al. [43] evaluating daily data on a surface with a slope equal to the local latitude in Botucatu, observed that Perez et al (PE), Hay (HA), Reindl et al (RE) and Liu and Jordan (LJ) models were better, due to less dispersion and overestimating or underestimating the estimation than observed values. These authors, concluded that the model of Hay has the lowest error and therefore the best model to estimate daily diffuse radiation on an inclined surface and Liu and Jordan (LJ) model underestimates the values of daily global radiation (-1.29%). The results obtained on others papers corroborate with data obtained in this paper, especially as to levels of scattering and model adjustment by different cloudiness conditions [10, 12, 15, 44, 46].

Except for models Bugler (BU), Steven and Unsworth (SU), Hay and Davies (HD) and Gueymard (GU), observed similar estimates in the higher levels of atmospheric transmissivity. The average values of hourly diffuse radiation measured and estimated by twenty models are showed in Table 7, occurring smaller errors for cloudy sky. The average values of hourly diffuse radiation measured and estimated by twenty models are showed in Table 7, occurring smaller errors for cloudy sky. The higher values of HDRD occurs in partially clear sky and partially cloudy sky for all tilted surfaces and also the higher energetic frequency by these two classes of cloudiness in climatic conditions of Botucatu (Brazil).

Considering the inclinations and sky conditions studied with an simplified approach of models (smaller number of measured variables), the best results were presented by anisotropic models: Ma and Iqbal (MI), Hay (HA), Reindl et al (RE) and Willmott (WI); isotropic: Badescu (BA) and Koronakis (KO) and Circunsolar (CIR). However others models need to be calibrated because presented adjustment index (d) above 0.95 and RMSE less than 0.27 MJ $m^{-2}$ $h^{-1}$ allowing used reliably to estimate hourly diffuse radiation on local climatic conditions.

**Table 7.** Average hourly diffuse radiation (MJ $m^{-2}$ $h^{-1}$) difference (measured) and estimated by circunsolar, isotropic and anisotropic models, in cloudiness conditions and tilted surfaces.

| Models | 12.85° | | | | 22.85° | | | | 32.85° | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CRS | PCRS | PCYS | CYS | CRS | PCRS | PCYS | CYS | CRS | PCRS | PCYS | CYS |
| Measures | 0.731 | 0.867 | 0.931 | 0.401 | 0.642 | 0.761 | 0.812 | 0.397 | 0.474 | 0.612 | 0.717 | 0.333 |
| CIR | 0.742 | 0.914 | 0.943 | 0.402 | 0.757 | 0.842 | 0.879 | 0.440 | 0.660 | 0.791 | 0.848 | 0.397 |
| LJ | 0.706 | 0.889 | 0.932 | 0.397 | 0.701 | 0.784 | 0.822 | 0.407 | 0.641 | 0.762 | 0.831 | 0.380 |
| KO | 0.701 | 0.883 | 0.925 | 0.395 | 0.684 | 0.765 | 0.802 | 0.398 | 0.608 | 0.724 | 0.789 | 0.361 |
| BA | 0.691 | 0.870 | 0.912 | 0.389 | 0.651 | 0.729 | 0.765 | 0.379 | 0.551 | 0.655 | 0.715 | 0.327 |
| TI | 0.656 | 0.826 | 0.866 | 0.369 | 0.612 | 0.685 | 0.718 | 0.356 | 0.524 | 0.623 | 0.680 | 0.311 |
| TC | 0.706 | 0.880 | 0.932 | 0.398 | 0.701 | 0.784 | 0.822 | 0.408 | 0.641 | 0.762 | 0.831 | 0.384 |
| BU | 1.110 | 1.126 | 1.014 | 0.399 | 1.116 | 1.025 | 0.910 | 0.404 | 1.038 | 0.993 | 0.896 | 0.365 |
| KL | 0.706 | 0.889 | 0.932 | 0.398 | 0.701 | 0.784 | 0.822 | 0.408 | 0.641 | 0.762 | 0.831 | 0.384 |
| HÁ | 0.713 | 0.892 | 0.928 | 0.394 | 0.708 | 0.786 | 0.810 | 0.395 | 0.622 | 0.737 | 0.787 | 0.356 |
| HD | 0.368 | 0.537 | 0.717 | 0.367 | 0.313 | 0.433 | 0.598 | 0.365 | 0.317 | 0.427 | 0.590 | 0.330 |
| SU | 1.079 | 1.355 | 1.412 | 0.602 | 1.066 | 1.191 | 1.246 | 0.620 | 0.925 | 1.103 | 1.195 | 0.552 |
| WI | 0.716 | 0.896 | 0.933 | 0.396 | 1.066 | 0.808 | 0.838 | 0.410 | 0.654 | 0.782 | 0.845 | 0.384 |
| MI | 0.725 | 0.906 | 0.939 | 0.399 | 0.742 | 0.821 | 0.851 | 0.417 | 0.656 | 0.783 | 0.843 | 0.391 |
| GU | 0.359 | 0.424 | 0.589 | 0.348 | 0.376 | 0.336 | 0.536 | 0.415 | 0.339 | 0.370 | 0.560 | 0.385 |
| SO | 0.705 | 0.888 | 0.931 | 0.396 | 0.698 | 0.782 | 0.819 | 0.402 | 0.634 | 0.756 | 0.823 | 0.372 |
| MU1 | 0.785 | 0.953 | 0.971 | 0.244 | 0.748 | 0.839 | 0.856 | 0.315 | 0.668 | 0.800 | 0.855 | 0.315 |
| PE | 0.620 | 0.749 | 0.819 | 0.367 | 0.559 | 0.643 | 0.700 | 0.364 | 0.475 | 0.665 | 0.746 | 0.356 |
| MU2 | 0.858 | 1.021 | 0.978 | 0.386 | 0.955 | 0.960 | 0.867 | 0.380 | 0.887 | 0.948 | 0.870 | 0.337 |
| RE | 0.713 | 0.892 | 0.928 | 0.394 | 0.708 | 0.786 | 0.810 | 0.395 | 0.622 | 0.737 | 0.787 | 0.356 |
| OL | 0.707 | 0.890 | 0.933 | 0.398 | 0.700 | 0.784 | 0.822 | 0.408 | 0.641 | 0.762 | 0.831 | 0.384 |

CRS: clear sky; PCRS: partially clear sky; PCYS: partially cloudy sky; CYS: cloudy sky. The models: CIR: circumsolar [9]; LJ: Liu and Jordan [17]; KO: Koronakis [18]; BA: Badescu [20]; TI: Tian et al. [19]; TC: Temps and Coulson [21]; BU: Bugler [22]; KL: Klucher [23]; HA: Hay [24]; HD: Hay and Davies [25]; SU: Steven and Unsworth [26]; WI: Willmott [27]; MI: Ma and Iqbal [29]; GU: Gueymard [30;31]; SO: Skartveit and Olseth [33]; MU1: Muneer [34]; PE: Perez et al. [35;36]; MU2: Muneer [37]; RE: Reindl et al. [38]; OL: Olmo et al [39].

The Circumsolar (CIR) model is the simplest (depends only on the geometric factor RB) and assumes that all diffuse radiation originates directly on the solar disc. The Hay (HA) model is most used by calibrations in different climatic regions through regressions [10, 43, 46, 47]. To Pandey and Katiyar [12], in Lucknow (26.75°N and 80.85°E) found that Klucher (KU) model presented best estimates, especially in cloudy sky and low intensities of inclination. For Evseev and Kudish [15], the Ma and Iqbal (MI) model provides the best performance for data clear sky and partly cloudy sky, while in cloudy sky, the best results was found with two Muneer models.

## 4. Conclusion

The variations in cloudiness sky as a function of atmospheric transmissivity of global radiation must be employed to assess the behavior of components circunsolar, isotropic and anisotropic diffuse radiation.

In climatic conditions of Botucatu, São Paulo State, Brazil, among the twenty models to estimate the diffuse radiation evaluated, considering all inclinations and variations of cloudiness, the best results are obtained by; i) anisotropic models: Ma and Iqbal (MI), Hay (HA), Reindl et al. (RE) and Willmott (WI); ii) isotropic models: Badescu (BA) and Koronakis (KO); and Circumsolar (CI) model. These models provide good estimates of global radiation, with decreased scattering when compared with the estimation of diffuse radiation.

The Perez et al (PE), Gueymard (GU) and two Muneer models (MU1, MU2) depends large number of variables adjusted regionally, while simplified models are important because they allow general applications. However, should be considered and calibrated if not possible to apply the model with fewer variables. The performance each model depends on atmospheric conditions regional.

The increase of the inclination angle allows for a reduction in the performance statistical of parametrized models for estimating the diffuse radiation due to increase scattering and decrease of adjustment index.

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