Physical and Statistical Analysis Procedure of Solar Irradiance Measurements Based on Sky Cover Conditions

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Abstract

The correct quality assessment of solar irradiance data allows public bodies, academic entities and non-governmental organizations to plan and manage renewable energy resources more appropriately in Brazil. This study presents a physical and statistical analysis procedure used by the Solar Radiometry Laboratory of the School of Agricultural Sciences (São Paulo State University - UNESP), in Botucatu/São Paulo/Brazil, to check the reliability of 5-minute instantaneous average measurements (Wm^{-2}) of global (I_G), sky-diffuse (I_D) and direct-beam (I_B) solar irradiances in horizontal surfaces. The procedure was implemented based on quality control of the International Commission on Illumination (CIE) to detect physically impossible events (absolute and consistency checks) and statistical ranges in function of sky cover conditions to identify uncertain events. A set of measurements (2005 to 2007) was used to demonstrate the application of this procedure. It was found by the physical analysis that the absolute check identified the least amount and the consistency check the largest amount of physically impossible and discrepant quantities measurement values, as well as the statistical ranges allowed to identify data points not signaled by the previous criteria, pointing uncertain solar irradiance observations (outliers). The procedure application indicated that 94.77% of global, 97.12% of sky-diffuse and 98.16% of direct-beam irradiances were flagged as validated, indicating a high quality of measurements, that can be used to assist Brazilian organizations in the planning of renewable energy systems.

Keywords: Solar radiation; Quality assessment of solar measurements; Statistical ranges; Sky coverage.

1. Introduction

The correct quality assessment of solar measurements allows public bodies, academic entities and non-governmental organizations to plan and manage renewable energy resources more appropriately in Brazil. Solar irradiance is crucial for the conversion of thermal energy, photovoltaic systems, residential and building heating and on agricultural crops (Pashiardis and Kalorigou, 2016). However, measuring solar irradiance is not an easy task because of process uncertainties, as is often the case for any type of measurements. Solar irradiance measurement errors are caused by problems in the instrumentation and operational negligence in the acquisition of these parameters (Younes et al., 2005). As such it is necessary to implement processes for analysis of such measurements before their submission to subsequent investigations, to ensure data reliability.

Some quality control procedures are proposed by government bodies, meteorological institutes and independent scientists, around the world, to verify the reliability of measured solar irradiances. The most used is the Baseline Surface Radiation Network of the World Radiation Monitoring Center (Long and Dutton, 2002). However, there are others that are also widely applied, such as the National Renewable Energy Laboratory of the U.S. Department of Energy (NREL, 1993), the International Commission on Illumination (Tregenza et al., 1994) and the Royal Meteorological Institute of Belgium (Journeé and Bertrand, 2011) procedures. The purpose of such procedures is to identify, from different methods (range test from physically and extremely rare limits, across-quantities relationships, model comparisons and visual inspection), measures suspected of being incorrect, pointing them with a flag (Ohmura et al., 1998). Leaving the decision to remove flagged cases for the data analyst (Urraca et al., 2017).

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The purpose of this study is presents a quality control procedure, combining physical and statistical analysis criteria, used by the Solar Radiometry Laboratory of the School of Agricultural Sciences (São Paulo State University - UNESP), in Botucatu/São Paulo/Brazil, to check the reliability of 5-minute instantaneous average measurements (Wm^{-2}) of global (I_G), sky-diffuse (I_D) and direct-beam (I_B) solar irradiance in horizontal surfaces. Most of the quality control procedures presented in the literature are designed mainly to identify physically impossible measurements or with discrepancies in the solar component comparisons. The criteria combination for identify impossible and inconsistency measurements, according to physical reason with a statistical criterion, routinely used after data acquisition, allows a different analysis (identifying statistical outliers) based on sky cover conditions, because this is one of the factors that most affect the amount of each solar component measured. In addition, an application of this procedure is presented to assess which analysis criteria is more rigorous, considering a set of measures from 2005 to 2007.

2. Methodology

2.1 Location and Climate

The proposed physical and statistical analysis procedure was developed based on daytime global (I_G), sky-diffuse (I_D) and direct-beam (I_B) solar irradiances (2005 to 2007) of Solar Radiometry Laboratory (22.54'S, 48.27'W, 786m) of the School of Agricultural Sciences (São Paulo State University - UNESP) in Botucatu/São Paulo/Brazil. Botucatu (Fig. 1) is a town located in the center-south region of the São Paulo state (SP), characterized mainly by intense agricultural activities (sugarcane and eucalyptus) and moderate industrial activities (Codato, et al., 2008). According to Köppen climatic criteria, Botucatu is classified as Cwa (mesothermal) with warm temperate climate. It includes dry winter (June to August) and hot and humid summer (December to February), with wide temperature variations throughout the year (Dal Pai et al., 2016).

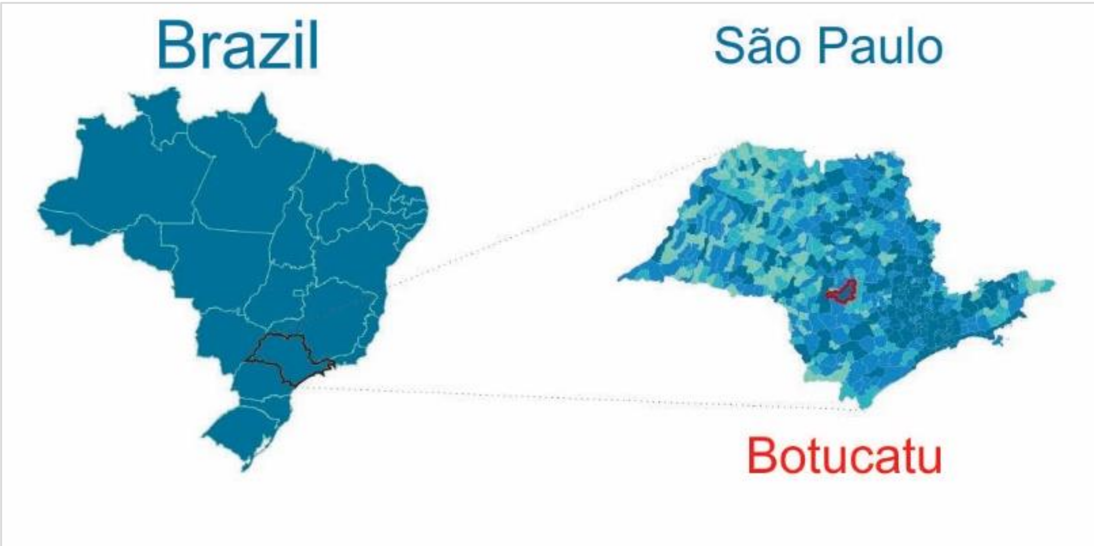

Fig. 1: Location of Botucatu Town in São Paulo State - Brazil.

The climatic series from 1971 to 2013 for the Botucatu town, obtained by the Lageado Weather Station (2019), indicates that the average air temperature for the coldest month (July) is around 17 ºC and for the warmest month (February) near 23 ºC. The average relative air humidity for the less humid month (August) is around 64% and for the wettest month (February) near 78%. Precipitation had its highest values in summer and spring (wet season), with maximum occurrence in January (around 250 mm), due to the great evaporation of wet and heated surfaces. The lowest precipitation values were obtained in winter and fall (dry season), with a minimum occurrence in July and August, around 40 mm, due to the meeting of cold and dry masses coming from the south with the hot and humid masses coming from north (Codato et al., 2008; Dal Pai et al., 2016). It is important to note that the rainy season is characterized by the presence of large cloud cover.

2.2 Measurement Acquisition and Instrumentation

Global irradiance (I_G) was measured by an unshaded Eppley Precision Spectral Pyranometer - PSP (Fig. 2a) on a horizontal surface. This instrument has a large thermal offset, that can be corrected using the output signal from a Pyrheliometer or reduced using an Eppley Standard Ventilator (Haeffelin et al., 2001). However, for this study, no correction was applied, because it is a preliminary study, as well as in the irradiance measured period no device was used to reduce this offset, due to limited financial resources. Direct-beam irradiance at normal solar incidence (I_{BN}) was measured by an Eppley Normal Incidence Pyrheliometer - NIP (Fig. 2b) fitted to a single axis Eppley Solar Tracker - ST3. To obtain the direct-beam irradiance on a horizontal surface, the values at normal solar incidence were multiplied by the cosine of the zenith angle (I_{BN} cosθ_Z), in degrees (eq. 1), according to Iqbal (1983).

$$\cos \theta_Z = \sin(\delta) \sin(\phi) + \cos(\delta) \cos(\phi) \cos(\omega) \quad \text{(eq. 1)}$$

where δ is the solar declination (eq. 2), ϕ is the geographical latitude of the measurements acquisition site (-22.85) and ω is the hour angle of the sun (eq. 3), both in degrees.

$$\delta = 0.3964 + 3.631 \sin(F) - 22.97 \cos(F) + 0.03838 \sin(2F) - 0.3885 \cos(2F) + 0.07659 \sin(3F) - 0.1587 \cos(3F) - 0.01021 \cos(4F) \quad \text{(eq. 2)}$$

such that F is $\frac{360\ D}{365}$, where D is the day of the year (1st to 365th).

$$\omega = (12 - Hd)\ 15 \quad \text{(eq. 3)}$$

where Hd is the hour and tenth hour of the day.

The sky-diffuse irradiance (I_D) was measured by an Eppley Precision Spectral Pyranometer - PSP (Fig. 2c) on a horizontal surface fitted to a shadowring (radius of 0.40 meters and width of 0.10 meters) developed and corrected using the geometric factors proposed by Oliveira et al. (2002), because it has low cost and has easy operation and maintenance. The geometric correction does not consider the anisotropic effect of radiation, tending to underestimate sky-diffuse component, mainly, in clear sky conditions. To overcome this deficiency, Dal Pai et al. (2016), were corrected the measurements based on atmospheric factors, that on average, brought an interesting result. However, in the most frequent measurements acquisition (10, 5 or 1 minute) there is a tendency of scattering of data, due to the fast effects of diffuse radiation in short time. This means that, for different types of sky cover, both corrections may imply possible underestimation or overestimation of the real sky-diffuse values.

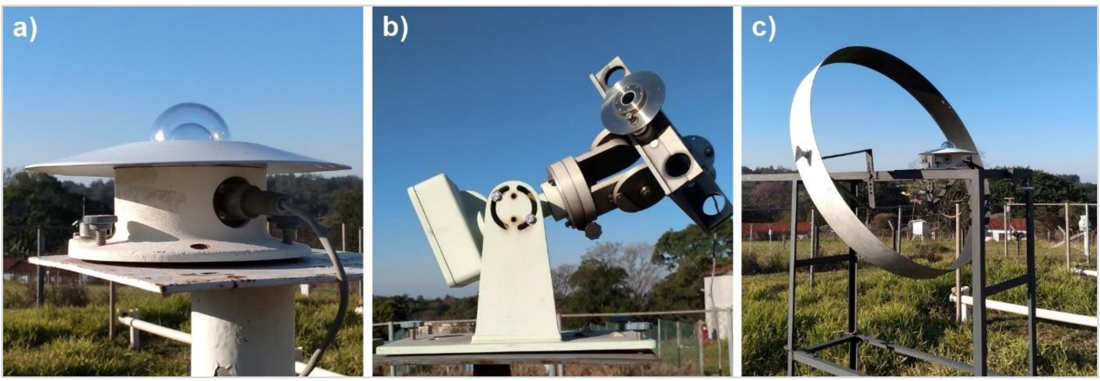

Fig. 2: Pyranometer of global irradiance (a), pyrheliometer of direct-beam irradiance (b) and pyranometer of sky-diffuse irradiance (c) with a shadowring.

All devices used were installed in a rural area with short green grass at least 1.5 meters from the ground. Regular maintenance was performed daily, ensuring perfect irradiance monitoring conditions, as well as additional instruments were annually used to calibrate the routine equipment using the comparative method. A Campbell Scientific (2006) Micrologger CR23X, operating at a frequency of 1 Hz, was used to collect, process and store the irradiances signals every 5 minutes (average of 60 measures collected at a scan time of 5 seconds) in the period used in this study. Tab. 1 shows the operating specifications of the instrumentation described, according by Eppley (1992) and Eppley (2019) manuals.

Tab. 1: Operational specifications of the global, direct-beam and sky-diffuse solar irradiance instruments.

Specification	Global Solar Irradiance (I_G)	Direct-Beam Solar Irradiance (I_B)	Sky-Diffuse Solar Irradiance (I_D)
Brand/Instrument	Eppley/Precision Spectral Pyranometer (PSP)	Eppley/Normal Incidence Pyrheliometer (NIP)	Eppley/Precision Spectral Pyranometer (PSP)
Classification	Secondary Standard/High Quality	Secondary Standard/High Quality	Secondary Standard/High Quality
Spectral Range	295 – 2800 nm	250 – 3000 nm	295 – 2800 nm
Sensitivity	Approx. 7.45 μV/Wm²	Approx. 7.59 μV/Wm²	Approx. 7.47 μV/Wm²
Output	0 – 12 mV	0 – 10 mV	0 – 12 mV
95% Response Time	5 seconds	5 seconds	5 seconds
Cosine Effect	Approx. 1% ($0^o < \theta_Z < 70^o$) Approx. 3% ($70^o < \theta_Z < 80^o$)	-	Approx. 1% ($0^o < \theta_Z < 70^o$) Approx. 3% ($70^o < \theta_Z < 80^o$)

2.3 Physical and Statistical Analysis Procedure

The statistical analysis of solar irradiances, performed after your acquisition, is a prerequisite for future investigations on the solar resource, essentially in sub-hourly databases, where the frequency of acquisition implies higher volumes of measurements and erroneous data. Due the uncertainties in the solar irradiance measurement process, it is necessary to use procedures based on physical reasoning to detect impossible events and statistical analysis to identify questionable events (Journée and Bertrand, 2010). The physical reasoning rules of the International Commission on Illumination - CIE (Tregenza, et al., 1994), including absolute - AC (AC_G, AC_D and AC_B criteria on Tab. 2) and consistency checks - CC (CC_G and CC_D criteria on Tab. 2), were first used in this study to ensure that major problems do not exist (unrealistic peaks or small variations), detecting impossible or inconsistent measures. In sequence, a statistical range - SR analysis was applied (SR_G, SR_D and SR_B criteria on Tab. 2) to determine ranges of allowable variations (minimum and maximum values) for the irradiances based on sky cover conditions. The irradiances outside the statistical ranges may be considered uncertain due to the high or low values for sky conditions at the time of your acquisition.

Tab. 2: Solar measurements analysis criteria of absolute checks (AC), consistency checks (CC) and statistical ranges (SR).

Label Check	Analysis Criteria	Verified Irradiance
AC_G	$0 < I_G \leq (1.2\ I_E)$	I_G
AC_D	$0 < I_D \leq (0.8\ I_E)$	I_D
AC_B	$0 \leq I_B \leq I_E$	I_B
CC_G	$0.75\ (I_D + I_B) \leq I_G \leq (I_D + I_B)\ 1.25$	I_G
CC_D	$I_D < (1.10\ I_G)$	I_D
SR_G	$\mu_{I_G} - (k\ \sigma_{I_G}) \leq\ I_G\ \leq\ \mu_{I_G} + (k\ \sigma_{I_G})$	I_G
SR_D	$\mu_{I_D} - (k\ \sigma_{I_D}) \leq\ I_D\ \leq\ \mu_{I_D} + (k\ \sigma_{I_D})$	I_D
SR_B	$\mu_{I_B} - (k\ \sigma_{I_B}) \leq\ I_B\ \leq\ \mu_{I_B} + (k\ \sigma_{I_B})$	I_B

Statistical ranges were obtained by the average (μ_{I_G}, μ_{I_D} and μ_{I_B}) and standard deviation (σ_{I_G}, σ_{I_D} and σ_{I_B}) of the global (I_G), sky-diffuse (I_D) and direct-beam (I_B) irradiances, respectively. The multiplier (k) of confidence level of 99.50% were also used, considering the normal probability distribution (in this study k value is 2.57). All the procedure (Tab. 2) was applied in measurements obtained in an interval of one whole day for each sky cover classification. The sky cover classification (dimensionless) is obtained by the clearness index interval (K_T), i.e., the ratio between global and extraterrestrial irradiances (I_G/I_E), and has four coverage conditions, according to Escobedo et al. (2009), as shown in Tab. 3.

Tab. 3: Clearness index interval and sky coverage condition.

Clearness Index Interval	Coverage Condition
$0 \leq K_T < 0.35$	Overcast Sky
$0.35 \leq K_T < 0.55$	Partially Cloudy Sky
$0.55 \leq K_T < 0.65$	Partially Clear Sky
$0.65 \leq K_T < 1$	Clear Sky

The extraterrestrial irradiance (I_E), used to obtain the sky cover classification and in the measurement analysis criteria, can be obtained in Wm^{-2} (eq. 4), according to Iqbal (1983).

$$I_E = 1361\ E_C \cos(\theta_Z) \qquad \text{(eq. 4)}$$

where 1361 is the solar constant (Wm^{-2}), E_C (eq. 5) is the dimensionless orbital eccentricity (Earth-Sun distance) and θ_Z the zenith angle in degrees.

$$E_C = 1 - 0.0009467 \sin(F) - 0.01671 \cos(F) - 0.0001489\ (2\ F) - 0.00002917 \sin(3\ F) - 0.0003438 \cos(4\ F) \qquad \text{(eq. 5)}$$

such that F is $\frac{360\ D}{365}$, where D is the day of the year (1^{st} to 365^{th}).

The possible diagnostics for the physical and statistical analysis for each measured data point are questionable (Q), that represents when a variable failed in a criterion (impossible or uncertain) and cannot be replaced, and valid (V) that represents when a variable passed in one of the criteria, however can still be downgraded to questionable by failing another subsequent analysis (Tregenza et al., 1994). This procedure should not delete questionable data point from the database, only signal them. Since this decision must be taken by the solar radiation data analyst.

3. Results and discussion

In the case of pyranometers and pyrheliometers there are several details that can influence the measurement of solar irradiance, affecting their reliability. The effect of circumsolar irradiation is the unique detail that can affect direct-beam measurements in the case of pyrheliometers. However there are other details that can influence the measures of global and sky-diffuse irradiance, acquired by a pyranometer, such as the directional response of the sensor on the elevation of the sun and the effect of inclination. In order to deviate from any problems caused by such circumstances, the CIE rules determine that only measurements above 4° of solar elevation (eq. 6), calculated according to Iqbal (1983), should be considered valid in the data set. But, in this study this criterion was not applied, and all measures obtained above 0° of solar elevation were used and considered valid until it proves to be questionable.

$$E = 90 - \theta_Z \qquad \text{(eq. 6)}$$

The dataset selected for analysis (2005 to 2007) contained 150878 of global (I_G), 148747 of sky-diffuse (I_D) and 144064 of direct-beam (I_B) irradiance data points. The measurement point numbers for each sky cover conditions can be seen in more detail in Tab. 4. These numbers express the amount measurements obtained before any analysis or data processing activity (raw data), indicating a greater number of irradiance values obtained under clear and cloudy sky conditions and a smaller amount under partially cloudy and partially clear conditions, respectively.

Tab. 4: Numbers of questionable measures by each rules of the analysis.

Sky Coverage Condition	Solar Irradiance	Number of Raw Measurement Points	Analysis Criteria: Number of Questionable Measurements			Total Amount of Questionable Measures
			Absolute Check	Consistency Check	Statistical Range	
Overcast	I_G	50803	0	1347	538	1885
	I_D	48997	0	1659	481	2140
	I_B	48848	0	0	1652	1652
Partially Cloudy	I_G	29625	0	1534	144	1678
	I_D	29525	0	351	249	600
	I_B	27959	0	0	433	433
Partially Clear	I_G	19361	0	976	92	1068
	I_D	19310	1	42	233	276
	I_B	18443	0	0	148	148
Clear	I_G	51089	23	2878	358	3259
	I_D	50915	131	23	1111	1265
	I_B	48814	0	0	417	417
Total Measurements	I_G	150878	23	6735	1132	7890
	I_D	148747	132	2075	2074	4281
	I_B	144064	0	0	2650	2650

Global irradiance had a higher number of measurements flagged as questionable in the consistency check criterion, with higher occurrence in clear sky (2878 data points of 51089 in this condition). Sky-diffuse irradiance had a greater number of measures flagged as questionable, also in the consistency check criterion, with higher occurrence in cloudy sky (1659 data points of 48997 in this conditions). Unlike the irradiance already mentioned (global and sky-diffuse), there is no criterion for direct-beam irradiance consistency check, a negative point in CIE rules, as this step showed to be the most efficient to identify questionable measures, despite having serious problems, as will be pointed out below. In this case, there were no values flagged as questionable by physical analysis in either of the two steps (absolute or consistency check). Therefore, the total amount of direct-beam measures flagged as questionable was pointed by the statistical range criterion, most occurring in cloudy sky (1652 data points of 48848 in this condition).

The highest irregularities (questionable measures) in global irradiance occurred on September 06, 2006 (Fig. 3a), such that 116 of the 139 data points were flagged (83.45%) by consistency check criterion, due to errors in direct-beam measurements. For sky-diffuse irradiance the largest irregularities occurred on December 13, 2007 (Fig. 3b), where 61 of the 159 data points were flagged (38.36%), also, by consistency check, due to the values exceeded global measurements more than 10%, this cannot occur because of the geometric relation between the solar components ($I_G = I_D + I_B$). In other words, in the absence of direct-beam the global irradiance must be equal to sky-diffuse. Such information allowed us to see that the consistency check criterion has a serious deficiency of flagging a measurement as questionable when, in fact, the failure happened in another irradiance. As an example, it could be seen that the plotted points (Fig. 3a) of global and sky-diffuse are correctly measured according to the values throughout the day (higher values around noon and lower at sunrise or sunset), but were flagged as questionable because of a failure in direct-beam data. This is one of the reasons why global has many measures flagged as questionable in the consistency check over the years.

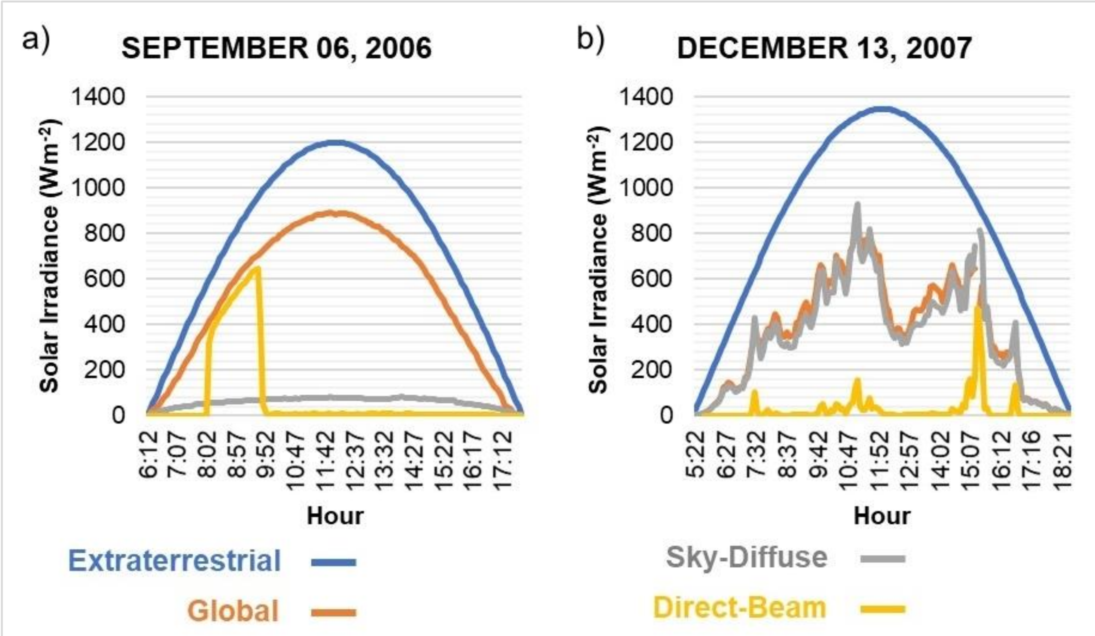

Fig. 3: Highest amount of questionable measurements in one day of global (a) and sky-diffuse (b) irradiance.

Under overcast sky conditions (Fig. 4a) sky-diffuse obtained the highest (4.37%) and direct-beam the lowest (3.38%) total amount of questionable irradiances measures. For partially cloudy (Fig. 4b) and partially clear sky conditions (Fig. 4c) the analysis presented similar results, where the global irradiance indicated the most questionable measures (5.66% and 5.52%) and the direct-beam less questionable (1.55% and 0.80%), respectively. Under clear sky (Fig. 4d), like previous conditions, the global had more questionable measures (6.38%) and the direct-beam less questionable (0.85%).

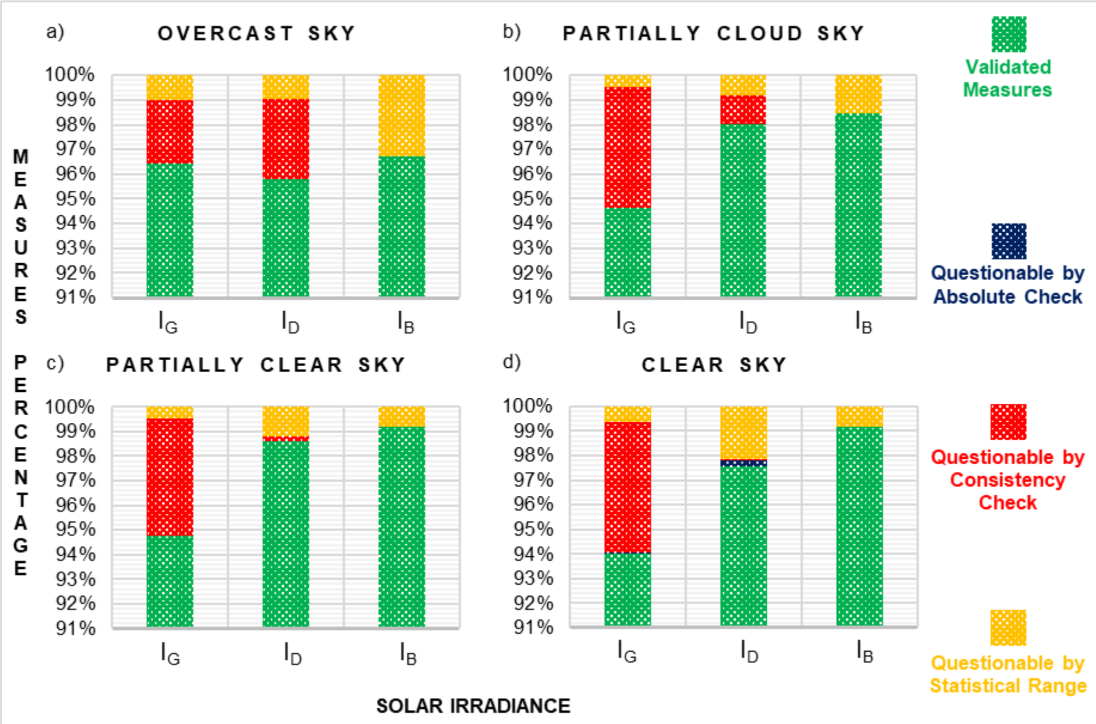

Fig. 4: Percentage of questionable and validated measures by each rules of the analysis in the overcast sky (a), partially cloud sky (b), partially clear sky (c) and clear sky (d) conditions.

The main contribution of this paper is the statistical analysis, which works by complementing the physical (absolute and consistency checks) procedure of CIE. This analysis was performed based on sky cover conditions, because this is the factor that most contributes to the irradiance amount that reaches the terrestrial surface. It was observed that for overcast and partially cloud sky the direct-beam irradiance had the largest amount of measurements flagged as questionable, approximately 3.38% (Fig. 4a) and 1.55% (Fig. 4b), respectively. For partially clear and clear sky the sky-diffuse irradiance had the highest amount of flagged questionable data points, approximately 1.21% (Fig. 4c) and 2.18% (Fig. 4d), respectively. In this context, four days samples (January 10 and 20, 2005, February 21, 2005 and March 1, 2005) that contained the largest amount of questionable measurements (direct-beam and sky-diffuse) were selected for each sky cover condition. The aim is to show the data points distribution and where they are considered questionable according to the statistical parameters (see Tab. 2).

For the values obtained under overcast sky on January 20, 2005 (Fig. 5a), the average of direct-beam irradiance (most flagged as questionable) was 0.5093 Wm^{-2}, the standard deviation was 0.8505 Wm^{-2}, the lower statistical range limit was -1.6765 Wm^{-2} and the upper was 2.6952 Wm^{-2}. For the other three sky cover classification there are several days with the same amount of questionable measures. For partially cloudy sky we selected January 10, 2005, to exemplify the analysis. For the values obtained on this day (Fig. 5b) the average of direct-beam irradiance (most flagged as questionable) was 11.0555 Wm^{-2}, the standard deviation was 22.1185 Wm^{-2}, the lower statistical range limit was -45.7890 Wm^{-2} and the upper was 67.9001 Wm^{-2}. For the partially clear sky we selected March 1, 2005 (Fig. 5c) which contained an average value of sky-diffuse irradiance (most flagged as questionable on this day) of 109.2171 Wm^{-2}, the standard deviation was 79.5554 Wm^{-2}, the lower statistical range limit was -95.2404 Wm^{-2} and the upper was 313.6745 Wm^{-2}. For the clear sky we selected February 21, 2005 (Fig. 5d) which contained an average of sky-diffuse measurements (most flagged as questionable) of 68.7960 Wm^{-2}, the standard deviation was 10.2437 Wm^{-2}, the lower statistical range limit was 42.4696 Wm^{-2} and the upper was 95.1225 Wm^{-2}.

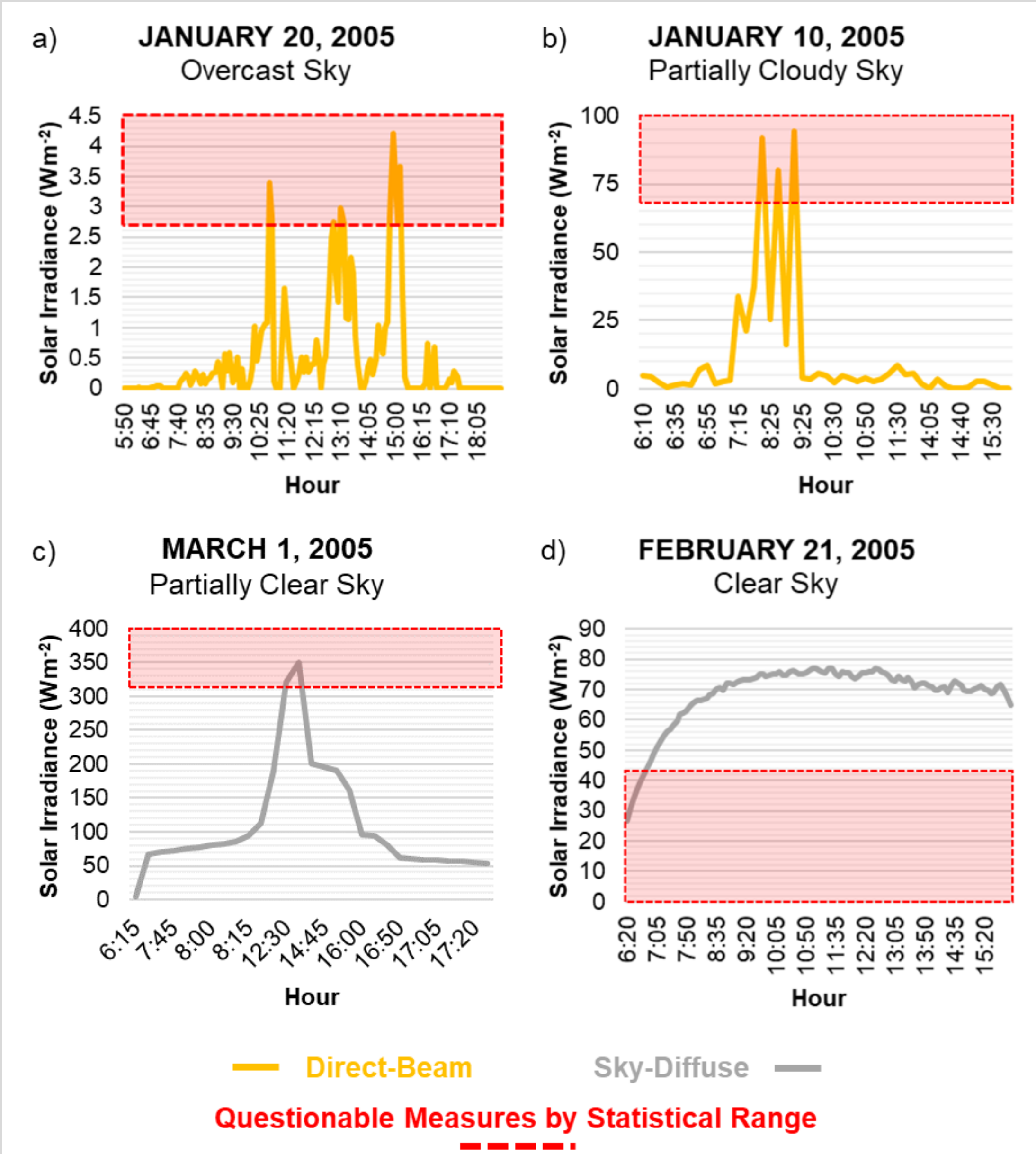

Fig. 5: Days with the largest number of measurements flagged as questionable by the statistical ranges procedure according to overcast (a), partially cloudy (b), partially clear (c) and clear (d) sky conditions.

For the irradiance values obtained under overcast sky (January 20, 2005 - Fig. 5a) out of 154 data points 10 were considered questionable (red area on graph). For partially cloudy sky (January 10, 2005 - Fig. 5b) out of 47 data points 3 were questionable, because their values were above the upper limit. For the partially clear sky (March 01, 2005 - Fig. 5c) 29 measurements were obtained of which 2 were considered questionable. This flag assigned by statistical analysis occurred in the same amount for other days under the same sky conditions. Finally, for the clear sky condition (21 February 2005 - Fig. 5d) 6 of the 118 measurements obtained were considered questionable because they were below the lower limit. From the total dataset, the global irradiance presented the greatest amount of questionable measures (5.23% or 7890 data points), followed by sky-diffuse (2.88% or 4281 data points) and direct-beam (1.84% or 2650 data points).

4. Conclusions

This study presents a physical and statistical analysis procedure used after the acquisition of global (I_G), sky-diffuse (I_D) and direct-beam (I_B) solar irradiance measurements to verify its reliability by the Solar Radiometry Laboratory of the School of Agricultural Sciences (São Paulo State University - UNESP), in Botucatu/São

Paulo/Brazil. The procedure consists of two steps of physical analysis (absolute and consistency checks) developed by the International Commission on Illumination (CIE) and one step of statistical analysis (outlier detection) proposed in this paper. According to the results presented from the solar irradiance measurements set used, it can be concluded that: absolute check rules identified the least amount of questionable measures (physically impossible); consistency check rules identified the largest amount (discrepant quantities of solar components) and has a limitation of not containing rules for direct-beam irradiance and flag as questionable measures that are actually correct; statistical ranges allowed to identify measurements not signaled by the physical analysis, pointing unusual solar irradiance observations (outliers); statistical analysis proved to be a complementary criterion to the CIE rules, allowing to verify the measurements in different sky coverage conditions (factor that causes great variation in the irradiances values) and finally the physical and statistical analysis procedure indicated that 94.77% of global, 97.12% of sky-diffuse and 98.16% of direct-beam irradiance on horizontal surface were flagged as validated, indicating that they can be used to assist Brazilian organizations in the planning of renewable energy systems.

5. Acknowledgments

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