Abstract

This paper describes statistical and climatic analyses of G, UV, PAR and NIR irradiations, and UV/G, PAR/G and NIR/G fractions using a data base obtained from 2001 to 2005 in Botucatu/SP/Brazil. Values of irradiations and fractions are presented in two systematic series: Diurnal and Annual. Diurnal series shows values of irradiations and hourly mean fractions in annual and monthly time intervals, while annual series shows values of irradiations and monthly mean (hourly and daily) fractions. Effects of clouds, water vapor and aerosols were analyzed and discussed in the seasonal variations of irradiations and fractions in both series.

1. Introduction

Knowing the relationship between global solar radiation (G) and ultraviolet (UV), photosynthetically active (PAR) and near infrared (NIR) spectral solar radiation by estimation models is important for many scientific and technological areas. Literature data have shown that most studies use statistical models, which are simple and accurate to estimate this radiation for specific places where measurement was performed. UV radiation has been investigated in many countries, and results show that the UV/G ratio is highly dependent on climatic conditions because of variation in cloud, water vapor and aerosol concentration in the local atmosphere. Total UV radiation is a fraction between 2.0 % and 9.5% of G radiation, in which the lowest values of UV/G are obtained in cloudless sky conditions and dry atmosphere with aerosols, while the highest values of UV/G are obtained in conditions of cloudy sky cover [1-6]. Similarly, the relationship between PAR and G has also been studied in many places with different climatic conditions. The results show that PAR/G represents a percentage between 40.8 % and 63.1 % [7-11]. Few studies have reported the relationship between NIR and G in the Earth’s surface. Some results have shown that NIR

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radiation depends mainly on the presence of clouds and water vapor in the atmosphere: the ratio NIR/G varies from 44.0% to 51.5% [12, 13]. Measurement of G, UV, PAR and NIR radiation, simultaneously or not, in a single place is still scarce, and there is little available information on the literature [14,15]. Further studies are required to better investigate seasonal variations of irradiations, as well as UV/G, PAR/G and NIR/G spectral fractions throughout the day and the year. Temporal series of irradiation are important in studies on spatial models and satellite calibration. In line with this thinking, the Solar Radiometric Station monitored G, UV and NIR radiation in the period from 2001 to 2005 in Botucatu/SP/Brazil, and results of statistical and climatic analyses of these measures were presented.

2. Methodology

2.1 Measurement of G, UV and NIR radiation

Global irradiance (IG) was monitored by an Eppley PSP pyranometer, ultraviolet irradiance (IUV) by a radiometer CUU-3 from Kip-Zonen and near infrared irradiance (INIR) by a pyranometer PSP Eppley with a selective dome in the spectral range from 0.7$\mu$m to 3.0$\mu$m, from 2001 to 2005 in Botucatu/SP/Brazil. The calibration factor of the NIR pyranometer is multiplied by the 0.92 factor to correct the transmission effect by the dome on the sensor. PAR irradiance (IPAR) was obtained by difference between IG and the sum of IUV and INIR calculated at the same frequency, using the equation: IPAR = IG - (IUV + INIR). In this study, PAR was expressed in Wm$^{-2}$ for irradiance, and in MJm$^{-2}$ for hourly and daily irradiation. The estimation error of PAR radiation is associated with inaccuracy in measurement of IG and INIR irradiance by the Eppley pyranometer, and IUV irradiance by the UV Kipp & Zonen radiometer. Uncertainty values of 4.1% and 5.0% are found for the PSP pyranometer [16] and UV Kipp & Zonen radiometer [17], respectively. Therefore, total uncertainty of PAR estimate is 7.7% [16]. The Solar Radiometric Station has additional solar radiometers used annually just for benchmarking of devices routinely used, through the comparative method suggested by OMM [18]. For data acquisition a Campbell CR23X data logger with a sampling frequency of 1 Hz was used, and means of 300 readings were stored. Data underwent a quality control, and later were processed by programs which calculated hourly and daily irradiations [19].

2.2 Diurnal evolution: Calculation of irradiations, atmospheric transmissivity and hourly mean fractions.

Diurnal values of hourly mean irradiations of HG, HUV, HPAR and HNIR were calculated each hour, from 5 a.m. to 7 p.m., using the Equation 1, in which “all” is the number of hourly radiation in 5 years. The X index represents G, UV, PAR and NIR radiation.

\[
H_X = (\sum_{i=1}^{all} H_{Xi})/all
\]  

(1)

Similarly, diurnal values of hourly mean atmospheric transmissivity KT, KUV, KPAR and KNIR were calculated using the Equation 2. The OX index is the extraterrestrial irradiation Hu0 = 5.7% of Ho[20], HPAR0 = 38.8% of Ho[21] and HNIR0 = 55.5% of Ho, difference between 100% Ho and 45.5% UV0 + PAR0 [22].

\[
K_X = (\sum_{i=1}^{all} H_{Xi}/H_0)/all
\]  

(2)

Similarly, diurnal values of hourly mean fractions KUV, KPAR and KNIR were calculated using the Equation 3. Y index represents hourly mean UV, PAR and NIR irradiations, respectively.

\[
K_Y = (\sum_{i=1}^{all} H_{Yi}/H_{G0})/all
\]  

(3)

2.3 Annual Evolution: Calculation of irradiations, atmospheric transmissivity and monthly mean fractions.

Annual values of monthly mean HG, HUV, HPAR and HNIR irradiations (hourly and daily) were calculated for each month using Equation 4

\[
H_X = (\sum_{i=1}^{all} H_{Xi})/all
\]  

(4)
Annual values of monthly mean atmospheric transmissivity $K_t$, $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ (hourly and daily) were calculated using Equation 5

$$K_t = \frac{\sum_{i=1}^{4} H_{Xi}/H_{Xi}}{\text{all}}$$ (5)

Annual values of monthly mean $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ fractions (hourly and daily) were calculated using the Equation 6

$$K_Y = \frac{\sum_{i=1}^{4} H_{Yi}/H_{Yi}}{\text{all}}$$ (6)

3. Results and Discussion

3.1. Diurnal evolution of hourly mean irradiations (annual and monthly)

Figure 1a shows annual diurnal evolution of $H_G$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ calculated by Equation 1. Values of $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ follow the values of $H_G$ according to the decreasing sequence, PAR, NIR and UV, in all hourly intervals. Diurnal evolution of $H_G$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ is dependent on variations in the solar elevation angle, optical mass and cloudiness. Values of irradiances increased from the beginning and end to the middle of the day, according to the increase in the solar elevation angle, decrease in optical mass and increase in hourly frequency of partially cloudy sky with a trend towards clear and cloudless conditions ($K_t < 0.65$).

Irradiations reached maximum values in the hourly interval of 11:30 a.m., the highest solar elevation angle, highest frequency of clear sky and lowest optical mass: $H_G = (2.53 \pm 0.09) \text{ MJ/m}^2$, $H_{UV} = (0.107 \pm 0.004) \text{ MJ/m}^2$, $H_{PAR} = (1.25 \pm 0.04) \text{ MJ/m}^2$ and $H_{NIR} = (1.25 \pm 0.04) \text{ MJ/m}^2$. Integration of the curves (fig2a) provides daily values of annual hourly mean irradiances: $H_G = 18.0 \text{ MJ/m}^2$; $H_{UV} = 0.75 \text{ MJ/m}^2$; $H_{PAR} = 8.89 \text{ MJ/m}^2$; $H_{NIR} = 8.39 \text{ MJ/m}^2$, and as a result, values of $H_{PAR}/H_G = 0.493$; $H_{NIR}/H_G = 0.465$ and $H_{UV}/H_G = 0.0415$ represent values of annual hourly mean fractions UV, PAR and NIR of G radiation. Values of $H_{PAR}/H_G = 49.3\%$, $H_{NIR}/H_G = 46.5\%$ and $H_{UV}/H_G = 4.2\%$ are in agreement with values of fractions statistically obtained by linear regression for all sky covers [15]. The standard deviation (SD%) shown in figure (1b) represents the variation range of G, UV, PAR and NIR irradiances in each hourly interval due to astronomical and climatic variations occurring along the year. At the beginning and end of the day, deviations are high as a consequence of variations in photoperiod. Values of SD% of $H_G$ decreased from 80.8% to 34.2%, $H_{UV}$ from 72.7% to 33.64%, $H_{PAR}$ from 100.0% to 34.0%, and $H_{NIR}$ from 84.6% to 35.0%.

For seasonal analysis of irradiations along the year, relative deviation ($D\%$) was calculated between integrated values of diurnal curves of annual irradiances ($a_a$) and integrated values of diurnal curves of irradiances in months ($a_m$) shown in Fig. 2(a, b, c) by the Equation $D(\%) = 100 \times (a_a - a_m)/a_a$. Deviations express the ability of annual irradiation to overestimate or underestimate monthly irradiation. Diurnal evolution of annual and monthly $H_{UV}$ and
H_{PAR} (fig2a,b) shows that values of annual $\bar{H}_{UV}$ and $\bar{H}_{PAR}$ overestimate values of $\bar{H}_{UV}$ and $\bar{H}_{PAR}$ by 25.5% and 23.6% in May; 32.0% and 27.6% in June; 30.3% and 25.9% in July; 15.0% and 10.3% in August, and underestimate them by 13.6% and 7.5% in January; 19.3% and 16.0% in February; 13.0% and 11.1% in March; 7.5% and 7.7% in October; 20.8% and 18.0% in November and 20.8% and 20.7% in December.

Similarly, Fig. 2 (c) shows that the annual value of $\bar{H}_{NIR}$ overestimates $\bar{H}_{NIR}$ by 0.2% in April; 22.1% in May; 25.7% in June; 22.9% in July; 4.3% in August, and underestimates it by 2.8% in January; 11.9% in February; 9.4% in March; 2.8% in September, 9.1% in October; 14.8% in November and 14.6% in December.

For the analysis of climate effect on the extinction of irradiations, atmospheric transmissivity of $K_t$, $K_{tUV}$, $K_{tPAR}$ and $K_{tNIR}$ was calculated using the Equation (2). Transmissivity is the indicator of total attenuation processes of G, UV, PAR and NIR radiation through absorption and scattering by atmospheric constituents such as ozone, dry air, clouds, water vapor and aerosols. Figure 3(a,b,c,d) shows diurnal annual evolution of $K_t$, $K_{tUV}$, $K_{tPAR}$ and $K_{tNIR}$. Values of annual $K_t$, $K_{tUV}$, $K_{tPAR}$ and $K_{tNIR}$ are higher following the descending sequence PAR, G, NIR and UV in all hourly intervals, and they show that absorption and scattering effects are higher in the descending sequence UV, NIR, G and PAR.
Transmissivity increases from the beginning and end to the middle of the day, according to the decrease in optical mass and concentration of clouds, water vapor and aerosols. In the intervals of higher optical mass (Mo = 21.5) and cloudy sky cover (beginning and end of the day), values of $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ were the lowest in the day, 22.5%, 18.5%, 30.0% and 17.0%, respectively. In the interval of the lowest optical mass $M_o = 1.0$ and higher frequency in the number of hours of clear and partially clear sky (middle of the day), transmissivity reached maximum values of 60.0%, 43.0% 76.0% and 49.5%, respectively.

Figure 4 shows diurnal evolution: a) hourly mean fractions $\bar{K}_{UV}$, $\bar{K}_{PAR}$ and $\bar{K}_{NIR}$, calculated using the Equation (3), b) standard deviations of $\bar{K}_{UV}$, $\bar{K}_{PAR}$ and $\bar{K}_{NIR}$. Diurnal seasonal variations of $\bar{K}_{UV}$, $\bar{K}_{PAR}$ and $\bar{K}_{NIR}$ (Fig.4a) are a result of variations in cloudiness, water vapor and aerosols in the atmosphere. Values of $\bar{K}_{UV}$ decreased at the beginning of the day from 4.9% and 52.8% to 4.1% and 49.4% (7:30 a.m.), respectively. Similarly, values of $\bar{K}_{PAR}$ also decreased at the end of the day from 42.2% to 46.7% at 3:30 p.m. In these hourly intervals, beginning and end of the day, the sky cover is virtually cloudy ($K_t<0.35$): clouds and water vapor absorbed proportionally more NIR radiation than G radiation, leading to an increase in $\bar{K}_{UV}$ and $\bar{K}_{PAR}$ values, and a decrease in $\bar{K}_{NIR}$ value. Between 7.30 a.m. and 4:30 p.m., values of $\bar{K}_{UV}$, $\bar{K}_{PAR}$ and $\bar{K}_{NIR}$ were virtually steady: value of $\bar{K}_{UV}$ ranged from 4.1% to 4.3%, $\bar{K}_{PAR}$ from 49.0% to 50.0% and $\bar{K}_{NIR}$ from 45.5% to 46.7%. Mean value from 7:30 a.m. to 4:30 p.m. was: $\bar{K}_{UV} = 4.25\%$, $\bar{K}_{PAR} = 49.7\%$ and $\bar{K}_{NIR} = 46.1\%$. Standard deviation (Fig. 4b) decreased from the beginning and end to the middle of the day due to decreasing variations in optical mass. Value of SD (%) followed the decreasing sequence $\bar{K}_{UV}$, $\bar{K}_{IV}$ and $\bar{K}_{PAR}$: value of $\bar{K}_{UV}$ decreased from 17.8% to 11.3%; $\bar{K}_{PAR}$ from 12.4% to 5.3% and $\bar{K}_{PAR}$ from 8.5% to 4.2%.

3.2. Annual evolution of monthly mean (hourly and daily) irradiations

Figure 5 shows annual evolution of (hourly and daily) $H_G$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ calculated by Equation 4. Seasonal variation of irradiations is a result of astronomical and climatic variations. Values of $H_G$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ are higher in months from October to March (south declination). In this period, concentrations of clouds and water vapor in the atmosphere are the highest in the year (fig 6). On the other hand, values of irradiations were the lowest from April to September, dry period, in which concentrations of clouds and water vapor are the lowest (fig 6), and concentration of aerosols in the atmosphere is the highest in the year (fig 7).
Variability of $H_G$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ in the rainy period is highly associated with variations in cloudiness, precipitation and water vapor in the atmosphere caused by microclimatic variations and macroclimatic synoptic phenomena, such as the South Atlantic Convergence Zone (SACZ) and Frontal System of the Atlantic Ocean. SACZ causes an increase in cloudiness and occurrence of intense and persistent precipitation. Their frequency is twice to four times a year, with mean duration up to 8 days in January, February and March [23]. Frontal System of the Atlantic Ocean consists of humid fronts coming from the Atlantic Ocean and leading to increased cloudiness and precipitation of average and high intensity in months of October, November and December.

In the dry period, values of $H_G$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ are also influenced by variations in cloudiness, precipitation and water vapor in the atmosphere, caused by the macroclimatic synoptic phenomenon called Polar Frontal System, and aerosols originated from burning of sugar cane (fig.7a).

The Polar Frontal System is a result of cold fronts coming from the polar region, causing an increase in cloudiness and precipitation of average and low intensity in May and June. The average frequency of cold fronts is 5 events a month [25]. Aerosols are annually originated from burning and harvesting of sugar cane from May to November, in which the maximum concentration of particulate matter is in September (fig 7b).
Figure 7. a) monthly mean aerosol optical depth (AOD) obtained from TERRA satellite from the year 2001 to 2005. b) Relationship between monthly mean AOD and concentration of particulate matter (PM) in ug.m\(^{-3}\) [24].

The standard deviation (Fig 8 a,b) shows that hourly \( \overline{H}_G, \overline{H}_{UV}, \overline{H}_{PAR} \) and \( \overline{H}_{NIR} \) range of variation is higher than their daily values in each month of the year. Hourly SD (%) ranged approximately from 60.0% to 80.0%, while the daily value ranged from 23.0% to 40.0% and was higher from October to March, in which higher variations in concentration of cloudiness and water vapor are found in the atmosphere. On the contrary, value of SD (%) was lower in the dry period from April to September.

Figure 8. Annual evolution of standard deviations of \( \overline{H}_G, \overline{H}_{UV}, \overline{H}_{PAR} \) and \( \overline{H}_{NIR} \): a) hourly and b) daily.

Figure (9a) shows that evolution of hourly \( \overline{K}_t \) is a little higher than the daily value in each monthly interval. The frequency distribution shows that this difference exists because the frequency of the number of hours of clear sky is greater than the number of days of clear sky. However, in the confidence interval of 99.0%, the Student’s T-test shows that hourly \( \overline{K}_t \) values are not statistically different from daily \( \overline{K}_t \) values. Figure (9b) shows that values of \( \overline{K}_{PAR}, \overline{K}_{G}, \overline{K}_{NIR} \) followed the value of \( \overline{K}_t \) (fig9a) in all monthly intervals and decreased in the following sequence PAR, G, NIR and UV.

Seasonality of \( \overline{K}_t, \overline{K}_{PAR}, \overline{K}_{G}, \overline{K}_{NIR} \) is highly associated with variations in cloudiness, water vapor in the atmosphere and aerosol concentration in each month of the year: transmissivity is lower in the rainy period, months from October to March, in which concentrations of clouds and water vapor in the atmosphere are the highest in the year. January, the most humid and cloudy month, has the lowest transmissivity for all radiation \( \overline{K}_t = 44.5\%; \overline{K}_{PAR} = 34.8\%; \overline{K}_{G} = 57.7\% \text{ and } \overline{K}_{NIR} = 36.4\% \). On the contrary, values of \( \overline{K}_t, \overline{K}_{PAR}, \overline{K}_{G}, \overline{K}_{NIR} \) are higher in the dry period, from April to September, in which concentrations of clouds and water vapor are the lowest, and aerosol concentration is the highest in the year.
In general, through all months, value of $K_{\text{PAR}}$ ranged from 57.7% to 74.8% (mean = 68.1%); value of $K_{T}$ from 44.5% to 60.8% (mean = 53.9%); value of $K_{\text{NIR}}$ from 36.4% to 53.2% (mean = 45.4%) and value of $K_{\text{UV}}$ from 34.8% to 42.3% (mean = 36.6%).

Figure (10) shows annual evolution of hourly and daily $K_{\text{UV}}, K_{\text{PAR}}$ and $K_{\text{NIR}}$ calculated by Equation 6. According to the Students’s T-test, hourly values (Fig. 10a) are statistically similar to daily values (Fig. 10b) in the confidence interval of 99.0%. Variations of $K_{\text{UV}}, K_{\text{PAR}}$ and $K_{\text{NIR}}$ throughout the day (fig. 10b) are associated with seasonal variations of cloudiness and water vapor in the atmosphere, caused by meteorological phenomena of micro and macro scale in months from October to March (humid period), and by variations in concentrations of dry air and aerosols, caused by burning of sugar cane in months from April to September (dry period).

![Diagram](image)

Figure 10- Annual evolution of $K_{\text{UV}}, K_{\text{PAR}}$ and $K_{\text{NIR}}$: a) hourly; b) daily

Values of $K_{\text{UV}}$ and $K_{\text{PAR}}$ decreased almost linearly from the highest value of 4.6% and 50.7%, in the most cloudy and humid month (January), to the lowest values of 3.9% and 48.2%, in the driest month, cloudless and with aerosols (August), respectively. From August to December, values of $K_{\text{UV}}$ and $K_{\text{PAR}}$ increased from 3.9% and 48.2% to 4.5% and 50.5% as a function of the increase in concentration of clouds and water vapor in the atmosphere. On the contrary, value of $K_{\text{NIR}}$ increased almost linearly from the lowest value of 44.6%, in the most cloudy and humid month (January), to the highest value of 48.3%, in the driest, cloudless month and with aerosols.
(August). After that, the value of $K_{NIR}$ decreased from 48.3% to 45.0% in the month with high concentration of clouds and water vapor (December). Values of $K_{UV}$ and $K_{PAR}$ are higher and value of $K_{NIR}$ is lower in cloudy and humid atmosphere, because of absorption of NIR radiation by the water vapor.

Values of hourly standard deviation (fig 11a) followed the decreasing sequence of $K_{UV}$, $K_{PAR}$ and $K_{NIR}$, and in most months, values of $K_{PAR}$ and $K_{NIR}$ were lower than 10.0%, while $K_{UV}$ was lower than 16.0%. Similarly, values of daily standard deviation (Figure 11b) for $K_{PAR}$ and $K_{NIR}$ in most months were lower than 5.0%, while for $K_{UV}$, they were lower than 10.0%.

4. Conclusions

Diurnal evolution of $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ irradiation is dependent on the solar elevation angle, optical mass and climatic variations. Values of annual $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ overestimate their monthly values in the dry period (April to September), in which the concentration of clouds and water vapor is the lowest, and concentration of aerosols is the highest in the year. On the contrary, values of annual $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ underestimate their monthly values in the humid period (October to March), in which the concentration of clouds and water vapor is the highest, and aerosol concentration is the lowest in the year.

Diurnal values of atmospheric transmissivity $K_t$, $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ increase according to the decrease in optical mass and increase in frequency of number of hours of clear sky conditions.

Diurnal variations of fractions $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ are a result of variations in photoperiod, optical mass and sky cover. Values of $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ were approximately steady: $K_{UV}$ ranged from 4.1% to 4.3%, $K_{PAR}$ from 49.0% to 50.0% and $K_{NIR}$ from 45.5% to 46.7%.

Annual evolution of $H_{G}$, $H_{UV}$, $H_{PAR}$ and $H_{NIR}$ irradiation (hourly and daily) depend on astronomical and climatic variations. They are higher from October to March (humid period), in which concentrations of clouds and water vapor in the atmosphere are the highest in the year. On the contrary, they are the lowest from April to September, in which concentrations of clouds and water vapor and aerosols are the lowest and concentration of aerosols is the highest in the year.

Annual values of atmospheric transmissivity $K_t$, $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ depend on climatic variations. They are the lowest in the humid period (October to March), in which the concentration of clouds and water vapor in the atmosphere is the highest in the year. On the contrary, they are the highest in the dry period (April to September), in which concentration of clouds and water vapor is the lowest, and concentration of aerosols is the highest in the year. For all cover sky conditions, value of $K_t$ ranged from 57.7% to 74.8% (mean = 68.1%); value of $K_{UV}$ from 44.5% to 60.8% (mean = 53.9%); value of $K_{PAR}$ from 36.4% to 53.2% (mean = 45.4%) and value of $K_{NIR}$ from 34.8% to 42.3% (mean = 36.6%).

Annual evolution of $K_{UV}$, $K_{PAR}$ and $K_{NIR}$ depend on seasonal variation of cloudiness and water vapor in the atmosphere in the humid period, and on concentration of dry air and aerosols in the dry period. Values of $K_{UV}$ and $K_{PAR}$ decreased from the highest value of 4.6% and 50.7%, in the most cloudy and humid month (January), to the lowest value of 3.9% and 48.2%, in the driest, cloudless month with aerosols (August), respectively. On the other
hand, value of $\bar{K}_{\text{NIR}}$ increased from the lowest value of 44.6%, in the most cloudy and humid month (January), to the highest value of 48.3% in the driest, cloudless month with aerosols (August).

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