VALIDATION OF INCIDENT SOLAR RADIATION USING ORBITAL AND SURFACE DATA IN LAVRAS, MINAS GERAIS

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Abstract: Incident solar radiation (Rs) is a key input variable for various agrometeorological models. However, Rs daily record is limited by insufficient number of weather stations that measure this variable. This research was conducted with the objective of comparing the daily Rs obtained from satellite data products with the Rs obtained from weather station data for the 2010 year in Lavras, Minas Gerais State, Brazil. The surface weather data were collected by two weather stations located at the campus of the Federal University of Lavras in order to determine Rs. Daily insolation values were recorded by the National Institute of Meteorology (INMET) Conventional Meteorological Station (CMS) and Rs data from the National Institute for Space Research (INPE) Automatic Weather Station (AWS). The Land Surface Analysis-Satellite Application Facilities Down-welling Surface Short-wave Radiation Flux (LSA SAF DSSF) is a product obtained from the Meteosat Second Generation satellite (MSG-2) images. The results showed a high coefficient of determination between the methods discussed, above 70% ($r^2 > 0.70$) and performance ranging from moderate to strong, which show very close values of radiation for the three different methods of data acquisition. However there was more agreement between the DSSF product and the CMS Rs according to the statistical analysis performed. Thus, it can be assumed that in the absence of surface data Rs, the equivalent DSSF product can replace the Rs data obtained from weather stations.

Keywords: Weather station; remote sensing; LSA SAF DSSF; satellite product.

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INTRODUCTION

The incident solar radiation (Rs) is the directly energy responsible for the regiment of physical, chemical and biological processes, which drives the exchange phenomena in the soil-plant-atmosphere system (Borges et al., 2010). Also called global radiation by some researchers, it refers to the total of direct and diffuse radiation received by a horizontal surface throughout the day (Roerink et al., 2012). The Rs is a weather variable applied for various purposes in meteorology, climatology, hydrology and agriculture, among others, as well as being crucial to the weather and the climate of a given location (Bosch et al., 2010). Rs assumes great importance because it can be used as a key input data for modeling evapotranspiration (ET) at the regional and global scale (Cristóbal and Anderson, 2013).

Although it can be directly measured in meteorological surface stations by instruments such as radiometers, Rs daily record is often limited by the high costs of the instruments used for measurements. These facts contributes to the existence of a low number of weather monitoring stations for those observations (Journée and Bertrand, 2010). Consequently, Rs is usually excluded out of various solar radiation spatiotemporal analysis applications (Polo et al., 2011). Thus, due to the limited availability of Rs records the use of other meteorological data becomes necessary for estimation methods that require solar radiation data (Bojanowski, Vrieling and Skidmore, 2013; Roerink et al., 2012).

Most of the empirical models used in the Rs estimation process are based on the insolation data (Angstrom, 1924; Prescott, 1940) and air temperature data (Bristow and Campbell, 1984; Meza and Varas, 2000). One of the first models and the most widely used method was originally proposed by Angström (1924) and modified by Prescott (1940). This method, named Angstrom-Prescott equation, is based on the relationship between the radiation reaching the earth surface and the solar extraterrestrial radiation, taking into account the ratio of the actual duration of sunshine, to the maximum possible duration of sunshine or daylight hours (Journée and Bertrand, 2010).

The recording of Rs data from weather stations is restricted to a small number of sites and to areas with limited extension (Pinto et al., 2010). This information is critical to adjust solar radiation models, especially for remote sensing database validation (Journée and Bertrand, 2010). In the absence of instruments for collecting solar radiation data it is possible to estimate it by mathematical models but they must be calibrated to become useful (Borges et al., 2010).

Considering the necessity of monitoring the variation of Rs data, which is influenced by the local latitude, by topography, by the position of the sun throughout the day and by the weather, the use of geostationary satellites, such as Meteosat, has positioned itself as an alternative in absence of a dense grid of weather stations, since it has a large spatial coverage and can provide fast information with reliability (Janjai et al., 2011; Linares-Rodriguez et al., 2013; Silva et al., 2012). Over the last few years, the use of satellite images and products has assumed a prominent role to monitor the Rs (Bojanowski et al., 2013; Journée and Bertrand, 2010; Martínez-Durbán et al., 2009; Moreno et al., 2013; Roerink et al., 2012).

The European generation series of geostationary weather satellites, called Meteosat Second Generation (MSG), began in 2004 with the launch of MSG-1 satellite, renamed Meteosat-8, and continuing in 2005 and 2012 with the respective launches of satellites MSG-2, also called Meteosat-9 and MSG-3, also called Meteosat-10 (Roerink et al., 2012; Moreno et al., 2013). The MSG satellites carry on board the Spinning Enhanced Visible and Infrared Imager sensor (SEVIRI), an instrument that generates an image every 15 minutes, totaling 96 daily observations (LandSAF, 2011). The SEVIRI operates in 12 spectral channels, 3 channels for solar radiation (0.6, 0.8 and 1.6 μm) and 8 in the infrared region (3.9, 6.2, 7.3, 8.7, 9.7, 10.8, 12.0 and 13.4 μm) with a spatial resolution of 3 km at nadir and one high resolution channel in the visible region (0.3 - 0.7 μm) with spatial resolution of 1 km at nadir (Linares-Rodriguez et al., 2013; Schmetz et al., 2002).

In addition to the high regularity, another advantage of MSG/SEVIRI is that the European Meteorological Satellite Organization (EUMETSAT) and the European Space Agency (ESA), the organizations responsible for the MSG program, have been generating, supplying and disseminating products derived from MSG satellite images (Geiger et al., 2008). The Institute of Meteorology of Portugal is responsible for coordinating the Land Surface Analysis-Satellite Application Facilities (LSA-SAF) project. This project started in 2005 and was created with the aim of decentralizing the processing tasks the Meteorological Satellites products (Trigo et al., 2011). In 2007, the LSA SAF began to disseminate the Down-welling Surface Short-wave Radiation Flux product, (DSSF), with a temporal resolution of 30 min and a spatial resolution of 3 km at nadir, generated data from three channels of the SEVIRI instrument (LandSAF, 2011).

This study was conducted with the objective of verifying and validating the agreement between the solar radiation data from different sources, specifically the daily incident solar radiation DSSF product compared to Rs estimated from insolation data from the National Institute of Meteorology (INMET) Conventional Meteorological Station (CMS) and compared to R_s collected from the INPE Automatic Weather Station (AWS) for the year 2010 in Lavras, Minas Gerais State, Brazil.

MATERIAL AND METHODS

We used meteorological data collected during the year 2010 in Lavras, Minas Gerais State, Brazil. The weather stations are located in the Federal University of Lavras (UFLA) at an altitude of 918.84 m. The geographical coordinates are 21°14′41″ S latitude and 44°59′59″ W Greenwich longitude. The climate is Cwa according to Köppen climate classification (Dantas, Carvalho and Ferreira, 2007).

The solar radiation data were recorded by the same weather stations located in the UFLA. The insolation data were retrieved from heliograph charts recorded at the CMS station of INMET. The incident radiation Rs was recorded from the LI200X pyranometer of the AWS of INPE. The records were obtained from the virtual environment of the Center for Weather Forecasting and Climate Studies (CPTEC / INPE).

As mentioned by Teramoto, Carvalho and Dantas (2009), the CMS of INMET have instruments with high degree of reliability and follow the international standards established by the World Meteorological Organization (WMO). Data from INMET stations are official Brazilian database.

Daily insolation values recorded by CMS were used to estimate the solar radiation incident on the surface. Those data are systematically monitored by meteorological observers responsible for storing the information in databases.

To obtain Rs, we used the Angstrom Prescott equation, showed in Equation 1.

$$Rs = \left(a + b * \frac{n}{N}\right) * Ra \quad (1)$$

where,
Rs – incident solar radiation (MJ m^{-2} d^{-1})
a – linear coefficient of the equation
b – angular coefficient of the equation
n – insolation (h)
N – daylight hours (h)
Ra – extraterrestrial radiation (MJ m^{-2} d^{-1})

The a and b coefficients are 0.25 e 0.50, respectively, as suggested by Food and Agricultural Organization of the United Nations (FAO), Allen et al. (1998).

The daylight hours N and the extraterrestrial radiation Ra were obtained as Equation 2 and Equation 3, respectively:

$$N = \frac{24\omega s}{\pi} \quad (2)$$

where,
N - daylight hours (h)
ωs - sunset hour angle (rad), obtained by Equation 4.

$$Ra = 37{,}586 * dr * [(\omega s * sin\emptyset * sin\delta) + (cos\emptyset * cos\delta * sin\omega s)] \quad (3)$$

where,
Ra – extraterrestrial radiation (MJ m^{-2} d^{-1})
Ø - local latitude (rad);
δ - solar declination (rad);
The relative distance Earth-Sun, dr was obtained by Equation 4:

$$dr = 1 + 0{,}033 \cos\left(\frac{2\pi}{365}J\right) \quad (4)$$

where,
dr - relative distance Earth-Sun (dimensionless)
J - number of day in the year

The sunset hour angle was obtained by Equation 5:

$$\omega s = arc\cos(-\tan\emptyset * \tan\delta) \quad (5)$$

where,
ωs - sunset hour angle (r-ad)
Ø – local latitude (rad);
δ – solar declination (rad);

The Down-welling Surface Short-wave Radiation Flux product (DSSF) was obtained from the Land Surface Analysis-Satellite Application Facilities (LSA SAF) for the 2010 year. This product is generated from Meteosat Second Generation (MSG- 2) images and was downloaded directly from http://www.landsaf.meteo.pt portal. Since the product has a time interval of 30 minutes, theoretically 48 products are generated per day. In fact, as the product represents solar radiation, only about 24 products per day are useful. There are no products during the night time.

The DSSF product represents the radiant energy in the wavelength range from 0.3 to 4.0 µm, which reaches the earth's surface per unit of area and time. It is generated from MSG images obtained every 15 minutes by SEVIRI sensor (Spinning Enhanced

Visible and Infrared Imager) using three channels, the channels 1 and 2 corresponding to the bands in the visible region (0.6 µm and 0.8 µm) and channel 3 which corresponds to the near infrared band (1.6 µm) (LandSAF, 2011).

The short-wave radiation flux, F↓ (W m^{-2}), given in Equation 6 can be expressed as:

$$F^{\downarrow} = F_0\, dr \cos\theta_s\, T \tag{6}$$

where,
F_0 - the solar constant (W m^{-2})
d_r - relative distance Earth-Sun (dimensionless)
θ_s - is the zenith angle (rad)
T - effective transmittance of the atmosphere (dimensionless)

The effective transmittance of the atmosphere is used to calculate the DSSF product algorithm.

Two different parameterizations are used for different atmospheric conditions. On a clear day, the model uses the methodology proposed by Frouin et al. (1989). In cloudy days the model employs the methodologies proposed by Gautier, Diak and Masse (1980) and Brisson, Le Borgne and Marsouin (1999) to consider the radiative transfer in the cloud-atmosphere-surface system (Geiger et al., 2008).

Afterwards a time series with all daily DSSF products were created. The products were then integrated to give the daily amount of solar radiation (Rs), now in MJ m^{-2} d^{-1}.

Until this step, the maps were in the original projection of the MSG products and with spatial resolution of 3 km for the whole South America. The maps were then reprojected to the geographic projection and WGS84 datum. In order to determine more accurately the geographical location of the weather stations, the pixel size was resampled to 1 km spatial resolution. The interpolation method used was the nearest neighbor. This method does not change the pixel radiometric value and is an easy handling procedure according to Novo (2010).

Rs values were extracted from the daily maps exactly on the geographic coordinates of the meteorological station located at the UFLA. Once obtained the estimated Rs from satellite product and Rs from weather stations for the year 2010, we verified the normality of data using the Kolmogorov-Smirnov test at the significance level of 0.05. According to this test, the distribution is considered normal when the maximum divergence values of the series do not exceed the critical value at the considered significance level as described by Assis, Arruda and Pereira (1996).

The data were analyzed applying t test with significance level of 0.05, and then compared to obtain the statistical performance by the following indexes: coefficient of determination (r^2), mean absolute error (MAE), mean percentage error (MPE), root mean square error (RMSE) and index of agreement (d) of Willmott (1982).

The MAE, MPE and RMSE were given by Equations 7, 8 and 9:

$$MAE = \frac{\sum_{i=1}^{N} |Pi - Oi|}{N} \tag{7}$$

$$MPE = \frac{\sum_{i=1}^{N} \left|\frac{Pi - Oi}{Oi}\right|}{N} * 100 \tag{8}$$

$$RMSE = \left[\frac{\sum_{i=1}^{N} (Pi - Oi)^2}{N}\right]^{\frac{1}{2}} \tag{9}$$

where,
P_i – estimated values of Rs (MJ m^{-2} d^{-1})
O_i – observed values of Rs (MJ m^{-2} d^{-1})
N – number of observations

The Willmott concordance index (d) given by Equation 10, and the determination coefficient (r^2), are dimensionless and express how the estimated values are close to those observed in a range from 0 to 1, such that 1 means maximum agreement.

$$d = 1 - \left[\frac{\sum (Pi - Oi)^2}{\sum (|Pi - O| + |Oi - O|)^2}\right] \tag{10}$$

where,
d - Willmott concordance index
Pi - R_s estimated value (MJ m^{-2} d^{-1})
O - R_s observed value (MJ m^{-2} d^{-1})

Admitting the possibility of data gaps alter the correlation between the methods only the days with all 3 products were evaluated.

RESULTS AND DISCUSSION

The values of the incident solar radiation (Rs) obtained for Lavras during the year 2010 were analyzed by the Kolmogorov-Smirnov test at a significance level of 0.05. Table 1 shows data from the analysis process for the DSSF product, the Rs from AWS data and Rs from CMS data.

Table 1: Kolmogorov-Smirnov normality test for the solar radiation obtained from the 3 different sources in MJ m^{-2} d^{-1}, at 0.05 significance level.

	DSSF	AWS	CMS
Mean	19.19	16.81	18.65
Standard deviation	6.01	5.24	5.30
Minimum value	2.40	2.70	6.00
Maximum value	31.50	30.80	30.40
Kolmogorov-Smirnov Z test	0.77	0.78	0.76
p-value	0.59	0.58	0.62
Corrected p-value	0.57	0.57	0.60

DSSF - Down-welling Surface Short-wave Radiation Flux; AWS - Automatic Weather Station; CMS - Conventional Meteorological Station.

It can be seen from Table 1 that the variables have the p-value of the Kolmogorov-Smirnov test with Lilliefors correction (corrected p-value) greater than 0.05. Thus, the hypothesis of normality of the population should be accepted at that significance level according to Assis, Arruda and Pereira (1996).

After confirming the hypothesis that the Rs data are normally distributed, we used the t test to compare the mean values obtained. The results can be seen in Table 2.

Table 2: T-test analysis comparing DSSF product vs AWS and DSSF product vs CMS at 0.05 significance level.

t-test	DSSF vs AWS	DSSF vs CMS
t_{calc}	5.41	1.21
t_{tab}	1.96	1.96

DSSF - Down-welling Surface Short-wave Radiation Flux; AWS - Automatic Weather Station; CMS - Conventional Meteorological Station.

Table 2 shows the comparison between DSSF product and AWS mean values, the calculated where value of t (t_{calc}) is greater than the tabulated t value (t_{tab}), meaning that there is a significant difference for the t test analysis at the 0.05 significance level. In opposite the analysis of the DSSF product versus CMS data, returned a smaller calculated t value compared to the tabulated t value, meaning that there is no significant difference between DSSF and CMS mean values.

Table 3 and Table 4 show the results for the statistical comparison between the DSSF product and AWS Rs data and for the DSSF product and CMS Rs data.

In Table 3 we observe determination coefficients (r^2) varying from 0.67 to 0.96. The

Table 3: Statistical results for the comparisons between the DSSF product and AWS Rs data.

Month	DSSF vs AWS					
	r^2	MAE	MPE	RMSE	d	c
January	0.80	2.79	0.48	15.03	1.00	0.89
February	0.93	3.08	0.55	16.29	0.99	0.96
March	0.85	1.79	0.37	9.31	1.00	0.92
April	0.76	1.90	0.43	10.06	1.00	0.87
May	0.96	1.04	0.30	5.29	1.00	0.98
June	0.86	0.86	0.26	4.32	1.00	0.93
July	0.71	0.59	0.17	3.01	1.00	0.84
August	0.71	1.62	0.30	8.73	1.00	0.84
September	0.71	3.13	0.62	16.85	0.99	0.84
October	0.67	4.56	1.01	24.11	0.98	0.81
November	0.95	3.58	0.76	19.30	0.99	0.96
December	0.89	3.19	0.64	16.27	0.99	0.94

DSSF - Down-welling Surface Short-wave Radiation Flux; AWS - Automatic Weather Station; MAE - Mean Absolute Error; MPE - Mean Percentage Error; RMSE - Root Mean Square Error.

highest r^2 values were in May (r^2 = 0.96) and November (r^2 = 0.95), whereas in Table 4 the highest r^2 values were obtained in June (r^2 = 0.96) followed by February, September and November (r^2 = 0.94). These values are close to those obtained by Moreno et al. (2013) in validation studies of solar radiation in Spain. In contrast, October was the month with the smallest r^2 values for both DSSF versus AWS comparison with r^2 values of 0.67 (Table 3) and DSSF versus CMS with r^2 values of 0.78 (Table 4).

In general, the results obtained from statistical analysis, expressed by the indices MAE, MPE and RMSE showed an overestimation for the values of DSSF product compared to Rs values estimated from CMS for the less cloudy months. This condition is a result of the high atmospheric transmissivity. In contrast, there was an underestimation of the values for the months with more cloudy days due to the low atmospheric transmissivity. These results are in agreement with those found by Moojen, Cavalcante and Mendes (2012) and Silva et al. (2012), confirming that the cloud factor is a crucial variable in the Rs estimation process.

Analyzing the Rs values obtained by AWS, the DSSF product overestimated the values of the solar radiation for each month of the year. In similar study, Roerink et al. (2012) concluded that the observed differences are not necessarily related to the spatial variation of the DSSF product, but related to the quality of the measurements at meteorological stations depending on the surface conditions of the equipment used by them.

When comparing the DSSF product with Rs estimated from CMS data the good agreement was expressed by the d index. Therefore, it is possible to observe high concordance between the DSSF product and Rs estimated by CMS data. In fact, CMS offers reliable data following the standards of the World Meteorological Organization (WMO), as also referred by Teramoto, Carvalho and Dantas (2009).

The results also corroborate the statements of Perez, Seals and Zelenka (1997). They found that estimates of solar radiation obtained by numerical models in combination with satellite data show smaller deviations compared to the values observed at the surface.

Table 5 shows the monthly mean variation for the DSSF product, for the Rs estimated from CMS data and for the Rs from AWS measurements.

The maximum Rs value obtained for the DSSF product in January was 31.5 MJ m^{-2} d^{-1}. The maximum Rs value estimated from CMS data occurred in December and was 30.4 MJ m^{-2} d^{-1}. In both cases, the Rs values are in agreement with the period of highest incidence of solar radiation in the southern hemisphere (summer). For the Rs measured at the AWS the maximum value was observed in September, 30.8 MJ m^{-2} d^{-1}. The incident radiation is strongly affected by cloudiness, and the variation found for these months are consistent with the studies

Table 4: Statistical results for the comparisons between the DSSF product and CMS Rs data.

Month	DSSF vs CMS					
	r^2	MAE	MPE	RMSE	d	c
January	0.82	1.80	0.29	9.68	1.00	0.90
February	0.94	0.53	0.08	2.81	1.00	0.97
March	0.87	0.54	0.11	2.82	1.00	0.93
April	0.84	-0.18	-0.04	0.93	1.00	0.92
May	0.80	-0.50	-0.13	2.53	1.00	0.89
June	0.96	-0.29	-0.04	1.44	1.00	0.98
July	0.82	-0.44	-0.12	2.22	1.00	0.91
August	0.79	0.43	0.08	2.32	1.00	0.89
September	0.94	1.19	0.21	6.40	1.00	0.97
October	0.78	1.82	0.35	9.65	1.00	0.88
November	0.94	0.29	0.05	1.54	1.00	0.97
December	0.90	0.97	0.18	4.94	1.00	0.95

DSSF - Down-welling Surface Short-wave Radiation Flux; CMS - Conventional Meteorological Station; MAE - Mean Absolute Error; MPE - Mean Percentage Error; RMSE - Root Mean Square Error.

of Teramoto and Escobedo (2012). Also, the incident radiation values in summer are larger because the sun declination angle approaches to the local latitude angle. Instead, in winter the incident radiation values are smaller when the sun angle declines further from the local latitude.

Tabela 5: R_s monthly mean variation for 2010 year at Lavras, Minas Gerais.

Month	Minimum and maximum Rs (MJ m^{-2} d^{-1})		
	DSSF	CMS	AWS
January	13.7 - 31.5	12.8 - 29.9	11.9 - 28.4
February	3.9 - 29.9	9.7 - 28.0	2.9 - 26.7
March	4.8 - 26.7	9.6 - 24.7	4.8 - 30.2
April	7.3 - 22.4	8.6 - 22.7	6.7 - 19.9
May	6.3 - 19.3	8.5 - 19.3	6.6 - 17.6
June	2.4 - 16.8	6.0 - 17.0	2.7 - 26.3
July	8.4 - 18.7	9.4 - 18.9	8.3 - 17.5
August	17.1 - 22.6	15.5 - 22.0	1.8 - 21.0
September	4.7 - 25.4	8.9 - 23.5	3.4 - 30.8
October	7.1 - 29.0	9.1 - 27.3	5.5 - 25.7
November	6.5 - 31.1	10.2 - 28.7	3.6 - 27.1
December	11.8 - 30.9	12.3 - 30.4	9.2 - 27.4

DSSF - Down-welling Surface Short-wave Radiation Flux; CMS - Conventional Meteorological Station; AWS - Automatic Weather Station.

CONCLUSIONS

From the study, it appears that for the analysed period the results showed good agreement between the three different Rs values, with r^2 determination coefficients above 0.70, even reaching values higher than 0.90. Those results obtained from the concordance index showed a good agreement, between Rs from the LSA SAF DSSF product and Rs estimated from CMS data, showing the high performance and quality of the LSA SAF DSSF product.

Thus, it is possible to recomend that in places devoid of surface weather stations, the LSA SAF DSSF product can be used as a surrogate data to represent incident solar radiation.

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