FIRST CORRELATIONS FOR SOLAR RADIATION ON CLOUDY DAYS IN ITALY

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ABSTRACT

First relationships between sky cloud cover and solar radiation for the site of Rome, Italy, are presented in this work. This topic is useful for forecasting solar resources, because of the strong bond between cloud cover and the fraction of solar radiation convertible in electric or thermal power. Satisfactory interpretations of departures of the results from the literature's ones obtained in different European countries are attempted taking into account climatic features of the sites. One of the most important issue relevant for the prediction of actual solar energy available at ground, is to correlate the amount of solar radiation to cloudiness of the sky that occur in the same period. Moreover mean monthly, seasonally and global values were considered, whereas simulation models reliability needs to estimate hourly realistic values of the radiant power, so that its correlations with the predictable cloudiness become necessary. In our approach, meteorological and solar data by the station of FTA Laboratories of the University of Rome Tor Vergata were used, recorded since April 15th 2009 to January 31th 2010. Complementary information about technological applications are ongoing by means of radiometric spectrum analyses.

INTRODUCTION

One of the most important issue relevant for the prediction of actual solar energy available at ground, is to correlate the amount of radiation to the simultaneous cloudiness of the sky. This topic is relevant because of the strong bond between cloud cover and the fraction of solar radiation convertible in electric or thermal power.

Clouds play a key role in the radiative energy budget of the earth and in transfer of energy between the surface and the atmosphere. However, due to the great variety and variability of cloudiness and the lack of methods to measure cloudiness quantitatively, the dependence of radiation fluxes on cloud amount and type has been parameterized by some authors in the past.

In 1969 Kimura and Stephenson [1] proposed an estimating method to value solar intensities for the design of air-conditioning building system. Their main purpose was to determine the relationship between solar intensity on a horizontal surface and hourly observation of cloud cover for Ottawa, Ontario (45° 27' N, 75° 37' W). Their cloud cover observations have been made every hour (Standard Time) by experienced observers who estimate the amount of cloud on a scale of 0 to 10. The analysis were made in 1967, for March, June, September and December months to see if there was a seasonal variation in the relationship between the ratio of global solar radiation for a specific value of cloud cover and global solar radiation for clear sky condition (I_{rec}/I_{TH}), and the cloud cover (CC). For this relationship they proposed a second order polynomial function.

Some years later Kasten and Czeplak [2] presented a work based on the records of hourly sums of solar and terrestrial downward and upward radiation flux densities that has been evaluated with regard to simultaneous hourly cloud observations. Their investigation was intended to give additional information on the correlation between solar radiation and sky cloudiness, using continuous measurements of solar data, made in Hamburg (53° 33'N, 9° 58'E) from 1964 to 1973. The authors proposed seasonal and annual trend for the ratio of global radiation at total cloud amount N okta (G(N)), to global radiation at cloudless sky (G(0)); they carried out a power function wherein coefficients are site dependent.

Both works were based on the estimation of global solar radiation at ground in cloudless sky condition. In the present work the clear-sky irradiance models for standardizing irradiance measurements were investigated to evaluate which give the best approximation for the latitude of Rome using meteorological and solar data recorded by the station of FTA Laboratories of the University of Rome Tor Vergata (41° 51' 28.17'' N, 12° 37'23.9'' E), since April 15th 2009. Those data were associated to hourly cloud human observations recorded in the same site, in order to calculate the ratio of global radiation at the actual total cloud amount N (okta), G(N), over the global radiation at cloudless sky, G(0). The purpose was to find out a model in overcast sky condition for Rome, and verified if it is in agreement with the previous models.

INSTRUMENTS AND EXPERIMENTAL PROCEDURE

FTA Laboratories of the University of Rome Tor Vergata include a meteorological – solar station, located on the rooftop of the building hosting the Department of Enterprise Engineering. Solar instruments consist of one Kipp&Zonen 2AP sun tracker that supports a shaded ventilated pyranometer (CM 21) for diffuse radiation measurements and a pyrheliometer (CH 1)for direct radiation measurements; global and reflected fluxes were measured by two pyranometers (Kipp and Zonen CM 21) mounted on a dedicated plate [6].

Meteorological instruments consist of one MP101A barometer for pressure measurements; one thermoigrometer and relative humidity (RH) measurements. A SKPS810/I barometric pressure sensor was used to measure the local pressure and one ARG100/LX pluviometer to gather and measure the amount of liquid precipitation. Data are collected by a Campbell Scientific CR1000 data logger via RS485. All the facilities are connected to the web and data are downloaded every 30 minutes in a database of a dedicated server.

In the present work only hourly data were use according to clouds observations, performed by human observer in the same site. Meteorological data were used to calculate global radiation at clear sky condition, following two different methods. Duchon and O'Malley [4] model used the formula:

$$G(0)= I_0*\cos\theta*\tau_R*\tau_g*\tau_w*\tau_a \qquad (1)$$

where I_0 is the irradiance at the top of the atmosphere normal to the solar beam; θ_z is the solar zenith angle; and the τ_i's are transmission coefficients for Rayleigh scattering (*R*): permanent gas absorption (*g*), water vapor absorption (*w*), and scattering by aerosols (*a*). A simplified approach proposed by Spena [4], was investigated and shown in Eq. (2):

$$G(0)= I_0* \cos\theta * \tau \qquad (2)$$

where τ is total atmospheric transmission coefficient, as function of the air mass.

Duchon and O'Malley model was developed using a constant value of I_0 of about 1370 W/m^2, instead of Spena [5] model where it was calculated by:

$$I_0=C*\left\{1+0.033*\cos\left[(i-3)*\frac{360}{365.25}\right]\right\} \qquad (3)$$

Where *i* is a progressive day counter.

Figure 1 shows a comparison between both models to evaluate the best behavior for Rome latitude, during a completely cloudless day.

As results Spena's formula give the best approximation and this approach was used for the next computation.

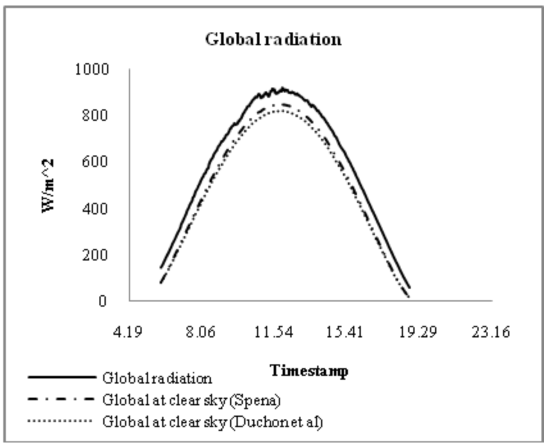


Figure 1. One clear sky day in August 2009: global measured radiation is plotted and compared with calculated function of clear sky model for Duchon and O'Malley and for Spena approach.

Hourly cloud observations were performed from April 15th 2009 to January 31th 2010 using the World Meteorological Organization cloud-type-code at the beginning of each hour on weekdays during most daylight hours. Total cloud amount (N) was evaluated in okta as shown in Table 1:

Table 1. WMO cloud cover classification.

Code figure		
0	0	0
1	1 okta or less, but not zero	1/10 or less, but not zero
2	2 oktas	2/10–3/10
3	3 oktas	4/10
4	4 oktas	5/10
5	5 oktas	6/10
6	6 oktas	7/10–8/10
7	7 oktas or more, but not 8 oktas	9/10 or more, but not 10/10
8	8 oktas	10/10
9	Sky obscured by fog and/or other meteorological phenomena	
/	Cloud cover is indiscernible for reasons other than fog or other meteorological phenomena, or observation is not made.	

The G(N)/G(0) ratio was calculated for each hour where N was estimated and all this values were analyzed in monthly, seasonal and globally range. In the same way the D(N)/G(N) ratio was carried out. For both ratios power and polynomial fitting were achieved, to make a comparison with the previous described models.

RESULTS

As shown in Figure 2, total mean data set trough power and polynomial functions were investigated and their both correlation coefficients were compared. Standard deviation of the recorded data was also shown for each value of N. Therefore, could be evident the higher value of the correlation coefficient related to power function than the polynomial one, but it does not seem to be realistic in a physical way. The comparison with Kasten and Czeplak power function for the ratio G(N)/G(0) was proposed in Figure 2 with polynomial trend and power trend that best approximates Tor Vergata's data. Polynomial trend has a maximum value (1.13) for N=3 (partially overcast) and decrease till 0,6 for N=8 (overcast condition. Power fit starts from 1.1 at N=0 and decrease till 0.3 for N=8. Otherwise the function's trend of Kasten and Czeplak has a maximum value for N=0 (clear sky condition) and decrease till 0,25 for N=8 (overcast condition).

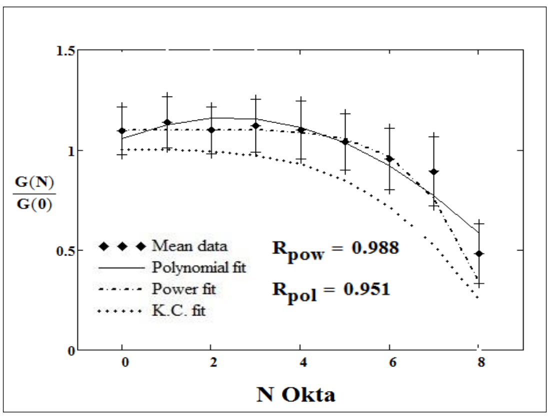


Figure 2. Data trend of global radiation from April 15th 2009 to January 31th 2010 are presented with their standard deviation. Polynomial and power function related to mean data plot are presented. In addition Kasten and Czeplak fit is shown.

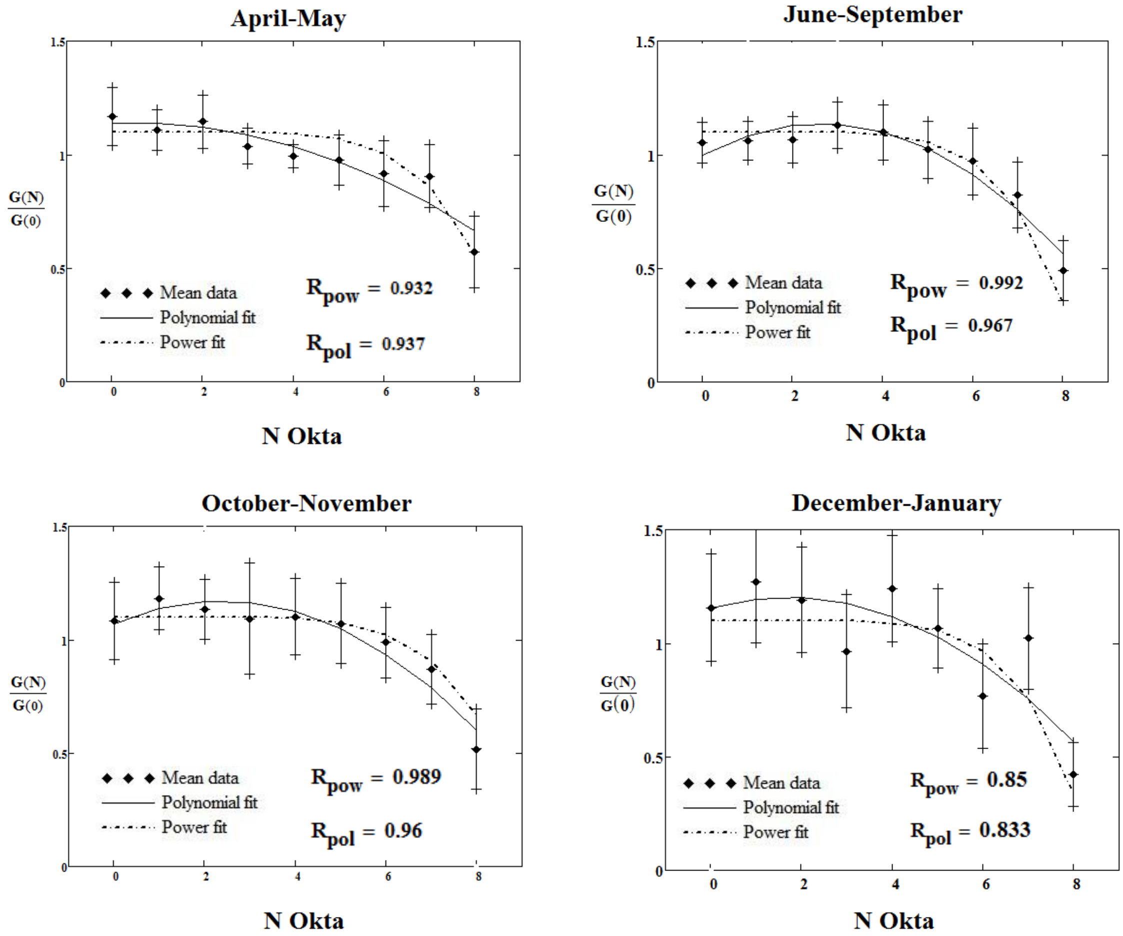
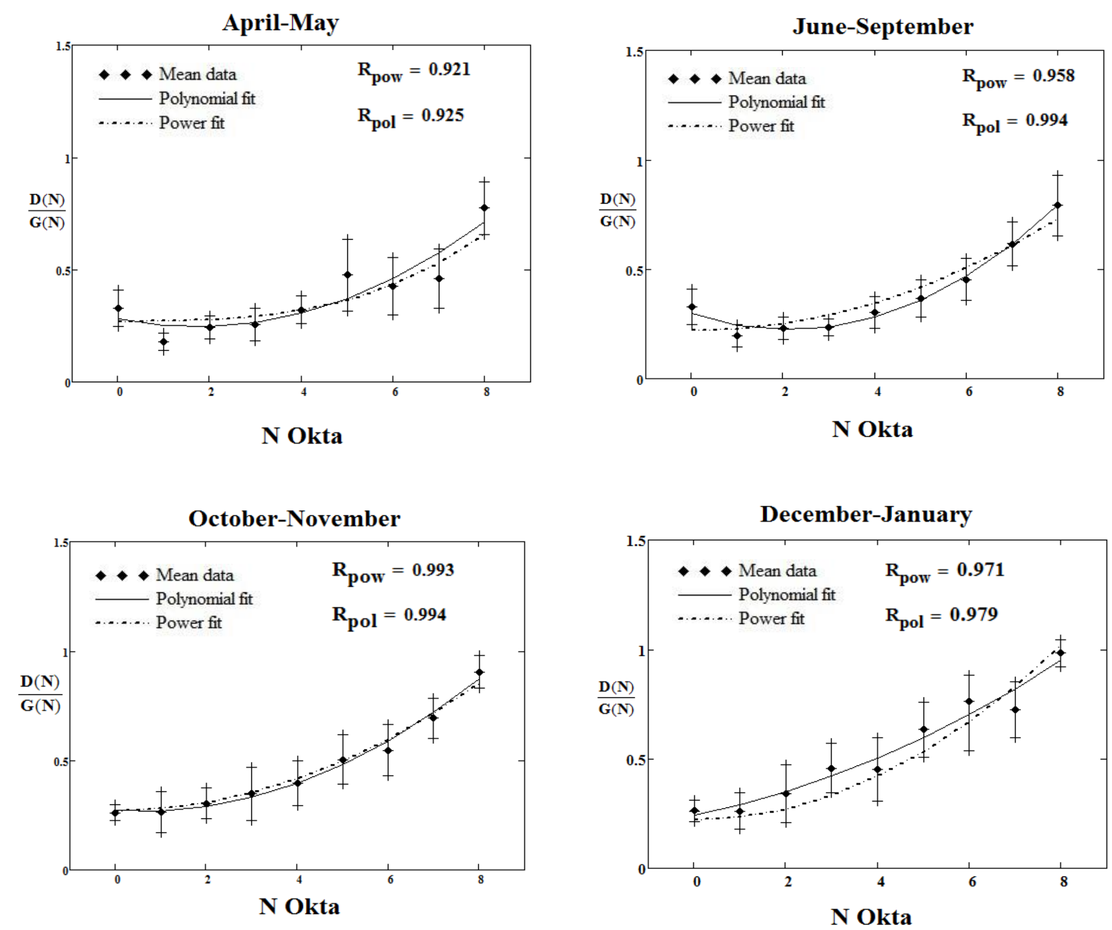


Figure 3. Seasonal data trend are presented with their standard deviation. Polynomial and power functions for global radiation are shown (Up). Figure 4. Seasonal data trend are presented with their standard (Down).



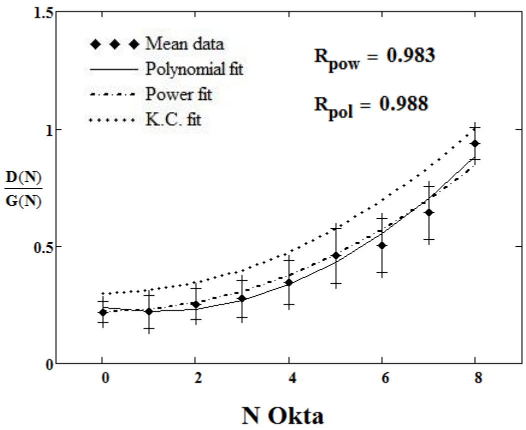


Figure 5. Data trend of diffuse radiation rate from April 15th to January 31th 2010 are presented with their standard deviation. Polynomial and power function related to mean data plot are presented.

Figure 2 shows, in addition, Kasten and Czeplak fit is shown. The different climate and cloudiness prevalence is the cause of this different behavior between Tor Vergata's fit and the function proposed by Kasten and Czeplak:

$$\frac{G(N)}{G(0)} = 1 - 0{,}75 * \left(\frac{N}{8}\right)^{3{,}4} \quad (3)$$

The same type of equation calculated with Tor Vergata's data is proposed as follow:

$$\frac{G(N)}{G(0)} = 1{,}1 - 0{,}757 * \left(\frac{N}{8}\right)^{6} \quad (4)$$

Kasten and Czeplak model is a satisfactory approximation also for Tor Vergata site when the new coefficient are used to fix the mean data as in equation (4): this coefficient are higher than in equation (3) because of the upper solar irradiance in Italy than in Hamburg. Moreover for the latitude of Rome the ratio G(N)/G(0) remained high till $5 \leq N \leq 6$.

In figure 3 seasonal data trends compared with polynomial and power functions are shown in order to specify the different behaviour of solar radiation range available at ground during each season. From April to May 2009 less data than other season were collected and for this reason trend's curve is differ from other trends, as is shown also by correlation coefficients. Instead, from December 2009 to January 2010 data set had a very large range for each value of N, as shown by each deviation standard and for this reason correlation coefficient was lower than others. The physical meaning could be connected to the high variability of climate during the current winter.

In figure 4 are shown the curve of diffuse radiation rate. Also in this case are represented polynomial an power fit in order to make a complete comparison with Kasten and Czeplak work. Correlation coefficient shows that the fit that best approximate Tor Vergata's data is polynomial.

In figure 5 is presented the diffuse rate D(N)/G(N) collected from April 15th 2009 to January 31th 2010 in Tor Vergata's solar station. Again the best approximation is given for polynomial fit. Two consideration were necessaries: during summer time D(N)/G(N) decreases for $1 \leq N \leq 3$ because direct component is strongest than the scattered one. During coldest season the decrease for $1 \leq N \leq 3$ is lower because the scattered is strongest than the direct component.

The comparison with Kasten and Czeplak trend shows, moreover, the overestimation that their formula performs in Mediterranean climate. The equation of the ratio D(N)/G(N) for Hamburg and Rome are proposed below:

$$\frac{D(N)}{G(N)} = 0{,}3 + 0{,}15 * \left(\frac{N}{8}\right)^{2} \quad (5)$$

$$\frac{D(N)}{G(N)} = 0{,}7 + 0{,}65 * \left(\frac{N}{8}\right)^{2} \quad (6)$$

CONCLUSIONS

Satisfactory correlations have been obtained for the site of Rome. Departures from results obtained in different European sites appear due to meaningful climatic reasons. So implemented, the simulation model appears a useful tool for weather predictions.

Polynomial fit trend, as a matter of fact, presented a maximum value for N between 2 and 3 okta and it means that global radiation values grow with the growing of diffuse radiation rate, but only for middle - low cloudiness. This behaviour is known in literature, but often not so extensively with respect to N values: when compared with the classical curves from Kasten and Czeplak [2], the results obtained for Rome show as a matter of evidence a wider platform of high values of G(N)/G(0). For a complete comparison between different climates we propose also another Italian work carried out in Bologna by Nardino and Georgiadis [8].

Table 2. Coefficients of the power function proposed by Kasten and Czeplak, for G(N)/G(0) ratio calculated in three different sites.

G(N)/G(0)	Hamburg	Rome	Bologna
a	-0,75	-0,757	-0,99±0,06
b	3,4	6	1,3±0,1

Table 3. Coefficients of the power function proposed by Kasten and Czeplak, for D(N)/G(N) ratio calculated in two different sites.

D(N)/G(N)	Hamburg	Rome
a	0,3	0,15
b	0,7	0,65

A possible explanation of this fact is attempted in the paper, by means of the role played by the simultaneous effects of either water vapour content of the air (high), and wind speed (low), both at the ground level.

Beside this occurrence gives new information about the relationship between solar radiation and clouds in Mediterranean climate (between the latitudes of 30° and 45°) that is characterized by warm to hot, dry summers and mild, wet winters with moderate temperatures and changeable, rainy weather.

The second order polynomial correlations proposed in this work were representative of Mediterranean climate and high value of standard deviation for winter period are probably dependent on the nature of the observations, made empirically out by the authors, and because of the short time of observation in itself (of the order of 1 year at the time of this paper).

Future develop will enclose the analysis of all others solar radiation component, direct and reflected. Correlation results are going to be usefully enriched with more cloud cover and solar radiation experimental data, and with radiometric spectrum analyses.

NOMENCLATURE

Symbol	Quantity	SI Unit
N	Cloud cover	okta
G(0)	Global radiation in clear sky condition	W/m^2
G(N)	Global radiation calculated for a given N	W/m^2
D(N)	Scattered radiation calculated for a given N	W/m^2
I_0	Irradiance at the top of the atmosphere	W/m^2
τ	Transmission coefficient	non dimensional
θ	zenith angle	rad
R	Correlation coefficient	non dimensional

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