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A simple approach to the synthetic generation of solar irradiance time series with high temporal resolution

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Abstract

Modeling the performance of some concentrating solar systems for thermal power plants may require high temporal resolution irradiance as input, in order to account for the impact of the cloud transient effects. This work proposes a simple method of generating synthetic irradiance of 10-min intervals from the hourly mean values. Boundary conditions are imposed to preserve the expected behavior under clear sky situations. The procedure consists basically on adding a random fluctuation, which characteristic amplitude depends on the sky conditions, to the hourly interpolated values. The assessment of the method with ground data have shown to main aspects to remark: daily and monthly means from the synthetic data are below 5% of root mean squared deviation compared to the original time series; despite the noticeable uncertainty in the 10-min synthetic irradiance values, the dynamic behavior of the fluctuations is comparable to the original data.

Keywords: Solar radiation models; Synthetic data; Cloud transients

1. Introduction

The availability of solar irradiance time series at a given point of the Earth's surface is of major interest in many scientific and technology applications. In particular, electrical generation by solar energy needs detailed site-specific irradiance data for designing or modeling systems and/or plant performance.

The requirements in terms of temporal resolution (monthly means, daily, hourly or sub-hourly values) and accuracy depend strongly on the technology and on the final purpose of the modeling, as well as on the availability of data.Time series of solar irradiance for systems and electrical plant analyses usually come from ground measurements or they can be frequently derived from satellite images. However, there would be situations that force to the use of mathematically or synthetically generated time series, that employ stochastic methods (Markov chains or autoregressive models) and Fourier analysis for constructing a synthetic time series of irradiance data. These kinds of methods try to fill gaps between generally available data resources and the parameters requested by solar applications. Meteonorm, for instance, is one of the most well-known and widely used tool for mathematically generated time series (Remund and Page, 2002; Remund, 2008). On the synthetic generation of solar radiation data it should be remarked the method based upon Markov chain for generating daily global irradiation from monthly means (Aguiar et al., 1988) and the TAG (Time-dependent Autoregressive Gaussian) method of generation of hourly global irradiance from daily values (Aguiar and Collares-Pereira, 1992), as well as the work of Boland with autoregressive and Fourier based methods (Boland, 1995, 2008).

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Electrical generation by solar thermal electric power systems is directly proportional to the available direct normal irradiance. Historical solar resource data are frequently available for hourly values; this is the case of data included in typical meteorological years (TMY) or in many widely used models concerning solar irradiance derived from satellite information. Hourly time resolution could be unsatisfactory in simulating transient processes in the power plant, which may have some influence on energy fields (Meyer et al., 2009). Moreover, some proposed technologies for concentrated solar thermal power plants like the parabolic trough collector loops with direct steam generation could be particularly sensitive to the cloud transients (Eck and Hirsch, 2007; Montes et al., 2009), so that plant performance analysis would require direct normal irradiance of high temporal resolution (10-min time intervals for example).

This paper presents a quite simple method for generating synthetic solar irradiance time series at 10-min intervals from hourly values of global horizontal and direct normal irradiance. Two main boundary conditions have been imposed to the presented method: the overall potential of the solar resource should remains reasonably constant and the dynamics of the fluctuations should be coherent with the state of the sky. The former indicates that the daily sums and monthly means of the new generated solar irradiance series should be absolutely comparable to those calculated from the input hourly values. The later refers that the frequency and the amplitude of the irradiance fluctuations generated synthetically should be statistically representative of the actual conditions and should vary according to how much cloudy or clearly the sky is, e.g. the distribution functions of the original 10-min and those generated from the hourly means should be comparable. The proposed method has been developed using ground measurements at six locations in Spain during 2008 and 2009.

2. Data used

Measurements every 10 min of the three solar radiation components at six places in Spain during 2008 and 2009 have been used in this work. The stations are equipped with pyranometer and pyrheliometer sensors of high precision and a two axis solar tracker system. The measurements were checked in quality according to the methodology established in the MESoR project (Hoyer-Klick et al., 2009) and in the Task 36 IEA/SHC (http://project.mesor.net/web/guest/home), that are based upon the BSRN recommendations (McArthur, 1998).

3. Analysis of the variability of the irradiance data

The variability of the irradiance data is studied by analyzing the probabilistic density distribution of the standard deviation of 10-min irradiance data within every hour, for both global horizontal and direct normal irradiances. In order to do this different sky conditions have been identified according to the values of the normalized clearness index. The normalized clearness index, *kt'*, is a zenith angle-independent expression of the clearness given by the following expression (Perez et al., 1990),

$$Kt' = \frac{kt}{1.031\ \exp[\frac{-1.4}{0.9+9.4/m}] + 0.1} \tag{1}$$

where the denominator of the quotient is the well-known pyheliometric formula of Kasten (Kasten, 1980), being m the relative air mass.

The analysis of the normalized standard deviation of 10-min global horizontal irradiance and direct normal irradiance has shown dependence with the normalized clearness index. The sky conditions have been divided into four stages, from cloudy to clear sky, according to the values of the normalized clearness index: $0 < kt' \leqslant 0.35$, $0.35 < kt' \leqslant 0.50$, $0.50 < kt' \leqslant 0.65$, and $kt' \geqslant 0.65$. The procedure to make this analysis was to compute, from the ground data, the standard deviation of the 10-min irradiance data with respect to the hourly mean generating thus a time series of standard deviations. The two time series of standard deviations, one for global horizontal and one for direct normal irradiance were normalized by diving by their maximum values, to impose them to be constrained to the (0, 1) interval. The two time series were then distributed into four groups according to the normalized clearness index stages. For each group the pdf was computed and fitted to a beta distribution, whose probability density function is defined as (Press et al., 1998),

$$\begin{aligned} f(x|a,b) &= \tfrac{1}{B(a,b)} x^{a-1}(1-x)^{b-1} \\ B(a,b) &= \int_0^1 t^{a-1}(1-t)^{b-1}dt \end{aligned} \tag{2}$$

Figs. 1 and 2 show the pdf of the normalized standard deviations for the four sky conditions and their corresponding pdf of the beta distributions fitted for global horizontal and direct normal irradiance, respectively. Table 1 shows the characteristic parameters of the beta function, a and b, resulted from the fitting process for each component of the solar irradiance and each sky stage.

5. Methodology for the synthetic generation

The methodology for generating 10-min synthetic irradiance from a given hourly time series consists basically of two contributions to be added: the contribution from the hourly mean and the stochastic fluctuation from the mean. The former can be computed from the cubic interpolation of the hourly means in the 10-min time scale, allowing thus to incorporate in the time series a proper envelope or shape. The stochastic fluctuations are incorporated by the following procedure:

1. Generate numbers from the beta distribution with the parameters specified according to the sky stage and solar radiation component from Table 1, yielding thus to normalized standard deviation values which are beta

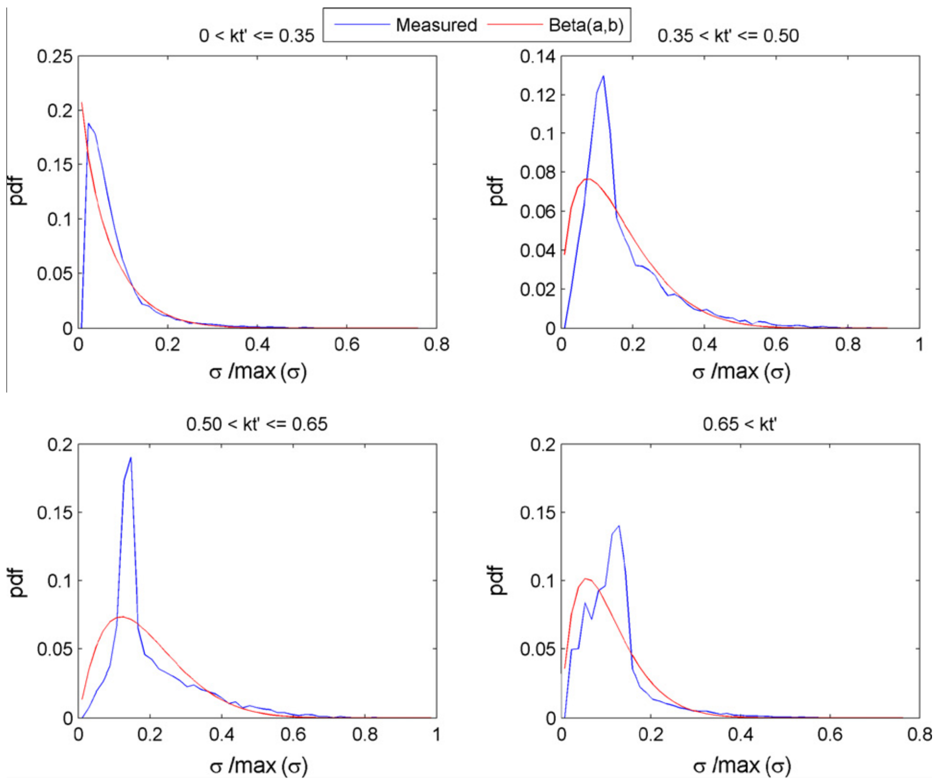

Fig. 1. Pdf of the normalized standard deviation of 10-min global horizontal irradiance and their corresponding beta distribution for each stage of the normalized clearness index.

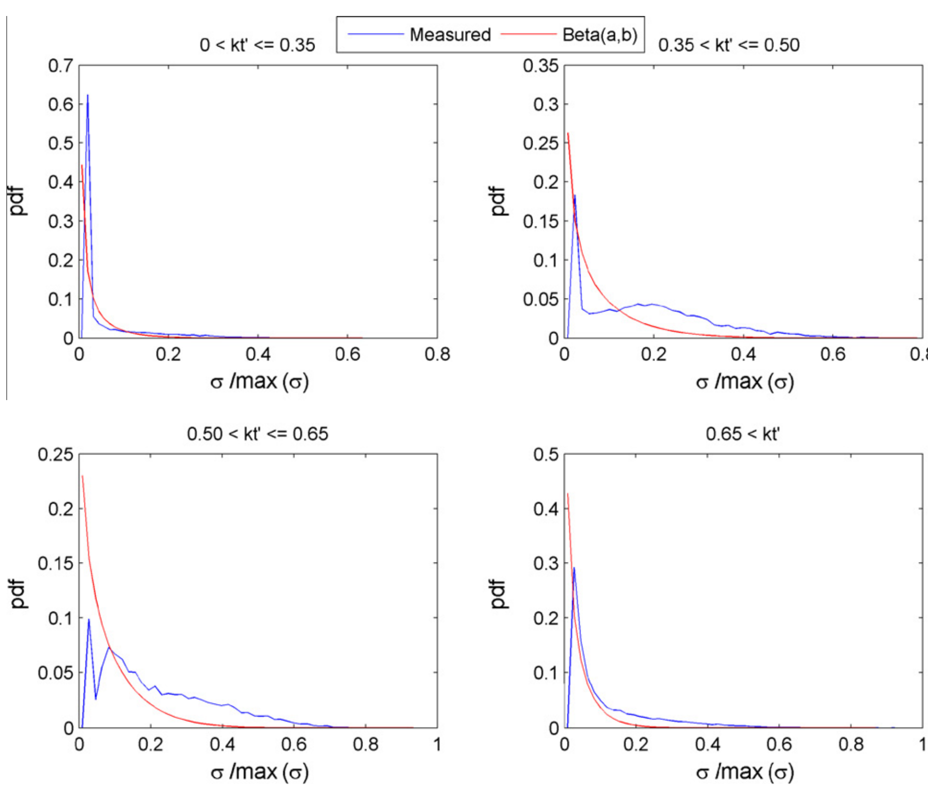

Fig. 2. Pdf of the normalized standard deviation of 10-min direct normal irradiance and their corresponding beta distribution for each stage of the normalized clearness index.

Table 1
Characteristic parameters of Beta distribution at different sky conditions.

	Global horizontal		Direct normal	
	a	*b*	*a*	*b*
$0 < kt' \leqslant 0.35$	0.91	12.85	0.28	5.44
$0.35 < kt' \leqslant 0.50$	1.59	8.45	0.60	3.18
$0.50 < kt' \leqslant 0.65$	2.09	8.91	0.77	3.30
$0.65 < kt'$	1.92	16.34	0.58	5.31

distributed with parameters a and b. This values can be obtained by first selecting random numbers form a Uniform distribution on [0, 1], and then finding the inverse beta value corresponding to that probability.

2. Multiply the normalized standard deviation randomly generated from the beta distribution by the maximum value of the standard deviation founded in the previous analyses to obtain the amplitude A of the fluctuation.

3. Generate a random sign to randomly add or subtract the Amplitude to the mean value. This parameter can be obtained by taken the sign of r, being r a random number normally distributed with zero mean and unit standard deviation.Mathematically the expression of the irradiance for the time instant i (in 10-min units) can be formulated as,

$$I_{10m}^{i} = I_{h}^{i} + \mathrm{sign}(r)A \tag{3}$$

where the subscript represents the time scale (*10m* for 10-min and h for hourly), I_h^i is the cubic interpolated value of the hourly irradiance for the time instant i, r is a random number from a normal distribution with zero mean and unit standard deviation, and A is the amplitude of the irradiance fluctuation in W m^{-2}.

The Boundary condition of zero amplitude for clear sky conditions is imposed to the method based on Eq. (3) to preserve the expected behavior under clear sky conditions.

Table 2
MBD and RMSD of the 10-min synthetic irradiance data compared to ground measurements.

	Global horizontal	Direct normal
MBD (W m^{-2})	−10 (−3%)	1.1 (0.3%)
RMSD (W m^{-2})	87 (25%)	116 (31%)

Daily clear sky situations are selected by using a methodology proposed by the authors in a previous work (Polo et al., 2009), consisting of the analysis, for the whole day, of the correlation coefficients between the global horizontal hourly irradiance to be checked and the global horizontal hourly values computed with a clear sky transmittance model. Under clear sky conditions for the whole day the 10-min irradiance values are generated by simply cubic interpolation of the hourly values. However, this method for selecting clear sky conditions is valid only when clear sky remains during the whole day. There are many situations in which partial clear sky conditions are found during some hours, and the selecting method do not work. In order to avoid the generation of fluctuations in such situations the condition of zero amplitude for kt' beyond 0.75 has been imposed.

Finally, two other conditions are imposed to avoid that the generated data yield values beyond the physical limits. On the one hand, all the irradiance values during night time are fixed to cero, and during daytime a minimum possible value of zero is also imposed to both global horizontal and direct normal. On the other hand, an upper bound limit to the global horizontal and direct normal irradiances estimated for a pure dry Rayleigh atmosphere is set for all the generated data. The global horizontal and direct normal irradiances for a pure dry Rayleigh atmosphere were estimated with the ESRA transmittance model with a Linke turbidity factor of unity (Rigollier et al., 2000).

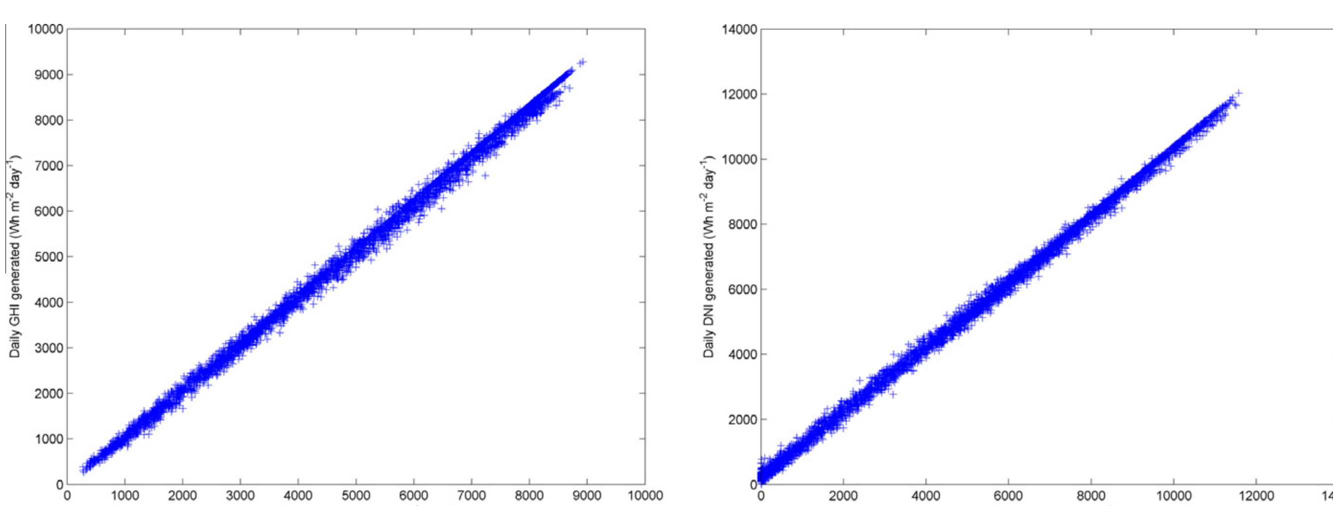

Fig. 3. Scatter plot of the daily irradiation data from the generated time series compared to those obtained from ground measurements: Global horizontal irradiation on the left, direct normal irradiation on the right.

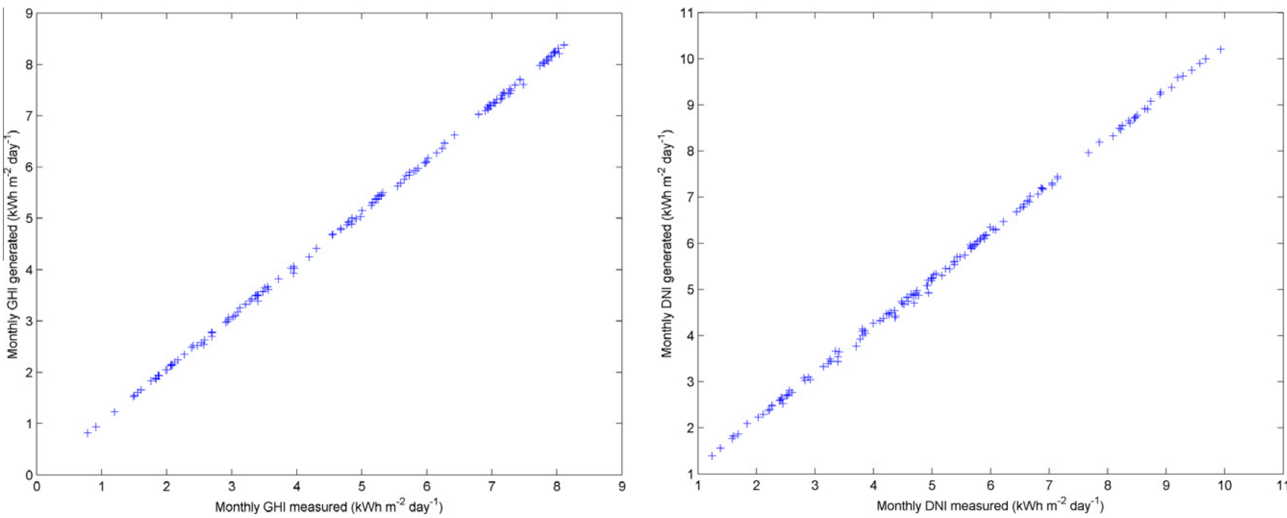

Fig. 4. Scatter plot of the monthly means from the generated time series compared to those obtained from ground measurements: Global horizontal irradiation on the left, direct normal irradiation on the right.

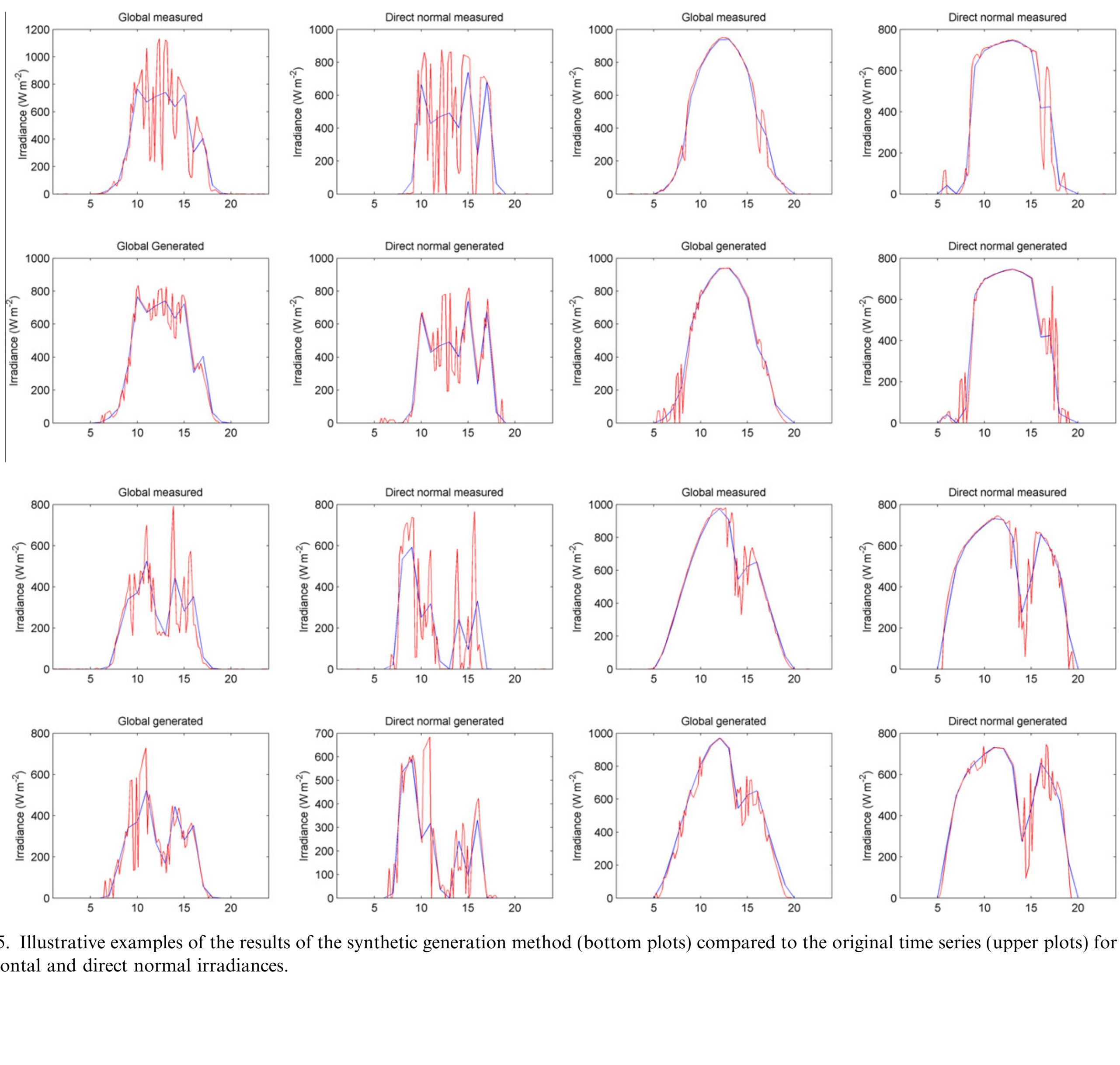

Fig. 5. Illustrative examples of the results of the synthetic generation method (bottom plots) compared to the original time series (upper plots) for global horizontal and direct normal irradiances.

6. Assessment

The assessment of a method for generating data synthetically should not be made in terms of how accurate the method is able to reproduce the original ground data point by point, since that is not the purpose of synthetic data generation. Nevertheless, it can be illustrative to make a traditional assessment exercise with the ground data in terms of Root Mean Squared Deviation (RMSD) and Mean Bias deviation (MBD).

Using the ground data of global horizontal and direct normal 10-min irradiance of the 12 years available (over 500,000 data points), the hourly means have been computed and the synthetic generation method above described has been used for generating again 10-min global horizontal and direct normal irradiance time series. Table 2 shows the RMSD and MBD of the new synthetically generated global and direct irradiance. As expected, since the proposed method is based on fluctuations randomly generated, the uncertainty in the 10-min irradiance data is noticeable.

The main purpose of the method for synthetic generation of 10-min irradiance is to generate data statistically representative, with physical meaning and preserving, as much as possible, the total energy. These constrains mean that the solar resource energy, characterized by the monthly means and by the daily sum should remain fairly constant when are compared to the same quantities obtained from the original time series. In addition, despite the 10-min data are not intended to be strictly reproduced point by point, the dynamics of the fluctuations should be comparable in the original and synthetic time series. Figs. 3 and 4 show the scatter plot of the daily global and direct irradiation and of the monthly means, respectively. Both figures exhibit a highly degree of correlation and the RMSD for daily sums and monthly means are around 2–4% for both global horizontal and direct normal irradiation. Finally, in the case of the hourly means the RMSD of those computed from the synthetic irradiance data compared to the hourly means from the original time series is 15% for both global horizontal and direct normal irradiance.

The goodness of the method in reproducing the irradiance fluctuations is qualitatively illustrated by Fig. 5, where some examples of the daily profiles of 10-min irradiance measured and generated synthetically are shown for some different sky conditions. The method is able to preserve the expected behavior under complete and partial clear sky conditions. The dynamic behavior of the 10-min irradiance data generated by the method is comparable to the original time series. Higher fluctuations both in frequency and amplitude are generated for partial overcast sky conditions. Despite the method results in partial overcast conditions do not fit accurately to the original values, the overall dynamic behavior is coherent with what is observed in the measurements. The cumulative distribution functions of the 10-min irradiance original data and the generated ones are quite comparable for both global horizontal and direct normal irradiances (Fig. 6).

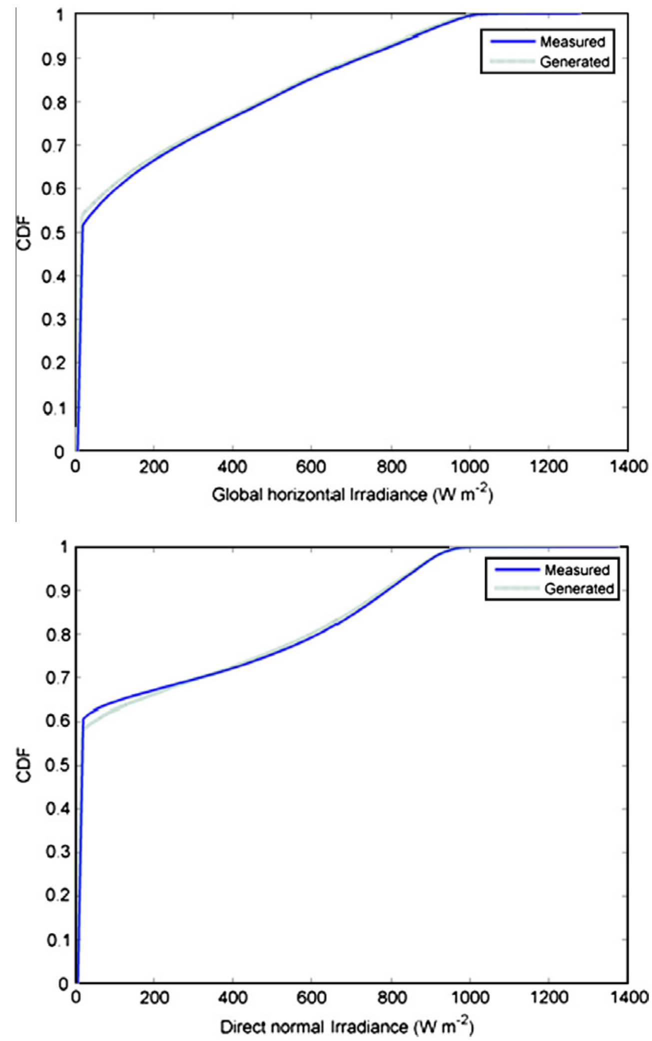

Fig. 6. Comparison of the cumulative distribution functions of original and generated 10-min irradiance data.

7. Conclusions

The work presented here proposed a quite simple procedure to generate synthetic global horizontal and direct normal irradiance of 10-min time intervals taken as input the hourly mean values. Analysis of 12 years of ground measurements through six Spanish locations has been performed to identify the characteristic amplitudes of the irradiance fluctuations within every hour according to four sky categories which are determined by the values of the normalized clearness index and the solar elevation angle in radians. The procedure for generating synthetic irradiance data assumes that the fluctuations due to cloud transients are stochastic and hence they can be dynamically reproduce using random numbers from beta distribution function whose characteristic parameters have been fitted to the original pdfs at each sky category. A main boundary condition of amplitude zero for clear sky situations (complete and partial clear skies) has been imposed to the method.

The assessment of the 10-min irradiance generated has shown important uncertainties when they are compared point by point with the ground measured values. However, synthetic generation of data is not intended to fit the exact values but to reproduce the main characteristics of the time series. In this sense, the methodology presented here has proven to acceptability preserve the energy content of the irradiance (daily and monthly means computed from the synthetic series were below 5% of RMSD). In addition, the method generates irradiance data that are comparable in their dynamic behavior and in their probabilistic functions to the original data measured. Thus, clear sky situations are preserved without fluctuations of the irradiance, conditions close to clear sky exhibit small fluctuations, and fluctuations with high amplitude and frequency occurs in variable sky conditions.

Therefore, despite the uncertainties of this procedure in the 10-min global horizontal and direct normal irradiance, the incorporation of a dynamic behavior with physical meaning can give usefulness to the method for modeling purpose to explore processes where the cloud transient effects could have an important impact in the performance.

Finally, the method proposed here is quite simple, easy to be implemented and rapid in computational time. Nevertheless, new approaches and studies are planned to be performed soon in other to explore better solutions to the problem.

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