

***Interactive comment on “Topographic effects on solar radiation distribution in mountainous watersheds and their influence on reference evapotranspiration estimates at watershed scale” by C. Aguilar et al.***

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Received and published: 10 June 2010

We would like to acknowledge the review of anonymous referee 3. We have corrected some spelling and editing mistakes, added some paragraphs in order to better explain certain statements or assumptions, and we have included some references into the text (please find attached the modified text as well as figures 5 and 7). Answers to the review comments are given below, where the original reviewer's comments are highlighted in quotation marks.

C1107

"1. The main task of this study is to quantify the effects of surface slope and orientation on solar radiation on instantaneous, hourly and daily scales. Hence, the introduction section is not good enough as it did not give a clear description about the studies on the methods and algorithms from the references. As a consequence, the innovation of the manuscript is not easy to stand out."

The need to simulate dry periods in arid and semi-arid locations with distributed hydrological models determines the importance to properly interpolate solar radiation, as it constitutes the main forcing to the system. But the interpolation procedure must be cautious as topography strongly affects this variable. The main objective of the study is not to quantify per se the effect of topography on solar radiation but to quantify such effects on the water losses through evapotranspiration estimates, especially in mountainous watersheds as stated in the abstract section (lines 10-11) as well as in the introduction section (lines 2-3 in page 2379 in the original text). The formulation of new relations for the partition of the different components of solar radiation was not the objective of this study. Neither was it the development of new methodologies for the topographic correction. This is why just references and short comments to previous research in this matter are provided (e.g. pages 2376 and 2377 in the original text). However, despite the numerous studies concerning spatial and temporal interpolation of solar radiation, common GIS-based hydrological models do not include these approaches (page 2378 in the original text). Instead, they apply simple corrections which when there is lack of meteorological stations, quite common in numerous locations all over the world, but also in very rough terrain, can lead to considerable over or underestimations in the water and energy balance. Therefore, the main contribution of this study is to couple the different algorithms available in the literature that can be applied with conventional measurements in large areas in order to incorporate topographically interpolated solar radiation surfaces in hydrological modelling. Thus, the use of topographically interpolated solar radiation surfaces for the calculation of evapotranspiration surfaces, addresses the hydrologic importance of using topographically corrected solar radiation fields.

C1108

In order to make it clearer the paragraph with the objectives of the study have been rewritten as below (line 15 in page 5 in the revised text): The aim of this study is to address the importance of incorporating in hydrological models the effects of topography on the spatial distribution of global solar radiation at watershed scale. To this purpose, different topographic algorithms have been coupled in order to estimate series of distributed solar radiation values and calculations have been made to quantify such influence on evapotranspiration estimates in mountainous areas in Mediterranean locations. Thus, an algorithm was derived from Dozier (1980) and Jacovides et al. (1996) to take into account the lack of meteorological stations at high altitudes. To be exact, it should estimate hourly global values as well as the separation between its beam and diffuse components from the common measurements obtained on horizontal surfaces. The resulting algorithm was implemented on a GIS-based routine and applied to data from a mountainous watershed on the south coast of Spain. The distributed results were compared to those obtained from simpler interpolating methods and experimental data. Finally, in order to address the hydrologic importance of using topographically corrected solar radiation fields over uniform values, a simple evaluation in terms of their influence in the computation of reference evapotranspiration fields is carried out.

"2. The method employed in this study (equations in section 2.2 and 2.3) comes from the references, and the references are quite old. It weakened the substantial contribution of the manuscript to the scientific community."

As it has been said in the previous reply, the development of new algorithms was not the main purpose of this study. Instead, it is the coupling of the different methodologies available in the literature for each step of the interpolation process. We must admit that these algorithms are old, but these are the methods that up to now are working reasonably well in large areas, regions with a considerable lack of data registering sites or when available, registering the usual data at the conventional temporal scales (daily global radiation). Therefore, different recent studies which are already cited as well in both sections 2.2 and 2.3 (Zaksek et al. 2005; Allen et al., 2006; Tasumi et al.,

C1109

2006) are based on the same references. Moreover, as recently stated by Essery and Marks (2007), efficient algorithms (Dozier and Frew, 1990) for the simulation of solar radiation over large grids became possible with the availability of gridded elevation data sets and powerful computers and, even though since then many models for calculating distributions of solar radiation over topographic grids have been developed, all of them implement the same basic geometric principles.

Thus, the following new paragraph was inserted in section 2.3 (line 4 in page 10 in the revised text): According to Essery and Marks (2007), even though since the availability of gridded data and powerful computers many efficient algorithms for calculating distributions of solar radiation over topographic grids have been developed, all of them implement the same basic geometric principles. Thus, the calculation of horizons in this study was made following the modification to the method by Dozier (1980), made more computationally efficient by Dozier et al., (1981) and Dozier and Frew (1990).

"3. Page 2376, line 11 to 13, "At the local scale . . . and surface geometry". Atmosphere conditions (aerosol, water vapor) are also important to solar radiation."

We agree with the reviewer. The final sentence is as follows (line 11 in page 3 in the revised text): "At the local scale, the amount of solar radiation reaching a given location is called global solar radiation and it depends mainly on the cloud cover, the turbidity of the clean air, the time of the year, latitude, and surface geometry (Iqbal, 1983; Essery and Marks, 2007)."

"4. Page 2380, line 25 to 26, there should be one more term in global radiation, i.e., the contribution of multi-scattering between land surface and atmosphere. It should not be ignored especially for bright surfaces such as snow cover and ice."

This comment is definitely true. However, for hydrological modelling in large areas, the inclusion of multi-scattering would add too much complexity to the algorithms, considering the usual lack of data in most watersheds for an accurate characterization of this term. A simplification is assumed and therefore global radiation is considered as the

C1110

sum of just direct, diffuse and reflected radiation, which on the other hand is implicitly assumed in the daily partition between direct and diffuse fractions since the available relationships are derived from aggregated measurements of diffuse and multiscattered fluxes.

"5. Page 2382, line 17 to 19, "the hourly values: : :during the day." You should give references here."

This is an assumption that we had to make due to the lack of data in the spatial interpolation process. The application of hourly relations between hourly CI and hourly diffuse radiation values was initially considered following previous work in the literature (Orgill and Hollands, 1977; Bugler, 1977; Erbs et al., 1982). However, the aim of this work was to provide a feasible method to include topographic effects on radiation at watershed scale, and the size and heterogeneity of the study site together with the lack of meteorological stations, which unfortunately are usual circumstances in many locations, make it unreasonable to spatially interpolate hourly CI values as the spatial distribution of diffuse and direct radiation shows a better correlation at a daily scale. Then, for the temporal downscaling of the variable we took as a first approximation the hourly behaviour of extraterrestrial radiation as we assume that four stations in the watershed are not able to provide a reliable framework for the spatial distribution of hourly values in the whole area. This argument has been included in the text in order to support such assumption and so the paragraph remains as follows (line 16 in page 8 in the revised version): The application of hourly relations between hourly CI and hourly diffuse radiation values was initially considered following previous work in the literature (Orgill and Hollands, 1977; Bugler, 1977; Erbs et al., 1982). However, the aim of this work was to provide a feasible method to include topographic effects on radiation at watershed scale, and the size and heterogeneity of the study site together with the lack of meteorological stations, which unfortunately are usual circumstances in many locations, make it unreasonable to spatially interpolate hourly CI values as the spatial distribution of diffuse and direct radiation shows a better correlation at a daily

C1111

scale. Besides, the application of hourly correlations would require the availability of some other variables such as solar altitude or air mass (González and Calbó, 1999). However, as pointed out by Zaksek et al. (2005), the use of more sophisticated models depends on the scale and purpose of the study, so that under certain circumstances it would be better to use a less complex model. Thus, a simpler approach is proposed so that once the daily values of each component are obtained for each cell, the hourly values ( $r_b$  and  $r_d$ ), are computed by distributing the daily amounts along the day following the temporal pattern of extraterrestrial hourly radiation during the day. The hourly values of beam and diffuse radiation on horizontal surfaces can then be transposed to give hourly radiation on tilted surfaces, since hourly methods of computing radiation on inclined planes, when available, should give slightly more accurate results than those obtained by the daily methods (Iqbal, 1978).

"6. Suitability of the method at different temporal scales should be addressed with more results and discussions."

Even though we consider that the results address the aims of the study, the reviewer poses an interesting challenge and so the following paragraph has been included in the results section (line 12 in page 17 in the revised text): To conclude, the accuracy of predicted hourly values was assessed in station 802, where measurements at this time scale were available. Despite the scattering effect observed in Fig. 7, which shows the agreement between predicted ( $r_{gp}$ ) and measured ( $r_{go}$ ) hourly values for the evaluation period, we can say that the algorithm reasonably predicts the observed data with a  $R^2$  of 0.83, especially considering the time scale and some of the assumptions of the algorithm which at this time step might appear rather simplistic. In this way, the installation of a denser monitoring network provided with solar devices recording hourly direct and diffuse radiation data may improve the results. Firstly, it would provide the spatial scheme required for the spatial interpolation of hourly values. Secondly, it would allow including more factors for the spatial distribution of the CI as previously suggested. Finally, the derivation of hourly correlations between the hourly diffuse ra-

C1112

diation and the CI would be reasonable in the study area. To sum up, the possibility to work at finer scales would be the ideal as the geometrical relationships involved in the calculation of extraterrestrial radiation are continuous in time. However, independently of this continuous nature of extraterrestrial radiation, the time scale of the computation of the incoming solar radiation is determined by the temporal frequency of the monitoring network. Nevertheless, the calculations with aggregated hourly values at higher temporal scales such as the daily time step showed the same degree of detail that at hourly time scale (R2 around 0.8).

Specific comments:

"1. Page 2379, line 4, "puspose" should be "purpose"?"

Thank you very much for this correction. Even though the paragraph has been rewritten the same we use again the same word and so, the spelling error has already been corrected (line 17 in page 5 in the revised text).

"2. Page 2387, line 19, "sensible heat flux" should be "soil heat flux"."

We acknowledge this suggestion and so the term "sensible heat flux" has been replaced by "soil heat flux" (line 5 in page 13 in the revised text).

"3. Equation (14) is not correct."

We fully agree with the reviewer as it should be the difference between incident long-wave radiation and outgoing longwave radiation, and so in this latter term the Stefan Boltzmann's law applies with the emissivity and the temperature of the soil. However, the common lack of measurements not only in terms of density of meteorological stations but also in terms of the registered variables (e.g. soil temperature) calls for simplifications to the original physical equations. This is the reason why, for the application of reference evapotranspiration equations, numerous authors show alternatives for certain meteorological variables when no measured data are available, in this case net longwave radiation (e.g. Doorenbos and Pruitt, 1977; Allen, 1986, Wang

C1113

and Georgakakos, 2007; Blonquist et al., 2010; etc.). Because at broad scales the soil temperature is not commonly available, most of these equations apply a modification to Stefan-Boltzmann's law due to the absorption and downward radiation from the sky. Thus, the product of the Stefan-Boltzmann's constant times the fourth power to the mean air temperature is modified with a cloudiness factor and an air humidity factor (Allen et al., 1998; Donatelli et al., 2006). In our study both factors are included in the term emissivity of the atmosphere following the expression obtained in Herrero et al. (2009) and so, together with the mean air temperature constitute the only inputs to the equation. Following the reviewer's comment, further explanation has been included. In this way, equation 14 has been replaced (line 4 in page 14 in the revised text) and the paragraph describing such equation has been rewritten (line 12 in page 13 in the revised text):

In the same way, the net long-wave radiation was calculated by Eq. (14) where  $\varepsilon_{atm}$  and  $\varepsilon_{sup}$  are the atmospheric and surface emissivity respectively, T (K) the mean air temperature,  $T_{sup}$  (K) the temperature of the soil surface and  $\sigma$  Stefan-Boltzmann's constant ( $4.903 \times 10^{-9}$  MJ/K<sup>4</sup>m<sup>2</sup>day). The atmospheric emissivity was calculated through a parametric expression by Herrero et al. (2009) based on near-surface measurements of solar radiation and relative humidity, valid for the local conditions of the study area. As  $\varepsilon_{sup}$  ranges from 0.985 in cotton crops to 0.94 in bare soil (Stefano and Ferro, 1997), a constant value of 1 was assumed. Besides, as soil temperature is not commonly available at broad scales it is assumed to be equal to the temperature of the air, and so the expression for net long-wave radiation remains as previously done by other authors (Doorenbos and Pruitt, 1977; Allen, 1986; Allen, 1998) as a modification to Stefan-Boltzmann's law due to the absorption and downward radiation from the sky. Thus, the product of the Stefan-Boltzmann's constant times the fourth power to the mean air temperature is modified with a cloudiness factor and an air humidity factor (Allen et al., 1998; Donatelli et al., 2006), both factors included in this study in the term  $\varepsilon_{atm}$  and so, together with the mean air temperature constitute the only inputs to the equation.

C1114

"4. RMSE should be shown in Fig. 5 and 7."

We acknowledge this suggestion. Both values have been incorporated and give more information regarding the degree of adjustment between observed and predicted values by the model at both temporal scales.

"5. In the caption of Fig. 6, the second Rgo should be Rgp."

We have solved this mistake and so caption of Fig. 6 remains as follows (page 33 in the revised text): Fig. 6. Extraterrestrial solar radiation ( $R_o$ ), observed ( $R_{go}$ ), and predicted ( $R_{gp}$ ) global radiation ( $MJ/m^2/day$ ) at station 802 for the evaluation period (4 November 2004 – 29 April 2007).

"6. Page 2385, line 7, label  $\phi$  has been used to represent latitude in page 2381, you should use another label for this term."

As the term latitude only appears in page 2381 (line 25 in page 7 in the revised text) and in equation 8, we have changed this symbol from  $\Phi$  to  $\phi_L$ :

"7. In equation (10), you should use another label for  $\phi$ ."

We keep equation as is as the symbol for latitude has already been changed after the previous comment.

#### References

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C1115

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Please also note the supplement to this comment:

<http://www.hydrol-earth-syst-sci-discuss.net/7/C1107/2010/hessd-7-C1107-2010-supplement.zip>

Interactive comment on *Hydrol. Earth Syst. Sci. Discuss.*, 7, 2373, 2010.

C1116

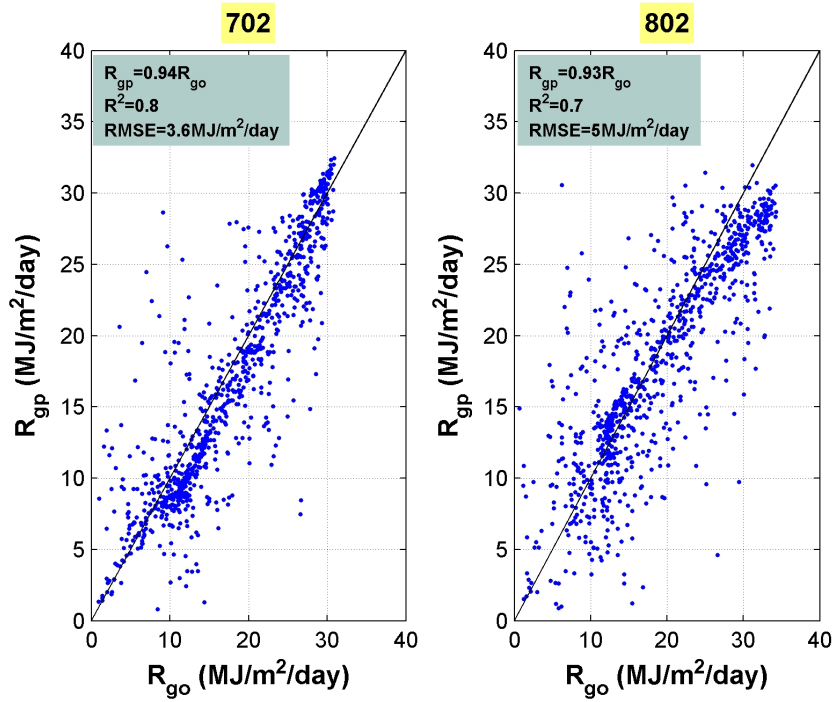


Fig. 1.

C1117

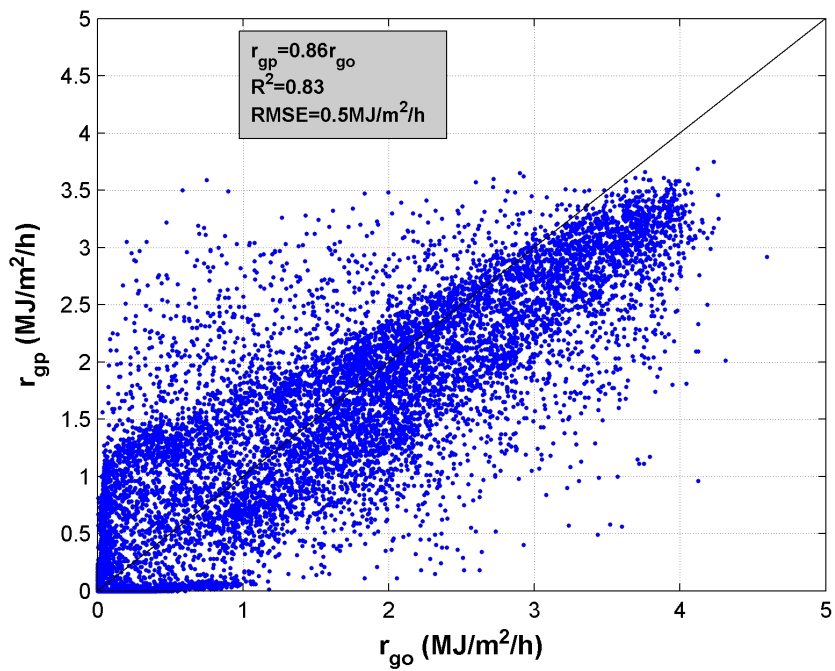


Fig. 2.

C1118