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A single method to estimate the daily global solar radiation from monthly data

A. Manzano [a], M.L. Martín [b,*], F. Valero [a], C. Armenta [c]

[a] Dpto. Astrofísica y Física de la Atmósfera, Facultad de Física, Universidad Complutense de Madrid, Ciudad Universitaria s/n., 28040 Madrid, Spain
[b] Dpto. Matemática Aplicada. E. de Informática, Universidad de Valladolid, Pza. Alto de los Leones, 1., 40005 Segovia, Spain
[c] Dpto. Física Atómica, Molecular y Nuclear, Universidad Complutense de Madrid, Ciudad Universitaria s/n., 28040 Madrid, Spain

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ABSTRACT

The performance of Ångström–Prescott (A–P) linear equation to estimate global solar radiation on a horizontal surface at daily and monthly mean daily time bases over Spain is studied. The pretty good performance obtained for both time bases ensures a fast first estimation of the global solar radiation. Here, new sets of A–P coefficient values over Spain for the selected stations are provided. Moreover, the impact of both time bases on the A–P performance is analysed concluding that the A–P obtained coefficients can be permutated between daily and monthly mean daily time bases. Therefore, the monthly mean daily (daily) calibrated A–P coefficients can be directly applied for estimating the global solar radiation using daily (monthly mean daily) data. In order to test the validity of the A–P model coefficients' permutability for estimating global solar radiation over Spain, the performance of the permutated A–P model has been compared with that of other sunshine hour-based models (polynomic, exponential, logarithmic, regional and global A–P calibration and latitudinal dependent models). According to the results, the permutated A–P linear expression can be selected to estimate the solar radiation instead of the remainder models. The obtained results also remark the importance of the local calibration on the accuracy of global solar radiation estimation instead of using a single pair of coefficients for the whole domain.

1. Introduction

Solar radiation is the main renewable energy source supporting the biosphere and stimulating the chemical, physical and biological processes in the Earth. The solar energy amount received by the Earth-atmosphere system is also crucial to the energy balance. Therefore, knowledge of solar radiation reaching the Earth's surface is a key factor since it affects the social systems such as agriculture, ecology and hydrology (Kumar and Skidmore, 2000; Reuter et al., 2005). Moreover, understanding the local solar radiation is important for other numerous applications, including energy planners, engineers, architectural design and solar energy systems (Porter, 1993; Zekai, 2008).

Spain is a high insolation country with about an average of 2500 h year^{-1} of sunshine (Sánchez-Lorenzo et al., 2007). Therefore, qualification of this renewable energy capacity plays a significant role in emerging new energy technologies. However and in spite of the importance of determining solar radiation, its measure is not as widespread as other variables such as temperature and humidity, due to the higher cost, maintenance and calibration of the pyranometers. Consequently, models for accurately estimating the solar radiation from most of available data (cloud cover, sunshine hours, temperature or precipitation) have been developed (Ångström, 1924; Prescott, 1940; Bristow and Campbell, 1984; Thornton and Running, 1999).

It is well known that the performance of the Ångström–Prescott (A–P) model shows good fit and simplicity (Almorox and Hontoria, 2004; Trnka et al., 2005). Ångström (1924) proposed a linear relationship between the proportions of global solar radiation on a horizontal surface (H) compared to that for a clear sky and the ratio between the sunshine hours (n) and day length (N). However, radiation under clear sky conditions involves some ambiguity. Thus, Prescott (1940) suggested to replace it for the extra-terrestrial radiation on a horizontal surface (H_0), an amount that has also the advantage of being estimated theoretically. The so-called A–P equation, developed for monthly average data, then results to:

$$\overline{H}/\overline{H}_0 = a + b(\overline{n}/\overline{N}) \quad (1)$$

where day length and radiation at the top of the atmosphere are obtained according to the expressions:

$$\overline{H}_0 = 37.6 \cdot \left(1 + 0.033 \cdot \cos\left(\frac{2\pi}{365} J\right)\right) \cdot (\cos\phi \cos\delta \sin\omega_s + \omega_s \sin\phi \sin\delta) \quad (2)$$

$$\delta = 0.4093 \cdot \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (3)$$

* Corresponding author. Tel.: +34 3944520.
E-mail address: mlmartin@eii.uva.es (M.L. Martín).

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$$\omega_s = \arccos(-\tan\phi \tan\delta) \quad (4)$$

$$N = \frac{24}{\pi}\omega_s \quad (5)$$

J being the Julian day, ϕ the latitude (rad), δ the solar declination angle (rad) and ω_s the hour angle (rad) corresponding to sunrise/sunset. The *a* and *b* values rely respectively on the kind of cloudiness and on the transmittance characteristics of the cloudless atmosphere which are mainly specified by the content of water vapour and turbidity.

From the A–P equation, several authors have proposed modifications in order to improve the accuracy in the estimation of solar radiation, giving it as well with wider application. These modifications consist on adding other terms to Eq. (1) increasing the degree of polynomial in the relative brightness (n/N) (Ertekin and Yaldiz, 2000), or relating the A–P coefficients with geography or other weather variables (Glover and McGulloch, 1958; Dogniaux and Lemoine, 1983). Other studies have proposed regional or even worldwide calibrations for the A–P coefficients (Rietveld, 1978; Almorox and Hontoria, 2004). With these modifications, Eq. (1) has been modified from single linear to multi-linear relational pattern. Other studies have used more sophisticated techniques such as artificial neural network, wavelet or adaptive methods to estimate and predict the global solar radiation, some of them even performing an A–P implementation in those techniques (Pandey and Soupir, 2012; Boata and Gravila, 2012; Pyrina et al., 2015). However, in some cases the comparative advantage with respect to the single A–P equation doesn't provide a remarkable improvement against the used higher computational cost.

Ångström (1956) restricts the application of the methodology to monthly average databases, probably due to their greater availability. Thus, the A–P coefficients have been usually calibrated from monthly mean daily records in measurement observatories around the globe. However, certain applications such as the crop growth modelling (Hunt et al., 1998) demand forecasts at lower time scales, for instance daily scale, in which Eq. (1) has not been properly verified (Moradi et al., 2014). Liu et al. (2009) assert in their study on the Yellow River basin that differences in calibration due to the time scale do not lead to significant differences in the estimated radiation. Concerning Spain, several studies have been developed to estimate the solar radiation in Spain. In Almorox and Hontoria (2004), sets of several regression models are obtained using monthly average global solar radiation and sunshine hours from 16 meteorological stations over Spain, pointing out that the differences between the obtained results by such models were negligible, and therefore they recommend the use of the linear equation with a single pair of calibrated coefficients for all the country. In Ruiz-Arias et al. (2011) monthly-averaged daily global radiation in the southern Spain was mapped using three different topographic geostatistical approaches. In Antonanzas-Torres et al. (2013) 24 different parametric models to estimate the daily global radiation in 17 meteorological stations in a small region of Spain were analysed, evaluating stability and accuracy under different initial conditions. Other authors have evaluated different daily radiation models using test errors to assess the capacity of generalization under unproven data (Almorox et al., 2011). Other approaches such as Kernel Ridge Regressions have been used to estimate solar irradiation through temperature and precipitation data (Moreno et al., 2011). However, most of these studies use single coefficients for all stations over Spain instead of choosing particular coefficients for every station in the calibration process which turns into less accuracy in the global radiation estimation.

In this paper, a database is used to perform the local calibration of the A–P model for both daily and monthly mean daily global solar radiation on a horizontal surface at selected locations in Spain. Thus, new daily and monthly mean daily sets of calibrated A–P coefficients are provided in each Spanish station, increasing the skill estimation of global solar radiation. From the obtained results, the permutability of A–P coefficients calibrated at different time bases is assessed, evaluating the interchangeable effect on the accuracy of the global radiation estimations. To confirm the suitability of the coefficient permutability, additional models have been considered for the estimation of both daily and monthly mean daily global radiation. Moreover, several sunshine hour-based models have been considered to check the use of local calibration against a single calibration for the whole spatial domain. The study is organized as follows. A brief description of the datasets used is given in Section 2, indicating as well the different statistics to evaluate the model accuracy. Section 3 is devoted to show the results of the calibration and validation of the A–P model in daily and monthly mean daily time bases and to analyse the permutability of A–P coefficients. Finally, in Section 4 the permutability is assessed by comparing the resulting performance with that for other sunshine-based models. A summary of the main results is drawn in Section 5.

2. Data and methods

2.1. Datasets

The database consists of 25 time series of daily global radiation (H) and sunshine hours (n) during all years in Spain. These radiometric data (Fig. 1) come from in-situ measurements of the station radiation network of the Spanish Meteorological Service (Agencia Estatal de Meteorología, AEMET), that ensures that measurements meet the standard procedures recommended by the World Meteorological Organization. Table 1 shows the geographical information of the selected stations.

The locations correspond to the meteorological stations in which latitude range from 36.50°N to 43.39°N, longitude from 8.42°W to 2.20°E and elevation range from 2 to 1082 m, comprising the main Spanish climatic regions: Atlantic and Mediterranean areas (Font, 2000; Morata et al., 2006; Sotillo et al., 2006; Pascual et al., 2013). From the 25 stations, six of them have been chosen to show the different graphical results as representatives of the different areas of Spain. Four of them show Atlantic climatic characteristics: Coruña, Oviedo, Madrid and Toledo. The first two stations (Coruña and Oviedo) are located in the northern Iberia while Madrid and Toledo are representatives of the central part of Spain; two more places (Málaga and Almería) are characteristic stations of the Mediterranean climate.

According to Persaud et al. (1997), in order to avoid missing data that can distort the results caused by possible malfunction of the radiometric instruments, a quality control was carried out in the datasets taking into account three different requirements, resulting on the loss of the 12% of the data:

(a) if there are missing data of global solar radiation, sunshine hours, or both, such data for that day are omitted;
(b) if the ratios H/H_0 or n/N are greater than 1, the corresponding data are omitted and,
(c) if ten daily or more data in a particular month are missing, the whole month's data are disregarded.

Monthly mean daily datasets are built to calibrate the models in a monthly time basis from the daily databases. Time records in all stations were used to calibrate the models, excepting the last two years of available data that were used for validation purposes.

In a preliminary analysis of the two databases, the distribution of observed *H* was obtained for both daily and monthly mean daily datasets (Fig. 2). The uniform shape of the both distributions can be noted; except for a very low percentage of data, corresponding to nearly cloudy days and clearly days, the distribution of data in both time bases is very similar in all intervals, highlighting that Spain can be considered as one of the main European countries in solar renewable energy source.