Analysis of cloud effects on long-term global and diffuse photosynthetically active radiation at a Mediterranean site

Lozano, I.L.[a,b], Sánchez-Hernández, G.[a,c], Guerrero-Rascado, J.L[a,b], Alados, I.[a,d], Foyo-Moreno, I.[a,b]

[a]Andalusian Institute for Earth System Research, Granada, 18006, Spain

[b]Department of Applied Physics, University of Granada, Granada, 18071, Spain

[c]Department of Physics, University of Jaén, Jaén, 23071, Spain

[d]Applied Physics II Department, University of Málaga, Málaga, 29071, Spain

Corresponding author: Inmaculada Foyo Moreno (ifoyo@ugr.es)

Abstract. - This study addresses the analysis of the cloud effects on photosynthetically active radiation (PAR, 400-700 nm) for global (PAR_{Global}) and its diffuse component ($PAR_{Diffuse}$). To this aim, a 11-year database of measured PAR_{Global} and modeled PAR_{Difuse} recorded in a Mediterranean site was analyzed, for both clear-sky and all-sky scenarios. PAR_{Global} mean values for the entire period were estimated in (200 ± 50) Wm^{-2} and (240 ± 50) Wm^{-2} for all- and clear-sky scenarios, respectively, while the values obtained for $PAR_{Diffuse}$ were (59 ± 6) Wm^{-2} for all-skies and (51 ± 5) Wm^{-2} for clear-skies. PAR_{Global} monthly averages show the typical annual pattern driven by the annual course of solar position and $PAR_{Diffuse}$ presents a similar but less marked pattern. The observed seasonal behavior was explained in terms of cloud cover, cloud frequency, liquid and ice content for all-sky scenarios. Higher variability during spring was detected due to the more complex cloud features in this season. Cloud Radiative Effect (CRE) showed negative values associated with a decrease in PAR_{Global} (-36 ± 14) Wm^{-2} and positive values corresponding to an increase in $PAR_{Diffuse}$ (+7 ± 5) Wm^{-2}. A clear seasonal pattern was found for CRE_{Global} and $CRE_{Diffuse}$ with higher values in spring and autumn, and lower values in summer and winter. Additionally, the PAR-to-Total ratio and diffuse fraction (k_{PAR}) values were evaluated under different sky conditions. Monthly mean values of the PAR-to-Total ratio showed steady values around 0.44 and any dependence on clearness index (k_t) nor total cloud cover (TCC) was found. However, k_{PAR} seemed to increase with TCC, taking averages values of 0.45 for all-sky and 0.28 for clear-sky scenarios. For all-sky conditions a clear seasonal pattern was observed with higher values in colder months. A secondary maximum value for k_{PAR} was found in summer for clear-sky scenarios, revealing the important effect of the Saharan dust intrusions in the Mediterranean region. Finally, a well-defined logistic relationship was found between k_{PAR} and k_t, leading to estimate k_{PAR} from total solar irradiance measurements.

Keywords: global photosynthetically active radiation, diffuse photosynthetically active radiation, cloud radiative effect, diffuse fraction, PAR-to-Total ratio

1.- INTRODUCTION

Solar radiation is the main driver for the Earth's climate and, therefore, for many of the life forms (Stocker et al., 2013; Trenberth et al., 2009). Approximately half of the Sun's energy is supplied in the so-called photosynthetically active radiation (PAR) range (Yu et al., 2015), which corresponds to the solar radiation in the spectral interval between 400 and 700 nm (McCree, 1972). This definition is associated to the crucial role played by the solar radiation at this spectral interval for plant photosynthesis and related processes such as biomass production or greenhouse gases emitted by crops (Keane et al., 2017; Manevski et al., 2017; Roebroek et al., 2020; Tan et al., 2018). Partitioning of PAR radiation into its direct and diffuse components is of special interest. This partitioning highly influences canopy photosynthesis being the light-use efficiency, defined as the ratio between grams of accumulated biomass and intercepted PAR radiation, higher under cloudy conditions due to the enhancement of the $PAR_{Diffuse}$ radiation under these situations (Gu et al., 2002; Kanniah et al., 2012).

Despite the PAR's relevance, fundamental aspects such as the aerosol and cloud effects on PAR, and its role on climate change, remain unclear (Cohan et al., 2002; Lozano et al., 2021; Stocker et al., 2013). Clouds are the main factor determining the PAR amount and are a key for the diffuse-to-direct partitioning and, consequently, of special interest for the plant primary production (e.g. Gu et al., 2002; Mercado et al., 2009). Important changes in the cloud features affecting the solar radiation trends have been reported over many different regions during the last and the present century (Hatzianastassiou et al., 2020; Wild, 2009, 2016). These variations on cloudiness and their effect on solar radiation take special relevance on sensitive climate change regions such as the Mediterranean basin. Several authors have reported significant trends in total solar irradiance (280-4000 nm), up to +0.82 $Wm^{-2}decade^{-1}$ over the western Mediterranean, associated with cloud changes in the last decades (Hatzianastassiou et al., 2020; Kambezidis et al., 2016; Sánchez-Lorenzo et al., 2017). Cloud effects have been widely analyzed over short- and long-wave spectral intervals in the Mediterranean area (Córdoba-Jabonero et al., 2011; Dong et al., 2017; Freile-Aranda et al., 2017; Mateos et al., 2013a, 2013b; Nikitidou et al., 2017; Pyrina et al., 2015; Tzoumanikas et al., 2016) but very few studies have addressed them for the PAR spectral range (Alados et al., 2000; Jacovides et al., 2007). To our knowledge, only the study carried out by Trisolino et al. (2018) has focused on the analysis of the cloud effects of long-term series of PAR measurements. In this study, Trisolino et al. (2018) applied a multi-linear model to relate the deseasonalized cloud radiative effect and cloud properties. They observed that, while global PAR interannual variability may be associated with cloud variability in winter, diffuse PAR can not be described by a simple multi-linear model due to its non-linear dependency on cloud properties, particularly on the cloud optical depth.

Several authors have pointed out the scarcity of PAR measurements (e.g. Ferrera-Cobos et al., 2020; Niu et al., 2019; Wang et al., 2016) and the absence of a worldwide measurement network with standardized protocols (Ge et al., 2011) as the main reasons explaining the reduced number of studies about PAR. This lack of measurements is much more remarkable for the $PAR_{Diffuse}$ component, which requires a shading device that prevents the sensor from the direct component. Although shadow-rings and Sun-trackers are commonly employed to measure diffuse radiation in the total solar spectrum (Sánchez et al., 2012), it is extremely rare to use these devices for measuring the diffuse component in the PAR spectral interval (Alados & Alados-Arboledas, 1999). In this context, it should be noted the effort at constructing a PAR dataset during 1961-2014 in China for 2474 CMA (Chinese Meteorological Administration) stations by applying a model with highest accuracy and strongest robustness (Qin et al., 2019). Besides, Feng et al. (2018) studied the spatial and temporal variations of the annual mean PAR value over mainland China using the genetic model.

In order to address this worldwide measurement gap, several authors have proposed different models to estimate PAR values. Among these models, empirical algorithms to derive global PAR (PAR_{Global}) from Total solar irradiance (e.g. Alados et al., 1996; Alados & Alados-Arboledas, 1999; Foyo-Moreno et al., 2017; Mizoguchi et al., 2014; Peng et al., 2015; Wang et al., 2013), from spectral band measurements (e.g. Trisolino et al., 2016), parametric models (e.g. Alados et al., 2002; Alados-Arboledas et al., 2000) and from satellite data (Hao et al., 2019; Harmel & Chami, 2016; Vindel et al., 2018) stand out. A very common practice is to estimate the PAR_{Global} as a constant fraction of the Total solar irradiance (Britton & Dodd, 1976; Janjai et al., 2015; Yu et al., 2015; Zhang et al., 2000), with values around 0.41 commonly assumed for the PAR-to-Total ratio (Jacovides et al., 2004). Although in a much more limited number, several models have been specifically proposed for the $PAR_{Diffuse}$ component (e.g. Foyo-Moreno et al., 2018; Jacovides et al., 2010).

However, several authors have highlighted important dependences of the PAR-to-Total ratio on specific atmospheric conditions (Alados et al., 1996; González & Calbó, 2002; Su et al., 2007). Thus, a clear dependence of the PAR-to-Total ratio on air mass under cloudless conditions have been reported at several sites (González & Calbó, 2002; Yu et al., 2015; Zhang et al., 2000) and particularly at Granada, in the Western Mediterranean basin (Alados-Arboledas et al., 2000). However, very few studies have analyzed the PAR-to-Total ratio values under cloudy conditions, for which this ratio can reach values up to 0.48 for hourly averages (Jacovides et al., 2004; Wang et al., 2015). Moreover, the $PAR_{Diffuse}$ component is commonly analyzed by its PAR diffuse fraction (k_{PAR}), defined as the ratio between the $PAR_{Diffuse}$ and PAR_{Global}. Several models have been proposed to estimate k_{PAR} from the PAR clearness index ($k_{t,PAR}$), defined as the ratio between the PAR_{Global} at the surface and the PAR radiation at the top of the atmosphere. Most of these models are based on linear or polynomial functions of $k_{t,PAR}$ and have been developed for clear-sky conditions (Foyo-Moreno et al., 2018; Jacovides et al., 2010). These one-parameter models describe the general behaviour of k_{PAR} but they do not reproduce the variability due to the different sky scenarios, being clouds the main factor driving this variability.

In this context, this study aims to analyze the cloud effects on PAR_{Global} and $PAR_{Diffuse}$ at an urban Northern mid-latitude site, in the Mediterranean basin. To this goal, an empirical model has been applied to derive $PAR_{Diffuse}$ from PAR_{Global} and Sun-geometry parameters. Then, a long-term database of measured PAR_{Global} and modelled $PAR_{Diffuse}$, covering the period (2008-2018), have been analyzed, for both clear- and all-sky scenarios, and the cloud radiative effect (CRE) have been assessed for both, PAR_{Global} and $PAR_{Diffuse}$. Additionally, the PAR-to-Total ratio and k_{PAR} have been evaluated versus the clearness index (k_t) and total cloud cover (TCC) and for all- and clear- sky scenarios.

2.- Experimental site and instrumentation

2.1 Experimental site

The experimental dataset has been acquired at the IISTA-CEAMA radiometric station located at Granada (37.164 ^{o}N, 3.605 ^{o}W, 680 m.a.s.l.), a non-industrialized Southeastern Spanish city in the Western Mediterranean region. The city is located within a natural basin surrounded by mountains with a continental Mediterranean climate characterized by dry and hot summers and cold winters, with mean daily maximum surface temperature of (32 ± 3) ºC and (14.6 ± 2.4) ºC, respectively (AEMET, Spanish Meteorology Statal Agency; period 1981-2010). The orography at Granada favors winter-time thermal inversions with prevalence of very low wind speeds (Lyamani et al., 2012). The main local aerosol sources are traffic, re-suspended local mineral dust in the dry season and domestic heating during winter (Titos et al., 2012, 2017) and bioaerosols (Cariñanos et al., 2021), while the most important allochthonous aerosol particles are anthropogenic pollution from the European continent, mineral dust particles from Sahara desert in North Africa (Guerrero-Rascado et al., 2008, 2009; Lyamani et al., 2006; Valenzuela et al., 2012) and smoke from fires occurring in the Iberian Peninsula and North America (Alados-Arboledas et al., 2011; Ortiz-Amezcua et al., 2017). IISTA-CEAMA facilities are part of the observatory AGORA (Andalusian Global ObservatoRy of the Atmosphere) in the framework of ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure).

2.2 Radiation measurements

Two solar radiation datasets have been employed in this study. The first dataset is composed by two years (1994-1995) of one-minute experimental measurements of PAR_{Global} and $PAR_{Diffuse}$. Both components were measured by two LICOR-190 SA quantum sensors (Lincoln, NE, USA), consisting of a diffuser, a visible bandpass interference filter, and a Si-photodiode. The LICOR-190SA quantum sensors has a relative error of less than 5% with a systematic spectral error below 1 % (Ross & Sulev, 2000) and an angular response with a maximum deviation from the ideal cosine response of 7 % at 80º (LICOR Sensor SA Type Manual, 1992). One of these sensors was mounted on a polar axis shadowband in order to measure the diffuse component. Due to its structure, this device causes an underestimation in the measurements because the band screens not only the Sun's disk but also a substantial portion of the sky and, therefore, these measurements must be corrected. In this study the method proposed by Batlles et al. (1995) has been applied to correct for the shadowband error (Alados & Alados-Arboledas, 1999). PAR_{Global} and $PAR_{Diffuse}$ measurements in this two-year dataset guarantee the inclusion of a wide range of seasonal conditions and solar zenith angles and have been used to fit and validate the proposed model for the diffuse component described in Section 3.1.This dataset has been employed to reproduce $PAR_{Diffuse}$ values and analyze the cloud effect on PAR_{Global} and $PAR_{Diffuse}$ (Foyo-Moreno et al., 2018). In this study, this data set, the only period with experimental values of PAR_{Global} and $PAR_{Diffuse}$ in our location, has been employed to get the empirical coefficient involved in the k_{PAR} model described in Section 3.1. and from which the long-term time series of $PAR_{Diffuse}$ radiation analyzed in this study has been built. The approach proposed by Foyo-Moreno et al. (2018) could not be applied in this study due to the lack of the total diffuse irradiance measurements required for this model.

The second dataset is composed of eleven years (2008-2018) of experimental 1-minute measurements of PAR_{Global} and global total (280-2800 nm) irradiance. PAR_{Global} measurements were recorded by a SKP 215 PAR Quantum Sensor (#28715) manufactured by Skye Instruments. This sensor uses a blue enhanced planar diffused silicon detector with a sensitivity of 0.015 μA/μmol $m^{-2}s^{-1}$, and a maximum relative error of 5%. A conversion factor of 4.57 μmol $m^{-2}s^{-1}$/ Wm^{-2} (McCree, 1972) were used to convert PAR photons measurements into energy units. Simultaneous measurements of total global irradiance were recorder with a CM11 radiometer (#861452) manufactured by Kipp&Zonen. The CM11 sensor is based on the Moll–Gorczynski thermopile with a black-painted ceramic disk. The pyranometer is provided with two hemispherical glass domes that are essentially transparent to solar radiation within the interval 280-2800 nm and opaque to larger wavelengths. The CM11 complies with the International Organization for Standardization (ISO) 9060 criteria for an ISO secondary standard pyranometer. It is classified as high quality according to the WMO nomenclature (WMO, 2008), with a directional error lower than 10 Wm^{-2} for zenith angles up to 80º (Kipp &

Zonen, 2000). Radiometers involved in this study have been intercompared with reference instruments several times along the 11-year period analyzed. A detailed description of this issue can be found in Lozano et al. (2021). Particularly, a variation of only 0.4 mV/Wm^{-2} in the calibration factors applied for the entire period analyzed in this study (2008-2018) has been detected for the SKP 215 PAR Quantum Sensor.

In order to guarantee the data quality a control analysis has been performed to detect and remove anomalous and low-accurate measurements. Thus, the constraint $0 < k_t < 1$, being k_t the clearness index defined as the ratio between the global irradiance at the surface and the total irradiance at the top of the atmosphere, both on a horizontal surface, has been applied to both datasets. Additionally, only measurements recorded at zenith angles lower than 80º have been considered to avoid the cosine response error in radiation measurements. Then, a visual inspection was performed to detect outliers as well as malfunctioning related to power supply and temperature. This high-quality, 11-year database guarantees the representativeness of a great variety of meteorological scenarios, seasonal conditions and solar geometries.

2.3 Cloud data

Cloud data employed in this study have been taken from the European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis Fifth Generation (ERA5) database. This reanalysis has been generated using a 4-dimensional variational (4D-Var) analysis of the ECMWF's Integrated Forecast System (IFS). The process involves vast amounts of historical observations, including satellite, aircraft and surface data, to obtain globally consistent time series of multiple climate variables (C3S, 2017). ERA5 provides hourly estimates of many atmospheric, land-surface and sea-state variables together with their uncertainties along the period 1950-to-present. Particularly, atmospheric variables are on regular latitude-longitude grids at 0.25º x 0.25º resolution on 37 pressure levels. Thus, ERA5 provides data with a high temporal resolution for the long-term series analyzed in this study and with the suitable spatial resolution to account for the complex orography of our region (close to the coast and at the foothills of the highest Iberian mountain), which highly determines the development of different cloud types affecting the city of Granada. This reanalysis is an open access dataset available after registration at the Climate Data Store (https://cds.climate.copernicus.eu/cdsapp#!/home).

Particularly, the cloud variables used in this study are the total cloud cover (TCC), total column cloud liquid water (TCLW), total column cloud ice content (TCIW) and the total cloud cover for low- (LCC), mid- (MCC) and high-cloud (HCC). Cloud cover variables are estimated as the proportion of the grid box covered by clouds. Low-, mid- and high-cloud cover are defined as the integration of all clouds from the surface to 800 hPa, 800 hPa to 450 hPa and from 450 hPa to the top of the atmosphere (TOA), respectively (Forbes, 2017). Total cloud cover integrates all clouds from the surface level to the TOA with overlap assumptions (Barker, 2008; Jakob & Klein, 2000). Total column cloud liquid water is the amount of liquid water contained within cloud droplets in a column extending from the surface to the TOA and averaged for the model grid box. These ERA5 cloud variables have been analyzed and compared in several regions against surface and satellite cloud observations with good agreements in both comparisons (Danso et al., 2019; Lei et al., 2020; Yao et al., 2020). Thus, in the analysis performed by Yao et al. (2020) for the period 2007-2016, ERA5 shows monthly mean cloud cover with relative errors below 10% with respect to MODIS, with special good behaviour for latitudes between 0-30º.

3.- Methodology

3.1 Diffuse PAR modelling

Many authors have studied the functional relationship between the diffuse and global irradiance in the total solar spectrum (280-4000 nm). This relationship is usually quantified using irradiance ratios due to their lower uncertainty with respect to the absolute values (Badarinath et al., 2007; Meloni et al., 2006). Thus, several empirical models to estimate/derive the diffuse fraction (k), defined as the ratio between diffuse and global irradiance, and from the clearness index (k_t) , can be found in the literature (Kuo et al., 2014; Ridley et al., 2010; Torres et al., 2010). This relationship has been translated into other spectral intervals such as the ultraviolet (e.g. Sánchez et al., 2017) and PAR (e.g. Foyo-Moreno et al., 2018; Tsubo & Walker, 2005).

Similarly to the total solar spectrum, k_{PAR} and $k_{t,PAR}$ are defined at the PAR interval as:

$$k_{PAR} = \frac{PAR_{Diffuse}}{PAR_{Global}} \quad (1)$$

$$k_{t,PAR} = \frac{PAR_{Global}}{I_{PAR,TOA}} \quad (2)$$

Following (Iqbal, 1983), the PAR irradiance at the top of the atmosphere, $I_{PAR,TOA}$, has been calculated as:

$$I_{PAR,TOA} = I_{PAR,0} E_0 cosSZA \quad (3)$$

where SZA is the solar zenith angle, E_0 is the eccentricity correction factor of the Earth's orbit, computed by the expression developed by Spencer (1971), and $I_{PAR,0}$ is the solar constant for the PAR range, with an estimated value of 634.40 W m^{-2} (Iqbal, 1983).

Different functional forms of the relationship between k_{PAR} and $k_{t,PAR}$ were analyzed in previous studies. Thus, Jacovides et al. (2010) revealed the good performance of the model proposed by Ridley et al. (2010) (usually known as BRL model), originally proposed to estimate the diffuse fraction in the total spectrum, when applied at the PAR spectral interval. Later, Kathilankal et al. (2014) analyzed a more complete version of the Ridley's model for the k_{PAR} given by:

$$k_{PAR} = \frac{1}{1+exp(a_1+a_2 k_{t,PAR}+a_3\alpha+a_4 AST+a_5 K'_{t,PAR}+a_6\Psi_{PAR})} \quad (4)$$

where a_i are the coefficients to be fit and $k_{t,PAR}$ is the PAR hourly clearness index. The rest of variables involved in this model have been included in order to reproduce the k_{PAR} variability under different sky conditions. Thus, α is the solar elevation in degrees and accounts for the enhancement in the Rayleigh scattering as α decreases, while AST is the apparent solar time and considers differences in the atmosphere between the morning and afternoon. Moreover, $K'_{t,PAR}$ is the daily clearness index which is a measurement of the daily variability in PAR mainly associated with clouds. Finally, Ψ_{PAR} is defined as a persistence index and takes into account the very slow rate of change in the radiation under cloud-free or overcast skies evaluated in a given interval (from "time-1" to "time+1"). These two last variables are directly related with the cloud characteristics and are defined at the PAR interval as:

$$K'_{t,PAR} = \frac{\sum_{i=1}^{24} PAR_{Global}}{\sum_{i=1}^{24} I_{PAR,TOA}} \quad (4.a)$$

$$\Psi_{PAR} = \frac{k_{t,time-1} + k_{t,time+1}}{2} \quad (4.b)$$

An important advantage of this model is that it proposes a continuous curve, instead of a set of piecewise linear fittings and, despite its complex appearance, it is easily linearizable and fitable. Additionally, the variables included in this model to account for the k_{PAR} variability do not require additional data than PAR_{Global} and the date and time at which each measurement is recorded, allowing for its application to generate long-term series.

This model has been analyzed for our location using the 2-year database described in Section 2.1. In our knowledge, this is the first time that this model has been applied to our location using PAR radiation measurements. This dataset has been hourly averaged and randomly splitted into two subsets: (1) a fitting subset containing the 75 % of data, to obtain the model coefficients, and (2) a validation subset composed by the remaining 25 % of data, for the model validation. The fitting coefficients obtained for this model at Granada are summarized in Table 1. The model performs notably well with determination coefficient (r^2) higher than 0.85, and low values of root mean square error (RMSE) and mean bias error (MBE), below 0.10 Wm^{-2} and 0.007 Wm^{-2}, respectively. These results are similar to those obtained by other authors at different locations (e.g. Jacovides et al., 2010; Kathilankal et al., 2014) and have been confirmed by the statistics obtained in the validation process (r^2=0.87, RMSE = 0.10 Wm^{-2}, MBE = 0.008 Wm^{-2}). Figure 1 shows the k_{PAR} values obtained using both experimental measurements and the logistic empirical model described by the Eq. (4) with respect to $k_{t,PAR}$ for the validation dataset. This figure also confirms the agreement between k_{PAR} values derived from experimental measurements and the empirical model not only in their general behavior but also in the $k_{t,PAR}$ dispersion due to the different sky conditions resulting in the same $k_{t,PAR}$ value.

3.2 Data analysis

Once the time series of k_{PAR} were built, $PAR_{Diffuse}$ irradiance for the analyzed period was obtained from Eq. (1). Clear- and all-sky conditions have been differentiated in this study. Clear-sky scenarios were extracted by the application of the test #1 and #3 proposed by the Long and Ackerman method (Long & Ackerman, 2000). These two tests identify clear-sky conditions using local values of normalized total solar irradiance and analyzing the total solar irradiance variability at the surface with respect to its variation at the TOA, respectively. Due to the lack of total diffuse solar irradiance measurements, tests #2 and #4 of this methodology could not be applied. Instead, a thorough supervised inspection of the whole data set was made in order to detect misclassified data points.

After that, the monthly mean and annual evolution of PAR_{Global} and $PAR_{Diffuse}$ have been obtained from daily average values derived from hourly mean values. A detailed monthly statistic computing the arithmetic mean (Ave), standard deviation (SD), median (Md), minimum (Min), maximum (Max), 5th, 25th, 75th and 95th percentiles (P5, P25, P75 and P95, respectively), skewness (Ske), kurtosis (Kur) and the variation coefficient (VC), estimated as the percentage of the ratio between the standard deviation and the mean, have been analyzed for both clear- and all-sky scenarios.

The influence of clouds on the PAR_{Global} and $PAR_{Diffuse}$ has been assessed through the analysis of the so-called Cloud Radiative Effect (CRE). This variable is defined as the difference between all- and clear-sky radiation (Harrison et al., 1990; Ramanathan et al., 1989), and can be computed at PAR range as follows:

$$CRE_{PAR} = PAR_{All} - PAR_{Clear} \quad (5)$$

Finally, cloud effects on the PAR-to-Total ratio and k_{PAR} along with the annual evolution for all- and clear-sky scenarios of both variables have been analyzed. Additionally, their dependence on different sky conditions have been considered. To this aim, two parameters have been selected in order to determine the sky conditions, namely k_t and TCC. The first parameter considers the atmosphere transparency accounting for the attenuation effects of all the atmospheric components (gases, clouds and aerosols). Due to the low variability of atmospheric gases at a given location (compared with other atmospheric constituents), the most dominant factors controlling solar radiation variations, and therefore k_t values, are clouds and aerosols. Then low values of k_t are usually associated with the presence of clouds and aerosols while high k_t values indicate the opposite situation. For its part, TCC quantify the cloud presence. This analysis has been performed with the dataset composed of the coincident cases in the ERA5 and 11-year radiation databases.

4.- Results and discussion

4.1 Cloud radiative effect on PAR_{Global} and $PAR_{Diffuse}$

Figure 2 shows the time series of monthly mean values of PAR_{Global} and $PAR_{Diffuse}$ during the whole period 2008-2018 differentiating between all- and clear-sky scenarios. Under clear-sky scenarios the expected annual cycle is observed for PAR_{Global}, with higher values during warm months and minimum values during cold ones, due to the different course of the solar zenith angle along the year (also highlighted from the statistical analysis shown in Figure 3). This behaviour is roughly found for PAR_{Global} under all-sky situations, where the cloud presence slightly modified the monthly mean radiative field. Moreover, the time series of monthly mean $PAR_{Diffuse}$ values for both all- and clear-sky scenarios are noisier as a consequence of the high variability in the presence of clouds and aerosols over the study area. Thus, a value of (279 ± 15) Wm^{-2} is found for all-skies in July 2014 and (320 ± 40) Wm^{-2} for clear-skies in May 2013 for PAR_{Global}, while for $PAR_{Diffuse}$ the maximum values reached (74 ± 13) Wm^{-2} in April 2011 and (76 ± 22) Wm^{-2} in March 2018 for all- and clear-skies, respectively. Additionally, notable interannual variability has been observed with differences between the maximum and minimum annual mean values, being estimated in 20 Wm^{-2} and 16 Wm^{-2} for PAR_{Global} in all- and clear-sky conditions, respectively, and around 5 Wm^{-2} for $PAR_{Diffuse}$ in all-sky and 9 Wm^{-2} for clear-sky scenarios.

As it was expected, in clear-sky situations PAR_{Global} reaches higher values than in all-sky situations due to the cloud attenuation. The opposite behaviour was observed for $PAR_{Diffuse}$ which increases under cloudy conditions due to the increase of the scattering processes. The average values of PAR_{Global} for the entire period 2008-2018 has been estimated in (200 ± 50) Wm^{-2} and (240 ± 50) Wm^{-2} for all- and clear-sky scenarios, respectively (i.e. 17% less). These values agree with those reported by other authors over the Mediterranean area. Thus, Alados et al. (2000) and López et al. (2001) reported values of PAR_{Global} for different periods at Granada and Almería (Southern Spain) ranging between 205 and 234 Wm^{-2} for all-sky conditions, and between 205 and 276 Wm^{-2} for clear-sky scenarios, while Zempila et al. (2016) reported an average value for PAR_{Global}

of 223 Wm^{-2} in 2005 over Greece. On the other hand, average $PAR_{Diffuse}$ takes values of (59 ± 6) Wm^{-2} and (51 ± 5) Wm^{-2} for all- and clear-sky scenarios, respectively (16% more). These values are clearly higher than those reported by Trisolino et al. (2018), who estimated mean $PAR_{Diffuse}$ values of 26 Wm^{-2} and 35 Wm^{-2} for clear- and all-sky scenarios, respectively, for the period 2002-2016 at Lampedusa, in central Mediterranean. These large differences for $PAR_{Diffuse}$ can be attributed to differences in altitude, surface albedo, atmospheric aerosols and clouds which determine the diffuse component.

Figure 3 displays the annual evolution of the statistics for PAR_{Global} and $PAR_{Diffuse}$ under all- and clear-sky scenarios for the entire dataset. The seasonal distribution of PAR_{Global} shows an evident cycle with its maximum median values around 271 Wm^{-2} in July for all-sky and 289 Wm^{-2} both in May and July under clear-sky situations. The minimum values occurred in winter with median PAR_{Global} reaching 127 Wm^{-2} in January for all-sky and 159 Wm^{-2} in December for clear-sky scenarios. For all-sky conditions, the behavior driven by the annual course of solar position is reinforced by the annual evolution of the cloud cover over our location, which shows the same pattern both in cloud frequency (Figure 4.a) and total cloud cover (TCC; Figure 4.c). On the other hand, as it was expected, PAR_{Global} for cloud-free situations presents low variability, below 6% observed in March. However, all-sky situations present high variability ranging between 2% in July and 20% in March, with winter- and springtime showing the highest variability, explained by the higher cloud frequency and a wider range of the TCC, TCLW and TCIW values during these seasons.

The seasonal pattern observed in Figure 3 for $PAR_{Diffuse}$ is notably less marked than for PAR_{Global}, mostly due to the high complexity of the processes involved in the diffuse component. While median $PAR_{Diffuse}$ values show a similar annual evolution than those observed for PAR_{Global}, the maximum and minimum values, as well as its variability, show a more complex pattern. Thus, the maximum median values for $PAR_{Diffuse}$ have been detected in May for all-sky situations, with values of 66 Wm^{-2}, and in July and August for clear-sky scenarios with a value of 59 Wm^{-2}. The minimum median values for $PAR_{Diffuse}$ occurred in December reaching 49 Wm^{-2} and 45 Wm^{-2}, for all- and clear-sky scenarios, respectively. $PAR_{Diffuse}$ variability also shows more vague differences between all- and clear-sky conditions. Thus, $PAR_{Diffuse}$ variability for all-sky scenarios varies from 6% to 13% with its maximum found in February and December, under cloud-free situations $PAR_{Diffuse}$ variability ranges from 4% to 20% with its maximum in February and March. These lower differences in $PAR_{Diffuse}$ between all-sky and clear-sky conditions are probably due to the higher sensitivity of the diffuse component with respect to the geometric and microphysical characteristics of cloudiness, and the atmospheric aerosol particles, which highly increase the scattering processes under clear-sky conditions. This last factor also could explain the high variability of $PAR_{Diffuse}$ under clear-skies. Besides, due to its proximity to the Sahara Desert, Granada is frequently affected by large dust loads favoring the increase of $PAR_{Diffuse}$ during clear-skies, even during wintertime (e. g. Foyo-Moreno et al., 2014). Particularly, the maximum values observed for clear-skies in February and March are related to winter-time extreme dust events over Granada (i.e. Cazorla et al., 2017; Fernández et al., 2019). In fact, Lozano et al. (2021) found relatively high values of maximum AOD at 500 nm (0.66) for this database in these months. Variability of the all-sky situations seems to be associated with the cloud characteristics similarly to the PAR_{Global} variability in these same conditions.

Figure 4 shows a detailed characterization of clouds for the period 2008-2018 at

Granada. Three different sky conditions have been differentiated: “overcast”, “broken clouds” and “clear”. This classification has been built from the TCC values taking as “overcast” those situations for which TCC> 0.9, as “broken-cloud” those cases with 0.1< TCC < 0.9 and “clear-skies” when with TCC<0.1. During winter- and springtime the frequency of cloudy skies (overcast and broken clouds) are around 70%, meanwhile in summer frequency of overcast and broken cloud situations fall down to 0% and 24%, respectively (Figure 4a). High clouds presence is at least 50% of the total, with the exception of July when its minimum percentage has been detected (37%; Figure 4b). In agreement with the frequency of sky scenarios, TCC decreases from January to July and then increases, similarly to that observed for with the TCLW (Figure 4c and 4d). However, the TCIW does not follow the same pattern and reaches its maximum values in spring (0.029 kgm^{-2}) and autumn (Figure 4e), in concordance with the maximum values observed for the high clouds frequency.

Figure 5a and 5b present a boxplot of the monthly values of CRE_{Global} and $CRE_{Diffuse}$ estimated from eq. (5). The negative sign of CRE_{Global} indicates a decrease in surface PAR due to cloud effects meanwhile the positive sign of $CRE_{Diffuse}$ involves the opposite effect, that is, an increase of the diffuse component. The average value of the full period of study is about (-36 ± 14) Wm^{-2} for CRE_{Global} and (+7 ± 5) Wm^{-2} for $CRE_{Diffuse}$. Trisolino et al. (2018) found a value of -14.7 Wm^{-2}and +8.1 Wm^{-2} for CRE_{Global} and $CRE_{Diffuse}$, respectively. Both CRE_{Global} and $CRE_{Diffuse}$ show a clear seasonal pattern with two maxima, in absolute values, in spring (more intense) and autumn and minimum values in summer and winter. Thus, CRE_{Global} reaches its maximum value, in absolute terms, in April (-61.8 Wm^{-2}) and its minimum value in July (-16.7 Wm^{-2}). Similarly, the maximum $CRE_{Diffuse}$ has been detected in April (+16.9 Wm^{-2}) and its minimum in January (+1.2 Wm^{-}

^{2}). For $CRE_{Diffuse}$, this particular behavior seems to be related with the annual pattern observed in high clouds frequency and the TCIW values, as shown in Figure 4.b and 4.e. High clouds are mainly composed of non-spherical ice crystal particles with effective radius in the range of 20-140 microns (Liou et al., 2008). These characteristics are responsible for an increase of the scattering processes favoring the pattern clearly observed in $CRE_{Diffuse}$. In the case of CRE_{Global} this pattern is the result of a more complex combination of the different cloud characteristics that entails higher cloud opacity in autumn but mainly in spring when the maximum absolute values of CRE_{Global} are observed. This seasonal pattern with maximum values (in absolute terms) in April for both CRE_{Global} and $CRE_{Diffuse}$ was also found by Trisolino et al. (2018) for PAR and Pyrina et al. (2015) in the shortwave range in the Mediterranean basin, who associated this pattern to elevated values of cloud optical thickness in this month.

4.2 Effect of sky conditions on PAR-to-Total ratio and PAR diffuse fraction (k_{PAR})

Figure 6 shows the relationship between the PAR-to-Total ratio and k_t and TCC, respectively, for 1-minute data and the entire period of study. No significant dependence on k_t nor TCC has been observed for the PAR-to-Total ratio, which for bin-averaged values vary from 0.43 ± 0.03 to 0.46 ± 0.05. However, a great point spread can be appreciated for the whole range of k_t and TCC. This behavior is stronger for low values of k_t and high values of TCC, when the PAR-to-Total ratio can reach values between 0.25 and 0.55. Other authors, such as Ferrera-Cobos et al. (2020), have recently reported a reduction in the relationship of PAR-to-Total ratio when k_t increases, using data from three stations located in mainland Spain and Akitsu et al. (2015) in Tsukuba (Japan) found a slight negative correlation with dependence k_t. Some studies with long-term series such as Niu et al. (2019) reported slightly lower values in China for 1961-2016, with variations in the PAR-to-Total ratio from 0.39 in winter to 0.42 in summer. Meanwhile, Peng et al. (2015) reported values from 0.38 in winter to 0.43 in summer for the Tibetan Plateau in 2006-2012. Yu et al. (2015) compiled values from various studies in which the annual mean of the PAR-to-Total ratio varied from 0.42 to 0.52. Zhang et al. (2020) found a mean value of 0.43 for Xinzhou, a suburban site on the North China Plain. Jacovides et al. (2004) reported higher values for overcast skies (0.44 ± 0.02 against 0.41 ± 0.01), indicating that clouds reduce total irradiance more than PAR. Wang et al. (2015) for data in Mongolia from 1990 to 2012 found also higher values for overcast conditions, 0.44 against 0.41.

Focusing on the monthly statistics of PAR-to-Total ratio, Figure 7 presents the annual evolution of the statistics of these values for all- and clear-sky situations, showing a very similar behavior of the PAR-to-Total ratio for both sky conditions. The higher values of the PAR-to-Total ratio have been detected in summer while the lower values occur during winter months. This behavior under clear-skies is explained because of the higher water vapor concentration in summer, which absorbs radiation in the infrared range of the total solar spectrum but barely affects the PAR range. This result has been also reported in previous works such as Akitsu et al. (2015), with values of 0.47 for summer and 0.42 for winter, also associated with higher values of water vapor pressure. A higher variability is observed for all-sky conditions, mainly during winter months, related with the higher frequency of clouds together with the wide range of TCC. Both, total and PAR irradiance decrease under cloud presence but the percentage of attenuation in each spectral range will depend on the specific characteristics of the cloud cover.

Figure 8a and 8b shows the relationships between k_{PAR} and k_t and TCC, respectively, for the entire period of study. In contrast to the PAR-to-Total ratio, there is a clear dependence of k_{PAR} on both variables. The functional form describing the k_{PAR}-k_t relationship is a logistic function similar to that observed between k_{PAR} and $k_{t,PAR}$ in Section 3.1. This is a direct consequence of the mostly constant behavior observed previously for the PAR-to-Total ratio and suggests a potential modeling of k_{PAR} from global total irradiance data. A fitting has been performed between k_{PAR} and k_t, using the same database as in Section 3.1. This fitting shows a RMSE of 0.74 and r^2 of 0.77. The corresponding fitting coefficients are summarized in Table 2. In this new fitting, the coefficients associated to the daily values of the total clearness index (K'_t) and AST, takes a non-significant value, and, therefore, these terms could be removed from this new model.

As it was expected, k_{PAR} increases with increasing TCC, although in all the bins analyzed k_{PAR} shows a wide range of variation. A significant slope of 0.47 ± 0.03 with a r^2 of 0.95 and with a p-value < 0.001 was found to this relation. The dispersion of k_{PAR} is higher for TCC values between 0.5 and 0.8 with a standard deviation of 0.35. The average values vary between 0.29 ± 0.20 for TCC of 0.1 and 0.8 ± 0.3 for TCC of 1. These results point out the relevant role of the TCC but also the relevance of other cloud characteristics in the scattering processes increasing the contribution of the diffuse component.

The mean values k_{PAR} has been estimated in 0.45 and 0.28 for all- and clear-skies, respectively. This large difference highlights the relevant role of clouds over the increase of the diffuse component. In order to detect seasonal patterns, Figure 9 presents the statistical analysis of the monthly values of k_{PAR} for both skies conditions. For all-sky situations, a clear annual behavior was observed, with higher values of k_{PAR} in colder months (0.55 in January) and minimum values in warmer ones (0.32 in July). This behavior relates the higher cloud cover and higher frequency of overcast skies with the higher values of k_{PAR}, while, in summer the lower frequency of clouds favors a high penetration of solar radiation to the surface, and therefore the decrease in k_{PAR}. Similar results were reported by Trisolino et al. (2018) who estimated a mean value of 0.39 ± 0.08 with a marked seasonal trend with maxima around 0.50 in winter and minima at about 0.25-0.30 in summer. On the other hand, k_{PAR} maximum values for clear-sky were also found in winter months, due to the lower solar elevation angles in this season which involve a higher atmospheric path for the solar radiation favoring the attenuation of PAR_{Global} and the increase of $PAR_{Diffuse}$. A secondary maximum value was found after an increased trend from spring to summer, in August. This increase in k_{PAR} in the warmer months matches with the high occurrence of Saharan dust intrusions events (Salvador et al., 2014). Thus, the clear seasonal pattern found under all sky conditions is smaller for clear skies. For these skies, Trisolino et al. (2018) found a mean value of 0.24 ± 0.04 with also a lower seasonal variation.

5. CONCLUSIONS

This study thoroughly analyzes the cloud effects over the photosynthetically active radiation (PAR, 400-700 nm) at an urban site located in a mid-latitude in the Western Mediterranean region (Granada, Spain). An unprecedented eleven-year time series (2008-2018) of experimental PAR_{Global} measurements in this region has been analyzed together co-located cloud features obtained from the ERA5 reanalysis. Additionally, this PAR_{Global} data set has been the base to build a simultaneous $PAR_{Diffuse}$ time series. This $PAR_{Diffuse}$ data set has been obtained through the first adaptation of the Ridley et al. (2010) BRL model at this location, which allows for reproducing both the amount and the variability of the diffuse component. This is the first study in the area in which the cloud radiative effects on PAR_{Global} and $PAR_{Diffuse}$ as well as on the PAR-to-Total ratio and PAR diffuse fraction have been simultaneously assessed for such period. The main conclusions of this study are listed below:

1. This study confirms the results observed in previous analysis regarding with the higher values of PAR_{Global} under clear-sky than all-sky scenarios and the opposite for $PAR_{Diffuse}$. However, it should be stand out the high variability (2-20%) for both variables under both sky types, which is explained by the cloud type diversity and the Sahara dust events over the region. In this location, the diffuse component (with respect to the PAR_{Global}) has been estimated in a 21% for clear skies, increasing up to a 30% under the presence of clouds.

2. CRE was obtained from the differences between all- and clear-sky, with a mean value of (-36 ± 14) Wm^{-2} for PAR_{Global} and (+7 ± 5) Wm^{-2} for $PAR_{Diffuse}$. A seasonal pattern was found for CRE_{Global} and $CRE_{Diffuse}$ with two maxima (in absolute terms) in spring and autumn (the former more intense) and minimum values in summer

and winter. The pattern for $CRE_{Diffuse}$ seems to be related with the annual pattern observed for the frequency of high clouds and the total cloud ice water, whereas the pattern for CRE_{Global} is caused by a more complex combination of cloud characteristics, dominated by the cloud opacity.

3. The PAR-to-Total ratio was evaluated for different sky conditions, showing no dependence on clearness index (k_t) and cloud cover total (TCC), with average values from 0.43 ± 0.03 to 0.46 ± 0.05, respectively. Higher values were found in summer for both all- and clear-sky scenarios because the higher water vapour concentration in the atmosphere during this season implies more absorption in the infrared region and, consequently, more reduction of Total irradiance. Although these mean values are similar to those reported in previous studies, it should be highlighted the great range of PAR-to-Total values under cloud presence. Depending on the cloud type and cloud cover, PAR-to-Total ratio can be modified up to 50%.

4. In contrast to the PAR-to-Total ratio, there was a clear dependence of k_{PAR} (ratio between $PAR_{Diffuse}$ and PAR_{Global}) on k_t and TCC, decreasing with k_t and increasing with TCC. The mean values were 0.45 and 0.28 for all- and clear-sky scenarios, respectively. A clear seasonal pattern was found for all-sky conditions with maximum values during the coldest months associated to the presence of high clouds, while the maximum values found under clear-sky scenarios in winter were caused by the lower solar elevation angles, i.e. higher atmospheric path for the travelling solar radiation, favoring the attenuation of PAR_{Global} and the increase of $PAR_{Diffuse}$. A secondary maximum value found in summer for clear-sky

scenarios was explained by the predominance of Saharan dust events during this season.

5. A well-defined logistic relationship was found between k_{PAR} and k_t, leading the possibility to estimate k_{PAR} from total solar irradiance measurements and, consequently, an estimation of $PAR_{Diffuse}$ was available.

ACKNOWDLEGMENTS This work was supported by the Spanish Ministry of Economy and Competitiveness through projects CGL2016-81092-R, CGL2017-83538-C3-1-R, CGL2017-90884-REDT, PID2020-120015RB-I00 and PID2020-117825GB-C21, by the Andalusia Regional Government, University of Granada and FEDER funds through projects B-RNM-496-UGR18, P18-RT-3820, A-RNM-430-UGR20 and B-RNM-524-UGR20. The financial support in the ACTRIS Research Infrastructure Project by the European Union's Horizon 2020 research and innovation program through project ACTRIS-2 (grant agreement No 654109) and ACTRIS-IMP (grant agreement No 871115). The authors thankfully acknowledge the FEDER program for the instrumentation used in this work and the University of Granada that supported this study through the Excellence Units Program. I. López Lozano was funded by the Spanish Ministry of Education, Culture and Sport through grant FPU15/05436. Authors thank to the anonymous reviewers for their comments and suggestions, which notably improved this manuscript.

REFERENCES

Akitsu, T., Kume, A., Hirose, Y., Ijima, O., Nasahara, K.N. (2015). On the stability of radiometric ratios of photosynthetically active radiation to global solar radiation in Tsukuba, Japan. *Agricultural and Forest Meteorology*, *209-210*, 59–68. https://ttp://dx.doi.org/10.1016/j.agrformet.2015.04.026

Alados, I., & Alados-Arboledas, L. (1999). Direct and diffuse photosynthetically active radiation: Measurements and modelling. *Agricultural and Forest Meteorology*, *93*(1), 27–38. https://doi.org/10.1016/S0168-1923(98)00107-5

Alados, I., Foyo-Moreno, I., & Alados-Arboledas, L. (1996). Photosynthetically active radiation: Measurements and modelling. *Agricultural and Forest Meteorology*, *78*(1–2), 121–131. https://doi.org/10.1016/0168-1923(95)02245-7

Alados, I., Foyo-Moreno, I., Olmo, F. J., & Alados-Arboledas, L. (2002). Improved estimation of diffuse photosynthetically active radiation using two spectral models. *Agricultural and Forest Meteorology*, *111*(1), 1–12. https://doi.org/10.1016/S0168-1923(02)00010-2

Alados, I., Olmo, F. J., Foyo-Moreno, I., & Alados-Arboledas, L. (2000). Estimation of photosynthetically active radiation under cloudy conditions. *Agricultural and Forest Meteorology*, *102*(1), 39–50. https://doi.org/10.1016/S0168-1923(00)00091-5

Alados-Arboledas, L., Müller, D., Guerrero-Rascado, J. L., Navas-Guzmán, F., Pérez-Ramírez, D., & Olmo, F. J. (2011). Optical and microphysical properties of fresh biomass burning aerosol retrieved by Raman lidar, and star-and sun-photometry. *Geophysical Research Letters*, *38*(1). https://doi.org/10.1029/2010GL045999

Alados-Arboledas, L., Olmo, F. J., Alados, I., & Pérez, M. (2000). Parametric models to estimate photosynthetically active radiation in Spain. *Agricultural and Forest Meteorology*, *101*(2–3), 187–201. https://doi.org/10.1016/S0168-1923(99)00163-X

Badarinath, K. V. S., Kharol, S. K., Kaskaoutis, D. G., & Kambezidis, H. D. (2007). Case study of a dust storm over Hyderabad area, India: Its impact on solar radiation using satellite data and ground measurements. *Science of The Total Environment*, *384*(1), 316–332. https://doi.org/10.1016/j.scitotenv.2007.05.031

Barker, H. W. (2008). Representing cloud overlap with an effective decorrelation length: An assessment using CloudSat and CALIPSO data. *Journal of Geophysical Research: Atmospheres*, *113*(D24). https://doi.org/10.1029/2008JD010391

Batlles, F. J., Olmo, F. J., & Alados-Arboledas, L. (1995). On shadowband correction methods for diffuse irradiance measurements. *Solar Energy*, *54*(2), 105–114. https://doi.org/10.1016/0038-092X(94)00115-T

Britton, C. M., & Dodd, J. D. (1976). Relationships of photosynthetically active radiation and shortwave irradiance. *Agricultural Meteorology*, *17*(1), 1–7. https://doi.org/10.1016/0002-1571(76)90080-7

Cariñanos, P., Foyo-Moreno, I., Alados, I., Guerrero-Rascado, J. L., Ruiz-Peñuela, S., Titos, G., Cazorla, A., Alados-Arboledas, L., & Díaz de la Guardia, C. (2021). Bioaerosols in urban environments: Trends and interactions with pollutants and meteorological variables based on quasi-climatological series. *Journal of Environmental Management*, *282*, 111963. https://doi.org/10.1016/j.jenvman.2021.111963

Cazorla, A., Casquero-Vera, J. A., Román, R., Guerrero-Rascado, J. L., Toledano, C., Cachorro, V. E., Orza, J. A. G., Cancillo, M. L., Serrano, A., Titos, G., Pandolfi, M., Alastuey, A., Hanrieder, N., & Alados-Arboledas, L. (2017). Near-real-time processing of a ceilometer network assisted with sun-photometer data: Monitoring a dust outbreak over the Iberian Peninsula. *Atmospheric Chemistry and Physics*, *17*(19), 11861–11876. https://doi.org/10.5194/acp-17-11861-2017

Cohan, D. S., Xu, J., Greenwald, R., Bergin, M. H., & Chameides, W. L. (2002). Impact of atmospheric aerosol light scattering and absorption on terrestrial net primary productivity. *Global Biogeochemical Cycles*, *16*(4), 37-1-37–12. https://doi.org/10.1029/2001GB001441

Copernicus Climate Change Service (C3S). (2017). ERA5: fifth generation of ECMWF atmospheric reanalysis of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). Available at: https://cds.climate.copernicus.eu/cdsapp#!/home [Accessed Junary 2021]

Córdoba-Jabonero, C., Sorribas, M., Guerrero-Rascado, J. L., Adame, J. A., Hernández, Y., Lyamani, H., Cachorro, V., Gil, M., Alados-Arboledas, L., Cuevas, E., & de la Morena, B. (2011). Synergetic monitoring of Saharan dust plumes and potential impact on surface: A case study of dust transport from Canary Islands to Iberian Peninsula. *Atmospheric Chemistry and Physics*, *11*(7), 3067–3091. https://doi.org/10.5194/acp-11-3067-2011

Danso, D. K., Anquetin, S., Diedhiou, A., Lavaysse, C., Kobea, A., & Touré, N. E. (2019). Spatio-temporal variability of cloud cover types in West Africa with satellite-based and reanalysis data. *Quarterly Journal of the Royal Meteorological Society*, *145*(725), 3715–3731. https://doi.org/10.1002/qj.3651

Dong, B., Sutton, R. T., & Shaffrey, L. (2017). Understanding the rapid summer warming and changes in temperature extremes since the mid-1990s over Western Europe. *Climate Dynamics*, *48*(5–6), 1537–1554. Scopus. https://doi.org/10.1007/s00382-016-3158-8

Feng, L., Qin, W., Wang, L., Lin, A., & Zhang, M. (2018). Comparison of Artificial Intelligence and Physical Models for Forecasting Photosynthetically-Active Radiation. *Remote Sensing*, *10*(11), 1855. https://doi.org/10.3390/rs10111855

Fernández, A. J., Sicard, M., Costa, M. J., Guerrero-Rascado, J. L., Gómez-Amo, J. L., Molero, F., Barragán, R., Basart, S., Bortoli, D., & Bedoya-Velásquez, A. E. (2019). Extreme, wintertime Saharan dust intrusion in the Iberian Peninsula: Lidar monitoring and evaluation of dust forecast models during the February 2017 event. *Atmospheric Research*, *228*, 223–241.

Ferrera-Cobos, F., Vindel, J. M., Valenzuela, R. X., & González, J. A. (2020). Analysis of Spatial and Temporal Variability of the PAR/GHI Ratio and PAR Modeling Based on Two Satellite Estimates. *Remote Sensing*, *12*(8), 1262. https://doi.org/10.3390/rs12081262

Forbes, R. (2017) Clouds and precipitation: from models to forecasting. Use and interpretation of ECMWF products (p. 38). Available at: https://confluence.ecmwf.int/display/FUG/Clouds

Foyo-Moreno, I., Alados, I., & Alados-Arboledas, L. (2017). A new conventional regression model to estimate hourly photosynthetic photon flux density under all sky conditions: A new conventional regression model to estimate photosynthetic photon flux density. *International Journal of Climatology*, *37*, 1067–1075. https://doi.org/10.1002/joc.5063

Foyo-Moreno, I., Alados, I., & Alados-Arboledas, L. (2018). A new empirical model to estimate hourly diffuse photosynthetic photon flux density. *Atmospheric Research*, *203*, 189–196. https://doi.org/10.1016/j.atmosres.2017.12.012

Foyo-Moreno, I., Alados, I., Antón, M., Fernández-Gálvez, J., Cazorla, A., & Alados-Arboledas, L. (2014). Estimating aerosol characteristics from solar irradiance measurements at an urban location in southeastern Spain: Aerosol properties from solar irradiance. *Journal of Geophysical Research: Atmospheres*, *119*(4), 1845–1859. https://doi.org/10.1002/2013JD020599

Freile-Aranda, M. D., Gómez-Amo, J. L., Utrillas, M. P., Pedros, R., & Martínez-Lozano, J. A. (2017). Seasonal analysis of cloud characteristics and radiative effect over the Iberian Peninsula using MODIS-CERES observations. *Tethys*, *2017*(14), 3–9. Scopus. https://doi.org/10.3369/tethys.2017.14.01

Ge, S., Smith, R. G., Jacovides, C. P., Kramer, M. G., & Carruthers, R. I. (2011). Dynamics of photosynthetic photon flux density (PPFD) and estimates in coastal northern California. *Theoretical and Applied Climatology*, *105*(1–2), 107–118. https://doi.org/10.1007/s00704-010-0368-6

González, J. A., & Calbó, J. (2002). Modelled and measured ratio of PAR to global radiation under cloudless skies. *Agricultural and Forest Meteorology*, *110*(4), 319–325. https://doi.org/10.1016/S0168-1923(01)00291-X

Gu, L., Baldocchi, D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M., & Dowty, P. R. (2002). Advantages of diffuse radiation for terrestrial ecosystem productivity: ADVANTAGES OF DIFFUSE RADIATION. *Journal of Geophysical Research: Atmospheres*, *107*(D6), ACL 2-1-ACL 2-23. https://doi.org/10.1029/2001JD001242

Guerrero-Rascado, J. L., Olmo, F. J., Avilés-Rodríguez, I., Navas-Guzmán, F., Pérez-Ramírez, D., Lyamani, H., & Alados Arboledas, L. (2009). Extreme Saharan dust event over the southern Iberian Peninsula in september 2007: Active and passive remote sensing from surface and satellite. *Atmospheric Chemistry and Physics*, *9*(21), 8453–8469. https://doi.org/10.5194/acp-9-8453-2009

Guerrero-Rascado, J. L., Ruiz, B., & Alados-Arboledas, L. (2008). Multi-spectral Lidar characterization of the vertical structure of Saharan dust aerosol over southern Spain.

Atmospheric Environment, *42*(11), 2668–2681. https://doi.org/10.1016/j.atmosenv.2007.12.062

Hao, D., Asrar, G. R., Zeng, Y., Zhu, Q., Wen, J., Xiao, Q., & Chen, M. (2019). Estimating hourly land surface downward shortwave and photosynthetically active radiation from DSCOVR/EPIC observations. *Remote Sensing of Environment*, *232*, 111320. https://doi.org/10.1016/j.rse.2019.111320

Harmel, T., & Chami, M. (2016). Estimation of daily photosynthetically active radiation (PAR) in presence of low to high aerosol loads: Application to OLCI-like satellite data. *Optics Express*, *24*(22), A1390–A1407. Scopus. https://doi.org/10.1364/OE.24.0A1390

Harrison, E. F., Minnis, P., Barkstrom, B. R., Ramanathan, V., Cess, R. D., & Gibson, G. G. (1990). Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment. *Journal of Geophysical Research: Atmospheres*, *95*(D11), 18687–18703. https://doi.org/10.1029/JD095iD11p18687

Hatzianastassiou, N., Ioannidis, E., Korras-Carraca, M.-B., Gavrouzou, M., Papadimas, C. D., Matsoukas, C., Benas, N., Fotiadi, A., Wild, M., & Vardavas, I. (2020). Global Dimming and Brightening Features during the First Decade of the 21st Century. *Atmosphere*, *11*(3), 308. https://doi.org/10.3390/atmos11030308

Iqbal, M. (1983). An Introduction to Solar-Radiation. *Bulletin of the American Meteorological Society*, *65*(10), 1113–1113.

Jacovides, C. P., Boland, J., Asimakopoulos, D. N., & Kaltsounides, N. A. (2010). Comparing diffuse radiation models with one predictor for partitioning incident PAR radiation into its diffuse component in the eastern Mediterranean basin. *Renewable Energy*, *35*(8), 1820–1827. https://doi.org/10.1016/j.renene.2009.11.015

Jacovides, C. P., Timvios, F. S., Papaioannou, G., Asimakopoulos, D. N., & Theofilou, C. M. (2004). Ratio of PAR to broadband solar radiation measured in Cyprus. *Agricultural and Forest Meteorology*, *121*(3), 135–140. https://doi.org/10.1016/j.agrformet.2003.10.001

Jacovides, C. P., Tymvios, F. S., Assimakopoulos, V. D., & Kaltsounides, N. A. (2007). The dependence of global and diffuse PAR radiation components on sky conditions at Athens, Greece. *Agricultural and Forest Meteorology*, *143*(3), 277–287. https://doi.org/10.1016/j.agrformet.2007.01.004

Jakob, C., & Klein, S. A. (2000). A parametrization of the effects of cloud and precipitation overlap for use in general-circulation models. *Quarterly Journal of the Royal Meteorological Society*, *126*(568), 2525–2544. https://doi.org/10.1002/qj.49712656809

Janjai, S., Wattan, R., & Sripradit, A. (2015). Modeling the ratio of photosynthetically active radiation to broadband global solar radiation using ground and satellite-based data in the tropics. *Advances in Space Research*, *56*(11), 2356–2364. https://doi.org/10.1016/j.asr.2015.09.020

Jiang, H., Yang, Y., Wang, H., Bai, Y., & Bai, Y. (2020). Surface Diffuse Solar Radiation Determined by Reanalysis and Satellite over East Asia: Evaluation and Comparison. *Remote Sensing*, *12*(9), 1387. https://doi.org/10.3390/rs12091387

Kambezidis, H. D., Kaskaoutis, D. G., Kalliampakos, G. K., Rashki, A., & Wild, M. (2016). The solar dimming/brightening effect over the Mediterranean Basin in the period 1979–2012. *Journal of Atmospheric and Solar-Terrestrial Physics*, *150–151*, 31–46. https://doi.org/10.1016/j.jastp.2016.10.006

Kanniah, K. D., Beringer, J., North, P., & Hutley, L. (2012). Control of atmospheric particles on diffuse radiation and terrestrial plant productivity: A review. *Progress in Physical Geography: Earth and Environment*, *36*(2), 209–237. https://doi.org/10.1177/0309133311434244

Kathilankal, J. C., O'Halloran, T. L., Schmidt, A., Hanson, C. V., & Law, B. E. (2014). Development of a semi-parametric PAR (Photosynthetically Active Radiation) partitioning model for the United States, version 1.0. *Geoscientific Model Development*, *7*(5), 2477–2484. https://doi.org/10.5194/gmd-7-2477-2014

Keane, B. J., Ineson, P., Vallack, H. W., Blei, E., Bentley, M., Howarth, S., McNamara, N. P., Rowe, R. L., Williams, M., & Toet, S. (2017). Greenhouse gas emissions from the energy crop oilseed rape (Brassica napus); the role of photosynthetically active radiation in diurnal N2O flux variation. *GCB Bioenergy*, *10*(5), 306–319. https://doi.org/10.1111/gcbb.12491

Kipp, Z., & Zonen, B. V. (2000). CNR1 net radiometer instruction manual. *Kipp & Zonen, Delft*.

Kuo, C.-W., Chang, W.-C., & Chang, K.-C. (2014). Modeling the hourly solar diffuse fraction in Taiwan. *Renewable Energy*, *66*, 56–61. https://doi.org/10.1016/j.renene.2013.11.072

Lei, Y., Letu, H., Shang, H., & Shi, J. (2020). Cloud cover over the Tibetan Plateau and eastern China: A comparison of ERA5 and ERA-Interim with satellite observations. *Climate Dynamics*, *54*(5), 2941–2957. https://doi.org/10.1007/s00382-020-05149-x

LI-COR Terrestrial Radiation Sensors, Type SB Instruction Manual. Publication No. 8609-58. February 1992

Liou, K. N., Gu, Y., Yue, Q., & McFarguhar, G. (2008). On the correlation between ice water content and ice crystal size and its application to radiative transfer and general circulation models. *Geophysical Research Letters*, *35*(13). https://doi.org/10.1029/2008GL033918

Long, C. N., & Ackerman, T. P. (2000). Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects. *Journal of Geophysical Research: Atmospheres*, *105*(D12), 15609–15626. https://doi.org/10.1029/2000JD900077

López, G., Rubio, M. A., Martínez, M., & Batlles, F. J. (2001). Estimation of hourly global photosynthetically active radiation using artificial neural network models. *Agricultural and Forest Meteorology*, *107*(4), 279–291. https://doi.org/10.1016/S0168-1923(01)00217-9

Lozano, I. L., Sánchez-Hernández, G., Guerrero-Rascado, J. L., Alados, I., & Foyo-Moreno, I. (2021). Aerosol radiative effects in photosynthetically active radiation and total irradiance at a Mediterranean site from an 11-year database. *Atmospheric Research*, *255*, 105538. https://doi.org/10.1016/j.atmosres.2021.105538

Lyamani, H., Fernandez-Galvez, J., Perez-Ramirez, D., Valenzuela, A., Anton, M., Alados, I., Titos, G., Olmo, F. J., & Alados-Arboledas, L. (2012). Aerosol properties over two urban sites in South Spain during an extended stagnation episode in winter season. *Atmospheric Environment*, *62*, 424–432. https://doi.org/10.1016/j.atmosenv.2012.08.050

Lyamani, H., Olmo, F. J., Alcántara, A., & Alados-Arboledas, L. (2006). Atmospheric aerosols during the 2003 heat wave in southeastern Spain I: Spectral optical depth. *Atmospheric Environment*, *40*(33), 6453–6464. https://doi.org/10.1016/j.atmosenv.2006.04.048

Manevski, K., Lærke, P. E., Jiao, X., Santhome, S., & Jørgensen, U. (2017). Biomass productivity and radiation utilisation of innovative cropping systems for biorefinery. *Agricultural and Forest Meteorology*, *233*, 250–264. https://doi.org/10.1016/j.agrformet.2016.11.245

Mateos, D., Antón, M., Sanchez-Lorenzo, A., Calbo, J., & Wild, M. (2013a). Long-term changes in the radiative effects of aerosols and clouds in a mid-latitude region (1985-2010). *Global and Planetary Change*, *111*, 288–295. https://doi.org/10.1016/j.gloplacha.2013.10.004

Mateos, David, Antón, M., Valenzuela, A., Cazorla, A., Olmo, F. J., & Alados-Arboledas, L. (2013b). Short-wave radiative forcing at the surface for cloudy systems at a midlatitude site. *Tellus B: Chemical and Physical Meteorology*, *65*(1), 21069. https://doi.org/10.3402/tellusb.v65i0.21069

McCree, K. J. (1972). Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. *Agricultural Meteorology*, *10*, 443–453. https://doi.org/10.1016/0002-1571(72)90045-3

Meloni, D., di Sarra, A., Pace, G., & Monteleone, F. (2006). Aerosol optical properties at Lampedusa (Central Mediterranean). 2. Determination of single scattering albedo at two wavelengths for different aerosol types. *Atmospheric Chemistry and Physics*, *6*(3), 715–727. https://doi.org/10.5194/acp-6-715-2006

Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., & Cox, P. M. (2009). Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, *458*(7241), 1014–1017. https://doi.org/10.1038/nature07949

Mizoguchi, Y., Yasuda, Y., Ohtani, Y., Watanabe, T., Kominami, Y., & Yamanoi, K. (2014). A practical model to estimate photosynthetically active radiation using general meteorological elements in a temperate humid area and comparison among models. *Theoretical and Applied Climatology*, *115*(3), 583–589. https://doi.org/10.1007/s00704-013-0912-2

Nikitidou, E., Tzoumanikas, P., Bais, A. F., & Kazantzidis, A. (2017). The Effect of Clouds on Surface Solar Irradiance, from an All-Sky Camera, in Thessaloniki, Greece. In T. S. Karacostas, A. F. Bais, & P. T. Nastos (Eds.), *Perspectives on Atmospheric Sciences* (pp. 1157–1162). Springer. https://doi.org/10.1007/978-3-319-35095-0_166

Niu, Z., Wang, L., Niu, Y., Hu, B., Zhang, M., & Qin, W. (2019). Spatiotemporal variations of photosynthetically active radiation and the influencing factors in China from 1961 to 2016. *Theoretical and Applied Climatology*, *137*(3–4), 2049–2067. https://doi.org/10.1007/s00704-018-2727-7

Ortiz-Amezcua, P., Guerrero-Rascado, J. L., Granados-Muñoz, M. J., Benavent-Oltra, J. A., Böckmann, C., Samaras, S., Stachlewska, I. S., Janicka, Ł., Baars, H., Bohlmann, S., & Alados-Arboledas, L. (2017). Microphysical characterization of long-range transported biomass burning particles from North America at three EARLINET stations. *Atmospheric Chemistry and Physics*, *17*(9), 5931–5946. https://doi.org/10.5194/acp-17-5931-2017

Peng, S., Du, Q., Lin, A., Hu, B., Xiao, K., & Xi, Y. (2015). Observation and estimation of photosynthetically active radiation in Lhasa (Tibetan Plateau). *Advances in Space Research*, *55*(6), 1604–1612. https://doi.org/10.1016/j.asr.2015.01.002

Pyrina, M., Hatzianastassiou, N., Matsoukas, C., Fotiadi, A., Papadimas, C. D., Pavlakis, K. G., & Vardavas, I. (2015). Cloud effects on the solar and thermal radiation budgets of the Mediterranean basin. *Atmospheric Research*, *152*, 14–28. https://doi.org/10.1016/j.atmosres.2013.11.009

Qin, W., Wang, L., Zhang, M., & Niu, Z. (2019). First Effort at Constructing a High-Density Photosynthetically Active Radiation Dataset during 1961–2014 in China. *Journal of Climate*, 32, 2761-2780. https://doi: 10.1175/JCLI-D-18-0590.1

Ramanathan, V., Cess, R. D., Harrison, E. F., Minnis, P., Barkstrom, B. R., Ahmad, E., & Hartmann, D. (1989). Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment. *Science*, *243*(4887), 57–63. https://doi.org/10.1126/science.243.4887.57

Ridley, B., Boland, J., & Lauret, P. (2010). Modelling of diffuse solar fraction with multiple predictors. *Renewable Energy*, *35*(2), 478–483. https://doi.org/10.1016/j.renene.2009.07.018

Roebroek, C. T. J., Melsen, L. A., Hoek van Dijke, A. J., Fan, Y., & Teuling, A. J. (2020). Global distribution of hydrologic controls on forest growth. *Hydrology and Earth System Sciences*, *24*(9), 4625–4639. https://doi.org/10.5194/hess-24-4625-2020

Ross, J., & Sulev, M. (2000). Sources of errors in measurements of PAR. *Agricultural and Forest Meteorology*, *100*(2), 103–125. https://doi.org/10.1016/S0168-1923(99)00144-6

Salvador, P., Alonso-Pérez, S., Pey, J., Artíñano, B., de Bustos, J. J., Alastuey, A., & Querol, X. (2014). African dust outbreaks over the western Mediterranean Basin: 11-year characterization of atmospheric circulation patterns and dust source areas. *Atmospheric Chemistry and Physics*, *14*(13), 6759–6775. https://doi.org/10.5194/acp-14-6759-2014

Sanchez, G., Serrano, A., & Cancillo, M. L. (2017). Modeling the erythemal surface diffuse irradiance fraction for Badajoz, Spain. *Atmospheric Chemistry and Physics*, *17*(20), 12697–12708. https://doi.org/10.5194/acp-17-12697-2017

Sánchez, G., Serrano, A., Cancillo, M. L., & García, J. A. (2012). Comparison of shadow-ring correction models for diffuse solar irradiance. *Journal of Geophysical Research: Atmospheres*, *117*(D9). https://doi.org/10.1029/2011JD017346

Sanchez-Lorenzo, A., Enriquez-Alonso, A., Calbó, J., González, J.-A., Wild, M., Folini, D., Norris, J. R., & Vicente-Serrano, S. M. (2017). Fewer clouds in the Mediterranean: Consistency of observations and climate simulations. *Scientific Reports*, *7*(1), 41475. https://doi.org/10.1038/srep41475

Spencer, J. W. (1971). Fourier series representation of the position of the sun. *Search*, *2*(5), 172.

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P. M. (2013). IPCC, 2013. *Climate Change*.

Su, W., Charlock, T. P., Rose, F. G., & Rutan, D. (2007). Photosynthetically active radiation from Clouds and the Earth's Radiant Energy System (CERES) products. *Journal of Geophysical Research: Biogeosciences*, *112*(G2). https://doi.org/10.1029/2006JG000290

Tan, C., Wang, D., Zhou, J., Du, Y., Luo, M., Zhang, Y., & Guo, W. (2018). Remotely Assessing Fraction of Photosynthetically Active Radiation (FPAR) for Wheat Canopies Based on Hyperspectral Vegetation Indexes. *Frontiers in Plant Science*, *9*. https://doi.org/10.3389/fpls.2018.00776

Titos, G., Del Águila, A., Cazorla, A., Lyamani, H., Casquero-Vera, J. A., Colombi, C., Cuccia, E., Gianelle, V., Močnik, G., Alastuey, A., Olmo, F. J., & Alados-Arboledas, L. (2017). Spatial and temporal variability of carbonaceous aerosols: Assessing the impact of biomass burning in the urban environment. *The Science of the Total Environment*, *578*, 613–625. https://doi.org/10.1016/j.scitotenv.2016.11.007

Titos, G., Foyo-Moreno, I., Lyamani, H., Querol, X., Alastuey, A., & Alados-Arboledas, L. (2012). Optical properties and chemical composition of aerosol particles at an urban location: An estimation of the aerosol mass scattering and absorption efficiencies. *Journal of Geophysical Research: Atmospheres*, *117*(D4). https://doi.org/10.1029/2011JD016671

Torres, J. L., De Blas, M., García, A., & de Francisco, A. (2010). Comparative study of various models in estimating hourly diffuse solar irradiance. *Renewable Energy*, *35*(6), 1325–1332. https://doi.org/10.1016/j.renene.2009.11.025

Trenberth, K. E., Fasullo, J. T., & Kiehl, J. (2009). Earth's global energy budget. *Bulletin of the American Meteorological Society*, *90*(3), 311–324.

Trisolino, P., di Sarra, A., Anello, F., Bommarito, C., Di Iorio, T., Meloni, D., Monteleone, F., Pace, G., Piacentino, S., & Sferlazzo, D. (2018). A long-term time series of global and diffuse photosynthetically active radiation in the Mediterranean: Interannual variability and cloud effects. *Atmospheric Chemistry and Physics*, *18*(11), 7985–8000. https://doi.org/10.5194/acp-18-7985-2018

Trisolino, P., Sarra, A. di, Meloni, D., & Pace, G. (2016). Determination of global and diffuse photosynthetically active radiation from a multifilter shadowband radiometer. *Applied Optics*, *55*(29), 8280–8286. https://doi.org/10.1364/AO.55.008280

Tsubo, M., & Walker, S. (2005). Relationships between photosynthetically active radiation and clearness index at Bloemfontein, South Africa. *Theoretical and Applied Climatology*, *80*(1), 17–25. https://doi.org/10.1007/s00704-004-0080-5

Tzoumanikas, P., Nikitidou, E., Bais, A. F., & Kazantzidis, A. (2016). The effect of clouds on surface solar irradiance, based on data from an all-sky imaging system. *Renewable Energy*, *95*, 314–322. https://doi.org/10.1016/j.renene.2016.04.026

Valenzuela, A., Olmo, F. J., Lyamani, H., Antón, M., Quirantes, A., & Alados-Arboledas, L. (2012). Aerosol radiative forcing during African desert dust events (2005–2010) over Southeastern Spain. *Atmospheric Chemistry and Physics*, *12*(21), 10331–10351. https://doi.org/10.5194/acp-12-10331-2012

Vindel, J. M., Valenzuela, R. X., Navarro, A. A., Zarzalejo, L. F., Paz-Gallardo, A., Souto, J. A., Méndez-Gómez, R., Cartelle, D., & Casares, J. J. (2018). Modeling Photosynthetically Active Radiation from Satellite-Derived Estimations over Mainland Spain. *Remote Sensing*, *10*(6), 849. https://doi.org/10.3390/rs10060849

Wang, L., Gong, W., Lin, A., & Hu, B. (2013). Analysis of photosynthetically active radiation under various sky conditions in Wuhan, Central China. *International Journal of Biometeorology*, *58*(8), 1711–1720. https://doi.org/10.1007/s00484-013-0775-3

Wang, L., Gong, W., Hu, B., & Zhu, Z. (2015). Analysis of photosynthetically active radiation in Northwest China from observation and estimation. *International Journal of Biometeorology*, 59(2), 193–204. https://doi.org/10.1007/s00484-014-0835-3

Wang, L., Kisi, O., Zounemat-Kermani, M., Hu, B., & Gong, W. (2016). Modeling and comparison of hourly photosynthetically active radiation in different ecosystems. *Renewable and Sustainable Energy Reviews*, *56*, 436–453. https://doi.org/10.1016/j.rser.2015.11.068

Wild, M. (2009). Global dimming and brightening: A review. *Journal of Geophysical Research-Atmospheres*, *114*, D00D16. https://doi.org/10.1029/2008JD011470

Wild, M. (2016). Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming. *Wiley Interdisciplinary Reviews-Climate Change*, *7*(1), 91–107. https://doi.org/10.1002/wcc.372

WMO. (2008). *Guide to Meteorological Instruments and Methods of Observation, 7th ed, p716*.

Yu, X., Wu, Z., Jiang, W., & Guo, X. (2015). Predicting daily photosynthetically active radiation from global solar radiation in the Contiguous United States. *Energy Conversion and Management*, *89*, 71–82. https://doi.org/10.1016/j.enconman.2014.09.038.

Yao, B., Chao Liu, Yan Yin, Zhiquan Liu, Chunxiang Shi, Hironobu Iwabuchi, and Fuzhong Weng, 2020. Evaluation of cloud properties from reanalyses over East Asia with a radiance-based approach. Atmos. Meas. Tech., 13, 1033–1049, 2020

Zempila, M., Taylor, M., Bais, A., & Kazadzis, S. (2016). Modeling the relationship between photosynthetically active radiation and global horizontal irradiance using singular spectrum analysis. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *182*, 240–263. https://doi.org/10.1016/j.jqsrt.2016.06.003

Zhang, X., Zhang, Y., & Zhoub, Y. (2000). Measuring and modelling photosynthetically active radiation in Tibet Plateau during April–October. *Agricultural and Forest Meteorology*, *102*(2), 207–212. https://doi.org/10.1016/S0168-1923(00)00093-9

Zhang, J., Zhu, J, & Xia, X. (2020). Properties of summer radiation and aerosols at Xinzhou, a suburban site on the North China Plain. Atmospheric and Oceanic Science Letters, 13:6, 493-499, DOI: 10.1080/16742834.2020.1820302

Table 1. Fitting coefficients obtained for the PAR diffuse fraction (k_{PAR}) model.

Table 2. Fitting coefficients obtained for the logistic function fitting k_{PAR} - k_t.

Figure 1. Hourly PAR diffuse fraction (k_{PAR}) modeled (red) and measured (black) versus the hourly clearness index ($k_{t,PAR}$) for the validation subset during the period 1994-1995 at Granada.

Figure 2. Time series of monthly mean PAR_{Global} and $PAR_{Diffuse}$ for all-sky (solid lines) and clear-sky scenarios (dashed lines) for the entire analyzed period (2008-2018) at Granada.

Figure 3. Monthly statistics for PAR_{Global} for (a) all- and (b) clear-sky, and $PAR_{Diffuse}$ for (c) all- and (d) clear-sky, during the period 2008-2018 at Granada. In each box central lines are the median, and upper and lower limits refer to percentiles 75th and 25th. Limits of the segment represent minimum and maximum average month value in the period, and red stars are the mean values.

Figure 4. Cloudless description in 2008-2018 period. (a) Contribution of the clear-sky (white bars; TCC ≤ 0.1), broken clouds (gray bars; 0.1 < TCC ≤ 0.9) and overcast (black bars; TCC > 0.9), (b) percentage of low, medium and high clouds, (c) total cloud cover (TCC), (d) total column cloud liquid water (TCLW) and (e) total column cloud ice content (TCIW). Bars in box-plots correspond to the minimum and maximum values. The box limits are the P25 and P75 percentiles and the midline is the median.

Figure 5. Annual statistics of CRE for the period 2008-2018: (a) global and (b) diffuse component. Bars correspond to the minimum and maximum values. The box limits are the P25 and P75 percentiles and the midline is the median.

Figure 6. Relationship between PAR-to-Total ratio and sky conditions for instantaneous values at Granada during the entire period 2008-2018: a) PAR-to-Total vs clearness index (k_t); b) PAR-to-Total vs Total Cloud Cover (TCC). Black curve represents the bin-averaged values and the standard deviations.

Figure 7. Annual statistics of (a) all-sky and (b) clear-sky PAR-to-Total ratio, for the period 2008-2018. Bars correspond to the minimum and maximum values. The box limits are the P25 and P75 percentiles and the midline is the median.

Figure 8. Relationship between PAR diffuse fraction (k_{PAR}) and sky conditions for instantaneous values at Granada during the entire period 2008-2018: a) k_{PAR} vs clearness index (k_t); b) k_{PAR} vs Total Cloud Cover (TOC). Black curve represents the bin-averaged values and the standard deviations.

Fig 9. Annual statistics of (a) all-sky and (b) clear-sky k_{PAR}, for the period 2008-2018. Bars correspond to the minimum and maximum values. The box limits are the P25 and P75 percentiles and the midline is the median.