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# Predicting daily photosynthetically active radiation from global solar radiation in the Contiguous United States

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ABSTRACT

An investigation on the daily photosynthetically active radiation (*PAR*) with the global solar radiation ($R_s$) is conducted at 7 surface radiation budget monitoring stations across the Mainland United States by exploiting a 3 years (2009–2011) data achieve. The clearness index, the diffuse fraction and the skylight brightness along with the dew point temperature and the cosine of solar zenith angle are used to generate empirical relationships for predicting *PAR* from $R_s$. Records of 2009 and 2010 are employed for model establishment, while records of 2011 are used for validation. The accuracy of the models' predictions is evaluated by four statistics parameters, including the coefficient of determination, the root mean square error, the mean percentage error and the relative standard deviation. Results show that the polynomial model taking the clearness index as main parameter plus the cosine of solar zenith angle has the best performance out of ten proposed models. And the clearness index is capable to be the indicator for *PAR* prediction, as a substitute of the combination of the diffuse fraction and the skylight brightness.

## 1. Introduction

Photosynthetically active radiation (*PAR*) is a primary stream of incoming global solar radiation ($R_s$) reaching the earth surface designated from 400 to 700 nm, which photosynthetic organisms are able to use in the process of photosynthesis [1–4]. Thus, the knowledge of *PAR* spectral components of $R_s$ at the surface becomes an imperative requirement in different technological and scientific applications of solar radiation information [2]. *PAR* is a necessary variable for applications dealing with plant physiology, biomass production and natural illumination in greenhouses [5]. It plays an important role in providing energy to support photosynthetic processes and is the primary production of green plants through of chlorophyll synthesis and photosynthesis, which results in the conversion of radiation energy into chemical energy [6,7]. Therefore, *PAR* is indispensable for many agricultural and hydrological studies, and is also a necessary input in models accompanying with terrestrial photosynthesis, primary productivity calculations and ecosystem–atmosphere $CO_2$ exchange [8]. It contributes significantly in comprehensive studies of radiation climate, remote sensing of vegetation, and radiation regimes of plant canopy, photosynthesis and productivity models of vegetation [7].

Though *PAR* can be estimated from reanalysis methods or satellite imagery [9–11], ground stations are still widely applied for the accurate solar radiation monitoring. In the Contiguous United States, several surface radiation networks have been established for monitoring the surface energy budget and validation for satellite remote sensing products [12,13], including the SURFRAD, ISIS, BSRN, UVMRP, Ameriflux and NEUBrew network [14–17]. However, as the explicit requirements for the unique spectral component of *PAR*, it is not typically monitored at normal weather stations in the United States. Meanwhile, $R_s$ is widely monitored for the U.S. Climate Reference Network (USCRN) program [18]. It is noted that $R_s$ can also be estimated from sunshine duration hours [19–23], which provides abundant records for $R_s$ [23–25].

Numerous studies have been conducted for modeling *PAR* from $R_s$ at specific locations all around the world [1,2,5,30,36–42] (Table 1). Rao [36] studied a three-year (1980–1982) record of global solar radiation and *PAR* measurements made at Corvallis, Oregon, U.S.A. and established a simple ratio for $PAR/R_s$. Alados et al. [5] proposed four different models for estimating *PAR* from $R_s$ using the clearness of the sky, the brightness of the sky, the dew point temperature, the clearness index and the sine of sun elevation angle as indicators. Jacovides et al. [7] studied the ratio of

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## Nomenclature

| | |
|---|---|
| SURFRAD | the Surface Radiation budget network |
| $PAR$ | photosynthetically active radiation (MJ/m$^2$) |
| $R_s$ | global solar radiation (MJ/m$^2$) |
| $R_0$ | daily extraterrestrial solar radiation (MJ/m$^2$) |
| $R_d$ | diffuse radiation on the earth's horizontal surface (MJ/m$^2$) |
| $R_b$ | direct radiation on the earth's horizontal surface (MJ/m$^2$) |
| $S_0$ | solar constant (1361 W/m$^2$) |
| $n$ | Julian day of the calculated day |
| $E_0$ | the vector radius of the Earth's orbit |
| $\Phi$ | the longitude of the location |
| UTC | the standard time for the location, |
| $\Phi_{ST}$ | standard meridian for the local time zone |
| $r^2$ | coefficient of determination |
| $RMSE$ | root mean square error |
| $MPE$ | mean percentage error |
| $RSD$ | relative standard deviation |
| $K_t$ | clearness index (ratio of the horizontal global radiation to the corresponding radiation out of the atmosphere) (unitless) |
| $K_d$ | diffuse fraction (ratio of the diffuse horizontal radiation to global horizontal radiation) (unitless) |
| $\Delta$ | skylight brightness (ratio of the diffuse horizontal radiation to the corresponding radiation out of the atmosphere) (unitless) |
| $T_d$ | dew point temperature (°C) |
| $\cos\theta_Z$ | cosine of solar zenith angle (unitless) |

*PAR* to broadband solar radiation measured in Cyprus and found that it mostly depends on the sky condition. Li et al. [41] proposed a simple model for predicting monthly ratios of *PAR* to global solar radiation measured at northern Tibetan Plateau, China. Escobedo et al. [2] analyzed the relationship between *PAR* and $R_s$ under various sky conditions at Botucatu, Brazil. The range of the *PAR* fraction listed in Table 1 suggests the desirability for recalibration due to local climatic differences.

Yet, upon our knowledge, quite few recent researches analyze the relationship between *PAR* and $R_s$ across the Contiguous United States. The major objective of this paper is to investigate the daily *PAR* with $R_s$ at 7 surface radiation stations across the Mainland United States by exploiting a 3 years (2009–2011) data achieve. Three main factors, the clearness index ($K_t$, ratio of the horizontal global radiation to the corresponding radiation available out of the atmosphere), the diffuse fraction ($K_d$, ratio of the diffuse horizontal radiation to global horizontal radiation) and the skylight brightness ($\Delta$, ratio of the diffuse horizontal radiation to the corresponding radiation out of the atmosphere) along with the dew point temperature ($T_d$) and the cosine of solar zenith angle ($\cos\theta_Z$) are taken into account for generating empirical relationships to predict *PAR* from $R_s$. The results can enhance the knowledge of monitoring *PAR* from normally measured global solar radiation in the Contiguous United States.

## 2. Sites and measurements

As mentioned in the introduction part, it is quite rare to have a long time period and comprehensive data achieve including *PAR* and $R_s$ at the same time, along with other land surface radiation parameters, such as: direct solar irradiance, diffuse sky solar irradiance, upward solar irradiance and so on. However, the Surface Radiation budget network (SURFRAD) provides researchers such a chance for studying the U.S. national-scale surface radiation budget in a continuous mode [43].

### 2.1. Background of SURFRAD

SURFRAD is the first of its kind which operates across the United States. The network began in 1995 with four stations and expanded to seven in 2003 [44]. The primary objective of SURFRAD

**Table 1**
Summary of previous studies for estimating *PAR* from $R_s$.

| Location | Land use | Longitude latitude | Elevation (m) | $PAR/R_s$ (%) | Reference |
|---|---|---|---|---|---|
| Jerusalem, Israel | Urban | 31.78°N, 35.22°E | 736 | 48.0 | Stanhill and Fuchs [26] |
| Athalassa, Cyprus | Semi-urban | 35.25°N, 33.6°E | 165 | 42.0 | Jacovides et al. [7] |
| Rockville, USA | Urban | 39°N, 77.16°W | 90 | 49.0 | Stanhill and Fuchs [26] |
| Beijing, China | Urban | 39.4°N, 116.3°E | 57 | 43.5 | Hu et al. [27] |
| Wuhan, China | Urban | 30.51°N, 114.3°E | 30 | 45.3 | Wang et al. [28] |
| Texas, USA | Rural | 30.58°N, 96.35°W | 84 | 47.8 | Britton and Dodd [29] |
| Lusaka, Zambia | Biomass burning | 15.4°S, 28.3°E | 1150 | 43.6 | Finch et al. [30] |
| Tibet, China | Mountain | 39.68°N, 91.33°E | 3688 | 43.9 | Zhang et al. [31] |
| Athens, Greece | Urban | 38°N, 24°E | 205 | 42.9<br>43.7[a] | Jacovides et al. [32] |
| Sede Moshe, Israel | Rural | 31.62°N, 34.82°E | 130 | 47.1 | Stanhill and Fuchs [26] |
| San Joaquin Valley, USA | Rural | 36.66°N, 119.5°W | 104 | 44.9 | Howell et al. [33] |
| Cambridge, England | Semi-rural | 52°N, 0°E | 25 | 50.0 | Szeicz [34] |
| Botucatu, Brazil | Rural | 22.85°S, 48.45°W | 786 | 49.0<br>49.0[a] | Escobedo et al. [3] |
| Guelph, Canada | Urban | 43.55°N, 80.22°W | 334 | 47.0 | Blackburn and Proctor [35] |
| Corvalis, USA | Rural | 44.57°N, 123.23°W | 65.5 | 45.7 | Rao [36] |
| Athens, Greece | Urban | 37.10°N, 23.72°E | 205 | 47.3<br>43.6[a] | Papaioannou et al. [37] |
| Washington, USA | Urban | 38.9°N, 77°W | 22 | 49.0 | Stanhill and Fuchs [26] |
| Bet Dagan, Israel | Urban | 32°N, 34.87°E | 35 | 52.1 | Stanhill and Fuchs [26] |
| Ilorim, Nigeria | Rural | 8.53°N, 4.57°E | 375 | 45.5 | Udo and Aro [6] |

[a] Hourly fraction, otherwise daily fraction.