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Modeling the relationship between photosynthetically active radiation and global horizontal irradiance using singular spectrum analysis

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A B S T R A C T

We report on the construction of generic models to calculate photosynthetically active radiation (PAR) from global horizontal irradiance (GHI), and vice versa. Our study took place at stations of the Greek UV network (UVNET) and the Hellenic solar energy network (HNSE) with measurements from NILU-UV multi-filter radiometers and CM pyranometers, chosen due to their long ($\approx$1 M record/site) high temporal resolution ($\approx$1 min) record that captures a broad range of atmospheric environments and cloudiness conditions. The uncertainty of the PAR measurements is quantified to be $\pm$6.5% while the uncertainty involved in GHI measurements is up to $\approx \pm 7$% according to the manufacturer. We show how multi-linear regression and nonlinear neural network (NN) models, trained at a calibration site (Thessaloniki) can be made generic provided that the input–output time series are processed with multi-channel singular spectrum analysis (M-SSA). Without M-SSA, both linear and nonlinear models perform well only locally. M-SSA with 50 time-lags is found to be sufficient for identification of trend, periodic and noise components in aerosol, cloud parameters and irradiance, and to construct regularized noise models of PAR from GHI irradiances. Reconstructed PAR and GHI time series capture $\approx$95% of the variance of the cross-validated target measurements and have median absolute percentage errors <2%. The intra-site median absolute error of M-SSA processed models were $\approx 8.2 \pm 1.7$ W/m^2 for PAR and $\approx 9.2 \pm 4.2$ W/m^2 for GHI. When applying the models trained at Thessaloniki to other stations, the average absolute mean bias between the model estimates and measured values was found to be $\approx$1.2 W/m^2 for PAR and $\approx$0.8 W/m^2 for GHI. For the models, percentage errors are well within the uncertainty of the measurements at all sites. Generic NN models were found to perform marginally better than their linear counterparts.

1. Introduction

Photosynthetically active radiation (PAR) occupies the narrow spectral range ($\approx$400–700 nm) of solar irradiance and is a key variable in ecophysiological models where accurate estimates are critical [1]. PAR is used to estimate leaf photosynthesis [3,52], to measure the productivity of forests [44], to probe the structure of forest canopies [56], and to calculate the euphotic depth of the oceans [41]. Moreover, the need to better constrain agents involved in climate change, mean that accurate PAR measurements have become central to reliable determination of the level

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of radiation intercepted by high volume biomass and its forcing effect [76,83], as well as the impact of deforestation [14] and climate change on agriculture [48,55]. In terms of PAR measurement, optical instruments have been the most precise and direct method for obtaining PAR values [58,68] but are not routinely carried out at the vast array of global radiometric sites (e.g. [19,71–73]). As a result, in many areas strongly affected by biomass burning such as the vast Amazon region of South America or the southern African savannahs for example, few empirical studies have taken place [1,67]. Consequently, PAR estimates are derived from radiative transfer models (RTMs) or from application of empirical relationships which usually depend sensitively on local conditions ([1,19,23,26,36,70]; Lu et al., 2011). As a result, the advice is to use conversion relationships when combining solar measurements and meteorological parameters [4,25,58,68].

The strong dependence of PAR on global horizontal irradiance (GHI) levels [4] means that it can be derived from a potentially large pool of global measurements. Furthermore, due to the outstanding growth of technologies targeted at deploying the potential of solar energy for electricity production ([34,35]: Executive Summary) as an abundant renewable resource [12,61], a large number of studies [18,40,47,51,54,57,63,80,81] have proposed many methods to derive the GHI that is exploited in Photovoltaic systems (PV) [60], and to assess, map, validate and predict its abundancy worldwide.

While PAR and GHI are strongly inter-connected, a lack of coincidence in their measurements results in inhomogeneous time series that may contain large data gaps. In addition, the PAR to GHI ratio experiences large diurnal or/and seasonal variations due to cloud fraction, solar elevation and perceptible water in the atmosphere [2,58,68]. Thus, different models that assess PAR and GHI under the whole range of sky conditions can be found in the literature ([2–4,10,13,25,28,58,83]; Ross et al. (1998); Rubio et al., 2005).

In this work, we therefore develop and assess the performance of linear regression (LR), multiple linear regression (MLR) and nonlinear neural networks (NN) to generically calculate PAR from GHI (and vice versa). In the multivariate models we include the solar zenith angle (SZA), the columnar perceptible water vapor (WV) and the aerosol optical depth (AOD) at 500 nm in order to account implicitly for the combined effect of cloud and aerosol.

The rest of this report is arranged as follows. In Section 2 we describe the study region and overview the general characteristics of the substantive record of calibrated measurements from UVNET and HNSE used in this work. In Section 3, we carefully describe the data pre-processing and instrumental techniques applied to ensure the integrity of the time series used for model development and assessment. Multi-channel singular spectrum analysis (M-SSA) which we use for decomposition, noise regularization and reconstruction of the time series is described here. Section 4 then presents the construction of linear and nonlinear NN models of PAR from GHI (and vice-versa) together with a description of the procedure used to train and optimize them. Here, we also report their range of validity. In Section 5, we present simulation results for PAR and GHI obtained from feeding the models with satellite-calibrated inputs, and we discuss to what extent the models are generic. We sum up our findings in Section 6 and suggest further work and potential areas of application.

2. Study area and observations

We have selected Greece as the study region for two principal reasons: i) a substantive record (> 100 K measurements per monitoring site) of high temporal resolution (≈ 1 min) co-located data is provided by the two monitoring networks (PAR from UVNET and GHI from HNSE), ii) the region (latitude: 34°–42°N, longitude: 19°–28°E) is located at a crossroad of seasonal aerosol flows (influenced for example by dust episodes from Northern Africa and the Middle East as well as local and transcontinental clouds of biomass burning products) and is exposed to a broad range of atmospheric and cloud conditions. Greece (latitude: 34°–42°N, longitude: 19°–28°E) is located at the southeastern end of the European continent and is characterized by a mountainous peninsular mainland in the southeast Mediterranean basin, covering a region of nearly 132,000 km^2.

2.1. UVNET: NILU-UV PAR measurements

In line with the scientific objectives of UVNET, 7 monitoring stations were established during 2005 to monitor solar irradiance under different atmospheric environments (urban and rural) and climatological conditions. UVNET has the necessary infrastructure in place to ensure smooth and seamless operation and network interconnectivity of the UV monitoring instruments and, in particular, each station is equipped with a NILU-UV multi-filter radiometer that provides irradiance measurements in 5 UV wavelength bins (nominally at 305, 312, 320, 340 and 380 nm) together with a sixth channel for measuring PAR. For all channels, mean values are recorded at one-minute intervals together with the corresponding standard deviation.

2.1.1. Absolute calibration

The absolute calibration of the PAR channel of the NILU-UV radiometers is easy to achieve by comparison against a calibrated standard lamp. While this is available at LAP, it is not available at the other stations. Therefore an alternative, slightly less accurate method has been used based on simulations with the libRadtran radiative transfer model [50] and following the methodology proposed by [16]. In particular, irradiance spectra from 290 to 4500 nm were derived for each station of the network with the *uvspec* model based on the following input information: the total ozone column (TOC), the AOD at 550 nm, WV, SZA, the date, and the height above sea level. For all stations used in this study, TOC, AOD and WV were derived from satellite overpasses. In particular, daily overpass data (Collection 3, V8.3) from the ozone monitoring instrument (OMI) onboard the Aura platform was used for TOC and daily data gridded at $1° \times 1°$ (Collection 5, Level 3) from the moderate resolution imaging spectroradiometer