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An auto-calibration procedure for empirical solar radiation models

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ABSTRACT

Solar radiation data are an important input for estimating evapotranspiration and modelling crop growth. Direct measurement of solar radiation is now carried out in most European countries, but the network of measuring stations is too sparse for reliable interpolation of measured values. Instead of direct measurements, solar radiation may be estimated from empirical solar radiation models that employ more commonly measured variables or direct outputs of general and regional circulation models (such as air temperature). Coefficients for these models are site-dependent. This usually implies that they are estimated for stations with direct radiation measurements, but need to be interpolated for other locations. In this paper, we introduce a procedure to auto-calibrate empirical solar radiation models that are based on daily air temperature range, i.e. Bristow and Campbell (1984), and Hargreaves et al. (1985). Meteosat Second Generation data were used to create two static look-up tables of mean cloud cover and clear-sky transmissivity as input for the auto-calibration procedure. We demonstrate that daily solar radiation can be accurately estimated from daily air temperature range measurements without site-specific empirical coefficients that require stations that measure solar radiation. The average relative root mean square error for our auto-calibrated models was comparable to ground-measurement-based calibration; only 1% higher for the Bristow and Campbell model ($p < 0.05$, $n = 126$), and 2% higher for the Hargreaves model ($p < 0.05$, $n = 126$). The mean bias error, relative mean bias error and the slope of linear regression were not statistically different in comparison to ground-measurement-based calibration for the Bristow and Campbell model. When our new solar radiation retrieval algorithm is used to estimate evapotranspiration, we found similar accuracies when using solar radiation input from ground- and auto-calibration. We conclude that our auto-calibration procedure results in accurate solar radiation retrievals, and requires only daily air temperature time series as input. The same procedure could easily be applied to other empirical solar radiation models.

Software availability

Name of the software: Sirad
Developer: Jędrzej S. Bojanowski
E-mail: jedrzej.bojanowski@gmail.com
Availability: http://CRAN.R-project.org/package=sirad
Program language: R

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1. Introduction

Incoming global surface solar radiation is the main input for estimating evapotranspiration and the accumulation of plant biomass when simulating crop growth. High-quality solar radiation measurements are becoming increasingly available, but the network of measuring stations is too sparse for reliable spatial interpolation of measured values. In addition, prediction of crop yields requires solar radiation estimates at similar spatial and temporal resolutions as for other weather variables derived from global and regional circulation models. This cannot be achieved merely with ground solar radiation measurements.

Different approaches have been developed to estimate solar radiation, which can be grouped into (1) physically-based radiative transfer models, (2) empirical models, based on the statistical relationship between measured meteorological variables and incoming solar radiation, and, more recently, (3) Bayesian neural network methods (Tymvios et al., 2005; Yacef et al., 2012). Physically-based radiative transfer models generally require a large number of input variables. Although empirical models are less data-demanding with respect to input variables, the accuracy of these models largely depends on reference solar radiation data, required to calibrate model coefficients. Accurate calibration can only be achieved for locations where solar radiation is measured. For locations without solar radiation measurements, model coefficients are interpolated (e.g. Bechini et al., 2000; Fodor and Mika, 2011; Miller et al., 2008; van Kappel and Supit, 1998), which can result in larger errors (Bojanowski et al., 2013).

Most empirical models utilise the daily range between minimum and maximum air temperature. Clear days show a greater air temperature range: daytime air temperatures are high because clouds do not absorb incoming solar radiation; night-time air temperatures on the other hand are low because infrared radiation is emitted from the earth's surface to the atmosphere and not radiated back by clouds. This relationship is however weaker during conditions of advection, which reduces the performance of air temperature-based empirical models in some regions for specific periods during the year. Despite this limitation, these empirical models have proved effective to accurately estimate solar radiation at several locations (e.g. Abraha and Savage, 2008; Bristow and Campbell, 1984; Grant et al., 2004; Hargreaves et al., 1985; Trnka et al., 2005).

Two common empirical solar radiation models based on daily air temperature range are the models proposed by Bristow and Campbell (1984) and Hargreaves et al. (1985). The Bristow and Campbell model exploits a saturation-type, exponential relationship between daily total solar radiation and daily air temperature range. In contrast, the Hargreaves model uses a linear relationship between solar radiation and the square root of daily air temperature range. These models are typically calibrated based on measured solar radiation, resulting in site-specific coefficients. Locations measuring solar radiation are relatively sparse over Europe, so approaches for calibrating the models for weather stations without solar radiation measurements would be useful.

The auto-calibration procedure, which we present in this paper, can be used for the calibration of air temperature-based solar radiation models without solar radiation measurements. The term 'auto-calibration' is used here to indicate a calibration without reference solar radiation data. Our procedure is fundamentally based on the assumption formulated by Allen (1997) that on clear-sky days the model should approximate but not over-predict potential solar radiation. Potential radiation can easily be calculated for any location, as it is a function of location, day of the year, and atmospheric composition. Thus, the auto-calibration algorithm firstly identifies cloud-free days, and secondly optimises the model's empirical coefficients to meet Allen's assumption. This is done for a specific location using only a time series of daily air temperature ranges thereby allowing solar radiation to be estimated without prior calibration with measured solar radiation data.

The specific objectives of this paper are: (1) to introduce a procedure to auto-calibrate empirical solar radiation models, (2) to evaluate the performance of the auto-calibration procedure based on the Bristow and Campbell, and Hargreaves air temperature-based models for European weather stations, and (3) to analyse how retrievals of solar radiation through auto-calibrated models affect the estimation of evapotranspiration. We hypothesise that solar radiation retrieved from auto-calibrated models has an accuracy similar to retrievals from models calibrated with measured solar radiation data, and consequently evapotranspiration estimates are also similar.

2. Data

2.1. Data from weather stations

Meteorological data were obtained from 126 weather stations. These data were extracted from the Joint Research Centre's Monitoring Agricultural Resources Unit (JRC-MARS) database, which is the input for the MARS Crop Yield Forecasting System (Baruth et al., 2007; Boogaard et al., 2002). The stations range from latitude 34° N to 58° N, from longitude 9° W to 48° E and in altitude from −5 m to 1677 m. They are located in ten countries: France, Germany, Italy, the Netherlands, Poland, Portugal, Spain, Tunisia, Turkey, and the United Kingdom. Each station reported daily values of maximum (T_{max}) and minimum (T_{min}) air temperatures measured 2 m above the ground, and daily solar radiation measurements (I_s) for at least 60% of the days during 2005–2010. All but six stations provided daily wind speed and water vapour pressure means, thus allowing for the estimation of evapotranspiration.

2.2. Meteosat Second Generation data

We used Meteosat Second Generation data to create two look-up tables to be used within the auto-calibration procedure: (1) a map of mean annual cloud fractional cover, and (2) a map of clear-sky atmospheric transmissivity. The data used to estimate cloud fractional cover are described in Section 2.2.1. The data used for the clear-sky atmospheric transmissivity retrieval are described in Section 2.2.2. It should be emphasised that current satellite data are not required for using the auto-calibration procedure, since, once calculated, two satellite-derived maps (look-up tables) are stored within the auto-calibration algorithm. Alternative methods to those used here exist to derive both of these maps. Clear-sky transmissivity may alternatively be estimated based on atmospheric composition (e.g. Frouin et al., 1989), while a map of mean cloud fractional cover can be derived from interpolation of values measured at weather stations. However, the MSG-derived estimates have the advantage of being spatially continuous and thus allow deriving the mean cloud fractional cover and clear-sky transmissivity maps without interpolating ground measurements.

2.2.1. Cloud fractional cover

To obtain a map of mean annual cloud fractional cover we used five years (2007–2011) of the monthly cloud fractional cover product provided by EUMETSAT's Satellite Application Facility on Climate Monitoring (CM SAF). The product is derived from 15-min pixel-based cloud detection from visible and near-infra-red Meteosat Second Generation SEVIRI data (Derrien and LeGléau, 2005), developed by the Satellite Application Facility for the project 'Support to Nowcasting and Very Short Range Forecasting' (Geiger et al., 2008). The monthly cloud fractional cover is delivered by the CM SAF at 15 km × 15 km resolution. For each pixel, we calculate the average of all monthly values to obtain the mean annual cloud fractional cover (in %).

2.2.2. Surface solar radiation

To estimate clear-sky atmospheric transmissivity, we used six years (2005–2010) of the down-welling surface shortwave radiation flux (DSSF) daily product derived from the Meteosat Second Generation satellite data, for which the pixel size is 3 km at the equator and approximately 5 km in Central Europe (Geiger et al., 2008). The solar radiation product is generated and made freely available by the Land Surface Analysis Satellite Applications Facility (LSA SAF) and further processed by the Flemish Institute for Technological Research (VITO) on behalf of the Joint Research Centre's Monitoring Agriculture Resources (MARS) Unit. The solar radiation