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Validation of models that estimate the clear sky global and beam solar irradiance

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Abstract

The optimal utilization of solar energy requires a thorough characterization of the solar resource. The most accurate way is to measure that resource in situ. However accurate measurements are not a common commodity, especially over longer time spans. To circumvent the lack of ground based measurements, models can be applied to estimate solar irradiance components. A fundamental component is clear sky irradiance. In particular, clear sky irradiance is used as the normalization function in models that convert meteorological satellite images into irradiance, or in models that decompose global irradiance into diffuse/direct fraction. It is therefore important to evaluate and validate clear sky irradiance models.

This paper presents the results of a validation of hourly clear sky models spanning up to eight years. The validation relies on high quality measurements at 22 locations in Europe and around the Mediterranean region. Seven models are evaluated. They were selected on the basis of their published performance, their simplicity of use, and/or their computational speed; two different sources of the aerosol load are used as input to the models.

The three best models show a low bias and a standard deviation ranging from ±3% to ±5%. The standard deviation of the bias across the 22 locations is of the same order of magnitude. The observed bias patterns can be largely traced to inaccuracies inherent to the sources aerosol optical depth. No particular seasonal effects are noted. A consistent limitation across all selected models, even if their direct irradiance performance can be judged satisfactory based on the standard deviation metric, is that they tend to fall short of observations for a given clear sky global clearness index value.

Keywords: Clear sky solar irradiance; Model validation; Daily aerosol optical depth; Water vapor column

1. Introduction

Anthropogenic activities have become an important factor in climate change. One of the aspects of this activity is an impact on the solar irradiance reaching the ground over the long term. It is essential to understand the impact of such changes on the environment (Cutforth, 2007; Stanhill, 2001). Unfortunately, the number and geographic distribution of quality ground irradiance measurement stations is insufficient to accurately access the global impacts of changes to solar irradiance at the surface, especially for direct normal (beam) irradiance (*DNI*). To circumvent this lack of ground measured data, meteorological satellites can be of great help. Models converting the satellite images into different radiation components such as SolarGIS (Suri, 2004; Cebecauer, 2011), EnMetSol (Hammer, 2009), Helioclim (Blanc, 2011), IrSOLaV (Zarzalejo, 2009), Solemi (Meyer, 2003), CM-SAF (Müller, 2009) or Heliomont

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Nomenclature

Solar radiation
GHI or G_h horizontal global irradiance
DIF or D_h horizontal diffuse irradiance
DNI or B_n normal (beam) irradiance
B_h horizontal beam irradiance
I_o sun-earth distance corrected solar constant
K_t global irradiance clearness index
K_t' modified global clearness index
K_b beam clearness index

Solar geometry
AM optical air mass
z solar zenith angle

Meteorologic measurements
T_a ground ambient temperature
RH relative humidity

Atmospheric parameters
α size Angström coefficient
β turbidity Angström coefficient
aod aerosol optical depth
Δ_{cda} clear and dry panchromatic optical depth
Δ_a aerosol panchromatic optical depth
Δ_w water vapor panchromatic optical depth
O_3 atmospheric ozone
T_{LAM2} Linke turbidity coefficient at air mass 2
w atmospheric water vapor content (or column)

Statistics
mbd mean bias difference
sd standard deviation
bsd standard deviation of the bias

(Stoekli, 2013), are becoming increasingly efficient. The clear sky index (global irradiance normalized by the corresponding clear sky irradiance) is often effectively used in lieu of the clearness index (global irradiance normalized by the corresponding extra-atmospheric irradiance) to eliminate seasonal effects on stationary time series (Hansen, 2010), to derive typical meteorological years (TMY) from long term time series, or for forecasting purposes (Pelland, 2013; Engerer, 2014). The capability of these models to estimate the radiation reaching the ground is directly related to the precision of the clear sky model used as normalization function.

When the geographic and geometrical parameters are known (altitude, albedo, solar zenith angle, etc.), the two main input variables of clear sky models are the atmospheric aerosol optical depth (*aod*) and the total water vapor column (w). Whereas parameters like the total atmospheric amount of ozone or the NO_2 have a minor impact on solar radiation transmissivity, aerosol optical depth and water vapor have a substantial influence on the absorptivity and transmissivity of the radiation during its atmosphere crossing. Therefore, to obtain good estimates of the clear sky irradiance, these two inputs must be known with the best possible precision and a good time and space granularity. The atmospheric water vapor content (w) can be retrieved with relatively low uncertainty (±15%) from ground temperature (T_a) and relative humidity (RH) measurements (Smith, 1966; Atwater, 1976). Because of its higher spatial and temporal variability, accurate estimates of aerosol optical depth (*aod*) are based on photometric measurements. Unfortunately, measurements of *aod* are scarce, especially over the long term, and their spatial repartition is poor. It is therefore important to understand how the choice of a model and of its input data, influence the uncertainties of modeled clear sky irradiance.

In a previous study (Ineichen, 2006), the author presented a short-term (one-year) validation of clear sky models using Linke turbidity (Linke, 1922) climatic data banks as an input – Linke turbidity was converted to aerosol optical depth with the help of Ineichen model (Ineichen, 2002). In the present paper, a long term validation (up to eight years) of seven clear sky models is presented. This validation is based on daily aerosol atmospheric content derived from two sources: (1) ground measurements and (2) the MACC-II project (Kaiser et al., 2012).

2. Clear sky models

Seven of the best-performing and/or widely used models are selected for evaluation. The choice of models is based on their performance, their ease of use and their computation speed. These models require aerosol optical depth (*aod*) and water vapor column (w) as an input. Two of the models use Linke turbidity coefficient at air mass *2* (TL_{AM2}) as an input.

2.1. McClear model

The McClear is the most recent clear sky model. It is a fully physical model developed by Mines Paris Tech (Lefèvre, 2013). The core of the model consists of look-up tables (LUT) calculated with the help of the LibRadTran radiative transfer model (Mayer and Killing, 2005; Mayer et al., 2010) in a 10-dimensions space including aerosol optical depths at two wavelengths, partial aerosol optical depths for the determination of the aerosol type,