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Validation of direct normal irradiance predictions under arid conditions: A review of radiative models and their turbidity-dependent performance

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ABSTRACT

In this study, a detailed review of the performance of 24 radiative models from the literature is presented. These models are used to predict the clear-sky surface direct normal irradiance (DNI) at a 1-min time resolution. Coincident radiometric and sunphotometric databases of the highest possible quality, and recorded at seven stations located in arid environments, are used for this analysis. At most sites, an extremely large range of aerosol loading conditions and high variability in their characteristics are noticed. At one site (Solar Village), DNI was measured routinely with an active cavity radiometer with very low uncertainty compared to field pyrheliometers, which makes its dataset exceptional.

The reviewed models are categorized into 5 classes, depending on the number of aerosol-related inputs they require. One of the models (RRTMG) is considerably more sophisticated (and thus less computationally efficient) than the other models—which are all of the parametric type currently in use in solar applications, and specifically devised for cloudless conditions. RRTMG is more versatile and is selected here for benchmarking purposes.

The results show good consistency between the different stations, with generally higher prediction uncertainties at sites experiencing larger mean aerosol optical depth (AOD). Disaggregation of the performance results as a function of two aerosol optical characteristics (AOD at 1 μm, β, and Ångström exponent, α) shows that the simplest parametric models' performance decreases when subjected to turbidity conditions outside of what is "normal" or "typical" under temperate climates. Only a few parametric models perform well under all conditions and at all stations: REST2, CPCR2, MMAC, and METSTAT, in decreasing order of performance. The Ineichen and Hoyt models perform adequately at low AODs, but diverge beyond a specific limit. REST2 is the only parametric model that performs similarly to the RRTMG benchmark under all AOD regimes observed here—and even sometimes better.

The inspection of the models' performance when considering the simultaneous effects of both β and α reveals a clear pattern in the models' error, which is influenced by the frequency distribution of α values. This suggests most models may have difficulty in correctly capturing the effect of α, and/or that observational and instrumental issues at high AOD values may also enhance the apparent model prediction errors.

A study of the specific sensitivity of DNI on AOD confirmed previous findings. It is concluded that, assuming a "perfect" model, DNI can be modeled within 5% accuracy only if β is known to within ≈ 0.02.

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1. Introduction

The prediction of surface solar irradiance is necessary in a wide range of applications, particularly those pertaining to solar energy, atmospheric sciences, climate and meteorology. The latter two applications typically use a variety of heavyweight numerical weather prediction (NWP) models—including general circulation models, such as the Community Atmosphere Model (CAM; http://www.cesm.ucar.edu/models/atm-cam/), limited area models, such as the Weather Research and Forecasting Model (WRF; http://www.wrf-model.org/index.php), or near-real time diagnostic systems, such as the GOES Surface and Insolation Products (GSIP; http://www.ospo.noaa.gov/Products/land/gsip/index_v3.html). In such modeling environments surface solar irradiance prediction is most generally obtained with detailed radiative transfer models (RTMs), such as the short-wave Rapid Radiative Transfer Model for General Circulation Models (RRTMG; [1,2]). This type of model has the advantage of being derived in most part from physical principles, which makes the model inherently "universal", and normally flexible enough to accommodate any possible atmospheric condition. These models usually predict irradiance at many vertical levels through the atmosphere, and with sufficiently good spectral detail for most atmospheric applications. However, when the end result is specifically limited to *broadband surface* irradiance (as most often the case in solar energy, for instance), the spectral and vertically-resolved information becomes essentially superfluous (although it might be necessary for *intermediate* results, as part of the modeling of diffuse irradiance, for instance). The successful deployment of solar power systems requires a favorable solar resource, which means high values of Direct Normal Irradiance (DNI), and Global Horizontal Irradiance (GHI), and low values of Diffuse Horizontal Irradiance (DIF), most of the time. The design, performance analysis, and financial evaluation of such large systems also require long historical time series of DNI and GHI, which are currently generated by the combination of (i) clear-sky irradiance models and (ii) satellite observations of atmospheric radiance, used to derive cloud attenuation at any instant and location. The errors in clear-sky calculations themselves may represent a significant part of the total uncertainty in modeled irradiance time series [3]. Calculations for such applications must be done at relatively high temporal resolution (15- to 60-min time steps) and high spatial resolution (i.e., small cell sizes, of typically 3 km). This involves a considerable quantity of irradiance calculations, for which the detailed RTMs may not be the most appropriate or efficient. Additionally, they usually require specialized inputs about the state of the atmosphere, which are not easily obtained at the required temporal or spatial resolution. Under such circumstances, much faster and simpler calculations than those possible with the detailed RTMs are desirable.

One practical solution is to use simple RTMs that only calculate the surface irradiance without vertical or spectral detail. Such RTMs are indeed much faster, but this speed is obtained at the cost of considerable simplifications in the solution of the radiative transfer problem. Such simplifications are most typically employed to obtain the surface DIF, and also to evaluate the effects of aerosols on the direct and diffuse fluxes. These simplifications consist in parameterizations and/or empirical functions, whose validity may or may not cover the whole possible range of atmospheric conditions that are encountered in practice. For clarity, such simplified algorithms will be referred to as "parametric models" in what follows.

It is known that DNI is much more sensitive to various atmospheric constituents (particularly aerosols) than GHI (e.g., [4]). This is of concern because accurate DNI predictions are of utmost importance for concentrating solar systems, while the accuracy of various DNI models and their derived long time series has been seriously questioned, particularly over high-turbidity areas [5–8]. Before adopting such parametric models for "mission critical" applications, it is therefore essential to validate them extensively. This can be done by comparing their predictions to high-quality irradiance observations from research-class stations.

This contribution includes a review of models that are appropriate to predict DNI under cloudless-sky conditions, based on the solar literature from the last four decades. Since many such models have been proposed during that period, a pre-selection is in order for conciseness. The present review is thus limited to the best models identified in various multi-model validation studies, e.g., [6,8–11], as well as some models that have been overlooked so far, and recently published models. For benchmarking purposes, the more physical and universal RRTMG model has been added as reference. It solves the solar radiative transfer problem with a two-stream algorithm [12] at 14 distinct spectral bands from 0.2 to 12.2 μm. It accounts for extinction by water vapor, carbon dioxide, ozone, methane, oxygen, nitrogen, aerosols and Rayleigh scattering. Recently, [13] have evaluated the performance of RRTMG—as implemented in the WRF NWP model—at predicting clear-sky estimates of GHI, DNI and DIF over the contiguous US region. That study revealed an outstanding performance of the model, always predicting within the expected observational error range. Furthermore, RRTMG is used to solve the solar radiative transfer problem in many NWP models, including the Integrated Forecasting System (IFS) [14] of the European Center for Medium-Range Weather