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REST2: High-performance solar radiation model for cloudless-sky irradiance, illuminance, and photosynthetically active radiation – Validation with a benchmark dataset

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Abstract

REST2, a high-performance model to predict cloudless-sky broadband irradiance, illuminance and photosynthetically active radiation (PAR) from atmospheric data, is presented. Its derivation uses the same two-band scheme as in the previous CPCR2 model, but with numerous improvements. Great attention is devoted to precisely account for the effect of aerosols, in particular.

Detailed research-class measurements from Billings, OK are used to assess the performance of the model for the prediction of direct, diffuse and global broadband irradiance. These measurements were made in May 2003 during a sophisticated radiative closure experiment, which involved the best radiometric instrumentation currently available and many ancillary instruments. As a whole, these exceptional measurements constitute the only known modern benchmark dataset made specifically to test the intrinsic performance of radiation models. Using this dataset as reference, it is shown that REST2 performs better than CPCR2 for irradiance, illuminance or PAR predictions. The availability of the turbidity data required by REST2 or other similar models is also discussed, as well as the effect that turbidity has on each component of broadband irradiance, PAR irradiance and illuminance, and on the diffuse/global PAR ratio.

Keywords: Solar radiation; Irradiance; Illuminance; Photosynthetically active radiation; Radiation model; Validation; Radiative closure; Performance assessment; Radiometry; Diffuse radiation; Turbidity; Aerosols

1. Introduction

Many solar energy applications require an evaluation of the radiation input to solar energy systems from meteorological data. Cloudless-sky data are particularly important because they correspond to the maximum output of solar systems. They are also needed for the design and sizing of solar systems or air conditioning equipment in buildings or vehicles.

Recent studies (Gueymard, 2003b,a) have shown that the accuracy of many broadband models of the literature was not always satisfactory, primarily because of the extreme simplicity of their parameterizations. These studies also introduced two high-performance models to predict direct irradiance. However, in most applications, it is also necessary to predict diffuse and global irradiance. It is the purpose of this contribution to propose a complete and high-performance model to predict direct, diffuse and global irradiance. This goal is achieved by improving the algorithms that were used to obtain the earlier two-band CPCR2 model (Gueymard, 1989b), which has been validated by various studies (see, e.g., Battles et al., 2000; Gueymard, 1993a; Ineichen, 2006; Olmo et al., 2001). Despite these good results, modelling improvements are now deemed justified by the fact that CPCR2 has been developed in the early 1980s, a period after which the fields of atmospheric radiative transfer modelling and radiative

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measurements have made considerable progress. Four important scientific achievements of the 1980–2005 period can be specifically singled out for further discussion: (i) the high-resolution (e.g., line-by-line) absorption properties of many atmospheric gases have been obtained by spectrometry and are now described in large databases such as HITRAN (Rothman et al., 2005), to which many atmospheric radiative codes refer; (ii) better knowledge of the optical properties of aerosols and refined modelling of their scattering effects are now available; (iii) new experimental techniques and calibration procedures for the precise measurement of diffuse and global irradiance have emerged on the path of optimal measurement procedures (Michalsky et al., 1999), yielding significantly better accuracy under clear skies in particular (Michalsky et al., 2005), and therefore also better reference datasets for performance assessment studies; and (iv) specialized ancillary measurements describing the current atmospheric conditions are now carried out (from ground or space) more precisely, more frequently, and with a better spatial distribution than ever before, hence providing more complete and accurate inputs to the most detailed radiative models. All these factors do contribute to more efficient modelling and are appropriately used (directly or indirectly) in what follows. The goal here is to predict irradiances under cloudless conditions with accuracies comparable to that of the best radiometers, but without the need for spectral radiative models such as SMARTS (Gueymard, 2001) or SOLIS (Mueller et al., 2004), whose input data and file management requirements are substantially more challenging.

The present contribution is limited to the deterministic prediction of solar irradiance, illuminance and photosynthetically active radiation (PAR) under cloudless skies. Studies are underway to propose a cloud transmittance algorithm as well.

2. Modelling issues

As shown in previous studies (Gueymard, 1993a, 2003b,a) the performance of a broadband model under cloudless skies is determined in great part by that of the algorithm and input it uses to describe the aerosol transmittance, simply because aerosols are normally the major source of extinction under clear skies. A general finding common to these studies is that models that perform best are those whose aerosol algorithm is sufficiently detailed, and rely on spectral aerosol optical depth data. From the Bouguer–Beer–Lambert law, the spectral aerosol transmittance, $T_{a\lambda}$, can be obtained as

$$T_{a\lambda} = \exp(-m\tau_{a\lambda}) \quad (1)$$

where $\tau_{a\lambda}$ is the spectral aerosol optical depth (AOD) along a vertical atmospheric column and m is the relative slant pathlength (or "air mass"). Because $\tau_{a\lambda}$ is not constant over the spectrum, and the radiation impinging on the aerosol layer is already attenuated by the above atmospheric layers, the often-used extrapolation of Eq. (1) to the broadband domain

$$T_a = \exp(-m\tau_a) \quad (2)$$

(where T_a is the broadband aerosol transmittance and τ_a is the broadband AOD) cannot produce correct results. This fact led to the development of substantially more complicated – but also more accurate – transmittance expressions, as used in the MLWT2 or REST models (Gueymard, 2003a).

A related issue is that, until the late 1990s, there was no reliable, comprehensive, or readily available source of spectral AOD data covering the globe. This has changed dramatically with the development of various sunphotometric ground networks, such as AERONET (Holben et al., 1998). For even wider geographic coverage, it is also possible to use gridded AOD data from various satellite-borne sensors or from chemical transport models. Even though their current accuracy is still not comparable to that of ground-based sunphotometers, it is anticipated that major improvements in instrumentation, retrieval algorithms or aerosol transport modelling will provide a wealth of sufficiently accurate data in the coming years, as discussed further in Section 4.

3. Derivation of the REST2 model

Previous results from in-depth performance assessment studies (Battles et al., 2000; Gueymard, 1993a; Olmo et al., 2001) have shown that the CPCR2 two-band model (Gueymard, 1989b) was a top performer when compared to simpler broadband models. A recent and thorough study (Gueymard, 2003b,a) demonstrated that CPCR2 performed consistently well to predict direct normal irradiance (DNI), under both ideal and realistic conditions. However, two newly introduced models (Gueymard, 2003a) tended to perform as well or better than CPCR2 for that purpose. These new models, REST and MLWT2, are however limited to the prediction of DNI and are therefore not "all purpose" models, as mentioned earlier. In this contribution, a high-performance model is therefore developed to use the general features of CPCR2 (two-band structure for accuracy, modelling of direct, diffuse and global irradiance) and update its transmittance functions – which were based on now 25-year-old spectral information – using the same basis as in REST. Hence the REST2 acronym (Reference Evaluation of Solar Transmittance, 2 bands), a two-band version of the REST model but with more capabilities. A preliminary version of the model has been presented previously (Gueymard, 2004b). The present contribution describes some new features of the model, includes its latest algorithmic improvements, and proposes a benchmark dataset for the performance assessment of this or any other similar model.

The general structure of REST2 is almost identical to that of CPCR2, with a band separation at 0.7 μm. *Band 1* covers the UV and visible, from 0.29 to 0.70 μm. It is