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Recent improvements of the Meteorological Radiation Model for solar irradiance estimates under all-sky conditions

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ABSTRACT

This study presents the recent improvements of the Meteorological Radiation Model (MRM v6) against previous model versions for more accurate estimates of the solar radiation components, i.e. global, diffuse and direct. The MRM v6 follows a different approach for the simulation of the atmospheric conditions by selecting the most appropriate aerosol model (desert, urban, maritime or continental), and usage of look-up tables for the spectral variation of the aerosol optical depth (AOD) and single scattering albedo (SSA). Furthermore, the MRM v6 uses hourly data of sunshine duration in order to achieve better simulations under cloudy skies. The results show that the MRM v6 improves the estimates of the measured global, diffuse and direct solar irradiances at Athens, Greece since the **Root Mean Square Error** (RMSE) becomes 13.7%, 40.8% and 24.2%, respectively, against 18.0%, 44.5% and 34.1% for the MRM v5. A decrease is also found in **Mean Bias Error** (MBE), especially for the diffuse (from 26.2% to 19.5%) and direct (from −9.0% to −2.4%) irradiances, indicating that the inclusion of the aerosol properties in MRM v6 significantly improves the estimations. The MRM simulations are very satisfactory on monthly basis indicating that the model is suitable for solar energy applications.

1. Introduction

Solar radiation is the main source of energy and the most important condition for life on Earth; it is also a determinant factor for climate change [58,78]. The increasing demand of energy over the globe due to the growing population and the major concerns of environmental protection, reduction of the greenhouse gases and mitigation of the climate change impacts shift the interest towards renewable energy sources and more specifically to solar energy [52]. The design of many solar conversion devices and photovoltaic cells requires the knowledge of solar radiation availability on horizontal and inclined planes [13,65,77] as well as solar maps at different spatial and temporal domains over the globe [62]. Mapping solar radiation over an area is essential for exploring the spatial variability of solar radiation and analyzing the solar energy potential, thus helping engineers in using solar energy systems [34]. Due to unavailability of a dense network for solar radiation measurements over the globe, solar radiation maps may be prepared using satellite retrievals, artificial neural networks, radiative transfer codes [62,63,72], or simple solar broadband radiation models that have been developed during the early 1970s (e.g. [10,11,15,20,22,51,65]. The main advantage of these radiative models is the estimate of solar radiation at specific places that are used for mapping solar radiation at regional to global scales.

The atmospheric constituents attenuate solar radiation reaching the Earth's surface by the mechanisms of absorption and scattering [36,37], depending on multiple parameters like the amount, absorption capabilities, particle size and scattering processes of air molecules/aerosols/pollutants. Multi-decadal variations in the attenuation of solar radiation reaching the ground is a modulation factor for regional and global climate controlling the global dimming/brightening phenomenon [59,60,79]. Atmospheric aerosols play a very important role in the Earth's radiation budget [25,71] and, therefore, are very important in climate change. Thus, atmospheric turbidity is a major input parameter to radiative transfer codes [7,16,18,30,61], which has been replaced by more

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sophisticated expressions of the spectral aerosol optical properties [36,37].

Solar zenith angle (SZA) and cloudiness are the most significant factors affecting the variability of solar irradiance at the Earth's surface; SZA is readily estimated from astronomical functions [76,80], while cloudiness is characterized by a high variability in structure, thickness and composition, thus rendering the estimation of solar radiation under cloudy skies a real challenge [43,49,56]. Therefore, clouds play a fundamental role and may attenuate as much as 80% of the downwelling solar radiation reaching the Earth's surface, depending on cloud type, cloud optical depth (COD), and their distribution in the sky [1,12,66,68]. The COD is an inherent property of clouds and independent of SZA, surface albedo or aerosol loading [6,68]. An accurate determination of the COD and its spatial and temporal variation remains a serious concern in radiation and atmospheric studies, which implement different factors that relate atmospheric transmission with overcast skies [2,19,54,68].

In this respect, the Meteorological Radiation Model (MRM) was developed at the National Observatory of Athens (NOA) in the late 1980's [27–29,31] and has been under continuous improvements till its current version 5 (MRM v5) that has successfully been used for solar radiation estimates during the solar eclipse in Greece on 29 March 2006 [65]. On the other hand Gueymard [21], in an intercomparison study employing various broadband models found that MRM v4 did not perform so well compared to others. However, more recently Gueymard [23], checked the validity of 18 solar radiation models and classified MRM v5 in the 7th position after comparison with measured data from SURFRAD (Surface Radiation) network and usage of several statistical indicators. The MRM v5 is a simple radiation code based on meteorological parameters i.e. air temperature, relative humidity, barometric pressure and sunshine duration as inputs, which are easily available from many meteorological stations. Therefore, the main advantage of the MRM v5 against other simple radiation models is its easiness in being applied at any location over the globe. MRM v5 can be used for estimating solar radiation under different atmospheric conditions, for filling gaps in solar radiation data series and for solar-energy applications and engineering purposes. The various versions of MRM are described in detail in a book chapter [32] and in a study focusing on the accuracy of the latest version (MRM v5) in solar radiation simulations during the (almost total) solar eclipse conditions on 29 March 2006 over Athens, Greece [65].

The present work describes in detail the recent developments in the MRM v6 code, by inserting new techniques and functions for the aerosol transmittance by choosing the most appropriate aerosol model for representing the atmospheric conditions. The study provides comparisons of the MRM v6 solar irradiance (global, diffuse and direct) estimates with both real measurements taken at the Actinometric Station of NOA (ASNOA) during the period 2001–2005 and model estimates from the previous MRM v5. The model's performance is examined against SZA, sunshine duration and aerosol optical depth (AOD) in order to reveal the improvements of the solar radiation estimates that are attained in the new version.

2. Description of MRM v6

The MRM is a broadband algorithm for simulating solar irradiance on horizontal surface, using widely available meteorological parameters, viz air temperature, relative humidity, barometric pressure and sunshine duration as inputs. It is capable in performing calculations in various time steps dictated by the availability and temporal resolution of the meteorological input data, the majority of which are provided as hourly values. On the other hand, the measured sunshine duration is usually given as a total daily or hourly value; the latter case leads to more precise calculations from MRM. In the following, we analytically describe the new developments in the MRM v6 code against its predecessor; a detailed description of the MRM can be found elsewhere [32,65].

2.1. Direct radiation

The direct beam irradiance, I_b, received on a horizontal surface under cloudless skies can be expressed as:

$$I_b = I_{ex} \cos \theta_z \, T_w \, T_r \, T_o \, T_{mg} \, T_{aer} \quad (1)$$

where θ_z is the SZA, I_{ex} is the normal incidence extraterrestrial solar irradiance on the i-th day of the year; the term T_x stands for the broadband transmission functions for water vapor (T_w), Rayleigh scattering (T_r), absorption by ozone (T_o), absorption by uniformly mixed gases (CO_2, CO, N_2O, CH_4 and O_2) (T_{mg}) and aerosol total extinction (scattering and absorption) (T_{aer}). The expression for T_{aer} has changed in MRM v6, while the rest transmittances are kept the same as in MRM v5 (see analytical expressions in Ref. [65]. In MRM v5, the broadband T_{aer} was calculated using the formula proposed by Yang et al. [81]:

$$T_{aer} = \exp\{-m\,\beta\,[0.6777 + 0.1464\,m\,\beta - 0.00626\,(m\,\beta)^2]^{-1.3}\} \quad (2)$$

where β is the Ångström turbidity coefficient and m the relative optical mass. In the cases that β is not available from spectral radiation measurements it is estimated via the empirical Yang et al.'s [81] expression, which relates β to the geographical latitude, φ, and the altitude of the station, H, as:

$$\beta = \beta' + d\beta \quad (3)$$

$$\beta' = (0.025 + 0.1 \cos\varphi) \exp(-0.7H/1000) \quad (4)$$

$$d\beta = \pm(0.02 - 0.06) \quad (5)$$

where β′ represents the annual mean value of turbidity and dβ the seasonal deviation from the mean, i.e. low values in winter and high values in the summer. For Athens ($\varphi = 37.967^{o}$N and $H = 107$ m a.m.s.l.) $\beta' = 0.09$.

It is well-known that the AOD and, thus, the aerosol transmittance are highly wavelength dependent due to different aerosol types that take place in the solar attenuation processes within the atmosphere [36,37]. Therefore, inclusion of spectral functions of AOD or transmittance can definitely improve the model simulations. However, MRM was built as a broadband code. Thus, in MRM v6 the broadband T_{aer} is calculated by integrating the wavelength-dependent aerosol transmittance T_{aeri} as:

$$T_{aer} = \frac{\sum_{i=\lambda_1}^{\lambda_2} T_{aeri} Iext_i}{\sum_{i=\lambda_1}^{\lambda_2} Iext_i} \quad (6)$$

where λ_1, λ_2 are 280 and 3000 nm, respectively, i.e. the lower and upper limits of the solar spectrum. $Iext_i$ is the spectral extraterrestrial irradiance taken from SMARTS model, version 2.9.5 [22], with a spectral resolution of 0.5 nm between 280 and 400 nm, 1 nm between 400 and 1700 nm, and 5 nm between 1705 and 3000 nm. T_{aeri} is the spectral aerosol transmittance:

$$T_{aeri} = \exp(-m' AOD_i) \quad (7)$$

where m′ is the absolute air mass, corrected for the actual station