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Meteorological Radiation Model (MRM v6.1): Improvements in diffuse radiation estimates and a new approach for implementation of cloud products

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ABSTRACT

This work reviews techniques and models for solar radiation simulations and communicates further improvements performed in the Meteorological Radiation Model (MRM) developed at the National Observatory of Athens. The new version (MRM v6.1) considers a forward to-the-ground scattering as a function of solar altitude for the diffuse radiation estimates, while concurrently uses two running codes i.e., with sunshine duration as input (MRM v6.1a) and with cloud products (MRM v6.1b). The new scattering function leads to increase in diffuse radiation, especially for low zenith angles, and to better simulations with the measured diffuse (RMSE=36.3% and MBE=6.5%, against RMSE=42.0% and MBE=22.3% for the latest MRM v6). These changes lead also to better simulations of global radiation (RMSE=8.7% against RMSE=9.5% for MRM v6), while the direct radiation is not affected. The accuracy in the simulations increases significantly for clear-sky conditions, while it shows a small dependence on aerosol amount and solar altitude. Furthermore, in the sub-version MRM v6.1b the calculations for the cloud transmittance have been modified to allow for the inclusion of cloud products as inputs in case of non-availability of sunshine duration data. In this study, MRM v6.1b uses MERRA retrievals of cloud optical depth and cloud fraction for calculations of the cloud transmittance; these parameters usually lead to significant uncertainties in the simulations of the hourly direct and global radiations, especially for large cloud fractions. This indicates the need for high spatial and temporal resolution satellite data of cloudiness for accurate estimations of solar radiation under cloudy conditions and highlights the incapability of radiative transfer models on such simulations. However, on monthly basis both MRM v6.1a and v6.1b provide high accuracy in solar radiation estimates, thus rendering MRM v6.1 as a powerful tool for solar energy applications.

1. Introduction

1.1. Solar radiation and Earth climate system

The surface-solar radiation (SSR) is of vital importance for the life on Earth, radiation-energy balance [1,2], photosynthesis and photochemical reactions [3], meteorological and climatic conditions [4,5] and the water cycle [6]. SSR depends on several astronomical and geographic factors, such as Earth - Sun distance, solar altitude, season, latitude and altitude as well as on atmospheric transparency defined by the amount of clouds, aerosols, trace and mixed gases, water vapour and ozone [7–10]. Clouds and aerosols are the main factors that contribute to the attenuation (scattering and absorption) of SSR; on climatological basis, clouds can be about 4 times more efficient than aerosols in this attenuation [10]. In contrast, lateral scattering by thin or scarce clouds may enhance SSR [11], thus increasing the complexity and uncertainties in solar radiation modelling. Therefore, variations in clouds, aerosols, water vapour and well-mixed gases control the atmospheric transparency and SSR [12–15], with their effects being spectrally selective, especially for the mixed gases (specific narrow spectral bands), aerosols (mostly in the shorter wavelengths), water vapour (mostly in the near infrared). The combined effects of aerosols and clouds (aerosol and cloud radiative forcing) are still the largest uncertainties in the evaluation of the Earth radiation-energy budget and climate change over the globe [16–18]. Therefore, short- and long-term changes in the amount of SSR greatly influence sensible and latent heat fluxes, evaporation rates, temperature, ecological functions, atmospheric and oceanic circulation, and the hydrological cycle [19–21], thus necessitating accurate

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knowledge of the spatial variability and trends at long and short time scales [22–25]. In this respect, the studies dealing with the solar dimming/brightening phenomenon are mostly based on long-term analyses of SSR measurements or alternatively on analysis of parameters associated with SSR, like sunshine duration [4], model simulations for future predictions [14], combination of measurements and models [26] and usage of satellite data [27,28]. Especially over the Mediterranean Basin, multi-decadal changes in SSR are recently examined revealing large spatio-temporal variability along the different parts of the basin [29]. Moreover, the urbanization effect (i.e., increase in pollution levels over and around the cities and the industrialized areas) on SSR trends comprises a significant scientific issue, especially over the rapid growing cities in south and east Asia [25,30,31]; nevertheless, such evidences have also been seen over Mediterranean and Europe [32,33].

1.2. Solar radiation as a renewable energy source

Solar radiation is the most abundant renewable energy resource over the globe and, therefore, the demands for environmentally-clean energy resources and reduction of greenhouse-gas emissions have shifted the global interest towards solar-energy exploitation for sustainable development and electricity demands [34–37]. A rapid increase in PV systems installation over the globe has been seen during the last decade reaching a capacity of about 178 GW at the end of 2014 [38] with predictions of increase to 396–540 GW by 2019 [39]. The Mediterranean Basin receives large amounts of solar radiation due to large sunshine duration and high solar intensity and, therefore, many countries around it have shifted their energy demands to solar power plants [40–42]. In Greece, the installed PV capacity almost doubles every two years with total installations exceeding 2.5 GWe in 2013 [43,44]. The availability of solar radiation on horizontal and inclined planes has to be determined for the design of solar conversion devices, PV systems [45,46], as well as for the generation of solar potential maps at different spatial and temporal domains [47,48]. Therefore, an accurate knowledge of the global solar radiation and its direct and diffuse components at the ground is very important for the design of solar power systems as well as for climatological and agricultural issues [49–51]. Although nowadays many surface radiation networks (e.g. ARM, ASRB, BSRN, ESRL, GEBA, SURFAD, WRDC) have been widely used for recording SSR at various spatial and temporal domains [19,22,52], these networks are still incapable to provide a global coverage since the oceanic and remote-continental areas remain nearly unexplored. On the other hand, SSR is not so routinely measured as this is done for many meteorological parameters over the globe [53]. Therefore, this insufficient number of measurements leads to coarse spatial resolution and difficulties in drawing accurate solar radiation maps [41,44] and, in turn, it triggers the development of radiative transfer models (RTMs).

1.3. Satellite observations and advanced statistical techniques for solar radiation monitoring

During the last decades, satellite imageries and data have widely been used for monitoring the spatial-temporal variations and trends of SSR over the globe [27,54–58]. Since satellite remote sensing of SSR provides a better spatial coverage, various methods have been developed to derive it from space, with the main disadvantages to be the increased uncertainties and the required validations against ground-based measurements or modelling data [27,59]. In this respect, data series from the SEVIRI (Spinning Enhanced Visible and InfraRed Imager) sensor on-board the Meteosat Second Generation (MSG) satellite have been used for satisfactory assessment of SSR – the Heliosat-2 method – [60–62] and in combination with ground-based measurements [51,63,64]. In view of helping scientists and engineers over the globe, the SoDa website (www.soda-pro.com) provides access to various solar radiation databases [65], such as the HelioClim-3 (HC3) and the Copernicus Atmosphere Monitoring Service (CAMS), both derived from images acquired by the MSG satellite [66]. As a consequence, solar-energy maps have been performed over several regions aiming to serve as basic solar resource information [47,50,67]. On the other hand, solar radiation modelling may be performed via the synergy of satellite data, Artificial Neural Networks (ANN) and RTMs [68–74] by implementing advanced statistical and modelling techniques. An alternative approach may be the use of the MERRA (Modern-Era Retrospective Analysis for Research and Applications) or the ERA-Interim re-analysis [31,75,76] despite the uncertainties due to deficiencies in the clear-sky radiative transfer calculations – overestimation of solar radiation by MERRA – [76]. The top-of-atmosphere (TOA) solar irradiance values are also retrieved via the Clouds and the Earth Radiant Energy System (CERES) sensor and have been extensively used for estimations of the radiative forcing of aerosols [77–79]. The reliability of the satellite-derived and re-analysis SSR trends depends on the accuracy of the physical and empirical radiative-transfer algorithms as well as the accuracy of the observational input data used in the computations, such as clouds and aerosols [57].

1.4. RTMs for irradiance simulations

Solar irradiance models (either broadband or spectral) are commonly used in a variety of applications such as atmospheric science, biology, and renewable-energy technology (PV systems, high performance glazings, selective coatings, building applications) [80]. The solar radiation models are of different types, accuracy and spectral resolution. The first broadband solar radiation models were developed long back during the early 1970s [e.g. 81–85]. The limited measurements of diffuse and direct radiation components in contrast to the global one, led to the development of the so-called decomposition or separation models, which estimate the diffuse and direct radiations from the measured global one [86–90]; for this reason they use empirical functions implementing a combination of measured ambient temperature, relative humidity (RH), clearness index (K_t) and sunshine duration [91–94]. On the other hand, empirical models using meteorological parameters (air temperature, pressure, RH, cloud cover, etc) are very common [95–97], while non-linear and more complicated empirical models including functions of latitude, altitude and relationships between K_t and sunshine duration have also been utilised [50,98–106]. Nowadays the most rigorous RTMs for simulating the spectral components of SSR (global, diffuse and direct) with high spectral resolution are mostly used [107,108]. These models are based on the interactions of solar radiation with the atmospheric constituents, such as air molecules, water vapour, ozone, clouds and aerosols on specific wavelength bands [109], thus providing large accuracy in the estimates of the solar spectrum [108]. The spectral irradiance models used to predict SSR are of two types: i) sophisticated rigorous codes and, ii) simple transmittance parameterisations. The LOWTRAN family constitutes the most well-known example of the first category established more than 30 years ago that has been updated to the even more detailed code called MODTRAN [110,111]. This type of models considers the atmosphere as composed of different in-homogeneous layers and uses reference (standard) or measured vertical profiles of the atmospheric gases and aerosols in order to represent the attenuation processes within the multiple layers. Because of the several and detailed inputs that are required, long execution time and some output limitations, such rigorous codes are not so appropriate for all applications, particularly for engineering purposes. On the other hand, several simple parameterisation models belonging to the second type have been developed since the early '80s based on Leckner's [112] functions, in which the atmosphere is considered as one layer of medium attenuation [107,113–118]. For engineering and atmospheric applications, the SPCTRAL2 [107], SUNSPEC [119] and SMARTS2 [120] are the most commonly used. In addition, there are some simpler solar