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Modeling diffuse irradiance under arbitrary and homogeneous skies: Comparison and validation

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HIGHLIGHTS

- UMRP model improves predictions of diffuse irradiance under arbitrary conditions.
- The solution model allows for broken cloud arrays with arbitrary cloudiness.
- UMRP is validated using publicly available data from NREL and AERONET.
- CPU and MEM requirements are generally low with UMRP.
- Computational results are compared against conventional model of homogeneous skies.

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ABSTRACT

The optimum utilization of solar energy requires effective harvesting of both the direct and diffuse components of ground-reaching radiation. Although solar beams are typically key contributors to the total irradiance under cloudless conditions, the diffuse component becomes important especially in regions where clear skies are not dominant. Even if the cloud cover and cloud microphysics are known, it is not an easy task to estimate the diffuse irradiance at arbitrarily oriented sloped surfaces. This situation arises from the extreme difficulty in solving the radiative transfer equation in such a heterogeneous environment.

Models of Homogeneous Skies (MHS) with a set of discrete sky types are commonly applied in determining irradiance or illuminance. However, experimental data usually differ significantly from data predicted by MHS, for initially daylighting purposes where a simple sky luminance distribution is most useful. In this paper we show that the MHS error can be exceptionally large, especially for some cardinal directions. The use of MHS could also lead to misinterpretation of a momentary sky state if different sky types are required to accurately simulate irradiances on arbitrarily oriented surfaces. Nevertheless, use of multiple sky types at one moment in time has no theoretical basis and thus is generally unacceptable. Therefore, we have demonstrate that a new Unified Model of Radiance Patterns (UMRP) is more consistent with physical measurement and is generally applicable to all situations, including clear-, partly-cloudy, and, overcast-sky conditions and, could accurately predict vertical irradiances or illuminances more accurately than MHS. UMRP implements heterogeneity of cloud systems and provides radiance or luminance distributions depending on the characteristic size of clouds, their albedo and their altitude. While the error in the irradiance computations is approximately 6% for UMRP, it can reach a value of 70% or even more in case of MHS. UMRP-based modeling of radiative fields is now simple using the UniSky Simulator, a heavily optimized multithreading application (publicly available at www.unisky.sav.sk/?lang=en&page=aplikacia). We expect the UMRP concept to be a new choice for modelers and PV systems engineers to predict solar energy more accurately under any meteorological conditions.

1. Introduction

Energy use is increasing steadily imposing an unacceptable burden on natural resources and the quality of our life. This is why a substantial demand is now directed towards renewable resources

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and new energy saving technologies. Solar radiation is a renewable source of energy that is widely available and can be used as an alternative energy supply. Optimum condition for energy conversion in PV systems is usually reached under clear-sky situations at high solar elevations. However, a presence of broken clouds can make any predictions of downward radiative flux difficult or even impossible [1,2]. Because of the varied optical states of atmospheric environments, an accurate forecasting of radiative energy at the ground is required in many applications including solar concentrators [3,4] and in modeling photosynthetically active radiation (PAR). The information about PAR is essential in characterizing solar energy conversion into other forms, specifically chemical energy in vegetation [5] or in calculating an uptake of carbon dioxide during photosynthesis of plants [6].

The downward radiative flux is the sum of its direct and diffuse components. The latter is difficult to obtain since it depends on the angular distribution of the scattered radiation. Sky radiance patterns change with atmospheric conditions, reflectance of the ground, position of the sun and cloud coverage. For these reasons the numerical computation of the radiative field is CPU intensive for non-static cloud arrays with random geometries [7]. It is much easier to proceed with empirical methods [8,9] that homogenize, to a large extent, any sky radiance distribution. Horizontal irradiances determined in this way are consistent with real-time measurements if performed under quasi-homogeneous cloudless or overcast sky conditions. However, most of the empirical models fail to mimic the angular anisotropy in radiance observed over cloudy skies. The model introduced by Kocifaj [10,11] represents a trade-off between statistical and theoretically exact approaches and also allows for fast numerical simulations under arbitrary turbidity conditions and, accepts any Cloud Fraction (CF) from 0 to 1.

For low CF with direct sunlight the global irradiance is predominately due to unfiltered sunbeams. The situation becomes more complex if experiments are made for partly-cloudy skies with a shaded sun position, then the diffuse or diffusely reflected light are dominant sources of electromagnetic energy received at the ground. A statistical averaging over partly-cloudy skies indicates that the diffuse radiation can reach some tens of percent of direct radiation, even if direct sunlight is included. The fraction of diffuse radiation depends on the cloud fraction and atmospheric turbidity [12,13]. In fact, the diffuse component of the downwelling radiation can rarely be neglected since it is constantly present also under cloudless situations with a clear or a broader solar corona. Undoubtedly, a reasonable quantification of the diffuse radiation is needed to improve predictions especially to aid optimal planning of solar power plants [14–16].

The diffuse component of ground-reaching radiation is routinely determined at meteorological or actinometric stations, while atmospheric turbidity, cloud cover and solar altitude are input parameters [17–19]. In general, systematic monitoring of irradiances can only provide the statistical information that is suitable for analysis of long-term trends in the vicinity of any measuring point. However, it is difficult to infer anything about irradiances of inclined surfaces from such statistical data and quite impossible to estimate the radiative energy in distant places.

It is, however, a straightforward procedure to determine irradiances on arbitrarily oriented walls by integrating the cosine-projected radiance distribution over a dedicated part of the sky vault. Some experimental methods have been developed to retrieve sky radiances by using all-sky scanners [20,21] or CCD technology [22]. Unfortunately, sky radiance measurements are infrequently available, and in the absence of a well-established theoretical model they are not suitable for forecasting purposes. Any theoretical model usually requires information about site-specific parameters as well as the optical properties of the atmosphere. Both of these can be obtained from optical measurements and kept in database form for future use. For instance, aerosol properties in industrialized (urban) regions are typically linked to source emissions, thus showing a relationship between extinction and particle emission [23]. Taking into account actual wind direction, air mass origin, relative humidity, $PM_{2.5}$ or PM_{10}, and the known profile of surrounding terrain the presence of different aerosol populations can be deduced based on the local aerosol database. Here $PM_{2.5}$ or PM_{10} are commonly available air-pollution data characterizing the suspended particulates smaller than 2.5 μm or 10 μm in aerodynamic diameter, respectively. Based on these data, the aerosol optical depth can be estimated using Mie theory, while Rayleigh approximation predetermines the optical depth of gaseous constituents.

The aforementioned quantities are inputs to the Unified Model of Radiance Patterns (UMRP) [10,11] that is applicable to any cloud configuration and can mimic sky states that regularly occur in nature. The model is parameterized through cloud fraction, cloud type, and altitude of cloud base, these properties are commonly acquired by meteorological stations. The model can quite accurately predict diffuse irradiances at arbitrarily sloped surfaces. A heavily optimized algorithm guarantees low CPU and computer memory requirements.

The basic differences between UMRP and other approaches developed recently [24–26] is that the UMRP is applicable to any atmospheric conditions including any cloud configuration (such as broken cloud arrays or single clouds scattered randomly over the sky vault). The model has a clear theoretical basis and is parameterizable through physical characteristics. Most studies on diffuse irradiance prefer empirical modeling and statistical analyses of long-term data sets [27–29] rather than taking into account actual weather conditions and their spatial and temporal variability. Undoubtedly, empirical models, though expensive for estimating solar radiation, can be used to draw trends in monthly mean daily diffuse irradiance [30]. However, it is not the optimum approach to predict diffuse radiation for a specific time interval during a day. Therefore, a completely different procedure is used by predicting diffuse irradiance accurately at any time and for any locality using the data routinely recorded at actinometric or meteorological stations. Such an approach is advantageous since it reflects actual meteorological conditions and is, therefore, more accurate than the above cited empirical approaches.

In this paper the UMRP is validated using publicly available data and compared against well-known Models of Homogeneous Skies (MHS) such as that used by Li [31]. We have demonstrated the success of the method by comparing the computed ratios of vertical to horizontal irradiances with those measured in Denver under different cloud fractions. We have shown that UMRP is a convenient tool for exceptionally high accuracy modeling of any sky states compared to what we have found for models of homogeneous skies.

2. Theoretical background

An objective of many theoretical models is to simulate irradiance of arbitrarily oriented surfaces at any time during specific day. Basically, the N-stream radiative transfer models, or the exact solution to the 1D radiative transfer equation, can be applied to determine irradiances for horizontally uniform optical media [32,33]. However, cloud arrays impose additional complexities to the problem solution. Specifically, they are the cloud gap effect [34], cloud shadowing [2] and other difficulties associated with the solution of the 3D radiative transfer equation leading to an appropriate approximation being sought [35].

A treatment of cloud arrays requires special attention because clouds are invariably of various sizes and distributed randomly over the sky [36,37]. Therefore, we have derived formulae which