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Statistical cloud coverage as determined from sunshine duration: a model applicable in daylighting and solar energy forecasting

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ABSTRACT

A radiative/luminous energy budget is difficult to predict on a daily or hourly base if cloud coverage is obtained by subjective methods in discrete time points. A simple theoretical model that overcomes this shortcoming through interrelation of absolute cloud fraction and sunshine duration is presented. The latter is measured routinely at the meteorological stations worldwide. The model is based on statistical probability of clear line of sight, where Poisson spatial cloud distribution is analyzed for three different cloud shapes. A validation of the model using long-term measurements show a good correlation between experimentally determined and theoretically predicted data. The absolute cloud fraction obtained this way are a base for daylighting and solar energy applications including simulations of luminance/radiance sky distributions under different meteorological conditions. A simple calculation tool is developed and demonstrated on global horizontal illuminance (GHI).

1. Introduction

Clouds can significantly influence radiative and heat transfer and thus act as most important modulators of many atmospheric processes. The dynamics of inhomogeneous broken cloud arrays results in highly unstable radiative field which in turn make any reasonable predictions of global horizontal illuminance/irradiance or radiance/luminance difficult for any territory and in any season. Since clouds cover 50% of the globe at any time their statistical relevance for solar energy and daylighting applications is fairly high. Especially, broken cloud array has been identified as the greatest source of uncertainties in a sky luminance/radiance modeling as well as in prediction of the electricity production in solar power plants (Chen et al., 2016; El-Metwally, 2005; Paulescu et al., 2013). The decisive effects of clouds on atmospheric optics have been recognized, but remain poorly quantified.

Nowadays a number of empirical models are in use to imitate sky radiance or luminance patterns (e.g. Kittler, 1999; Perez et al., 1990). Many authors (Kittler and Ruck, 1984; Muneer et al., 1998; Tregenza, 1982, 1987), studied daylight illuminance as a function of cloud coverage, while Harrison (1991) also related a cloud field with directional sky luminance. A progress in light-scattering theory discerned in the last several years makes it possible to treat arbitrarily sized isolated clouds (Kocifaj, 2012) where the statistically relevant radiance distribution is computed as a function of cloud coverage.

The cloud coverage is sometimes referred to as the absolute cloud fraction (*N*) in the scientific literature (Kassianov et al., 2005; Zuev and Titov, 1996). It corresponds to the projection of the cloud cover on the ground and ranges from 0 to 1. We adopt *N* throughout the paper, while the symbol *T* is to characterize the sunshine duration (see e.g. Taylor and Ellingson, 2008) which is the average value in a given time interval. The paper is directed toward daily and hourly averaged data, but the model is applicable to any time resolution.

Because of varied properties of cloud field, interest has fermented recently in characterizing the clouds by statistical models (see e.g. Alexandrov et al., 2010a, 2010b) where the absolute cloud fraction acts as a crucial parameter in numerical computations. The more appropriate approximation to the cloudiness is found, the more accurate predictions of diurnal or hourly averaged GHI or solar resource for a given locality can be made (Almorox and Hontoria, 2004; Badescu and Dumitrescu, 2014).

Different experimental methods such as cloud mirrors, photogrammetric methods (Lund and Shnaklin, 1972), retrieval of cloud fraction from satellite images (Piper and Bahr, 2015) or retrospective calculation from surface solar radiation measurements (Harrison et al., 2008) have been developed to monitor the cloud coverage. However, in many countries the cloud coverage is still obtained by subjective methods in discrete time points, rather than being systematically gathered. Duration of sunshine is one of most commonly retrieved property at

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many meteorological stations worldwide. Therefore a theoretical relation between the sunshine duration and absolute cloud fraction is needed. It is a convenient approach to the statistical modeling of seasonal/diurnal/regional irradiances, illuminances or radiance and luminance patterns. A number of studies interrelating absolute cloud fraction and downwelling radiation (e.g. Butt et al., 2010), or sunshine duration and radiation at the ground level (e.g. Suehrcke et al., 2013) are well known. Although some estimates have been made by He et al. (2014) or Morf (2014) to link the sunshine duration and absolute cloud fraction there is a lack of efficient approximations. The solar radiation estimated from sunshine duration is a technique that appears useful in the localities where the illuminance/irradiance measurements are absent (Adaramola, 2012; Besharat et al., 2013; Khatib et al., 2012; Sun et al., 2015; Zhao et al., 2013).

Sunshine duration in a given time interval (also called sunshine number) is easy to obtain on a daily or yearly base, so the conversion of the above data to appropriate cloud coverage quantity is possible using statistical models considering so-called probability of clear line-of-sight (see e.g. Lund, 1966; Lund and Shnaklin, 1973; Rapp et al., 1973). Yu et al. (1986) and Ma and Ellingson (2004) reviewed various methodologies of the probability of clear line of sight (PCLoS) calculation. The time of sunshine varies with the cloud field geometry and also the path of the sun through the sky. The statistical models such as PCLoS allow for reconstruction of cloud field geometry based on known time series of the sunshine number and point cloudiness (Badescu et al., 2016).

In this paper we present a model for obtaining the absolute cloud fraction from experimentally determined sunshine duration and/or vice versa as the integral values for a time interval specified. A few numerical examples are presented in the paper for daily or hourly averaged data. A simple calculation tool was developed based on statistical method of PCLoS with Poisson cloud distribution and used for routine numerical computations. The mapping between sunshine duration and absolute cloud fraction is summarized in a more comprehensive tabulated form that can be easily used by daylight and solar energy modellers who are interested in statistically relevant values in a respective territory. The values of absolute cloud fraction determined this way can be used as an input to solar radiation models aiming to predict radiative field under arbitrary meteorological conditions. Such modeling can be made with help of publicly available tools, e.g. UniSky Simulator that is located at the web-page www.unisky.sav.sk under the section Applications and Outputs. Sunshine duration is still measured worldwide and there is also a vast database of such data. Therefore, a processing of such historical data might be important for backward modeling purposes and for estimation of trends in availability of the solar resources on a regional or even global scale.

2. Theoretical approach

2.1. Probability of clear line of sight (PCLoS) – Poisson cloud distribution

Statistical method to determine sunshine duration for arbitrary geographical location and any day in a year is based on the calculation of PCLoS, i.e. the probability of clear line of sight that depends on cloud field distribution, cloud shape, and, the position of the Sun on sky vault. Of the many approaches to the cloud field modeling we consider that clouds are distributed in accordance to the Poisson law. In fact, we have used Poisson model with 2D random cloud distribution to be consistent with other authors (see e.g. Kauth and Penquite, 1967). PCLoS appears independent of azimuth and can be written as follows

$$p(\theta) = (1 - N)^{f(\theta)}, \tag{1}$$

where N is the absolute cloud fraction, θ is the zenith angle, and $f(\theta)$ is a function of cloud shape. In general, we can write:

$$f(\theta) = \frac{\int\int a(\theta,\, r,\, h)\, p(r,\, h)\, drdh}{\int\int a(0, r,\, h)\, p(r,\, h)\, drdh}, \tag{2}$$

where $a(\theta, r, h)$ is the shadow area of a single cloud with radius of r and height h. The function $p(r, h)$ is a probability that cloud radius ranges from r to $r+dr$ and height is between h and $h+dh$. After a bit of mathematical manipulations one can find $f(\theta)$ for a few simple cloud geometries (Ma, 2004; Taylor and Ellingson, 2008):

- cuboidal

$$f(\theta)=1 + \beta\tan\theta \tag{3}$$

- cylindrical

$$f(\theta)=1 + \frac{4}{\pi}\beta\tan\theta \tag{4}$$

- semi-ellipsoidal

$$f(\theta) = \frac{1}{2}\left(\sqrt{1 + 4\beta^2\tan^2\theta} + 1\right) \tag{5}$$

The parameter β relates the cloud height to cloud base diameter, i.e. $\beta=h/d=h/(2r)$. Semi-ellipsoidal model reduces to a hemispherical cloud if $\beta=1/2$. Cubic cloud is a special case of the cuboidal cloud for $\beta=1$.

2.2. Prediction of sunshine duration from absolute cloud fraction and vice versa

The clouds tend to block the direct solar beams completely, so only unobscured fractions of the sky can influence sunshine duration in a given time interval. The main objective is therefore to determine the probability of seeing the Sun for a given moment at the zenith angle θ_S, which means that the clear line-of-sight is precisely towards the Sun, thus implying $\theta=\theta_S$ (read also Badescu et al. (2016)). Obtaining the zenith angle of the Sun is a trigonometry problem that is formulated as the cosine law for the spherical triange

$$\cos\theta_S = \sin\phi\sin\delta - \cos\phi\cos\delta\cos(H), \tag{6}$$

where ϕ is the geographical latitude of an observer, δ is the declination of the Sun, and H the solar hour angle (all angles are measured in radians). Declination of the Sun is determined as follows

$$\delta=(23.45\sin d)\frac{\pi}{180}, \tag{7}$$

where $d=[2\pi(J-81)/365]$. Note that J is counted from 1 to 365 (or 366) and represents the number of the day in a year. Hour angle of the Sun can be determined in radians as follows

$$H = \left(t + \frac{\lambda}{15} - 1 + ET\right)\frac{\pi}{12}, \tag{8}$$

where t is the local time (given in hours), λ is the geographical longitude. The term ET corresponds to the equation of time, which describes the discrepancy between the apparent solar time directly describing the real motion of the sun and the mean solar time. The latter tracks a "mean" theoretical motion of the sun. Many approximations are known to describe the above discrepancy (see e.g. Hughes et al., 1989 or Müller, 1989):

$$ET=0.17\sin\,[4\pi(J - 80)/373] - 0.129\sin\,[2\pi(J - 8)/355]. \tag{9}$$

Inserting Eqs. (7)–(9) into Eq. (6) together with $\theta=\theta s$ one can transform Eqs. (3)–(5) into more convenient forms

$$f(\mathrm{t})=1 + \beta\tan[A - B\cos(15\mathrm{t} + 15ET)], \tag{10}$$