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Spatial disaggregation of satellite-derived irradiance using a high-resolution digital elevation model

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Abstract

Downscaling of the Meteosat-derived solar radiation (~5 km grid resolution) is based on decomposing the global irradiance and correcting the systematic bias of its components using the elevation and horizon shadowing that are derived from the SRTM-3 digital elevation model (3 arc sec resolution). The procedure first applies the elevation correction based on the difference between coarse and high spatial resolution. Global irradiance is split into direct, diffuse circumsolar and diffuse isotropic components using statistical models, and then corrections due to terrain shading and sky-view fraction are applied. The effect of reflected irradiance is analysed only in the theoretical section. The method was applied in the eastern Andalusia, Spain, and the validation was carried out for 22 days on April, July and December 2006 comparing 15-min estimates of the satellite-derived solar irradiance and observations from nine ground stations. Overall, the corrections of the satellite estimates in the studied region strongly reduced the mean bias of the estimates for clear and cloudy days from roughly 2.3% to 0.4%.

Keywords: Solar irradiance; Satellite; Digital elevation model; DEM; Disaggregation

1. Introduction

Efficient planning and operation of solar energy systems require site- and time- specific knowledge of solar resource at high accuracy. Factors controlling the spatial and time distribution of solar radiation at global to regional scales are well described by operational satellite algorithms (Perez et al., 2002; Hammer et al., 2003; Rigollier et al., 2004; Müller et al., 2004, etc.). However, under complex terrains, irradiance estimates show systematic deviations compared to ground measurements due to terrain-related effects such as elevation gradient, obstruction and shadowing by the horizon and ground reflectance.

Influence of terrain features was already described by many authors (e.g. Dozier and Frew, 1990; Tovar et al., 1995; Dubayah and Loechel, 1997; Remund et al., 1998; Oliphant et al., 2003; Cebecauer et al., 2007). Terrain shadowing was already implemented in solar radiation models integrated within a Geographical Information System (GIS), such as *r.sun* (Šúri and Hofierka, 2004) or SRAD (Moore et al., 1993; Wilson and Gallant, 2000). However, these models use simplified atmospheric parametrizations based on lumped regional parameters and their use for operational modelling is limited (Ruiz-Arias et al., 2009).

Terrain effects have not been thoroughly analysed yet, and they are not considered sufficiently in the present satellite operational schemes. Based on a thorough analysis we propose a disaggregation method of the estimates of satellite-derived horizontal irradiance calculated with a spatial

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resolution of 3 arc min (cell size ~ 5 km) considering the terrain information derived from the 3 arc sec digital elevation model (DEM, cell size ~ 90 m). The method was evaluated in the region of Andalusia, Spain.

2. Terrain effects

Complex terrain introduces significant variations in the local micro-climate. The first factor of variability is the elevation. Under similar atmospheric turbidity, the total radiative attenuation at low elevation is bigger compared to the high elevation. In a cloudless Rayleigh atmosphere, ozone and uniformly mixed gases are mainly located in the upper layers with water vapour immediately below and the aerosols in the lower layer (Gueymard, 1998). While major absorbents, water vapour and aerosols, are particularly variable over the time, combined with changes in elevation may significantly influence spatial pattern of attenuation.

Diverse illuminance angles are source of large irradiance variability (Dubayah et al., 1989, 1990), and surrounding terrain configuration influences the total amount of received irradiance by horizon shadowing, sky interception and ground reflectance. For illuminance angles greater than $\pi/2$, the surface is self-shaded (behind its own horizon) and the solar irradiance is entirely composed of diffuse irradiance.

2.1. Elevation

The coarse resolution of the satellite grid cell (~5 km) may include internal elevation differences of more than 1000 meters in some regions. The vertical gradient of global irradiance is determined mainly by the beam irradiance and the change in the optical path length Δm, assuming constant the attenuative radiative properties of the atmosphere between the two extreme elevations within the grid cell. The change in the optical path length is $\Delta m = \Delta z \cos \theta_z$ (Fig. 1) if the Earth's curvature is not considered, where Δz and θ_z are the elevation change and solar zenith angle. The beam broadband irradiance B can be approximated, according to the Bouguer–Beer–Lambert law, as:

$$B = S_0 e^{-\kappa m}, \tag{1}$$

where S_0 is the extraterrestrial irradiance, and κ is the broadband attenuation coefficient. Therefore, according to Fig. 1, if $(B_A - B_B)/B_A \sim \Delta B/B$, where B_A and B_B is the beam irradiance in the points A and B, and $m_B = m_A + \Delta z \cos \theta z$ we can write:

$$\frac{\Delta B}{B} \sim 1 - e^{-\kappa \Delta z \cos \theta_z}. \tag{2}$$

This expression shows that beam irradiance should increase exponentially with altitude, given κ constant. Furthermore, according to Eq. (2), the change of irradiance is maximum when the sun is at the zenith and zero when the sun is at the horizon, assuming the Earth's curvature as negligible.

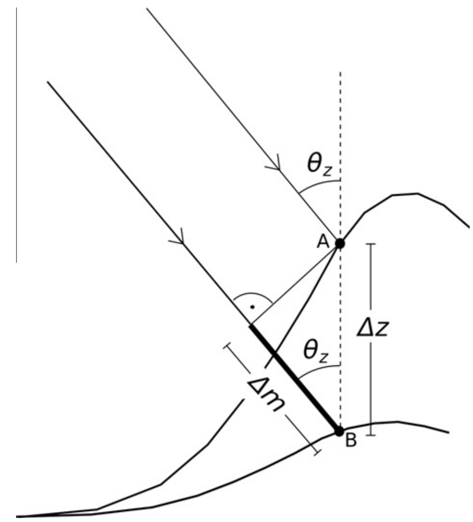

Fig. 1. Change of the optical path length Δm produced by a change of elevation Δz.

Satellite grid cell represents the spatial-time average irradiance, and let us assume the distribution of terrain elevation within the grid cell $\Phi(z)$. Let z_0 be the elevation at the satellite grid resolution. The global irradiance $G(z)$ within the grid cell can be described as a Taylor's expansion in the nearby of z_0 as:

$$G(z) = G(z_0) + \sum_{n=1}^{\infty} \frac{1}{n!} \frac{\partial^n G}{\partial z^n}\bigg|_{z=z_0} (z - z_0)^n, \tag{3}$$

where the Taylor's remainder has been neglected. Assuming the variability of atmospheric properties negligible along the grid cell and rejecting other terrain effects, the average global irradiance in a grid cell, given the distribution of elevations and Eq. (3) is:

$$\begin{aligned}\bar{G} &= \int_{z_{\min}}^{z_{\max}} G(z)\Phi(z)dz \\ &= G(z_0) + \sum_{n=1}^{\infty} \frac{1}{n!} \frac{\partial^{(n)} G}{\partial z^{(n)}}\bigg|_{z=z_0} \int_{z_{\min}}^{z_{\max}} (z - z_0)^n \Phi(z)dz,\end{aligned} \tag{4}$$

where $\Phi(z)$ is normalized to the unity. The integral in the right term is the nth moment of the elevations distribution $\Phi(z)$ centred in the average value z_0. Assuming $E[z] = z_0$ for the grid cell, the first moment ($n = 1$) is zero and the second moment ($n = 2$) is the variance of z, VAR[z]. As first approximation, $n = \{1, 2\}$, the mean global irradiance can be written as function of the elevation distribution within the grid cell:

$$\bar{G} \sim G(z_0) + \frac{1}{2} \frac{\partial^2 G}{\partial z^2}\bigg|_{z=z_0} \mathrm{VAR}[z]. \tag{5}$$

Therefore, the satellite irradiance at every grid cell should show a linear dependency with the intra-grid cell variability of the elevation, being the irradiance at the average elevation $G(z_0)$ the intercept of the curve. To verify this expression, Fig. 2 shows the intra-grid cell elevation