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Toward operational shortwave radiation modeling and retrieval over rugged terrain

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A B S T R A C T

Shortwave radiation (0.3–3.0 μm) is a dominant component of land surface all-wave radiation budget. Reliable estimation of shortwave radiation throughout the globe is particularly important for an in-depth understanding of global changes. Unfortunately, a large number of existing space-based algorithms ignore the effects of topography by simply assuming that the surface is ideally flat. As pointed out by many studies, such neglect toward topographic effects leads to significant errors in derived radiation. This study proposes a shortwave topographic radiation model (SWTRM) by quantifying solar direct radiation shielding, occlusion of sky radiation, reflected radiation from nearby terrain, and invisibility of certain targets. To drive the SWTRM, an artificial neural network (ANN) approach was employed to generate multiple components of the shortwave radiation budget. The new model was run over the Tibetan Plateau region and used MODIS products coupled with digital elevation data (DEM). Topographically corrected shortwave fluxes were derived by coupling SWTRM and ANN outputs. The results show that: (1) the proposed SWTRM works well over mountainous regions; (2) the ANN-based shortwave model provides reasonable retrieval accuracy (RMSE < 60 W/m^2, bias < 13 W/m^2 for all shortwave radiation components). More importantly, the ANN model can simultaneously provide all radiation components that are indispensable for driving the SWTRM; (3) over mountainous areas, the induced error can exceed 600 W/m^2 for shortwave net flux. Hence, topographic effects cannot be neglected; and (4) topography and solar illumination angle are key modulators in deriving shortwave radiation from space, which control the magnitude and spatial distribution of shortwave radiation over mountainous regions.

1. Introduction

As a dominant energy source, shortwave (SW) radiation (also called solar radiation) significantly influences the planet's energy and water cycles. Compared to traditional ground-based radiation measurements, which are usually characterized by sparse spatial coverage, satellite provides a unique advantage of mapping land surface radiation with continuous spatial and temporal scales. Since the 1970s, a number of missions such as the first Earth Radiation Budget Experiment (ERBE) (Barkstrom, 1984; Barkstrom and Smith, 1986), the Clouds and the Earth's Radiant Energy System (CERES) (Wielicki et al., 1998), and the Atmospheric Infrared Sounder (AIRS) (Sun et al., 2010) have been carried out. Radiation products from the above missions together with currently available global radiation budget datasets such as radiation products of the International Satellite Cloud Climatology Project (ISCCP) (Zhang et al., 2004) and the Global Energy and Water Cycle Experiment (GEWEX) (Pinker et al., 2003), have for a long time provided important basic data to the field of surface energy budget and global change. The spatial scales of these products are generally too coarse to be widely used in most applications and land models. Moreover, their reliability and physical consistency have not been fully evaluated. The Moderate Resolution Imaging Spectroradiometer (MODIS) (Masuoka et al., 1998; Justice et al., 1998, 2002) as a payload instrument that was launched in 1999 on board the Terra satellite, and in 2002 on board the Aqua satellite, can capture data in 36 spectral bands and at varying spatial resolutions (250 m, 500 m and 1 km). The two satellites measure the entire earth every 1–2 days. The high temporal frequency and high resolution of the MODIS has provided

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unprecedented access to the global radiation mapping. In this study, MODIS radiances of bands 1–7 as well as other products were used to derive SW radiation.

To date, numerous approaches have been used to derive shortwave radiation components, including SW Downward Radiation (SWDR), Net Radiation (SWNR), Solar Direct Radiation (SDR), Upwelling Radiation (SWUR) and Photosynthetically Active Radiation (PAR) based on remote sensing. These methods can be classified into four groups: (1) empirical approaches such as those suggested by Tarpley (1979) and Klink and Dollhopf (1986), which usually directly link the top of the atmosphere (TOA) radiance and coincident surface SW radiation. These methods are simple, but the results are site- and/or data-specific and are not easily applied to other regions; (2) physics-based methods such as those used by Dubayah (1995) and Dedieu et al. (1987), which utilize a physics-based radiative transfer model to calculate radiation given necessary driving data. Although theoretically accurate, they depend strongly on driving data that might not be readily available. Moreover, they are often computationally extensive owing to the complex property of the radiative transfer process; (3) parameterized methods such as those adopted by Li et al. (1993), Bisht et al. (2005), and Bisht and Bras (2010) which often develop parameterized formulae to estimate surface fluxes using key atmospheric variables such as water vapor, aerosols, etc. Compared to physics-based methods, they are computationally efficient, but some ancillary atmospheric parameters are still required and the global applicability of the selected empirical formula should be carefully considered; and (4) the so-called hybrid methods such as those proposed by Kim and Liang (2010), Zheng et al. (2008), Liang et al. (2006) and Zhang et al. (2014). These methods usually involve a vast amount of radiative transfer simulations given proper atmospheric, geometrical and surface conditions, followed by statistical regression modeling, machine learning or a Look-Up Table based on the simulated database. The hybrid methods have become increasingly popular in the scientific community as they do not depend on coincident atmospheric states and surface reflectance, so do not lose the physical properties of surface radiation. The hybrid approach has thus been chosen in this paper to derive SW radiation from the MODIS. The MODTRAN4 code (Berk et al., 1999) has been employed to perform extensive radiative transfer simulations, and an artificial neural network (ANN) model has been used to link SW radiation and MODIS measurements. The ANN is considered a typical statistical method for a variety of applications including pattern recognition, classification, signal processing, system control and optimization, medicine and geosciences. (Suzuki, 2011, chap. 1). More importantly, many studies have shown that an ANN with multilayer perception neurons is very powerful at solving geophysics-related inversion problems (Jiménez et al., 2003; Müller et al., 2003). Specifically, recent studies (Wang et al., 2009; Kim and Liang, 2010) have proven its potential in the radiation budget field.

However, the vast majority of existing algorithms (Tarpley, 1979; Klink and Dollhopf, 1986; Li et al., 1993; Bisht et al., 2005; Liang et al., 2006; Bisht and Bras, 2010; Kim and Liang, 2010; Wang et al., 2012; Zhang et al., 2014) as well as the recently released radiation products completely ignore topographic effects by assuming that the surface is flat. This assumption cannot work in mountainous areas (Dubayah and van Katwijk, 1992; Dubayah, 1992). As pointed out by Dubayah (1992), SWNR can vary largely at the meter scale owing to topographic and albedo variations. Tovar et al. (1995) studied solar radiation variations based on a ground network with 10 pyranometers deployed over a 20 × 10 km mountainous terrain, and concluded that hourly differences in solar radiation between pairs of stations can reach up to 50% due to topographic effects. This implies that the amount of solar radiation over mountainous areas cannot be estimated by simply interpolating nearby observations. Oliphant et al. (2003) also analyzed spatial patterns of surface shortwave radiation on alpine mountains on clear and sunny days. Garen and Marks (2005) emphasized that estimation of surface solar radiation over mountainous surfaces is an essential step in modeling melting snow on mountains. In addition, Yang et al. (2010) characterized downward short- and long-wave radiation over the Tibetan Plateau, pointing out that estimating radiation over high-altitude, mountainous regions is important and necessary. Williamson et al. (2016) also pointed out the topographic effect on the variation of surface albedo within and between 500 × 500 m MODIS pixels by multiple sampling along transects using pyranometers. Unlike flat surfaces, the interaction between SW radiation and the Earth's surface is particularly complex over mountainous areas. Solar incidence and observation angles constantly change with surface slope and aspect angles. In addition, obstructions and shadows frequently occur in mountainous regions increasing the difficulty in estimating radiation contributions from multiple sources. Comingled with these factors is the interaction between an observed object and its surrounding sloped surfaces. As a result, quantifying SW radiation over mountainous regions is certainly not trivial work.

Given the extensive global coverage of mountainous regions and their influence on climate, developing effective topographical models and retrieval strategies over rugged terrain is greatly necessary. Dozier (1989), Dubayah (1992) and Dubayah and Loechel (1997) have developed a shortwave topographic model which is frequently mentioned in various publications. It can be used to calculate SWDR and SWNR over mountainous regions. The required inputs for this model include SDR, diffuse solar radiation on unobstructed surfaces, surface albedo and atmospheric transmittance. However, this model has not been frequently adopted because of: (1) difficulties in preparing driving data, especially surface albedo and transmittance; and (2) the feasibility of driving the model based on generic satellite measurements such as the MODIS, as it was originally designed for Landsat Thematic Mapper (TM) or Geostationary Operational Environmental Satellite (GOES) data. Thus, the objective of this paper is to improve the existing topographic radiation model and to explore an operational strategy to estimate SW radiation components over mountainous areas based on readily available MODIS products. The Tibetan Plateau was selected for this study as its representative topography and modulation on the Asian monsoon and global climate make it a suitable test region for topographic modeling and radiation budget studies.

Section 2 describes the datasets employed in this study including remotely sensed products and in situ SW radiation measurements. Section 3 presents an ANN-based SW model and a SW topographic radiation model (SWTRM). Correction of effective SW fluxes for terrain shading is also provided in this section. Section 4 demonstrates the performance of the ANN-based method and the newly proposed SWTRM model. Finally, the discussion and conclusions are given in Sections 5 and 6, respectively.

2. Datasets

Multiple MODIS products were selected as the main data sources in this paper. The MODIS on board the Terra and Aqua satellites is deemed to be one of the most advanced systems currently available for global land and atmosphere detection, which can be evidenced by its relatively high spectral and spatial resolutions (Section 1). More importantly, various MODIS atmosphere and land products are readily available to the scientific community. These provide an unprecedented opportunity for accurately mapping high-resolution global surface SW radiation. The remotely sensed datasets used in this study are listed in Table 1.

MODIS products from Terra for November 4, 2009 as taken over the Tibetan Plateau were randomly selected for this case study. To ensure consistency, all MODIS products were first re-projected to the Albers projection with the WGS84 datum, and all projected products with coarse resolutions were then spatially resampled into a spatial resolution of 1 km using nearest-neighbor interpolation, to match the scale of MODIS radiance product (MOD021KM/MYD021KM).

Although ground measurements are usually restricted to sparse spatial coverage compared to space-based measurements, they are