Remote Sensing of Environment 172 (2016) 15–27

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Topographic radiation modeling and spatial scaling of clear-sky land surface longwave radiation over rugged terrain

Guangjian Yan [a], Tianxing Wang [a,b,*], Zhonghu Jiao [a], Xihan Mu [a], Jing Zhao [a], Ling Chen [c]

[a] State Key Laboratory of Remote Sensing Science, School of Geography, Beijing Normal University, Beijing 100875, China
[b] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100101, China
[c] The Academy of Forestry, Beijing Forestry University, Beijing 100083, China

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 17 October 2015
Accepted 25 October 2015
Available online 6 November 2015

Keywords:
Longwave radiation
Rugged terrain
Spatial scaling
Artificial neuron network
Tibetan Plateau
MODIS

ABSTRACT

Longwave radiation (5–100 μm) is a critical component of the Earth's radiation budget. Most of the existing satellite-based retrieval algorithms are valid only for flat surfaces without accounting for topographic effects. This causes significant errors. Meanwhile, the fixed spatial resolution of remote sensing data makes it difficult to link the satellite-derived longwave radiation to different land models running on various scales. These deficiencies result in an urgent need for topographic modeling and spatial scaling studies of longwave radiation. In this paper, a longwave topographic radiation model (LWTRM) is proposed that quantifies all possible radiation-affecting factors over rugged terrain. For driving the LWTRM, a hybrid method for simultaneously deriving multiple components of longwave radiation from MODIS data is suggested based on artificial neuron networks (ANN) and the radiative transfer simulation. Topographically corrected longwave radiation is then derived by coupling the ANN outputs and LWTRM. Based on this, a general upscaling strategy for longwave radiation is presented. The results demonstrate that: (1) both the proposed LWTRM and the upscaling strategy are rather effective and work well over rugged areas; (2) the ANN-based retrieval method can produce longwave radiation with better accuracy(RMSE <23 W/m^2, bias <9 W/m^2). More importantly, it can simultaneously derive multiple components of longwave radiation in a consistent manner; (3) over mountainous areas, the radiation cannot be accurately characterized in terms of either spatial distribution or specific values if topographic effects are neglected, for instance, the induced error can reach up to 100 W/m^2 for the longwave net flux; and (4) the topographic effects cannot be ignored below spatial scale of approximately 5 km in the selected study area.

1. Introduction

Longwave (LW) radiation (or longwave radiative flux) components, including longwave upwelling (LWUR), downward (LWDR) and net radiation (LWNR), are key components of the total energy that drives the surface energy balance at the interface between the earth's surface and the atmosphere. During the past several decades, there have been considerable efforts toward estimating the surface LW radiation based on various remotely sensed data. Examples include studies of LW upwelling (Wang, Liang, & Augustine, 2009; Wang et al., 2005; Wang & Liang, 2010) and downward radiation (Lee & Ellingson, 2002; Zhou & Cess, 2001; Zhou, Kratz, Wilber, Gupta, & Cess, 2007; Duarte, Dias, & Maggiotto, 2006; Wang & Liang, 2009a; Sridhar & Elliott, 2002; Kjaersgaard, Plauborg, & Hansen, 2007; Wang & Liang, 2009b). However, so far, LWNR (which is a key variable to estimate the surface energy budget) is usually indirectly determined by separately estimating the upwelling and downward LW radiation (Masuda, Leighton, & Li, 1995; Wang & Liang, 2009a; Wang & Liang, 2009b). As noted by most researchers, the uncertainties associated with each step may lead to large errors in the final net radiation (Li, Leighton, Masuda, & Takashima, 1993). Thus, effective algorithms that can directly retrieve the LW net radiation using readily available remote sensing measurements are highly desired. An effective method for directly deriving multiple components of surface longwave radiation from satellite data has recently been reported by Wang, Yan, and Chen (2012).

Although more and more attention has been paid to the derivation of surface radiation from space, most of the existing algorithms are only valid for flat surfaces without accounting for topographic effects on radiation. As pointed out by many researchers (Dubayah, 1992; Dubayah & van Katwijk, 1992), significant bias can be induced in the retrieved variables if topographic effects over rugged terrain are not considered. As a result, many studies have been carried out to quantify the effects of topography on thermal radiation. For instance, Lipton (1992) found that neglecting the terrain effect can cause an approximately 3 K bias in surface temperature retrieval. He further noted that the magnitude of the error was closely related to the observing angles of the satellite and the solar incidence, and the deviation becomes even larger if a fine DEM is used. With a simple approximation of the radiation contribution from

* Corresponding author at: State Key Laboratory of Remote Sensing Science, School of Geography, Beijing Normal University, Beijing 100875, China.
E-mail address: wangtx@radi.ac.cn (T. Wang).

http://dx.doi.org/10.1016/j.rse.2015.10.026

the surrounding terrain, Duguay (1995) constructed a simple thermal radiation model based on the work of Marks and Dozier (1979) and Olyphant (1986). However the model is only suitable for high resolution data (such as Landsat data). Compared to shortwave radiation, the topographic effect on thermal radiation is more complex. It involves coupling between temperature and emissivity, temperature under shaded areas, and the mutual interaction between terrain undulation and observing geometry, etc. Unfortunately, to the best of the authors' knowledge, few models are currently available to estimate surface longwave radiation from space over rugged terrain. Considering the large proportion of mountainous areas over the earth's surface and their important roles in climate change studies, it is particularly necessary to quantify the topographic effect and to develop operational topographic models, not always dealing with the surface as a flat plane. That is one of our motivations in this paper.

In addition to the topographic effect, how to upscale or downscale the radiation data is still a challenge today, especially over rugged terrain. Because the spatial resolution is relatively fixed for certain satellite instruments, it is an indispensable step to spatially downscale or upscale the retrieved radiation so that the data can be input into different application models, including hydrology models, crop growth models, ecological models and climate models that run at various spatial scales (McCabe & Wood, 2006). Moreover, to account for the topographic effect, the procedure for spatially matching the satellite data to DEM also needs spatial scaling. This is a critical issue we have been facing for a long time. Up to now, although a number of reports have been published on this topic (Schroeder, Hember, Coops, & Liang, 2009; Dubayah & Loechel, 1997; Zheng, Liang, & Wang, 2008), most of the above mentioned studies simply aggregate the DEM to a coarser scale corresponding to the resolution of the satellite data. All of the topographic parameters are then calculated on the coarser grid (Zheng et al., 2008; Schroeder et al., 2009) or by spatially averaging the satellite retrievals around certain DEM pixels to represent the value of that DEM (Dubayah & Loechel, 1997). Unlike those existing studies, in this paper, we propose a general upscaling method for the retrieved surface longwave radiation over rugged terrain by fully considering the topographic effect.

The remainder of this paper is structured as follows. Section 2 describes the basic information of our study site — (the Tibetan Plateau) as well as the datasets used in this study. Section 3 first presents a longwave topographic radiation model (LWTRM) that considers all of the possible factors that affect LW radiation over rugged terrain. Then, a consistent method to simultaneously retrieve multiple LW flux components based on the MODTRAN simulation and the artificial neuron network (ANN) technique is suggested, and a terrain shading correction is subsequently conducted to prepare driving data for LWTRM. Finally, Section 3 presents a spatial scaling method for surface LW radiation over rugged terrain. The retrieval results and issues related to the proposed model and methods are discussed in Section 4, and the conclusions are presented in Section 5.

2. Study site and datasets

2.1. Study site

In this study, we select the Tibetan Plateau as our study site because of its special topography and its important influence on Asia and even global climate change. This makes it an ideal study area for terrain modeling and climate change studies (Yang, He, Tang, Qin, & Cheng, 2010; Yang et al., 2008).

The Tibetan Plateau (across 25°–40°N, 74°–104°E) is a large, elevated plateau in East Asia. With an average altitude exceeding 4000 m, it is sometimes called “The Roof of the World” or the “Third Pole”. The Tibetan Plateau is surrounded by massive mountain ranges. Most parts of the Tibetan Plateau are dominated by topographically complex terrain, and different mountains are staggered with each other dividing the plateau into many basins, wide valleys and lakes. The Tibetan Plateau has a high altitude, low temperatures and large temperature differences between day and night, and in some areas it is covered by snow throughout the year. In addition, the Tibetan Plateau has a low population density and thin air. Therefore, aerosol optical thickness and water content of the atmosphere is generally small. In general, it receives more solar radiation but emits less longwave radiation than the surrounding areas. For instance, under all-sky conditions, the difference of monthly average LWDR between the Tibetan Plateau and its surrounding areas can reach up to 100 W/m^2, while for shortwave downward radiation, the maximum difference can be approximately 200 W/m^2 higher than its surroundings(Yang et al., 2010).

Given its complex terrain structure and its sensitivity to global climate change, the Tibetan Plateau is an ideal test region for this study to accurately model surface radiative fluxes over rugged terrain and to evaluate scaling issues under circumstances of complex terrain.

2.2. Datasets

The Moderate Resolution Imaging Spectroradiometer (MODIS), currently onboard the Terra and Aqua satellites, is one of the most advanced sensors available for large-scale terrestrial applications (Masuoka, Fleig, Wolfe, & Patt, 1998; Justice, Vermote, Townshend, et al., 1998; Justice et al., 2002). MODIS measures emitted and reflected radiances from the atmosphere and surface in 36 spectral channels with spatial resolutions of 250 m, 500 m and 1 km. Its relatively high spectral and spatial resolution makes it very appropriate to determine land surface shortwave and longwave radiation globally. Moreover, various MODIS atmospheric and land products are readily available to the scientific community. These will be definitely helpful and convenient for mapping global surface radiation from space. In this study, MODIS radiance data from MOD021KM, land surface temperature/emissivity from MOD11B1, geolocation data from MOD03, profiles of air temperature/moisture from MOD07 and cloud mask from MOD35 products were collected on November 4, 2009, over the Tibetan Plateau. All of the datasets were re-projected to equal-area Albers projections for subsequent use.

To quantify the topographic effect of surface longwave radiation, the digital elevation model (DEM) data are used to depict the terrain's 3D characteristics. The DEM data are collected from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) of version 2.0. Its horizontal resolution is 30 m. The average elevation error is 8.3 m, with an average standard deviation of 12.6 m. The geolocation error is 0.11 arc-seconds to the west and 0.20 arc-seconds to the south on average, and the standard deviation is 0.22 arc-seconds in the east–west and 0.14 arc-seconds in the north–south directions on average (Tachikawa, Hato, Kaku, & Iwasaki, 2011). The improved spatial resolution and increased horizontal and vertical accuracy are quite suitable for this study.

In addition to the above mentioned data, in situ measurements of longwave radiation were collected at seven Surface Radiation Budget Network (SURFRAD) stations over two years (2008 and 2009) for validation purposes. SURFRAD was established in 1993 over the United States with the support of NOAA's Office of Global Programs to understand the global surface energy budget and climate changes (Augustine, DeLuisi, & Long, 2000). Currently, there are seven stations in operation: Montana, Colorado, Illinois, Mississippi, Pennsylvania, Nevada and South Dakota (Augustine, Hodges, Cornwall, Michalsky, & Medina, 2005). These sites lie in disparate climatic regions and provide accurate, precise, continuous and long-term ground-based measurements of the surface radiation budget, including those of upwelling and downward shortwave and longwave radiation.

SURFRAD data are available in daily files of three-minute before January 1, 2009, and one-minute afterward. The downward and upwelling longwave radiation are measured by Eppley's Precision Infrared Radiometer (PIR) with a spectral range from 4.0 to 50 μm and an accuracy of $\pm$9 W/m^2 (Augustine et al., 2000).