Remote Sensing of Environment 113 (2009) 24–39

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

An empirical anisotropy correction model for estimating land surface albedo for radiation budget studies

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ARTICLE INFO

Article history:
Received 25 August 2007
Received in revised form 15 August 2008
Accepted 15 August 2008

Keywords:
Surface albedo
Bidirectional reflectance
BRDF model
POLDER
Empirical model
Surface radiation budget

ABSTRACT

Land surface albedo is one of the key parameters in the radiation budget, the hydrological cycle and climate modeling studies. It is now widely understood that large errors may occur in the estimation of surface albedo without taking into consideration the anisotropy reflectance effect, which is a general feature of the earth surface. Two major anisotropic correction methods exist for the retrieval of land surface albedo under clear sky conditions. One method involves linearly converting from top of the atmosphere (TOA) albedo to surface albedo, and another is based on the inversion of the Bidirectional Reflectance Distribution Function (BRDF) model of the surface. In the present study, a new approach that utilizes an empirical model for estimating surface albedo has been proposed for snow free land surfaces under clear sky conditions. We analyzed the bidirectional reflectance data set with numerous samples representing various land cover types, which derived from POLDER/ADEOS-1 multi-angle imagery data and distributed by MEDIAS-France. Through the analysis, an empirical relation between bidirectional reflectance and albedo was established and has been discussed in detail. The proposed model can be used for direct estimation of surface albedo from a single BRF observation when the sun-target-sensor geometry is known. No BRDF model inversion scheme is necessary. The present model has no or weak dependence on the existing land surface classifications, and is insensitive to wavelength. The theoretical absolute accuracy of the estimated albedo is approximately 0.010 for visible (0.4–0.7 μm), 0.023 for near infrared (0.7–3.0 μm) and 0.016 for shortwave (0.2–3.0 μm), respectively. Albedo consistency with viewing geometry has been verified, resulting in good agreement for albedo estimated from various viewing directions. Validation of the satellite estimated albedo derived by the proposed method, using field observations were also presented and results show it can give reasonably accurate estimation. The proposed method is expected to be a suitable candidate for practical applications of albedo estimation for sensors that do not perform multi-angle observations.

1. Introduction

Land surface albedo is a key parameter representing the outgoing solar flux fractions reflected by the surface. It is also used as an input parameter for numerical climate models and Atmospheric General Circulation Models such as the National Centers for Environmental Prediction (NCEP) models and ECHAM4 climate model (Roeckner et al., 1996) for surface boundary conditions. In model application, it is common to use seasonal albedo data set acquired from field observations and information on surface vegetation types. For example, Matthews (1983) seasonal surface albedo data set, which has 1° resolution and 32 surface types, has been used in NCEP models. Albedo data obtained from model, such as the Simple Biosphere Model (Sellers et al., 1986, 1996) are used in ECHAM4 and the International Satellite Land Surface Climatology Project (ISLSCP). These data sets have coarse spatial and temporal resolutions and the prescribed surface types are required as ancillary data.

For the past two decades, albedo estimates derived from satellite data have been produced by using various kinds of sensors. Radiation budget studies using satellite observations have been performed on both global and regional scales. Satellite derived albedo products, have the potential to provide higher accuracy with finer spatial and temporal resolutions than can be achieved with ground-based or model estimated albedo products. Satellite-derived albedo estimates can therefore be effective for use as input to climate models as well as for model validation. The accuracy of albedo required for model studies has been estimated as 0.02–0.05 in absolute value (e.g. Henderson-Sellers & Wilson, 1983; Jacob & Olioso, 2005). Among the numerous radiation budget studies that have been performed with satellite observations, two major ones are the Earth Radiation Budget Experiment (ERBE) (Barkstrom & Smith, 1986) and more recently, the Geostationary Earth Radiation Budget Experiment (GERB) (Harries & Crommelynck, 1999).

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0034-4257/$ – see front matter
doi:10.1016/j.rse.2008.08.007

Satellite measurements of the Earth or atmosphere radiation are usually restricted by the orbital characteristics of the satellite and the scanning characteristics of the sensor, such that only radiance reflected in certain directions can be measured. For estimating the total flux reflected by the surface, the observed directional reflectance should be converted into albedo, which is the ratio of the total reflected flux to the incident flux. Since the reflectance of the target is usually anisotropic, the angular dependence must be considered for accurate evaluation of albedo. The anisotropy effect to radiation budget at the TOA and its correction has been studied well. Taylor and Stowe (1984) developed the Angular Distribution Model (ADM) at the TOA, using data acquired by the ERB scanner onboard Nimbus-7. Similar kinds of angular radiance distribution models have been also developed (Koepke & Kriebel, 1986; Minnis & Harrison, 1984) and are widely used (Suttles et al., 1988; Pinker & Laszlo 1992). These models consist of anisotropy conversion factors that depend on the underlying scene types (including underlying surface cover types, optical properties of the atmosphere and cloud types of scenes) and the geometry including solar zenith angle (SZA), viewing zenith angle (VZA), and relative azimuth (RAZ). Using the multiangle measurements from CERES (the ERBE successor), new ADMs have been recently developed (Loeb et al., 2003a, 2003b, 2005) with improved accuracy, as compared to ERBE derived model. For clear sky conditions, surface albedo can be estimated from albedo at the TOA by utilizing linear functions (Pinker, 1985; Koepke & Kriebel, 1986; Pinty & Ramond, 1987; Li & Garand, 1994). Although there are studies on albedo estimation by above-mentioned method using multi-spectral sensors with finer spatial resolutions such as AVHRR (Csiszar & Gutman, 1999), two shortcomings limit its potential for practical applications. The first shortcoming is that the ADMs at TOA are developed from ERB or CERES observations, which have much coarser spatial resolutions. The second is that the linear functions used to convert TOA albedo to surface albedo are suitable only for the broadband case.

In recent years, with the development of sensor techniques and modeling of surface BRDF (Li & Strahler, 1992; Roujean et al., 1992; Wanner et al., 1995; Chen & Leblanc, 1997), estimation of surface albedo from surface directional reflectance has become a common alternative to approaches that rely on conversion from TOA albedo. Directional reflectance at the surface can be estimated by performing atmospheric corrections on the measured spectral radiance. Anisotropy effects of surface are corrected to estimate the spectral albedo, then broadband albedo can be estimated by a narrowband-to-broadband conversion. One of the advantages of this method is the possibility to estimate directional reflectance with improved accuracy by applying separated atmospheric correction for the different spectral bands. Moreover, albedo (including spectral albedo and broadband albedo) can be estimated with finer spatial resolution and temporal resolution. Algorithms used to produce satellite derived surface albedo products such as the MODIS/MISR BRDF/Albedo products (Wanner et al., 1997), POLDER land surface products (Leroy et al., 1997) and Meteosat Surface Albedo Product (Pinty et al., 2000) are based on the above method. The core part of the process is usually based on the specifications of the BRDF model of the target surface for anisotropy correction, in which the multi-angle observations are necessary for performing the BRDF model inversion. However, for most satellite sensors with just one observation per orbital pass, and even for multi-angle observation, it is still difficult to acquire sufficient data to represent the whole reflectance hemisphere simultaneously.

Long-term observation is especially important for monitoring the radiation balance. Since the existing methods have limitation as discussed above, they are not suitable for traditional singe-observation-angle sensors, which have been operating for more than three decades. Developing an easily used directional effect correction method that can be applied to data from traditional sensor types is necessary. At TOA, ADMs are successfully used for converting directional reflectance to albedo, however empirical relationship has not yet been developed for converting surface directional reflectance to surface albedo.

In the present study, the BRDF property of different land cover types and their common features are discussed by analyzing directional reflectance data from multi-angle satellite images. With the aim of estimating clear sky surface albedo from one directional observation, an empirical BRF (Bidirectional Reflectance Factor) to albedo conversion model for correcting anisotropy effect of land surface is developed. The theoretical accuracy of the model is also evaluated.

This paper is organized as: the nomenclature is clarified in Section 2. The data set and the data processing method are introduced in Section 3, including the BRDF model description and discussions on the BRDF property of different land surface cover types. The empirical anisotropic correction model is proposed in Section 4, with results and discussions. The conclusions are presented in Section 5.

2. Definitions and nomenclature

Since there are several definitions and nomenclatures concerning directional reflectance and albedo in the literature, it is important to clarify their use in this paper. The term “surface reflectance” used in the present study refers to the top of canopy (TOC) reflectance, excluding the underlying ground reflectance, especially for dense vegetation. The parameters used in the definitions are as follows: θ_s: solar zenith angle; φ_s: solar azimuth; θ_v: satellite view zenith angle; φ_v: satellite view azimuth; ξ: phase angle between solar and satellite direction viewing from target; λ: wavelength. Fig. 1 shows the geometry of these parameters mentioned above, the incident direction corresponds to the direction to the sun.

The general definition of BRDF, as that introduced by Nicodemus (1970), is the ratio of the radiance reflected in a certain direction to the irradiance with an incidence direction. BRDF describes the intrinsic reflectance property of the target. Since solar irradiance reaching the surface includes direct and diffuse components for actual satellite measurements, radiance reflected by the surface in a certain observation direction is the weighted sum of bidirectional reflectance fraction and hemispherical-directional reflectance fraction. Hemispherical-directional reflectance is defined as the fraction of incident irradiation in the incident hemisphere that is reflected by the object in a certain direction. However, the BRDF characteristics of the surface are unknown, so that the direct and diffuse components contained in the reflected radiance are therefore unable to be separated. The nomenclature “apparent bidirectional reflectance” (Jacob & Olioso, 2005) is used in this study, to denote the directional reflectance with both direct and diffuse part, and to distinguish it from the original bidirectional reflectance. Actually, most of the bidirectional reflectance derived from satellite or obtained at field measurements refers to the apparent one.

Apparent BRDF can be expressed as,

$$f_\lambda(\theta_s,\varphi_s) = \frac{I_{e,\lambda}(\theta_s,\varphi_s;\theta_v,\varphi_v)}{F_{i,\lambda}(\theta_s,\varphi_s)}\cdot\left(sr^{-1}\right) \tag{1}$$

Apparent BRDF takes the same form as the general definition of BRDF but with $F_{i,\lambda}(\theta_s,\varphi_s)$ expressed the incident spectral solar flux per unit area (W m^{-2} μm^{-1}) consisting of the direct and diffuse components. The term $I_{e,\lambda}(\theta_s,\varphi_s;\theta_v,\varphi_v)$ is the spectral radiance (W m^{-2} sr^{-1} μm^{-1}) reflected at a certain direction in the viewing hemisphere containing fraction of both directional-directional and hemispheric-directional reflectance. Apparent BRF is expressed as,

$$\rho_\lambda(\theta_s,\varphi_s) = \frac{I_{e,\lambda}(\theta_s,\varphi_s;\theta_v,\varphi_v)}{F_{i,\lambda}(\theta_s,\varphi_s)/\pi}. \tag{2}$$

It equals the apparent BRDF multiplied by π sr. Spectral albedo $\alpha_\lambda(\theta_s,\varphi_s)$ labels the fraction of the solar irradiance reflected within the whole upper hemisphere at a certain wavelength. It is the integration of apparent BRDF in Eq. (1) cross the whole viewing hemisphere and also can expressed as the integration of apparent BRF as follows:

$$\begin{aligned}\alpha_\lambda(\theta_s,\varphi_s) &= \int_0^{2\pi}\int_0^{\pi/2} f_\lambda(\theta_s,\varphi_s)\cos\theta_v\sin\theta_v\,d\theta_v\,d\varphi \\ &= \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2}\rho_\lambda(\theta_s,\varphi_s)\cos\theta_v\sin\theta_v\,d\theta_v\,d\varphi_v.\end{aligned} \tag{3}$$