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Estimating high-resolution top of atmosphere albedo from Moderate Resolution Imaging Spectroradiometer data

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ABSTRACT

High spatial resolution top-of-atmosphere (TOA) albedo data is needed to study the radiative forcing of natural or anthropogenic events at regional scales. However, existing products are typically estimated using broadband sensors with coarse spatial resolutions. This paper presents a hybrid method to retrieve TOA albedo over land from multispectral data collected by Moderate Resolution Imaging Spectroradiometer (MODIS) at its native spatial resolution. The approach is based on extensive atmospheric radiative transfer (RT) simulations using representative surface and atmospheric conditions as inputs. The clear-sky algorithm explicitly takes surface reflectance anisotropy into account using the POLDER3/PARASOL bidirectional reflectance distribution function database as the boundary condition of RT simulations to first generate TOA spectral albedos and then convert them to broadband albedo. In the cloudy-sky method, surfaces are assumed to be Lambertian and surface spectra over the shortwave spectrum are used to directly obtain TOA broadband albedo. The TOA albedo retrieved from MODIS was compared with the Clouds and the Earth's Radiant Energy System (CERES) TOA flux products, using twelve days of global data (one day each month) in 2007. The two data sets are in good agreement, with a root mean square difference (RMSD) of 0.036 (8.6%) for all Terra instantaneous data and 0.039 (9.1%) for all Aqua instantaneous data. Further analysis revealed that larger discrepancies mainly occurred at pixels of large solar or view zenith angles. RMSD between the two data sets was reduced to ~0.02 when the solar zenith angles were limited to 60° and the view zenith angles were limited to 30°.

1. Introduction

Top-of-atmosphere (TOA) albedo is a key component of Earth's radiation budget. High-spatial-resolution TOA albedo data is needed to understand the radiative forcing of natural or anthropogenic events at regional scales. Remote sensing is a unique way to map global TOA albedo on an operational basis. Several sensors specially designed to monitor Earth's radiation budget have been deployed or will be launched to measure broadband SW radiance directly from space. These include the Earth Radiation Budget Satellite (ERBE) (Barkstrom, 1984); the Clouds and the Earth's Radiant Energy System (CERES) (Wielicki et al., 1998); the Geostationary Earth Radiation Budget (GERB) (Harries et al., 2005); the Scanner for Radiation Budget (ScaRaB) (Kandel et al., 1998); and the Earth Clouds, Aerosols, and Radiation Explorer (EarthCARE) (ESA, 2001). While the products derived from Earth radiation broadband sensors are extensively used in studies of global climate, their coarse spatial resolutions limit application in investigating local or regional radiation budgets. For instance, CERES has a footprint of ~20 km at nadir and its high-level products are aggregated to an even coarser grid of 1°. Signals of TOA albedo variations caused by small-scale natural or anthropogenic events such as irrigation for agriculture, air pollution, urbanization, and wildfires, can hardly be detected from data sets with such coarse spatial resolution.

It typically involves two steps to estimate TOA albedo from Earth radiation broadband sensors. The radiance directly measured by the sensors is first corrected to account for the non-flat spectral response function. In the second step, angular distribution models (ADM), which define the conversion coefficient as a function of viewing geometry, type of surface, and atmospheric parameters, are used to facilitate conversion from directional radiances to all-directional flux (Loeb, Kato, Loukachine, & Manalo-Smith, 2005). The datasets used to establish empirical ADM can originate from either observation (Loeb et al., 2003) or model simulation (Domenech, Lopez-Baeza, Donovan, & Wehr, 2011). The ADMs can be expressed with analytical equations for some cases (Loeb et al., 2005) or with statistical regression models (e.g., Artificial Neural Network (Domenech & Wehr, 2011)). In addition, they may be simply stored in look-up tables (LUTs) (Domenech et al., 2011). With the advancement in sensor calibration and retrieval algorithms, spaceborne observations of TOA albedo such as CERES flux data are considered reliable in terms of temporal stability. However,

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since the CERES instrument absolute calibration accuracy to compute the Earth's net imbalance may not equal the ocean heat content imbalance (Trenberth, Fasullo, & Balmaseda, 2014), the CERES Energy Balanced and Filled (EBAF) product adjusts the CERES net imbalance to match the ocean heat content (Loeb et al., 2009). This net flux imbalance is not removed from the CERES Single Scanner Footprint (SSF) product used here.

Compared to Earth radiation broadband sensors, data from multi- or even hyper-spectral radiometers are more profuse and offer higher spatial resolution. It should be noted that such data may also suffer from the problem of calibration drifts (Wang et al., 2012), though advanced onboard and vicarious calibration technique has been developed. Some researchers have already attempted to take advantage of such multispectral satellite imagery to retrieve TOA broadband albedo (Niu & Pinker, 2012; Tang, Li, & Zhang, 2006). Tang et al. (2006) directly estimated TOA broadband albedo from MODIS narrowband apparent reflectance. Niu and Pinker (2012) developed a two-step approach to first convert narrowband radiance measured by Spinning Enhanced Visible Infrared Imager (SEVIRI) to broadband radiance and then apply ADMs to retrieve TOA albedo.

In this paper, we present a refined method to estimate TOA broadband albedo over land from MODIS TOA spectral reflectance. Our method explicitly accounted for anisotropy in surface reflectance when calculating clear-sky TOA albedo and used the water vapor absorption band (Band 19) to better capture the absorption of shortwave radiation by water vapor. A comprehensive comparison between the MODIS retrievals and CERES products was conducted using twelve days (one day each month) of global data collected in 2007. Following the introduction, Section 2 describes the data used in this study, and Section 3 introduces the methodology. Results of sensitivity analysis and data comparison are presented in Section 4, and a brief summary is given in Section 5.

2. Data

2.1. MODIS

A MODIS sensor is onboard each Terra and Aqua polar-orbiting twin satellites. Terra, launched in December 1999, has an equatorial crossing time of 10:30, whereas Aqua was launched in May 2002 and crosses the equator at 13:30 (Barnes, Xiong, & Salomonson, 2003). The quality of MODIS observations has been improved significantly compared with the previous generation of Earth observation radiometers. Finer spatial resolution, additional spectral channels, as well as improved bandwidths and radiometric calibration have been achieved (Townshend & Justice, 2002). A suite of high-level products has been produced using MODIS imagery to support terrestrial (Justice et al., 2002), atmospheric (King et al., 2003; Platnick et al., 2003; Remer et al., 2005), and oceanic research (Esaias et al., 1998). MODIS can be used to estimate various surface radiation fluxes with a high level of accuracy (Gui, Liang, Wang, Li, & Zhang, 2010; Liang et al., 2009; Wang, Liang, He, & Shi, 2015). MODIS products are also used to identify scene types in estimation of CERES TOA fluxes (Loeb et al., 2005). MODIS senses in a total of 36 spectral bands with spatial resolutions ranging from 250 m to 1000 m. MODIS Bands 1–19 and 26 are in the visible, near-infrared, or SW-infrared part of the spectrum and are known as reflective solar bands (RSBs) (Barnes, Pagano, & Salomonson, 1998; Xiong, Che, & Barnes, 2005). Among these, Bands 8–16 are used to study ocean color, and Band 26 is used to study cirrus clouds. Bands 17–19 are dedicated to atmospheric water vapor. In addition to Bands 1–7, which are commonly used in land remote sensing, Band 19, which presents the broadest spectral range among the three water-vapor bands, has been selected in this study (Fig. 1). Both Terra/MODIS and Aqua/MODIS L1B-calibrated radiance data at 1 km resolution (MOD021KM and MYD021KM, Collection 6) are used in addition to corresponding L1B geolocation data (MOD03 and MYD03) and L2 cloud mask products (MOD35_L2 and MYD35_L2).

2.2. CERES

CERES is a scanning broadband sensor with three channels used for measuring broadband radiances in the SW (0.3–5 μm), total (0.3–200 μm), and thermal window channels (8–12 μm) (Wielicki et al., 1998). CERES instruments are mounted onboard several satellite platforms, including Tropical Rainfall Measuring Mission (TRMM), Terra, Aqua and Suomi National Polar-orbiting Partnership (NPP). Both Terra/CERES and Aqua/CERES results were compared with MODIS retrievals in this study. The spatial resolution of CERES on Terra and Aqua is approximately 20 km at nadir. Two CERES sensors fly on each Terra and Aqua satellites: FM-1 and FM-2 are onboard the former, and FM-3 and FM-4 onboard the latter. CERES can be operated at three different azimuth plane scan modes: cross-track scan, rotating azimuth plane scan (RAPS), and fixed azimuth plane scan (FAPS). Data obtained with cross-track scanning are used here to match the MODIS geometry. The broadband radiance measured by the SW channel was converted to TOA upwelling radiation flux using a properly selected ADM (Loeb et al., 2005). For direct comparison with MODIS swath data, the L2 Single Scanner Footprint (SSF) TOA SW flux, from the latest edition (3 A), was used in this study. CERES does not directly generate TOA albedo (α_{TOA}) products. Instead, it provides TOA SW-reflected flux ($E\uparrow$). The updated solar constant $S_0 = 1361$ W/m^2 (Kopp & Lean, 2011) is used to calculate TOA albedo from reflected flux:

$$\alpha_{\text{TOA}} = \frac{E\uparrow}{S_0 * \cos\theta_s / a^2} \tag{1}$$

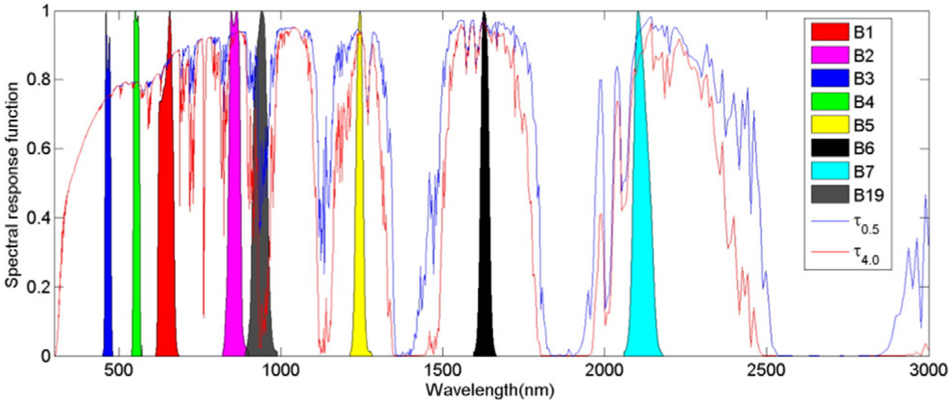

Fig. 1. Spectral response function of MODIS bands used in this study. The transmittance at two water vapor levels, 0.5 and 4.0 g/m^3, is also shown.