ARTICLE IN PRESS

Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Evaluating land surface albedo estimation from Landsat MSS, TM, ETM +, and OLI data based on the unified direct estimation approach

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ARTICLE INFO

Keywords:
Landsat
MSS
TM
ETM +
OLI
Surface albedo
BRDF
Direct estimation

ABSTRACT

Surface albedo is widely used in climate and environment applications as an important parameter for controlling the surface energy budget. There is an increasing need for albedo data to be available for use in applications that require a fine spatial resolution and for validating coarse-resolution datasets; however, such products with long-term global coverage are not available thus far. Existing algorithms for Landsat albedo estimation all require surface reflectance from explicit and reliable atmospheric correction, which may sometimes be unavailable or carry uncertainties due to saturated visible bands or a lack of dense vegetation. In addition, most of the existing algorithms require concurrent clear-sky observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) for bidirectional reflectance distribution function (BRDF) correction, which limited the data availability for Landsat albedo estimation. To overcome these problems, in this study, we adopt the direct estimation approach previously used with coarser resolution data, such as MODIS and Visible Infrared Imaging Radiometer Suite (VIIRS), and apply it to multiple Landsat data obtained by Multispectral Scanner (MSS), Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM +), and Operational Land Imager (OLI). By incorporating Landsat spectral response functions and a database of bidirectional reflectance distribution function (BRDF) into radiative transfer simulations, a unified algorithm is developed to estimate surface albedo directly from the Landsat top-of-atmospheric reflectance data obtained by MSS, TM, ETM +, and OLI with few ancillary inputs. To overcome the saturation problems in the visible bands of TM and ETM + over very bright surfaces, a refined approach is employed by using only non-saturated bands. The validation results against ground measurements over various land cover types and climate regions show that our algorithm is effective for both snow-free and snow-covered surfaces and can achieve root-mean-square errors (RMSEs) of not more than 0.034. In addition, we show the high potential of the earlier MSS data for producing consistent surface albedo estimations based on inter-comparison with TM-based results with RMSEs of 0.011–0.017 and R^2 of 0.858–0.963. This long-term, 30-m resolution surface albedo estimation can date back to the early 1980s, which allows for improved understanding of long-term climate change and land cover change effects.

1. Introduction

Land surface albedo is widely used as a controlling factor of the Earth's energy budget by regulating the amount of solar radiation reflected by the surface (Liang et al., 2010). Satellite remote sensing of land surface albedo has continuously improved during the past three decades, and many satellite products are now available for coarse resolution climate modeling applications (He et al., 2014a; Li and Garand, 1994; Liang et al., 2013; Martonchik et al., 1998; Muller et al., 2012; Pinty et al., 2000; Popp et al., 2011; Riihela et al., 2013; Schaaf et al., 2002; Wang et al., 2013).

Although satellite albedo products with a fine spatial resolution are in high demand, which describes the spatial heterogeneity of land surface albedo and represents the changes in albedo due to small-scale land cover changes (Roman et al., 2013; Shuai et al., 2011; Shuai et al., 2014). However, no such products with long-term global coverage are available. Factors such as scale differences between coarse-resolution data and ground measurements have prevented more accurate assessment of existing satellite data for research on climate modeling in the absence of fine-resolution data (e.g., Burakowski et al., 2015; Roman

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http://dx.doi.org/10.1016/j.rse.2017.10.031
Received 14 July 2016; Received in revised form 14 October 2017; Accepted 17 October 2017
0034-4257/

Please cite this article as: He, T., Remote Sensing of Environment (2017), http://dx.doi.org/10.1016/j.rse.2017.10.031

et al., 2013; Wang et al., 2012). As a result of the free access to Landsat data (Woodcock et al., 2008) and recent technical advancements in data processing (e.g., Masek et al., 2006), there is the potential for albedo data to be used in applications that require data at finer spatial resolutions, such as urban environmental assessment (Zhou et al., 2012), agricultural monitoring (Gao et al., 2014; Li and Fang, 2015), forestry management (Kuusinen et al., 2014; Vanderhoof et al., 2014), and ecosystem functioning evaluation (Lagomasino et al., 2015).

Physically-based or semi-empirical algorithms based on the temporal accumulation of angular samples have been widely used with coarse-resolution data, such as the algorithms developed for Moderate Resolution Imaging Spectroradiometer (MODIS) data (Lyapustin et al., 2011; Schaaf et al., 2002). For data from fine-resolution satellite sensors (e.g., Landsat) it is difficult to apply such physically-based or semi-empirical algorithms due to insufficient angular samples from one sensor within a short period for capturing surface anisotropy caused by the reduced revisit frequency. Previous studies reported that failure to correct the effects of surface bidirectional reflectance distribution function (BRDF) can introduce errors of up to 60% in fine-resolution data (e.g., Gao et al., 2014), which demonstrates the importance of converting surface directional reflectance to albedo.

To attempt to correct for the BRDF effects without BRDF model inversion and to produce land surface albedo from Landsat data, several previous studies have shown promising results over snow-free surfaces. Shuai et al. (2011) proposed a method of using the concurrent 500 m MODIS albedo/BRDF product to convert Landsat surface reflectance to albedo, by taking the advantage of surface BRDF information derived from coarse-resolution data which cannot be obtained directly from Landsat data. Two general assumptions were made in their method. First, land surface was assumed to be invariant within the 16-day compositing period of MODIS data. Second, the ratio of reflectance to albedo was assumed to be the same between a Landsat pixel and a MODIS pixel with the same land cover type. To avoid the selection of homogeneous MODIS pixels at Landsat spatial resolution and to reduce the gridding artifacts in MODIS 500 m data reported in Tan et al. (2006), Franch et al. (2014) presented a two-step method for Landsat albedo estimation. The first step is to estimate surface BRDF from the MODIS 0.05° surface reflectance data, assuming a stable BRDF shape with changing reflectance magnitude during a short period (Vermote et al., 2009) in which the seasonal BRDF shape variation is derived from the normalized difference vegetation index (NDVI). In the second step, the BRDF from MODIS data is then disaggregated to the corresponding Landsat pixels with the help of a land cover map. Both methods (Franch et al., 2014; Shuai et al., 2011) rely on clear-sky MODIS data close to Landsat acquisition date to produce accurate snow-free albedo estimation with root-mean-square errors (RMSEs) of 0.015–0.024; however, they are sometimes not applicable when clear-sky MODIS data are not available and are limited for application past 2000. In addition, a reliable atmospheric correction is required to generate surface reflectance from Landsat TOA reflectance (Masek et al., 2006), which is then used for albedo estimation. For sensors prior to Landsat-8 Operational Land Imager (OLI), Landsat-based atmospheric correction sometimes can be unreliable when accurate aerosol loadings are not available (Ju et al., 2012) with a possibility to obtain inaccurate albedo estimation.

For snow-covered albedo estimation, two studies have estimated shortwave albedo based on the method proposed in Shuai et al. (2011), which was originally designed for snow-free albedo estimation. Wang et al. (2012) reported biases from − 0.076 to 0.01 of isotropic version surface shortwave albedo estimated from non-saturated Landsat TM data versus ground measurements obtained at the Barrow site, in which Landsat albedo was used for MODIS albedo product inter-comparison over snow-covered surfaces. A recent study reported an RMSE of 0.043 for the snow albedos estimated from Landsat 8 data (Wang et al., 2016). While the reported snow-covered albedo estimation accuracies are reasonably good, it is difficult to apply such approaches to the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM +) data acquired over highly reflective surfaces because of saturation issue (Wang et al., 2016; Wang et al., 2012), which were designed with dynamic range to accommodate the variance in reflectivity over various surface types. However, the data of the visible bands are often saturated if the sensor is put in the low-gain mode (Karnieli et al., 2004). We found that the default AOD values were used (e.g., 0.06 over Greenland and 0.01 over the US) in the atmospheric correction for saturated scenes when producing the current version of the Landsat surface reflectance products, which may lead to biased surface reflectance estimation in certain regions. Benefiting from the improved radiometric characteristics, the OLI onboard Landsat 8 is not affected by the saturation issue.

To satisfy an increasing demand for studies on the surface energy budget related to long-term climate change (e.g., Ghimire et al., 2014; O'Halloran et al., 2012), the development of accurate and consistent surface albedo products is important. However, challenges in such product development includes but are not limited to difficulties in estimating surface albedo resulting from ephemeral snow at mid- to high-latitude regions and inter-sensor calibration of coarse-resolution data such as the Advanced Very High Resolution Radiometer (AVHRR) (Molling et al., 2010). Unlike AVHRR sensors onboard different satellites, each of Landsat satellites has a relatively long temporal coverage. In terms of its data consistency, long-term assessment of Landsat sensor calibration has shown that the sensor degradation has been well characterized for Landsat data since the 1980s (Chander et al., 2009; Kim et al., 2014), which enables the use of the legacy data in the determination of surface albedo. To extend Landsat albedo products to the pre-MODIS era for a comprehensive understanding of albedo consequences of forest disturbance and recovery at a fine spatial resolution, a BRDF look-up table (LUT) approach was proposed by considering factors including land cover type, forest disturbance age and severity, and the topography over the United States, as well as high-quality albedo/BRDF information from the MODIS BRDF product (Shuai et al., 2014). RMSE of 0.016 with measured albedo values ranging from 0.06 to 0.14 was achieved based on validation against tower measurements at six forest sites showed, which enabled extending Landsat albedo estimation back to mid-1980s as long as all the necessary information required by the forest disturbance BRDF LUT is available.

All the existing approaches for deriving surface albedo from Landsat data all require surface reflectance derived from a reliable atmospheric correction. However, it is unlikely to generate accurate surface reflectance when dark dense vegetation was not present in the scene or saturation occurred to visible bands. Applying the direct estimation approach to Landsat data could overcome such limitation; meanwhile it enables the exploration of possible means for further extending the albedo data records to the pre-TM era. This method has been developed and refined for data from several satellite platforms (He et al., 2015a; He et al., 2015b; Liang et al., 2003; Qu et al., 2014; Wang et al., 2013). The basic principle of this approach (Liang, 2003; Liang et al., 1999; Liang et al., 2005) is to employ the empirical relationship built from extensive radiative transfer simulations in estimating surface albedo from top-of-atmosphere (TOA) observations. To mitigate non-linearity issues, the empirical relationships between TOA observations and surface albedo are established on an angular-bin basis. Following this approach, an assumption of a stable surface BRDF during a certain period or an explicit atmospheric correction is unnecessary.

The main objective of this paper is to evaluate a unified approach for estimating surface albedo from Landsat TOA reflectance over different land cover types without being constrained by any concurrent high-level satellite products as the inputs. This method can use the legacy data obtained from the entire Landsat satellite series as long as their radiometric and geometric calibration accuracies permit. The algorithm is validated at different locations over various land cover types. These efforts will allow for an improved understanding of surface albedo changes that occur in finer scales, such as forest cover changes,