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An approach for the long-term 30-m land surface snow-free albedo retrieval from historic Landsat surface reflectance and MODIS-based a priori anisotropy knowledge

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ABSTRACT

Land surface albedo has been recognized by the Global Terrestrial Observing System (GTOS) as an essential climate variable crucial for accurate modeling and monitoring of the Earth's radiative budget. While global climate studies can leverage albedo datasets from MODIS, VIIRS, and other coarse-resolution sensors, many applications in heterogeneous environments can benefit from higher-resolution albedo products derived from Landsat. We previously developed a "MODIS-concurrent" approach for the 30-meter albedo estimation which relied on combining post-2000 Landsat data with MODIS Bidirectional Reflectance Distribution Function (BRDF) information. Here we present a "pre-MODIS era" approach to extend 30-m surface albedo generation in time back to the 1980s, through an *a priori* anisotropy Look-Up Table (LUT) built up from the high quality MCD43A BRDF estimates over representative homogenous regions. Each entry in the LUT reflects a unique combination of land cover, seasonality, terrain information, disturbance age and type, and Landsat optical spectral bands. An initial conceptual LUT was created for the Pacific Northwest (PNW) of the United States and provides BRDF shapes estimated from MODIS observations for undisturbed and disturbed surface types (including recovery trajectories of burned areas and non-fire disturbances). By accepting the assumption of a generally invariant BRDF shape for similar land surface structures as *a priori* information, spectral white-sky and black-sky albedos are derived through albedo-to-nadir reflectance ratios as a bridge between the Landsat and MODIS scale. A further narrow-to-broadband conversion based on radiative transfer simulations is adopted to produce broadband albedos at visible, near infrared, and shortwave regimes. We evaluate the accuracy of resultant Landsat albedo using available field measurements at forested AmeriFlux stations in the PNW region, and examine the consistency of the surface albedo generated by this approach respectively with that from the "concurrent" approach and the coincident MODIS operational surface albedo products. Using the tower measurements as reference, the derived Landsat 30-m snow-free shortwave broadband albedo yields an absolute accuracy of 0.02 with a root mean square error less than 0.016 and a bias of no more than 0.007. A further cross-comparison over individual scenes shows that the retrieved white sky shortwave albedo from the "pre-MODIS era" LUT approach is highly consistent ($R^2 = 0.988$, the scene-averaged low RMSE $= 0.009$ and bias $= -0.005$) with that generated by the earlier "concurrent" approach. The Landsat albedo also exhibits more detailed landscape texture and a wider dynamic range of albedo values than the coincident 500-m MODIS operational products (MCD43A3), especially in the heterogeneous regions. Collectively, the "pre-MODIS" LUT and "concurrent" approaches provide a practical way to retrieve long-term Landsat albedo from the historic Landsat archives as far back as the 1980s, as well as the current Landsat-8 mission, and thus support investigations into the evolution of the albedo of terrestrial biomes at fine resolution.

1. Introduction

Surface albedo, defined as the ratio of radiant flux reflected from the Earth's surface to the incident flux, has been documented by the Global Terrestrial Observing System (GTOS) as one of the essential climate variables governing Earth's surface energy budget (Pinty et al., 2008; Schaaf, Cihlar, Belward, Dutton, & Verstraete, 2009; Schaaf et al., 2008). The radiative forcing intercepted by the land surface is perhaps the most important initial energy source for biophysical processes, through a further conversion into latent, sensible, and stored heat terms and input to the soil–vegetation biophysical system (Betts,

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2000; Lyone, Jin, & Randerson, 2008; Ollinger et al., 2008; Peckham, Ahl, Serbin, & Gower, 2008; Randerson et al., 2006; Sellers, Los, et al., 1996; Sellers, Randall, et al., 1996; Zhang et al., 2009). Studies have shown that land cover change (and ecosystem disturbance) may have a significant influence on regional albedo, and hence long-term climate forcing (Bala et al., 2007; Betts, 2000; Claussen, Brovkin, & Ganopolski, 2001; Randerson et al., 2006). Terrestrial albedo varies enormously in space and time as a result of both natural events (e.g. weather disaster, insect, disease, wild fire, season-shifts, and vegetation phenological phase) and human activities (e.g. forest-thinning & clearing, crops-sowing & harvesting, urbanization, and other land use management methods) (Jin & Roy, 2005; Ju, Roy, Shuai, & Schaaf, 2010; O¡¯Halloran, et al., 2011; Shuai and Schaaf, 2010; Shuai, Schaaf, et al., 2013; Shuai, Xie, Wang, & Wu, 2013; Xu et al., 2013). As strategies emerge for managing ecosystem carbon in order to mitigate global warming, several studies have pointed out the potential risk of ignoring the physical consequences of land cover change, including changes to land surface albedo (Betts, 2000; Lyone et al., 2008; Peckham et al., 2008; Randerson et al., 2006).

Albedo datasets have been derived from existing coarse-resolution satellite sensors to parameterize global land surface and climate models. Compared with previous single-angle models, modern albedo algorithms rely on multiple directional reflectance measurements to first estimate a Bi-directional Reflectance Distribution Function (BRDF) model of the target, then integrate over incident and view hemispheres to calculate albedo. Studies have concluded that relative errors can reach up to 45% without the consideration of direction/angle effects in the albedo estimation (Kimes & Sellers, 1985; Kimes, Sellers, & Newcomb, 1987). Because most satellite sensors cannot collect multiple observations of a target in a single pass, the sequential accumulation of data over multiple days (for sun-synchronous orbit) or multiple hours (geostationary orbit), may be adopted as a relevant solution to achieve multi-angle measurements sampling the full sun–target–sensor geometry. Global surface albedo has been mapped from the Advanced Very High Resolution Radiometer (AVHRR) (Csiszar & Gutman, 1999; Key, Wang, Stroeve, & Fowler, 2001), Earth Radiation Budget Experiment (ERBE) radiometer data (Li & Garand, 1994), and the Along Track Scanning Radiometer (ATSR). With the advent of routine albedo products retrieved from Polarization and Directionality of the Earth's Reflectances (POLDER-I and II) (Bicheron & Leroy, 2000; Hautecoeur & Leroy, 1998; Leroy et al., 1997; Maignan, Breon, & Lacaze, 2004), Multi-angle Imaging SpectroRadiomenter (MISR) (Martonchik, Pinty, & Verstraete, 2002; Martonchik et al., 1998), Clouds and the Earth's Radiant Energy System (CERES) (Rutan et al., 2009), Meteosat Visible and Infrared Imager (MVIRI)/Meteosat and Meteosat Second Generation (MSG) (Carrer, Roujean, & Meurey, 2010; Geiger, Carrer, Franchisteguy, Roujean, & Meurey, 2008; Pinty et al., 2000), SPOT4/VEGETATION (Franchistéguy, Geiger, Roujean, & Samain, 2005), and the recently launched Visible Infrared Imager Radiometer Suite (VIIRS) (Justice et al., 2013; Liang, Yu, & Defelice, 2005), albedo maps with spatial resolutions of 500-m to tens of kilometer and temporal frequencies of daily to monthly are now available to serve for climate model refining and inter-annual exploration (Schaaf et al., 2008).

While global climate studies can utilize the coarse-resolution surface albedo datasets described above, there remains a need for consistent, fine-resolution albedo products for specific applications. Several publications have highlighted the importance of land cover change, including deforestation, afforestation, agricultural expansion, urbanization, and other human-induced land surface alteration, to the terrestrial carbon cycle and climate changes (Goward et al., 2008; Masek & Collatz, 2006; Pan et al., 2011; Randerson et al., 2006). However, spatial resolutions coarser than 250-m may be insufficient to capture patch-scale vegetation changes associated with human land use and forest disturbance (Townshend and Justice 1988; Masek et al., 2013). Fine resolution imagery (~30 m or better) can more accurately quantify the areas and rates of these anthropogenic land changes. In addition, for climate change investigations, long time series of albedo products are required. Although operational albedo datasets covering the last 30 years have been assembled from different sensors covering different periods, the merging of multiple records raises issues of data consistency and quality. Because of the differences among sensors (wavelength of spectral bands, orbit geometry, spatial resolution, and geographic region), the derived albedo products may differ depending on the specific product, the data source, and the production strategies (Schaaf et al., 2009). Therefore, datasets derived from a single continuous acquisition program offers a greater potential for consistency in data quality. Despite differences in sensor design over time, the Landsat program has acquired a 42-year record of Earth Observations that captured global land conditions and dynamics through six successful missions since 1972. With the launch of Landsat-8 in February 2013 (Loveland & Dwyer, 2012), this record has the potential of reaching 50 years. The opening of the Landsat archive for free distribution in late 2008 has invigorated the push for creating long-term biophysical and land cover products from new and archived Landsat data (Woodcock et al., 2008; Wulder, Masek, Cohen, Loveland, & Woodcock, 2012). It includes this effort to develop the long-term, consistent surface albedo products from the Landsat program.

In a previous study, we developed a "concurrent" approach for generating 30-m resolution albedo products for the post-2000 (MODIS) era by combining Landsat surface reflectance with MODIS surface anisotropy information (Shuai, Masek, Gao, & Schaaf, 2011). In this study, we propose and validate a new approach to generate Landsat albedo products for the pre-MODIS era, by using albedo-to-nadir reflectance ratios (Shuai et al., 2011) and an a priori anisotropy Look-Up Table (LUT) that has been built up from the high quality MCD43A BRDF retrievals over representative homogeneous regions. This approach yields both spectral and broadband albedos, and a quality assessment (QA) map based on the quality of MODIS anisotropy and Landsat surface reflectance. In this paper, we first address the theoretical basis of the "pre-MODIS-era" LUT approach, creation of the BRDF-LUT, and then demonstrate its application over more than 100 Landsat scenes in the Pacific Northwest of the United States where simultaneous ground measurements are available for validation.

2. Albedo definition

The spectral Directional–Hemispherical Reflectance (DHR) of a plane surface is defined as the ratio of radiant energy scattered upward from the surface in all directions to the down-welling incident irradiance on the surface within the target spectrum regime (λ_1, λ_2). It equals the integral of the BRDF over the view hemisphere for an incident beam at a given wavelength, as shown in formula (1). Under the extreme condition that no diffuse radiation but only the direct beam arrives from the solar incidence angle (θ, φ) defined by zenith angle θ, and azimuth angle φ ($L(\theta, \varphi)$), the albedo is referred to as "Black-Sky Albedo" (BSA) $\overline{R}(\theta_i, \varphi_i; \lambda)$ in the MODIS product series (Lucht, Schaaf, & Strahler, 2000; Strahler et al., 1999). Under the assumption that all irradiance is isotopic (purely diffuse skylight), a further integral over illumination hemisphere provides the Bi-Hemispherical Reflectance (BHR) $\overline{\overline{R}}(\lambda)$, or "White-Sky Albedo" (WSA) formulae (2) and (3) (Lucht et al., 2000; Strahler et al., 1999). The spectral BHR under actual atmospheric conditions (known as the "blue-sky albedo", or "actual albedo") can be approximated through a linear combination of BSA and WSA, weighted by the fraction of actual direct to diffuse skylight (Lewis & Barnsley, 1994; Lucht et al., 2000; Román et al., 2010). Because the upwelling radiance depends on not only the BRDF properties of the observed surface, but also atmospheric conditions, $\overline{\overline{R}}(\lambda)$ may change with the variation of the instantaneous cloud cover and aerosol loading, as well as over the course of the day as the solar geometry changes even for constant atmospheric and surface conditions (Lucht et al., 2000). In addition, multiple scattering between surface and atmosphere affects the angular distribution