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Long-term record of top-of-atmosphere albedo over land generated from AVHRR data

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ABSTRACT

Top-of-atmosphere (TOA) albedo is a fundamental component of Earth's energy budget. To date, long-term global land TOA albedo products with spatial resolution higher than 20-km are not available. In this study, we propose a novel algorithm to retrieve TOA albedo from multispectral imager observations acquired by Advanced Very High Resolution Radiometer (AVHRR), which provides the longest continuous record of global satellite observations since 1981. Direct estimation models were established first to derive instantaneous TOA broadband albedo under various atmospheric and surface conditions, including cloudy-sky, clear-sky (snow-free) and snow-cover conditions. To perform long-term series analysis, the instantaneous TOA albedo were then converted to daily/monthly mean values based on the diurnal curves from multi-year Clouds and the Earth's Radiant Energy System (CERES) 3-hourly flux dataset. Calibration differences between sequential AVHRR sensors were further mitigated by invariant targets normalization. The retrieved TOA albedo at 0.05° × 0.05° was validated against two TOA albedo datasets, CM SAF (Climate Monitoring Satellite Application Facility) flux data and CERES flux data, at spatial resolutions of 0.05° × 0.05°, 20 km × 20 km and 1° × 1°. The instantaneous TOA albedo had an overall Root-Mean-Square-Error (RMSE) of 0.047 when compared with 20-km CERES fluxes, whereas the 1° by 1° monthly mean TOA albedo showed closer agreements with both CM SAF and CERES, with RMSE ranging from 0.029 to 0.040 and from 0.022 to 0.031, respectively. Moreover, our product was found to be highly consistent with both CERES and CM SAF at long-term trend detection. The extensive validation indicated the robustness of our algorithm and subsequently, comparable data quality with existing datasets. With global coverage and long time series (1981–2017), our product is expected to provide valuable information for climate change studies.

1. Introduction

Top-of-atmosphere (TOA) albedo (also known as planetary albedo) is the fraction of the incoming solar flux reflected by Earth back into space. The variability of reflected energy influences our climate system by changing the Earth's energy budget (Palle et al., 2016; Stephens et al., 2015; Trenberth et al., 2009; Von Schuckmann et al., 2016). Since the TOA incoming solar flux is relatively constant, the reflected energy is mainly determined by TOA albedo. Therefore, TOA albedo is an important component in the climate system and Earth's radiation budget (ERB). The history of ERB measurements dates back to 1960s with the instruments on board the Explorer 6 and 7 satellites while the broadband instruments designed specifically for ERB monitoring started from the payloads of the Nimbus 6 and 7 satellites since 1975 (House et al., 1986; Jacobowitz et al., 1984). After Nimbus observations, the Earth Radiation Budget Experiment (ERBE) (Barkstrom, 1984; Jacobowitz et al., 1984), the Scanning Radiometer for Radiation Balance (ScaRaB) (Kandel et al., 1998), the Clouds and the Earth's Radiant Energy System (CERES) (Wielicki et al., 1996) and the Geostationary Earth Radiation Budget (GERB) (Harries et al., 2005) began operation in 1984, 1994, 1998 and 2002, respectively and these broadband measurements are vital radiation monitoring systems currently in use. The products from the broadband systems serve as irreplaceable data sources in the study of Earth's energy budget and climate change at the global scale (Dewitte and Clerbaux, 2017; Dewitte et al., 2013; Liang, 2017; Liang et al., 2010; Stephens et al., 2012; Trenberth et al., 2016; Wild, 2009; Wong et al., 2006).

There has been an increasing need for long-term, high-resolution

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Table 1
Current available TOA albedo products from broadband sensors.

Dataset	Spatial resolution	Spatial coverage	Time span	Temporal resolution	Sensors	Website	References
ERBE	40 km at nadir*/2.5°	Global	1984–1990	Instantaneous*/daily/monthly	ERBE	https://eosweb.larc.nasa.gov/project/erbe/erbe_table	(Barkstrom, 1984; Jacobowitz et al., 1984)
CERES	20 km at nadir*/1°	Global	1997–1998; 2000–present	Instantaneous*/hourly/3-hourly/daily/monthly	CERES	https://ceres.larc.nasa.gov/order_data.php	(Loeb et al., 2018; Loeb et al., 2005; Loeb et al., 2002; Wielicki et al., 1996)
GERB	50 km at nadir*/50 km	European	2002–present	Instantaneous*/15 min	GERB	http://ggsps.rl.ac.uk/	(Harries et al., 2005)
ScaRaB	40 km at nadir*/1°	30°S–30°N	1994–1995; 1998–1999; 2011–present	Instantaneous*/1–7 times daily	ScaRaB	http://www.icare.univ-lille1.fr/mt/products	(Duvel et al., 2001; Kandel et al., 1998; Roca et al., 2015)

* The asterisked spatial resolutions corresponded to the products with asterisked temporal resolutions.

TOA albedo products in monitoring the climate impacts of regional-scale events, such as air pollution, urbanization, forest fires, and other small-scale land cover changes (Chen and Loboda, 2018; Song et al., 2017; Zhang et al., 2015) while the broadband sensors are basically limited to the coarse resolutions: high-level CERES products provide 1-degree resolution, the ERBE data is approximately 250 km, and GERB data is 50 km at nadir (details shown in Table 1). Therefore, to meet the needs of regional energy balance and climate change applications, several studies have attempted to retrieve the high spatial resolution TOA albedo based on multispectral narrowband sensors. Wang and Liang (2016) proposed a direct estimation method based on radiative transfer simulations and applied this method to Moderate Resolution Imaging Spectroradiometer (MODIS) data. The TOA Albedo based on MODIS (hereafter TAL-MODIS) showed good agreement with CERES products and had a high spatial resolution of 1 km. Using Spinning Enhanced Visible Infrared Imager (SEVIRI) data, Niu and Pinker (2012) transformed the TOA narrowband apparent reflectance to broadband reflectance and then applied a newly developed Angular Distribution Model (ADM) to estimate the TOA albedo. However, due to the temporal limitations of the source data, the algorithms based on MODIS and SEVIRI could only provide data starting from the year 2000. By involving Meteosat observations, a recently released long-term high spatial resolution (0.05° by 0.05°) products from Climate Monitoring Satellite Application Facility (CM SAF), formed by European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), provided TOA albedo from 1983 to 2015 but their spatial coverage was limited to 70° N–70° S, 70° W–70° E (Urbain et al., 2017a). The Advanced Very High Resolution Radiometer (AVHRR) aboard National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites provides Global Area Coverage (GAC) data at 4-km resolution. The earliest AVHRR sensor was carried on TIROS-N in 1978, followed by NOAA-6 and to the most recent satellite, NOAA-19. Thus, the AVHRR data constitute the longest global satellite observation record. The AVHRR Polar Pathfinder Project and the Extended AVHRR Polar Pathfinder Project (App and App-x) (Key et al., 2001; Wang and Key, 2005a, 2005b) had utilized AVHRR data, but only provided TOA albedo over the Polar Regions. There are also some long-term time series surface albedo datasets based on AVHRR data (Liu et al., 2013; Riihelä et al., 2013; Sütterlin et al., 2015). However, to date, long-term high spatial resolution TOA albedo products with global coverage over land are not publically available (details shown in Table 2).

Typical approach for estimating the broadband albedo from narrowband radiation includes two steps: first, anisotropic correction from directional reflectance to semi-hemispherical albedo is applied, usually by ADM built by multi-angle observations; and second, narrowband-to-broadband albedo conversion is conducted. The reflected radiation at TOA is the sum of incoming solar energy reflected by both surface and atmosphere and therefore is both surface- and atmosphere- dependent. The typical TOA ADM is normally divided by different scene types for specific surface and atmospheric combination (Hucek and Jacobowitz, 1995; Loeb et al., 2003; Suttles et al., 1988). For the sensors onboard the solar-orbiting satellites, like MODIS and AVHRR, it is hard to collect multi-angle observations within a short period for a specific scene type. Instead, observations from multi-days were obtained and used for the ADM building (Hucek and Jacobowitz, 1995; Loeb et al., 2005). However, during the collecting days the scene type may have changed and the inconsistent scene type would lead to errors in ADM. Moreover, the two-step method may lead to the accumulation and propagation of errors from the anisotropic correction and narrowband-to-broadband conversion to the final results.

In this study, instead of building the ADM dependent on scene type classification, we develop models utilizing spectral information to correct the anisotropic impact. The essence of this method is to estimate albedo from spectral information by establishing the relationship between TOA multispectral reflectance and TOA albedo at a specific solar/viewing geometry. The independent variable of the model is the