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Estimation of all-sky instantaneous surface incident shortwave radiation from Moderate Resolution Imaging Spectroradiometer data using optimization method

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A R T I C L E I N F O

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A B S T R A C T

Surface incident shortwave radiation (ISR) is a crucial parameter in the land surface radiation budget. Many reanalysis, observation-based, and satellite-derived global radiation products have been developed but often have insufficient accuracy and spatial resolution for many applications. In this paper, we propose a method based on a radiative transfer model for estimating surface ISR from Moderate Resolution Imaging Spectroradiometer (MODIS) Top of Atmosphere (TOA) observations by optimizing the surface and atmospheric variables with a cost function. This approach consisted of two steps: retrieving surface bidirectional reflectance distribution function parameters, aerosol optical depth (AOD), and cloud optical depth (COD); and subsequently calculating surface ISR. Validation against measurements at seven Surface Radiation Budget Network (SURFRAD) sites resulted in an R^2 of 0.91, a bias of $-6.47\ W/m^2$, and a root mean square error (RMSE) of $84.17\ W/m^2$ (15.12%) for the instantaneous results. Validation at eight high-latitude snow-covered Greenland Climate Network (GC-Net) sites resulted in an R^2 of 0.86, a bias of $-21.40\ W/m^2$, and an RMSE of $84.77\ W/m^2$ (20.96%). These validation results show that the proposed method is much more accurate than the previous studies (usually with RMSEs of 80-150 W/m^2). We further investigated whether incorporating additional satellite products, such as the MODIS surface broadband albedo (MCD43), aerosol (MOD/MYD04), and cloud products (MOD/MYD06), as constraints in the cost function would improve the accuracy. When the AOD and COD estimates were constrained, RMSEs were reduced to $62.19\ W/m^2$ (12.12%) and $71.70\ W/m^2$ (17.74%) at the SURFRAD and GC-Net sites, respectively. This algorithm could estimate surface ISR with MODIS TOA observations over both snow-free and seasonal/permanent snow-covered surfaces. The algorithm performed well at high-latitude sites, which is very useful for radiation budget research in the polar regions.

1. Introduction

Surface incident shortwave radiation (ISR) is the irradiance that reaches the Earth's surface in the shortwave spectral range, usually between 300 and 3000 nm. As the main energy source for the Earth's surface, ISR drives energetic, hydrological, and ecological dynamics at the Earth's surface and controls the energy and water exchanges between the surface and atmosphere (Liang et al., 2010). Efforts have been made in the estimation of ISR for several decades. Currently, many global and regional networks provide ISR measurements, such as the Surface Radiation Budget Network (SURFRAD) (Augustine et al., 2000), FLUXNET (Baldocchi et al., 2001), Baseline Surface Radiation Network (Ohmura et al., 1998), Global Energy Balance Archive (Gilgen and Ohmura, 1999; Wild et al., 2013), Greenland Climate Network (GC-NET) (Steffen et al., 1996), and Atmospheric Radiation Measurement. In-situ measurements are believed to have higher accuracy than other sources but have limited spatial coverage and representativeness. For better spatial coverage, many reanalysis and satellite-derived ISR products have been published, which are often validated with in-situ measurements. However, existing reanalysis and satellite-derived products are usually limited by accuracy and spatial resolution for many applications. The World Meteorological Organization Observing System Capability Analysis and Review Tool proposed requirements for ISR: “Goal,” “Breakthrough,” and “Threshold” are three levels of requirements, ranging from “ultimate” to “acceptable” targets. Many researchers have evaluated widely used reanalysis and satellite-derived

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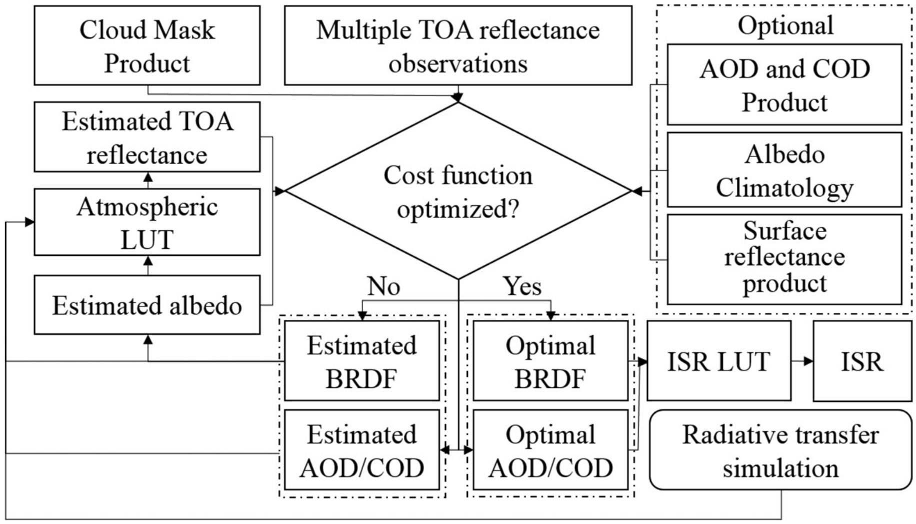

Fig. 1. Framework of the ISR estimation algorithm.

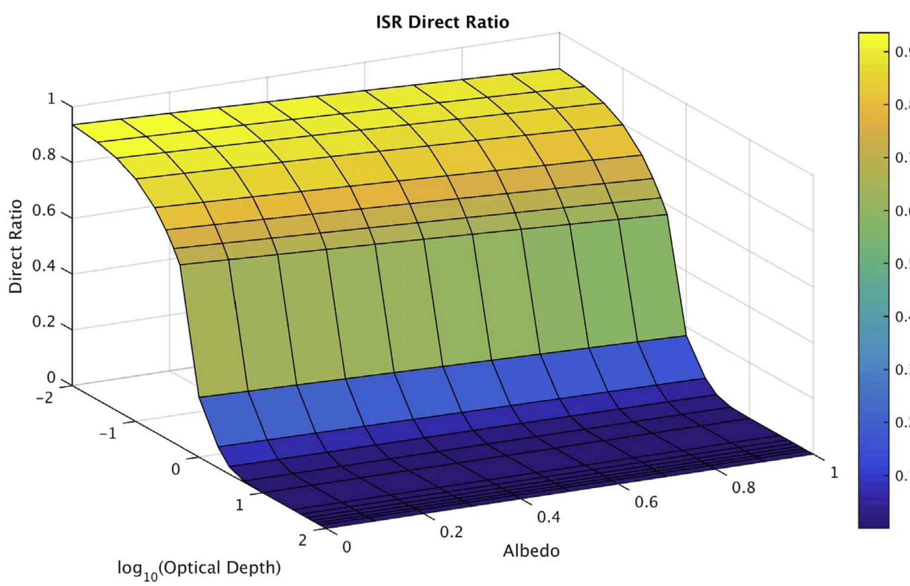

Fig. 2. Impact of optical depth and surface albedo on the direct ISR ratio from radiative simulation.

Table 1
SURFRAD and GC-Net sites for validation.

Site name	Latitude	Longitude	Elevation (m)
Fort Peck	48.31	−105.10	634
Sioux Falls	43.73	−96.62	473
Penn State	40.72	−77.93	376
Bondville	40.05	−88.37	230
Boulder	40.13	−105.24	1689
Desert Rock	36.62	−116.02	1007
NASA-U	73.84	−49.51	2334
Humboldt	78.53	−56.83	1995
Summit	72.58	−38.51	3199
Tunu-N	78.02	−33.98	2052
DYE-2	66.48	−46.28	2099
Saddle	66.00	−44.50	2467
NASA-SE	66.48	−42.50	2373
NEEM	77.50	−50.87	2454

ISR products. Zhang et al. (2015, 2016) showed the insufficient spatial resolution and accuracy among existing products. All the widely used ISR products' spatial resolutions are coarser than 0.3°, which fails to meet the 20 km basic "threshold" requirement for agricultural meteorology. Moreover, the best performance in terms of root mean square error (RMSE) among these products is Clouds and Earth's Radiant Energy System Energy Balanced and Filled (CERES-EBAF), which has a monthly RMSE of 18.8 W/m^2 and still fails to meet the basic "threshold" requirement for all applications in terms of either temporal resolution (daily) or uncertainty.

The published algorithms for estimating ISR from satellite data can be categorized into three groups: parameterization, look-up table (LUT), and machine learning methods. Most parameterization methods use satellite-derived atmospheric products to calculate ISR from parameterized equations (Bisht and Bras, 2010; Forman and Margulis, 2009; Qin et al., 2015; Tang et al., 2016; Van Laake and Sanchez-Azofeifa, 2004). Different components of atmospheric effects (such as aerosol absorption/scattering, cloud reflection, and gas absorption) are usually parameterized separately according to their physical bases. The general idea of LUT methods is a simplification of radiative transfer simulation (Huang, Li, Ma, et al., 2016; Huang et al., 2011; Liang et al., 2006; Zhang et al., 2014): ISR can be simulated by radiative transfer models with the input of atmospheric and surface parameters (e.g., aerosol, cloud, water vapor, and surface albedo), but due to the limited efficiency of the radiative transfer calculation, only selected cases of