Re-understanding of land surface albedo and related terms in satellite-based retrievals

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ABSTRACT

Land surface albedo is a critical variable in determining surface energy balance, and regulating climate and ecosystem processes through feedback mechanisms. Therefore, climatic modelers and radiative monitoring require accurate estimates of land surface albedo. With the instrument development, algorithm upgrade, spectral-band-adjustment in wavelength center or band width, and the increasing distinct requirement from diversified communities, various albedo terms have been generated in related satellite-based products. The lack of understanding on the divergence of these terminologies can introduce potential considerable errors in the subsequent applications, or an elevated probability to invert the deduced conclusion. We surveyed the basic concepts of reflectance quantities, retrieval strategies, and models developed since the 1970s, and discuss both strength and opportunity for improvements on land surface albedo extraction, and product generation. In addition, we exemplified the difference of albedo terms using the daily MODIS product (MCD43A) to emphasize the potential risk of the ambiguous usage, over typical IGBP land covers in Northern Kazakhstan. Our investigation shows that relative differences among various albedo terms can reach up to 181% and 50%, while 0.266 and 0.118 of absolute variance respectively in the narrow and broad-band surface albedo, which illuminated cautions against the ambiguous understanding of albedo terminologies or erroneous usage of albedo products.

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1. Introduction

Land surface albedo, simply defined as the ratio of the outgoing radiant flux reflected from the Earth’s surface to the total incoming flux over the whole solar spectrum (Dickinson, 1983), is a key physical variable directly affecting the solar energy absorbed
by land surface. Land surface albedo determines the partitioning of solar radiation between the land surface and atmosphere, which in turn, modifies various components of the climate system circulation including changes in hydrological processes (Dickinson, 1983; Sellers, 1985). Changes in land cover can affect albedo and have been thus hypothesized to affect regional or global climate. For example, the positive radiative forcing induced by increased forest cover and decreased albedo in temperate and boreal forest regions was concluded to offset the negative forcing expected from carbon sequestration (Betts, 2000). It was also demonstrated that feedbacks from the changes of sea ice and snow albedo are critical to the Arctic and North Atlantic Oscillation pattern with substantial contribution for the regional climate (Dethloff et al., 2006). In the coupled soil-vegetation-atmosphere ecological interaction processes, surface albedo controls the radiation absorption and microclimate conditions of soil and plant canopies. Therefore, it determines the fraction of energy transformed into sensible, latent, or other heat items, to put effect on the ecosystem through physical, physiological, and biogeochemical processes, such as evapotranspiration, plant photosynthesis, respiration, and decomposition (Chapin et al., 2005; Wang, Trishchenko, & Sun, 2007). Increased albedo due to tropical deforestation in Africa and South America has been hypothesized to lead to a loss of radiative energy absorbed at the surface, a reduction of convective overturning, and a significant decrease in precipitation (Dirmeyer & Shukla, 1994). Several studies report that the balance of albedo and carbon dioxide effects varies by latitude, with net cooling from boreal deforestation and disturbance, and net warming from tropical deforestation (Bala et al., 2007; Claussen, Brovkin, & Ganopolski, 2001). Therefore, land surface albedo varying in space and time as a result of both natural and human disturbance (e.g. deforestation, reforestation, fire, flooding, drought, insect damage, urbanization) is a driver for the Earth’s climate and energy cycle (GCOS 2004; Hu et al., 2019; Kuusinen, Tomppo, & Berninger, 2013; Lukeš, Stenberg, Möttus, Manninen, & Rautiainen, 2016; Potter, Elsasser, MacCracken, & Ellis, 1981; Wang, Liang et al., 2017; Weligepolage, Gieske, & Su, 2013).

Various aspects related to albedo quantities have been reviewed in several papers. Nicodemus, Richmond, and Hsia et al. (1977) first thoroughly summarized the basic framework of reflectance quantities based on the fundamental definition of bidirectional reflectance distribution function (BRDF). With advances in the observational techniques and data production, various albedo-related terms have been represented by the optical remote sensing community. Martonchik (2000) reviewed the distinction among several conceptual reflectance quantities to support the standardization of reflectance nomenclature. This work was followed by an extensive physical and mathematical description of different reflectance terminologies through the exemplification of peer-reviewed literature to highlight the caveat of frequent ambiguous usage (Schaepman-Strub, Schaepman, Painter, Dangel, & Martonchik, 2006). Because the main aspect explored in these studies was the illumination-viewing geometry, the spectral dependence of reflectance quantities was largely ignored. One of the primary goals for numerous space agencies is the long-term monitoring of key biophysical parameters of the Earth surface. A review of the surface albedo retrieval was documented by Schaaf, Martonchik, and Pinty (2008), from the Moderate Resolution Imaging Spectrometer (MODIS) and Multiangle Imaging SpectroRadiometer (MISR).
This concise review is distinguished from the previous reviews to focus on the hemispheric reflectance (so-called albedo) quantities in order to survey their basic concepts, measurements, retrieval strategies, and selected estimation models, as well as the research, of long-term operational products. After recalling the detailed physical definition of two fundamental reflectance quantities, Section 2 reviews the spectral hemispherical reflectance quantities including the spectral dimension, followed by the derived formulae for the broadband hemispherical reflectances. Section 3 focuses on the evolution of the retrieval strategies and models with an emphasis on recent improvements. The models used to estimate land surface anisotropy features are highlighted for their importance in the improvement of atmospheric correction quality and the retrieval accuracy. Section 4 then provides a survey of selected sporadic and operational hemispheric reflectance products, including several satellite-based datasets that have been widely used in climate and ecosystem communities. In addition, we investigate the difference between various albedo terms using operational MODIS albedo products. The last section discusses areas in the field that need further work.

2. Definition of hemispheric reflectance quantities

Various so-called “albedo” terminologies have been developed with special needs by different working groups, from the framework of reflectance originally proposed by Nicodemus et al. in 1977, since the solar light scattered by land surface relies on the illumination-view geometry and wavelength. Any confusion, or ambiguity in these concepts and product description may cause an error in the calculation of albedo or subsequent applications (Schaepman-Strub et al., 2006). Therefore, it is important to discern the difference among these definitions to increase their cross-comparison possibilities, deepen the understanding of the difference among albedo-related quantities, and also avoid the misuse of corresponding approaches and dataset (Martonchik et al., 2000; Schaepman-Strub et al., 2006).

2.1. Basic reflectance quantities

The fundamental concept, Bidirectional Reflectance Distribution Function (BRDF), systematically presented as $f_r$ by the first monograph (Nicodemus et al., 1977), specifies the behavior of surface scattering as a function of the parallel incident beam from one direction ($\theta_i$, $\phi_i$) in the illumination hemisphere to the reflected direction ($\theta_v$, $\phi_v$) in the viewing hemisphere, at a particular wavelength $\lambda$:

\[
f_r(\theta_i, \phi_i; \theta_v, \phi_v; \lambda) = \frac{dL_v(\theta_i, \phi_i; \theta_v, \phi_v; \lambda)}{dE_i(\theta_i, \phi_i; \theta_v, \phi_v; \lambda)} \text{ (Sr}^{-1})
\]  

(1)

where $\theta$ and $\phi$ are the zenith and azimuth; $dE_i$ is the irradiance from the illumination direction; and $dL_v$ is the radiance reflected into the differential solid angle at ($\theta_v$, $\phi_v$). Theoretically, $f_r$ cannot be directly measured because both $dL_v$ and $dE_i$ are defined in the infinitesimal solid angles. Therefore, a more convenient concept-Bidirectional Reflectance Factor (BRF) $R$ (see formula 2) is provided to measure the anisotropy feature of radiance reflected from an actual surface. The BRF is defined as the ratio of the reflected flux $d\phi_v$ from
the target surface area in a particular direction to the reflected flux $d\phi_v^{\text{lam}}$ from a Lambertian surface of the same view direction and under the identical illumination conditions (Nicodemus et al., 1977). Note the fact that $f_r$ for a Lambertian surface is $\frac{1}{\pi}$ (i.e. $f_r^{\text{lam}} = \frac{1}{\pi}$). Thus, the surface BRF for the area of interest can be obtained by measuring reflected fluxes $d\phi_v$ and $d\phi_v^{\text{lam}}$ at the land surface, whereas, if the measurements are obtained from the top-of-atmosphere (TOA), then this measurement results in a TOA BRF. The only distinction between these two BRFs is the atmospheric effect in each direction, which usually imparts a separate anisotropy (Lyapustin, 1999).

\[
R(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda) = \frac{d\phi_v(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda)}{d\phi_v^{\text{lam}}(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda)} = \frac{f_r(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda)}{f_r^{\text{lam}}(\theta_i, \varphi_i; \lambda)} \\
= \pi f_r(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda) \quad \text{(unitless)} \tag{2}
\]

The reflectance quantities adopted in the energy balance and radiant flux budget are not defined by an infinitesimal solid angle, but rather the total energy reflected or scattered away from the surface in all directions, and are usually integrated over the interested wavelength regime.

### 2.2. Spectral hemispherical reflectance

The spectral directional-hemispherical reflectance $\alpha_{\text{DH}}$ (formula 3) is defined as the integral of BRDF over the view hemisphere for an incident beam only at a given wavelength. Under the extreme condition that no diffuse radiation arrives from the background sky, it is referred as “Black Sky Albedo” (BSA) in the MODIS data series (Lucht, Schaaf, & Strahler, 2000; Schaaf et al., 2002; Strahler et al., 1999). Because the $\alpha_{\text{DH}}$ (or BSA) is only dependent on the BRDF (or BRF as an alternative way represented actual measurements) and independent of the atmospheric conditions, it is often considered as an inherent property of the surface (Martonchik et al., 2000). It is worth noting that BRDF typically cannot be measured in the field since any outdoor measurement will include contributions from diffuse skylight.

\[
\alpha_{\text{DH}}(\theta_i, \varphi_i; \lambda) = \int_0^{2\pi} \int_0^{\pi/2} f_r(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda) \cos \theta_v \sin \theta_v \ d\theta_v \ d\varphi_v \\
= \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} R(\theta_i, \varphi_i; \theta_v, \varphi_v; \lambda) \cos \theta_v \sin \theta_v \ d\theta_v \ d\varphi_v \tag{3}
\]

The concept of spectral hemispherical-directional reflectance $\alpha_{\text{HD}}$ is similar to the definition of the $\alpha_{\text{DH}}$, as a ratio of the upward flux in particular reflected direction to the downward flux, but theoretically the integral of incoming flux is performed over the entire illumination hemisphere to include both direct sunlight and probably non-isotropic (diffuse) sky light. Thus, $\alpha_{\text{HD}}$ depends not only on the intrinsic anisotropic properties of the land surface but also the distribution of skylight from the path radiance and multiple scattering between atmosphere and surface.

A double integral of BRDF over both view and illumination hemisphere at a given wavelength derives the bi-hemispherical albedo $\alpha_{\text{BH}}$ (see formula 4), as a ratio of the total
flux reflected from the surface area to the total flux received from all the incident directions (Martonchik et al., 2000). Note that the illuminating radiance \( L_i(\theta, \phi; \lambda) \), as we discussed for \( a_{\text{HD}} \), combines both the direct incident beam and sky irradiance scattered from the whole hemisphere, the angular distribution of which varies with the direction in the illuminating hemisphere. Thus, the integral of \( L_i(\theta, \phi; \lambda) \) cannot be directly cancelled from the denominator and numerator in Equation (4), except for the special case termed White Sky Albedo (WSA) \( a_{\text{WSA}}(\lambda) \), in MODIS43 products (see Equation 5). The WSA assumes only isotropic diffuse illumination and thus equally weights the integral over all irradiance positions (Lucht et al., 2000; Strahler & Muller, 1999). Sometimes, 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 diffuse skylight (Lucht et al., 2000).

\[
a_{\text{BH}}(\lambda) = \frac{\int_0^{\pi/2} \int_0^{\pi/2} f_i(\theta_i, \phi_i; \theta_v, \phi_v; \lambda) \cos \theta_v \sin \theta_v \, d\theta_v \, d\phi_v}{\int_0^{\pi/2} \int_0^{\pi/2} L_i(\theta_i, \phi_i; \lambda) \cos \theta_i \sin \theta_i \, d\theta_i \, d\phi_i}
\]

\[
= \frac{\int_0^{\pi/2} \int_0^{\pi/2} (a_{\text{DHR}}(\theta_i, \phi_i; \lambda)) L_i(\theta_i, \phi_i; \lambda) \cos \theta_i \sin \theta_i \, d\theta_i \, d\phi_i}{\int_0^{\pi/2} \int_0^{\pi/2} L_i(\theta_i, \phi_i; \lambda) \cos \theta_i \sin \theta_i \, d\theta_i \, d\phi_i}
\]

\[
a_{\text{WSA}}(\lambda) = \frac{1}{\pi} \int_0^{\pi/2} \int_0^{\pi/2} (a_{\text{DHR}}(\theta_i, \phi_i; \lambda)) \cos \theta_i \sin \theta_i \, d\theta_i \, d\phi_i
\]

Again, because the upwelling radiance depends not only on the BRDF properties of the observed surface, but also on atmospheric conditions, bi-hemispheric albedo can change with the variation of the instantaneous cloud cover and aerosol loading, as well over the course of the day with the sun’s path in the sky even for constant atmospheric and surface conditions (Strahler & Muller, 1999). In addition, multiple scattering between surface and atmosphere will change the angular distribution of sky radiance even if the atmosphere remains constant, due to the change of surface BRF. Therefore, bi-hemispheric albedo involves not only surface properties, but rather a function of solar beam direction, atmospheric state, and surface anisotropic features. Liang, Strahler, and Walthall (1999) also proposed the “inherent albedo” and “apparent albedo” to distinguish the intrinsic reflective properties of the land surface and the bi-hemispherical albedo measurements under instantaneous atmospheric conditions.

2.3. Spectral conversion for hemispheric reflectance quantities

For most of the applications involving energy balance, the reflectance quantity of interest is not the spectral reflectance but rather that integrated over a broad spectral interval \([\lambda_1, \lambda_2]\), to capture the desirable overall radiative properties. The spectral integrals for the hemispherical reflectances are functions of the down-welling solar spectrum as defined in the above formulae. The visible regime (0.4–0.7 \( \mu \)m) known as the photosynthetically active radiation (PAR) is of special interest to carbon cycle modelers for the estimation of carbon fixation via biospheric photosynthesis. For example, green vegetation always has an enhanced absorption of solar radiation in this visible regime, but
extremely strong reflection, and transmittance of the incident radiation in the near-infrared band (0.7–3.0 μm) due to the inherent structure and pigmentation in green leaf canopies (Dorman & Sellers, 1989). In contrast, the total shortwave regime (0.3–5.0 μm) as well as visible (0.3–0.7 μm) and near-infrared (0.7–3.0 μm) spectral bands, are typically needed by the surface energy balance studies and the surface interaction modules of global and regional climate models. Thus, the words “spectral-”, “narrow-/broad-” are often, respectively, used to refer to spectral, narrow/broadband reflectance quantities, with a highlight on the individual spectral response or a sub-regime of the solar spectrum adopted in deployed instruments and sensors. Note that the general so-called “albedo” under an actual scenario, without any specification of the sun-view geometry and integral wavelength, often implies the bi-hemispheric broadband albedo of the whole solar irradiance domain.

\[
a_{DH}(\theta_1, \varphi; \lambda_1 \rightarrow \lambda_2) = \frac{\int_{\lambda_1}^{\lambda_2} \left( \int_0^{\frac{\pi}{2}} \int_0^\varphi f_i(\theta_1, \varphi; \theta, \varphi; \lambda) \cos \theta \sin \theta d\theta d\varphi \right) L_i(\theta_1, \varphi; \lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} L_i(\theta_1, \varphi; \lambda) d\lambda} \\
\]

\[
a_{HD}(\theta_1, \varphi; \lambda_1 \rightarrow \lambda_2) = \frac{\int_{\lambda_1}^{\lambda_2} \left( \int_0^{\frac{\pi}{2}} \int_0^\varphi f_i(\theta_1, \varphi; \theta, \varphi; \lambda) \cos \theta \sin \theta d\theta d\varphi \right) L_i(\theta_1, \varphi; \lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} \left( \int_0^{\frac{\pi}{2}} \int_0^\varphi L_i(\theta_1, \varphi; \lambda) \cos \theta \sin \theta d\theta d\varphi \right) d\lambda} \\
\]

\[
a_{BH}(\lambda_1 \rightarrow \lambda_2) = \\
\]

Theoretically, it is straightforward to convert spectral to broadband albedo using formulae (6) – (8) if the spectra of the incident and reflected light are known. Otherwise, empirical or physical models are needed to calculate the distribution of upward and downward radiative flux in those portions of the broad spectral region where measurements or spectral response are not available, with some assumptions of the atmospheric state and ambient condition (Li & Garand, 1994; Liang, 2000; Liang et al., 1999). Because of the anisotropic reflectance behavior of land surfaces and the instantaneous atmosphere effect, any simple replacement of the bi-hemispheric albedo with a directional reflectance value observed from a single angle, may induce considerable errors, especially under a high heterogeneity ambient condition (Kimes & Seller, 1985; Toll, Shirey, & Kimes, 1997). Furthermore, since radiance measurements of the same surface cover vary with the view position, the incorrect classification may occur when a special land cover type is pursued under different geometries, or at different times of day or season. Ephemeral conditions, such as dew in the early morning, can also affect directional reflectance.
2.4. Measurement of hemispherical reflectances

Hemispheric reflectances can be measured by a portable albedometer at the ground, or from airborne or satellite-based instruments. The bi-hemispheric reflectance for the surface of interest can be directly acquired in the field using paired pyranometers looking upward and downward. Typically, the pyranometers measure the full solar shortwave spectrum. However, the data may be filtered to eliminate shorter wavelengths to get the bi-hemispheric reflectance in the required spectral domain, such as visible (0.3–0.7 \( \mu \)m), near-infrared (0.7–3.0 \( \mu \)m), shortwave bands (0.3–5.0 \( \mu \)m), and as that performed in the most recent developed spectral albedo-meter (Zhou, Wang, & Liang., 2018). These surface measurements are also referred to as “land surface albedo”. In contrast to measurements observed from the space which are referred to as TOA (top-of-atmosphere) albedo, observations collected under the actual atmospheric conditions, by satellite-borne radiometers which have limited instantaneous field-of-view (IFOV), are nominal hemispheric-directional reflectance at the designed sensor bands. Theoretically, the direct-hemispherical albedo cannot be directly acquired in the outdoor condition due to the impact of the atmosphere, but it may be estimated by subtracting the diffuse flux that is approximately measured with a black board to block the solar direct beam, from the total.

Ground measurement networks for long-term monitoring of continuous radiation quantities have been built up over several decades, at a limited number of sites globally distributed. The routinely observed incoming and outgoing fluxes across both full solar spectrum and the PAR spectral region can be used to calculate the related broadband bi-hemispheric reflectances. For example, there are tens of years of continuous observations provided by the Baseline Surface Radiation Network (BSRN) designated by the World Climate Research Program (WCRP), with frequent collection performed by International Long Term Ecological Research (ILTER). Similarly, regional flux towers have been set up at sites all over the world, including AmeriFlux, FLUXNET-Canada, AsiaFlux as well as ChinaFlux, etc. These in situ datasets collected over numerous land cover types in widely distributed sites have been used for the model development, satellite product validation, numerical simulation, and model development. These sites are useful for local studies and validation, while remote sensing estimates are the only practical approach to generating map products of albedo to support regional and global modeling.

3. Development of the retrieval strategy and methodology

3.1. Retrieval strategy

The retrieval of surface hemispheric reflectance \( (\alpha_{DH}, \alpha_{HD}, \alpha_{BH}; \text{and} \alpha_{blue-sky}) \) consists of four steps (Csiszar & Gutman, 1999) including (1) atmospheric correction to get the land surface radiative measures when TOA measurement is used as the initial data source, (2) conversion or normalization (at a required solar zenith angle) of the nominal bi-directional surface reflectance into the hemispheric reflectance at each given spectral band, (3) narrow-to-broadband conversion if broadband albedo covering a target spectral domain needed, (4) a time-averaging or compositing process depending on the application, such as conversion to daily, 16-day, or monthly average. In the actual retrievals, the order of these steps may vary. Generally, two alternative ways are often adopted for the timing of atmosphere correction. In early studies, because of the lack of accurate atmospheric states
serving for the atmospheric correction, the land surface hemispherical reflectance was often directly estimated from linear functions of measures at the TOA or at the surface (Koepke & Kriebel, 1986; Pinker, 1985; Pinty & Ramond, 1987), through the radiation algorithms by equating the TOA albedo with a model value (Pinty & Szejwach, 1985), or the empirical parameterization model combined with a simultaneous atmospheric correction (Li & Garand, 1994), for a variety of atmospheric and surface conditions. Whereas the less consideration of anisotropic effects in both atmosphere correction and the land surface response has limited the retrieval accuracy. Thus, with the development of atmospheric correction models (Lyapustin, 1999; Lyapustin et al., 2011a; Vermote, Tanre, Deuze, Herman, & Morcette, 1997), estimation of surface hemispheric reflectances from atmospherically corrected surface radiative measures has become a common strategy in the modern surface albedo products, no matter whether all other procedures combined together in one step or still performed in several individual steps. In addition, numerous studies on the multi-angular observation and the BRDF model significantly stimulate the further improvement of atmosphere correction (Lyapustin et al., 2011a) and angular correction for the surface albedo dataset retrieved from Advanced Very High Resolution Radiometer (AVHRR) (Csiszar & Gutman, 1999) and other satellite-based optical sensors.

3.2. Multi-directional retrieval solution

Based on the atmospherically-corrected directional surface reflectance, two solutions have been developed to generate the land surface hemispheric reflectances. One is the single-direction retrieval, while the other one is the multi-angle retrieval. For the sake of simplicity and because of the lack of available anisotropic information, the earliest studies often inferred the surface albedo, from the single near nadir directional reflectance measurement with the Lambertian assumption for terrestrial surfaces. But, it was concluded that errors using this assumption on the hemispheric reflectance retrieval for the ground-level AVHRR could reach 45% based on a set of 11 natural vegetation types and solar zenith angles (Kimes & Seller, 1985). Therefore, the remote sensing community has moved toward multi-direction-retrieval for modern satellite-based hemispheric reflectance products, such as the MODerate resolution Imaging Spectroradiometer (MODIS) (Lucht et al., 2000; Schaaf et al., 2002; Strahler & Muller, 1999), Multi-angle Imaging SepectroRadiometer (MISR) (Martonchik, 1997; Martonchik et al., 1998), and POLarization and Directionality of the Earth’s Reflectance (POLDER) (Bicheron & Leroy, 2000; Leroy et al., 1997; Maignan, Bréon, & Lacaze, 2004) albedo retrievals as well as Meteosat (Pinty et al., 2000) and the Meteosat Second Generation (MSG) (Schmetz et al., 2002). Any accurate model used to estimate the land surface BRDF requires multi-directional observations acquired near-simultaneously (such as POLDER and MISR), or by building up sequential angular views over a period of hours and days (such as Meteosat, MSG, MODIS, AVHRR, and SPOT-4 VEG, and VIIRS). The directional observation of land surface was initially brought up from the in-situ field measurements conducted as early as the 1960s (Kimes & Kirchner, 1983); and measured from airborne instruments, such as ASAS (airborne Advanced Solid-state Array Spectroradiometer), OMIS (Optical Multi-spectral Imaging System), and AMTIS (Airborne Multi-angle TIR/MR Imaging System); and finally collected from space via the satellite-based sensors listed above.
3.3. Estimation of the land surface anisotropy

A model which can be inverted using measurements at limited number of angles is usually required to estimate the bidirectional reflectance function (BRDF) over a particular land surface, especially for predicting direction reflectance in any sun-view geometry, then accurately computing the surface albedos (Roujean, Leroy, & Deschamps, 1992; Schaaf et al., 2002). During the last 40 years or so, a number of such models have been developed. Earlier models primarily focused on vegetated surfaces (such as forests and crops), and subsequently were developed for soil, snow, and ice as well as other surfaces (Asrar, 1989; Goel, 1988; Myneni, Ross, & Asrar, 1990). Goel (1988) contributed a substantial review article to summary several dozen models into the four categories – turbid medium models, geometric models, hybrid models, and computer simulation models. We do not intend to duplicate a review of all those models, but only give a snapshot of some representative models adopted in the modern hemispheric albedo generation. In the turbid medium models, the target land surface is assumed to be horizontally uniform with vertically parallel distinct thin layers. The elements in these layers are treated as small absorbing and scattering particles with constant optical features in each horizontal layer (Myneni, Asrar, Burnett, & Kanemasu, 1987). According to the Kubelka-Munk theory or the radiative transfer theory, the upward and downward radiance at different directions are approximated among the layers. The representative model is the SAIL model (Verhoef, 1984), the modified version with the consideration of hotspot and specular reflection (Goel & Kuusk, 1992), and the Ross-thick model (Ross, 1981). These models are considered as the best suite for homogenous surfaces, such as dense forest or full-cover mature crops. Geometric models treat the ground protrusions (such as forest canopy) as geometrical objects with different specified shape, dimension, and optical properties. The earliest geometrical models focused on the determination of direct and diffuse radiation via the empirical parameters or some measurements weighted by sunlit and shadowed regions (Jahnke & Lawrence, 1965), but then developed into an area-weighted sum of the reflectance of four components (sunlit and shadowed crown, sunlit and shadowed ground) in terms of surface scattering and geometric shadow casting theory (Jupp, Walker, & Penridge, 1986; Li & Strahler, 1985). GO_RT model is developed through a series of modifications on the gap probability and the consideration of turbid or transmission feature in the vegetation elements (Li, Strahler, & Woodcock, 1995; Ni, Li., Woodcock, Roujean, & Davis, 1997), with the further effort on the analytical GO-RT for the bidirectional reflectance over discontinuous plant canopies (Ni, Li, & Woodcock et al., 1999), and as well the automatic transit from sparse to density forest condition with the solar zenith angle changing from low to high (Li-Transit model) (Gao, Li, Strahler, & Schaaf, 2000). The four-scale bidirectional reflectance model considers the non-random spatial distribution at four levels (tree stands, tree crowns, branches, and shoots) to describe the canopy architecture and the bidirectional reflectance estimation (Chen & Leblanc, 1997). According to Goel’s theory (Goel, 1988), the GO-RT and four-scale models are also categorized as the hybrid models since they combine the geometric shape of plants with the turbid medium approach. Computer simulation models calculate the radiation interception and the canopy reflectance in a built-up scenario, by tracing the fate of each incident photon from “birth” to “death”, determining the possibility and direction of each
scatter, absorption, or transmission (Govaerts & Verstraete, 1998; Qin & Gerstl, 2000; Ross & Marshak, 1989).

Algorithms combined from the above models or developed from empirical approaches are widely adopted in several operational satellite-based hemispheric albedo retrieval systems. For instance, the kernel driven linear model, also known as Ross-Thick-Li-Sparse-Reciprocal (RTLSR) mode, is combined from the radiative-transfer-based model and geometrical model developed, respectively, by Ross (1981) and Li and Strahler (1992). This model relies on the weighted sum of an isotropic parameter and two functions of view and illumination geometry to estimate the bidirectional reflectance distribution. According to the least squares error rule, the kernel weights are inverted from a series of linear RTLSR equations with a few given directional observations (Lucht et al., 2000; Schaaf et al., 2002; Sun, Wang, Li, Erb, & Schaaf, 2017). Because of the suitability for the RTLSR for describing surface anisotropy globally, this combined model has been utilized as the operational MODIS albedo and anisotropy algorithm as well as the POLDER operational retrieval system. The three-parameter modified RVP (Rahman–Verstraete–Pinty) (Rahman, Pinty, & Verstraete, 1993) is developed from the early widely used empirical model describing the directional reflectance of moon (Minnaert, 1941), with additional functions to enhance the hot-spot, modulate the forward-backward scattering, and highlight subtle variations with changing sun-view direction. The Multi-angle Imaging SpectroRadiometer (MISR) on the EOS Terra platform simultaneously collecting observations of the land surface from nine view directions, has a unique capability to generate atmospherically corrected surface hemispherical-directional reflectance factor (HDRF) estimates using the RVP model, then the bidirectional reflectance factor with an additional diffuse illumination correction, resulting in the directional-hemispherical reflectance at four spectral bands (Martonchik et al., 1998).

In most recent, with the increasing requirement for near real-time surface hemispherical reflectances, a daily algorithm based on the linear kernel driven model was developed to estimate the daily albedo using observations provided by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) (Geiger, Carrer, Franchistéguy, Roujean, & Meurey, 2008). In parallel work, a rolling strategy of the dynamic MODIS observation stream was applied to the RTLSR model with an emphasis on the most recent observation to tune the anisotropy and approximate the surface albedos (Shuai, 2010). Another RTLSR algorithm named MAIAC (MultiAngle Implementation of Atmospheric Correction) was proposed to simultaneously perform the atmospheric correction and the BRF estimation from TOA MODIS observations (Lyapustin et al., 2011a; 2011b). An empirical relationship, as a second-order polynomial function, between bidirectional reflectance factor and directional-hemispherical albedo was presented in terms of the BRF derived from POLDER observation, to estimate the surface directional-hemispherical albedo from a single BRF observation with given sun-view geometry (Cui, Mitomi, & Takamura, 2009). An additional approach was proposed to generate 30-m resolution land surface albedo using Landsat surface reflectance and the classification-based high quality anisotropy information retrieved from concurrent MODIS 500-m observations, using the albedo-to-nadir reflectance ratio to link the fine-resolution retrieval and moderate-resolution BRDF (Shuai, Masek, Gao, & Schaaf, 2011; Shuai, Masek, Gao, Schaaf, & He, 2011).
On the other hand, some efforts have been put on the development of surface daily mean albedo under clear-sky days to serve for daily shortwave energy budget with the assumption that the daily atmospheric condition is represented by its instantaneous condition captured at the satellite overpass time (Wang, Schaaf et al., 2017).

4. Hemispheric reflectance products

Surface albedo with an absolute accuracy of 0.02–0.05 reflectance units is required by climate, biogeochemical, hydrological, and weather forecast models at different spatial and temporal resolutions (Sellers et al., 1994). In the earlier land surface model (LSM) and common land model (CLM), the snow-free albedos are prescribed with tabular values depending only on vegetation types without any dynamic variation (Liang, et al., 2005). Sporadic surface albedo products were first generated from earlier satellite sensors. A global 0.15° albedo data set over 6 years from 1985 to 1991 was retrieved from global area coverage (GAC) of the Advanced Very High Resolution Radiometer (AVHRR) data (Csiszar & Gutman, 1999). Also, from NOAA/AVHRR data, 4 years (1992–1996) polar albedo products with 1.25 km and 5 km resolution have been inverted by the CASPR algorithm (Key, Wang, Stoeve, & Fowler, 2001). A monthly 2.5° albedo data set from 1985 to 1989 has been generated from ERBE (Earth Radiation Budget Experiment) radiometer (Li & Garand, 1994), while CERES (Clouds and the Earth’s Radiant Energy System) uses broadband surface shortwave flux to produce monthly albedo over 5 years (2000–2004) with one degree resolution (Rutan, Charlock, & Rose et al., 2006). A snow-free albedo data set over 2 years (1987–1988) was acquired using the FASIR algorithm with AVHRR NDVI (Sellers et al., 1994). 10-day global maps of surface albedo over several months were generated from POLDER-I (Polarization and Directionality of the Earth’s Reflectances I) (Oct.1996-Jun.1997) and POLDER-II (Apr.-Oct. 2003) with a 6 × 7 km resolution (Maignan et al., 2004) as well as POLDER-III. In the most recent, 30-m surface shortwave band albedo map over Maryland & Washington DC region and six SURFRAD sites are produced through the data fusion of land surface and concurrent high-quality MODIS BRDF (Shuai et al., 2011, 2014). Consistent high-quality, global land albedo data sets have been generated from operational satellites, to serve the climate science and modeling communities. Surface albedo products are being generated every 8-day from the MISR (Multi-angle Imaging SpectroRadiometer) (Martonchik et al., 1998), while CERES (Clouds and the Earth’s Radiant Energy System) uses broadband surface shortwave flux to produce monthly albedo with one degree resolution (Rutan et al., 2006). A continuous global or continental albedo dataset at resolutions from 0.5-5km has been produced from MODIS, VIIRS, and as well AVHRR, with the temporal scale from daily, weekly, 8-day,10-day,16-day or monthly (Schaaf et al., 2002; Sun et al., 2017; Wang et al., 2015; Xiao et al., 2015). Some 20-day African land surface 3 km albedo maps were calculated from Meteosat data by a semi-empirical model, where the angular information was provided by temporal solar angle changes rather than view angles (Pinty et al., 2000), and new products are being produced from MSG (Meteosat Second Generation) (Carrer, Roujean, & Meurey, 2010; Geiger et al., 2008) as well. With the increasing need to monitor rapid changes on the land surface, the daily surface albedo dataset is being produced to detect the abrupt changes using 3 km MSG (Geiger et al., 2008) and 500-m MODIS observations (Shuai, 2010). In addition, with
the requirement of fine resolution on space and time scale, the 30-m Landsat land surface albedo dataset has been issued by USGS in terms of the “MODIS-concurrent” approach (Shuai et al., 2011), and the GLASS (Global Land Surface Satellite) data suit has published more than 30 years land surface 8-day albedo product with 5 km (before 2000) and 1 km (after 2000) resolution via http://www.bnu-datacenter.com and www.landcover.rog (Liang et al., 2016).

5. Case examination on differences between hemispheric reflectance quantities

To encompass the potential range of differences between various albedo-related quantities generated from satellite observations in the operational retrieval systems, a set of representative surface targets were compiled in terms of the IGBP (International Geosphere – Biosphere Programme) land cover classification scheme. Since the Northern Kazakhstan has rich biodiversity and fitting our particular focus of this exemplification, 12 representative classes (see Figure 1) with high confidence were selected from 2018 MCD12Q1 500 m Land cover map (Friedl et al., 2010) and its confidence layer to serve for this investigation. To examine the temporal variation, the time series of surface BSA and WSA in seven narrow and three broad bands were extracted for the selected pixels from 2018 MCD43A3 500 m surface albedo products (Schaaf et al., 2002; Wang, Liang, et al., 2017). We calculated the absolute difference between BSA and WSA (i.e. BSA-WSA) and its percentage of relative difference (i.e. \( \frac{\text{BSA} - \text{WSA}}{\text{WSA}} \times 100\% \)) for each selected pixel in MODIS tile h22v03 from the organized 10-day temporal series of year 2018. Due to frequent emergences of the ambiguous usage between albedo and directional reflectance, we also extracted the simultaneous MCD43A4 NBAR (Nadir-BRDF Adjusted Reflectance) data to exhibit the errors when albedo terms are replaced with directional reflectance quantity, and named it as “NBAR-like” albedo.

The BSA and WSA-two different albedo quantities that defined under two ideal illumination conditions, respectively, with no diffuse and isotropic diffuse sky-light, have apparent difference. Figure 2(a,b) shows the transition of BSA and WSA at MODIS seven narrow land bands and three combined broad bands (i.e. visible, near-infrared, shortwave) from spring to winter of 2018, over evergreen needle leaf forest (ENF) and mixed forest (MF). Figure 2(c,d) illuminate their absolute difference and percentage of relative difference between BSA and WSA, generally with the elevated divergence in summer and winter, respectively, up to (0.021, 0.082, 0.027, 0.021, 0.057, 0.022, 0.013, 0.021, 0.051, 0.028) and (26.6%, 30.8%, 16.3%, 20.4%, 31.5%, 36.7%, 43.3%, 20.8%, 28.3%, 17.6%) for ENF, and (0.086, 0.118, 0.093, 0.084, 0.145, 0.049, 0.037, 0.086, 0.1111, 0.098), and (43.4%, 36.0%, 34.3%, 37.0%, 62.0%, 59.0%, 100.0%, 35.5%, 43.0%, 39.2%) for MF at seven narrow and three broad bands. In addition, we took the statistics to examine the magnitude of both differences over all of the investigated land covers, and found that the absolute differences can reach up to (0.090, 0.118, 0.118, 0.144, 0.266, 0.090, 0.067, 0.118, 0.111, 0.108), and (43.4%, 36.0%, 34.3%, 37.5%, 70.9%, 70.6%, 181.0%, 35.5%, 50.0%, 39.2%) for the relative difference at 10 narrow and broad bands (see Tables 1 and 2). And Figure 3 exhibits an example for the spatial variation of BSA and WSA, as well their absolute and relative differences at near infrared, shortwave, and visible broadband surface albedo.
using MCD43A3 three tiles (h21v03, h22v03, and h23v03) combined albedo product on day 2018–181. The absolute discrepancy between two albedo terms can be captured clearly especially at the near infrared band, while the relative difference is apparent with a major percentage range in (5%, 20%), (5%, 15%), and (−1%, −20%) respectively, for near infrared, shortwave, and the visible albedo bands.

With a further investigation on the difference among directional reflectance, actual albedo, BSA, and WSA, we compared MCD43A-NBAR with MODIS BSA, WSA, and the actual albedo using the data from day 2018–181. The actual albedo is calculated from the BSA and WSA weighted by concurrent MOD04 atmosphere condition. The NBAR-like broadband reflectance is simulated from the spectral BRDF and coefficients reproduced from high spectrum datasets in terms of the narrow band to the broadband approach (Liang, 2000). Figure 4 shows the NBAR-like albedos are far away from BSA, WSA, and actual albedo (i.e. Blue-sky albedo), with extra high value over water body (WD), barren,

**Figure 1.** Distribution of the 12 IGBP land cover types (labeled solid dots) selected from MOD12Q1 2018 land cover map with high classification confidence over the northern Kazakhstan (solid boundary line).
Figure 2. Variation of every 10-day BSA (A) and WSA (B) collected from the daily MODIS 500 m products (MCD43A3) at seven narrow bands (Band1-7) and three broad bands (VIS, NIR, and Shortwave), as well their related absolute (C) and relative (D) difference for the evergreen needle leaf forest (ENF, in the left panel) and mixed forest (MF, in the right panel) in the year of 2018 over 12 typical IGBP Land cover type in the Northern Kazakhstan. Filled value is found in period (321, 341) due to continuous cloud contamination.
Table 1. Range of the absolute and relative difference of two MODIS albedo terminologies (BSA and WSA) at seven narrow bands over the 12 typical IGBP land covers located at the Northern Kazakhstan region from the daily MODIS albedo products (MCD43A3) of year 2018.

| Land cover type                        | Differ-encea | Band1  | Band2  | Band3  | Band4  | Band5  | Band6  | Band7  |
|----------------------------------------|--------------|--------|--------|--------|--------|--------|--------|--------|
| Evergreen Needleleaf Forests           | A_D          | −0.013 | −0.021 | −0.044 | −0.022 | −0.072 | −0.037 | −0.014 |
|                                        | R_D (%)      | −15.0  | 26.6   | −19.1  | 30.8   | −16.7  | 16.3   | −18.9  |
| Deciduous Broadleaf Forests            | A_D          | −0.021 | 0.011  | −0.067 | 0.034  | −0.011 | 0.026  | −0.016 |
|                                        | R_D (%)      | −16.9  | 12.1   | −22.5  | 13.9   | −26.7  | 7.0    | −16.5  |
| Mixed Forests                          | A_D          | −0.013 | 0.086  | −0.062 | 0.118  | −0.011 | 0.093  | −0.015 |
|                                        | R_D (%)      | −22.2  | 43.4   | −18.3  | 36.0   | −23.8  | 34.3   | −22.1  |
| Woody Savannas                         | A_D          | −0.012 | 0.056  | −0.038 | 0.069  | −0.007 | 0.071  | −0.012 |
|                                        | R_D (%)      | −26.7  | 25.0   | −13.2  | 19.4   | −26.9  | 22.2   | −19.7  |
| Savannas                               | A_D          | −0.016 | 0.032  | −0.073 | 0.067  | −0.007 | 0.075  | −0.013 |
|                                        | R_D (%)      | −18.2  | 10.4   | −15.9  | 23.5   | −20.8  | 15.4   | −18.2  |
| Grasslands                             | A_D          | −0.020 | 0.062  | −0.055 | 0.058  | −0.009 | 0.027  | −0.026 |
|                                        | R_D (%)      | −23.5  | 19.2   | −19.6  | 21.9   | −20.5  | 18.2   | −26.3  |
| Permanent wetlands                     | A_D          | −0.021 | 0.055  | −0.060 | 0.052  | −0.008 | 0.012  | −0.017 |
|                                        | R_D (%)      | −31.7  | 33.8   | −26.8  | 31.8   | −31.8  | 28.6   | −37.5  |
| Croplands                              | A_D          | −0.028 | 0.090  | −0.070 | 0.115  | −0.008 | 0.066  | −0.029 |
|                                        | R_D (%)      | −21.2  | 16.4   | −21.3  | 20.1   | −20.0  | 12.3   | −25.2  |
| Urban and Built-up Lands               | A_D          | −0.023 | 0.041  | −0.031 | 0.048  | −0.015 | 0.039  | −0.021 |
|                                        | R_D (%)      | −20.4  | 12.4   | −13.8  | 14.5   | −23.1  | 26.8   | −20.2  |
| Cropland Natural Vegetation            | A_D          | −0.012 | 0.051  | −0.079 | 0.074  | −0.006 | 0.058  | −0.013 |
|                                        | R_D (%)      | −15.8  | 19.0   | −19.3  | 21.9   | −17.7  | 20.0   | −20.6  |
| Barren                                 | A_D          | −0.008 | 0.033  | −0.002 | 0.022  | −0.013 | 0.073  | −0.012 |
|                                        | R_D (%)      | −1.8   | 4.1    | −3.3   | 9.1    | −17.7  | 12.2   | −10.6  |
| Water Bodies                           | A_D          | −0.008 | 0.087  | −0.011 | 0.047  | −0.010 | 0.118  | −0.013 |
|                                        | R_D (%)      | −3.9   | 13.3   | −14.7  | 5.4    | −3.9   | 14.6   | −4.8   |
| Maximum divergence Of all classes"     | A_D          | 0.090  | 0.118  | 0.118  | 0.144  | 0.266  | 0.900  | 0.090  |
|                                        | R_D (%)      | 43.4   | 36.0   | 34.3   | −37.5  | 70.9   | 70.6   | 181.0  |

# A_D: absolute difference between BSA (Black-Sky-Albedo) and White-Sky-Albedo. R_D (%): percentage of relative difference between BSA and WSA. Maximum divergence means the maximum divergence away the equal status, in which positive represents BSA value is higher than WSA, and whereas negative means BSA is lower.
Table 2. Range of the absolute and relative difference of two MODIS albedo terminologies (BSA and WSA) at visible, near-infrared, and shortwave broad bands over the 12 typical IGBP land covers located at Northern Kazakhstan region from the daily MODIS albedo products (MCD43A3) of year 2018.

| Land cover type                    | Absolute Difference between BSA and WSA (i.e. BSA-WSA) | Percentage of Relative Difference (BSA-WSA)/WSA*100 |
|------------------------------------|-------------------------------------------------------|---------------------------------------------------|
|                                    | Visible                                               | Neat Infrared                                     | Shortwave                          | Visible                      | Neat Infrared                                     | Shortwave                          |
| Evergreen Needleleaf Forests       | (−0.008, 0.021)                                       | (−0.031, 0.051)                                   | (−0.015, 0.028)                   | (−13.3, 20.8)               | (−17.7, 28.3)                                   | (−15.0, 17.6)                     |
| Deciduous Broadleaf Forests        | (−0.015, 0.016)                                       | (−0.069, 0.039)                                   | (−0.045, 0.029)                   | (−17.1, 11.1)               | (−22.9, 16.2)                                   | (−22.4, 15.3)                     |
| Mixed Forests                     | (−0.009, 0.086)                                       | (−0.042, 0.111)                                   | (−0.024, 0.098)                   | (−23.3, 35.5)               | (−18.0, 43.0)                                   | (−17.4, 39.2)                     |
| Woody Savannas                    | (−0.008, 0.051)                                       | (−0.030, 0.060)                                   | (−0.019, 0.055)                   | (−22.2, 25.0)               | (−13.3, 20.9)                                   | (−13.7, 20.2)                     |
| Savannas                           | (−0.010, 0.054)                                       | (−0.050, 0.051)                                   | (−0.025, 0.057)                   | (−18.8, 11.4)               | (−15.5, 19.7)                                   | (−14.0, 18.8)                     |
| Grasslands                         | (−0.016, 0.035)                                       | (−0.041, 0.048)                                   | (−0.024, 0.039)                   | (−24.6, 17.3)               | (−17.0, 22.9)                                   | (−15.9, 21.8)                     |
| Permanent Wetlands                 | (−0.014, 0.027)                                       | (−0.045, 0.075)                                   | (−0.028, 0.042)                   | (−32.4, 34.1)               | (−32.5, 35.9)                                   | (−23.9, 34.7)                     |
| Croplands                          | (−0.018, 0.075)                                       | (−0.045, 0.106)                                   | (−0.027, 0.085)                   | (−19.2, 15.8)               | (−18.1, 19.7)                                   | (−17.7, 16.0)                     |
| Urban and Built-up Lands           | (−0.019, 0.067)                                       | (−0.025, 0.060)                                   | (−0.020, 0.071)                   | (−21.6, 19.8)               | (−13.8, 20.5)                                   | (−14.8, 22.6)                     |
| Cropland Natural Vegetation        | (−0.006, 0.055)                                       | (−0.058, 0.069)                                   | (−0.025, 0.056)                   | (−18.2, 21.8)               | (−19.9, 21.4)                                   | (−15.6, 20.5)                     |
| Barren                             | (−0.007, 0.047)                                       | (−0.002, 0.034)                                   | (−0.004, 0.048)                   | (−9.0, 5.8)                 | (−50.0, 33.3)                                   | (−15.0, 8.0)                      |
| Water Bodies                       | (−0.010, 0.118)                                       | (−0.009, 0.093)                                   | (−0.006, 0.108)                   | (−3.2, 14.3)                | (−19.6, 14.7)                                   | (−6.5, 14.6)                      |
| Maximum divergence Of all classes  | 0.118                                                 | 0.111                                             | 0.108                             | 35.5                        | −50.0                                             | 39.2                              |

# Maximum divergence means the maximum difference away from the equal status, in which positive represents BSA value is higher than WSA, and whereas negative means BSA is lower.
evergreen needleleaf forest (ENF), permanent wetland (PW), woody savannas (WS) and Urban and Built-up Land (UBL), and companied by apparent lower value on types

Figure 3. Example for the spatial variation of BSA (1st row), WSA (2nd row), absolute magnitude (BSA-WSA, at the 3rd row) and relative difference percentage ((BSA-WSA)/WSA, at the 4th row) at near infra-red (1st column), shortwave (2nd column), and visible (3rd column) broadband on day 2018–181 of MCD43A3 combined by titles (h21v03, h22v03, and h23v03) covering Northern Kazakhstan region with selected IGBP land cover sample points (black stars).

Figure 4. Variation of NBAR, BSA, WSA, and actual albedo (columns series of each land cover type from left to right) extract from MODIS 500 m products (MCD43A3 and MCD43A4) at seven narrow bands (Band1–7) and three broad bands (VIS, NIR, and Shortwave), on day 2018–181 over 12 typical IGBP Land cover types in the Northern Kazakhstan.
deciduous broadleaf forest (DBF), savannas, cropland nature vegetation (CNV). The similar magnitude can be seen only over the mixed forest, grassland, and croplands. For actual albedo, its general variation is close to that from BSA and WSA. As an investigate instance, this case highlights the caveat of ambiguous usage on directional reflectance and various albedo quantities.

6. Summary and discussion

For a comprehensive understanding of hemispherical reflectance quantities, in this paper we have discussed the requirements, theoretical concepts, retrieval strategies, and a set of representative models, as well as the products followed by an exemplification using MODIS operational albedo products over Northern Kazakhstan. For the definition, we focused on the hemispherical geometry with an emphasis on both spectral and spectrally integrated reflectance. The spectral conversion over a target wavelength domain (such as narrow band of various sensors, or broadband over the relevant solar spectrum) has demonstrated that the result accuracy is strongly affected by instantaneous downward spectral sky irradiance, as well as the sensor’s spectral response function used as a weighting function.

The retrieval strategy and model of atmosphere correction and surface albedo extraction have been further developed with the increasing recognition of the anisotropy theory, which has demonstrated that “multiple-angles retrieval” strategy is a more reliable way to estimate the surface hemispherical reflectances. Numerous surface hemispherical reflectance products with the different spatial and temporal resolution have been mapped from various satellite-borne sensors to greatly serve for the researcher working in climate and biogeocological community. Though progress has been made, many challenges still exist.

The lack of standardized “albedo” terminology and product metadata is a potential source of error for further applications. The distinction among hemispherical reflectance quantities may induce a systematic uncertainty in the energy estimation if the inappropriate quantity is used. Therefore, a thorough description of the derived data, including the basic spectral, illumination-view geometry, atmosphere correction, and sensor FOV, is mandatory to reduce misuse and confusion.

Differences between various model retrievals for hemispherical reflectance are distinguishable, which may be the result of different algorithms, various object-oriented modeling, and distinct process chain and input data. For instance, the prominent feature of early radiative transfer theory is its delicate description of volumetric scattering, as opposed to the treatment of surface scattering for the earliest geometric models. Individual models developed over special surface types may have reduced accuracy when directly applied to other surface conditions. Various process chains, explicitly separated or combined procedures (such as atmosphere correction, directional reflectance calculation, and spectral integral) into 1–2 steps, may result in the accumulation of uncertainties to the simulated look-up-table usually used in the combined process. In addition, a barrier to building reliable and accurate long-term series of surface albedo dataset for climate monitoring and land-surface diagnostics is the fusion of modern and historical products generated from diverse sensors, distinct inputs as well as by different inverse strategies and various models. Though preliminary attempts in investigating discrepancies among albedo quantities have been made, though comparison over
extended land cover or special regions is still highly needed in the future work for advancing our understanding.

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**Data availability statement**

The data that support the findings of this study are openly available in NASA Earth Data pool at [https://search.earthdata.nasa.gov/search](https://search.earthdata.nasa.gov/search), reference number MCD43 and MCD12Q.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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