New land surface albedo parameterization based on MODIS data: Preliminary result

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ABSTRACT

A new parameterization of snow-free land surface albedo is developed using the MODerate resolution Imaging Spectroradiometer (MODIS) products of broadband black-sky and white-sky reflectance and vegetation information as well as the North American and Global Land Data Assimilation System (LDAS) outputs of soil moisture during 2000-2003. It represents the predictable albedo dependences on solar zenith angle, surface soil moisture, fractional vegetation cover, and leaf plus stem area index, while including a statistic correction for static effects specific of local surface characteristics. All parameters are estimated by solving optimization problems of a physically-based conceptual model for the minimization of the bulk variances between simulations and observations. A preliminary result showed that, for composites of all temporal and spatial samples of a same land cover category over North America, correlation coefficients between the new parameterization with the MODIS data range from 0.6 to 0.9, while relative errors vary within 5-20%. This is a substantial improvement over the existing state-of-the-art Common Land Model (CLM) albedo scheme, which has correlation coefficients from –0.5 to 0.5 and relative errors of 20-100%.

1. INTRODUCTION

Surface albedo greatly influences the surface energy budget and partition, which in turn regulate circulation patterns, change hydrological processes, and modify the absorption of photosynthetically active radiation (PAR) and thus determine the productivity of the Earth’s ecosystem. It also links climate changes to human activities through land cover/use alterations. As such, surface albedo is a crucial parameter in land surface models (LSMs). Yet, current land surface albedo models are oversimplified and/or contain substantial biases from observations4, 11, 13, 7, 10.

The recent increasing availability of high-quality, fine-resolution satellite data provides an unprecedented opportunity to develop more realistic dynamic-statistic land surface albedo parameterizations. In particular, the MODIS measurements facilitate the accurate retrieval of direct and diffuse albedos for visible, near-infrared and total solar bands using a semi-empirical kernel-driven Bidirectional Reflectance Distribution Function (BRDF) model5, 9. The data are currently available over the global land surfaces at 1 km resolution every 16-day composite period. In comparison with these satellite data, previous diagnostic studies have identified major model problematic areas, but none has yet developed improved parameterizations. In this study, we use the MODIS and other supplementary data to develop an improved dynamic-statistic parameterization for snow-free land surface albedo. The parameterization is initially designed for U.S. mesoscale modeling applications in the framework of the CLM coupled with the climate extension of the WRF4.

2. DATA

The data used in this study consist of the MODIS surface albedos9, the Land Data Assimilation System (LDAS)6, 1, 8 surface soil moisture, and other CWRF surface boundary conditions, including land cover category (LCC), fractional vegetation cover (FVC), leaf and stem areas index (LAI, SAI)4. The last 3 parameters are also based on MODIS products but necessary adjustments are made to ensure consistency with other conventional data sets (see below). All data, except for the static LCC and FVC, are time-varying samples from February 2000 to December 2003. Given that the MODIS albedo data are available at every 16-day composite period, other variables are processed to the same interval by time averaging.

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For U.S. applications, the CWRF domain is centered at (37.5ºN, 95.5ºW) using the Lambert Conformal Conic map projection and 30–km horizontal grid spacing, with total grid points of 196 (west–east) x 139 (south–north). The domain covers the whole continental U.S. and represents the regional climate that results from interactions between the planetary circulation and North American surface processes, including orography, vegetation, soil and coastal oceans. All variable data are processed onto this CWRF grid mesh before their use in development of the new land surface albedo parameterization.

3. METHODOLOGY

3.1 New conceptual model

We choose the following shape functions to depict the solar zenith angle and soil moisture dependence:

\[
R_{\mu,\lambda} = C_{0,\mu,\lambda} + C_{1,\mu,\lambda}\mu + C_{2,\mu,\lambda}\mu^2 \\
R_{\eta,\eta,\lambda} = C_{0,\eta,\eta,\lambda} + C_{1,\eta,\eta,\lambda}\exp(-C_{2,\eta,\eta,\lambda}\theta) \tag{1}
\]

where \(\lambda\) denotes for the visible (\(\text{vis}\)) or near-infrared (\(\text{nir}\)) spectral band, and \(\eta\) for direct beam (\(\text{b}\)) or diffuse radiation (\(\text{d}\)); \(\mu\) is the cosine of solar zenith angle, and \(\theta\) the surface volumetric soil moisture (\(\text{m}^3/\text{m}^3\)); \(C_{\mu,\lambda}\) and \(C_{j,\eta,\eta,\lambda}\) are fitting coefficients to be determined. For now we only concern the shape, which is assumed to be the same for all bare soil with or without any type of vegetation canopy.

We can now parameterize the bare soil albedo by the product of \(R_{\mu,\lambda}\) and \(R_{\eta,\eta,\lambda}\):

\[
\alpha_{g,b,\lambda} = \alpha_{0,g,b,\lambda}[C'_{0,g,b,\lambda} + C'_{1,g,b,\lambda}\exp(-C'_{2,g,b,\lambda}\theta)](1+C'_{1,\mu,\lambda}\mu+C'_{2,\mu,\lambda}\mu^2) \\
\alpha_{g,d,\lambda} = \alpha_{0,g,d,\lambda}[C'_{0,g,d,\lambda} + C'_{1,g,d,\lambda}\exp(-C'_{2,g,d,\lambda}\theta)] \tag{2}
\]

where the coefficients are redefined as:

\[
C'_{j,\eta,\eta,\lambda} \equiv C_{j,\eta,\eta,\lambda}^{-1} (C_{0,\eta,\eta,\lambda} + C_{1,\eta,\eta,\lambda})^{-1}, \; j = 0, 1 \\
C'_{\mu,\lambda} \equiv C_{\mu,\lambda}^{-1} \\
\alpha_{0,g,b,\lambda} = (C_{0,g,b,\lambda} + C_{1,g,b,\lambda})C_{0,\mu,\lambda} \\
\alpha_{0,g,d,\lambda} = (C_{0,g,d,\lambda} + C_{1,g,d,\lambda}) \tag{3}
\]

By this definition, \(\alpha_{g,\eta,\lambda} = \alpha_{0,g,\eta,\lambda}\big|_{\theta=0,\mu=0}\), which is referred as the maximum background soil albedo and may depend on LCC types. As such, the \(\mu\) or \(\theta\) dependence is normalized to a fractional shape varying between 0 and 1.

We choose to use the following general form of vegetation albedo:

\[
\alpha_{v,b,\lambda} = \alpha_{v,b,\lambda} \left[1 - \exp\left(-\frac{\Lambda_{b,\lambda} L_{\text{SAI}}}{\mu}\right)\right] + \alpha_{g,b,\lambda} \exp\left[-\left(\Gamma_{\mu} + \Gamma_{b}\right) L_{\text{SAI}}\right] \\
\alpha_{v,d,\lambda} = \alpha_{v,d,\lambda} \left[1 - \exp\left(-2\Lambda_{d,\lambda} L_{\text{SAI}}\right)\right] + \alpha_{g,d,\lambda} \exp\left(-2\Gamma_{d} L_{\text{SAI}}\right) \tag{4}
\]

where \(L_{\text{SAI}} = \text{LAI} + \text{SAI}\); \(\Lambda_{\eta,\lambda}\) depicts upward scattering coefficients. The transmittance or extinction coefficients \(\Gamma_{\eta}\) are defined as:
\[
\Gamma_b = \varphi_0, \quad \Gamma_d = \varphi_0^{-1}, \quad \text{if } \varphi_1 = 0
\]
\[
\Gamma_b = 0.5 \mu^{-1}, \quad \Gamma_d = 1, \quad \text{if } \varphi_1 = 0.5
\]
\[
\Gamma_b = \frac{G(\mu)}{\mu}, \quad \Gamma_d = \frac{1}{\varphi_2} \left( 1 - \frac{\varphi_1}{\varphi_2} \ln \frac{\varphi_1 + \varphi_2}{\varphi_1} \right), \quad \text{if } \varphi_1 \neq 0, 0.5
\]

where \(G(\mu)\) is the projected area of phytoelements in direction \(\mu\), and \(\varphi_0\) and \(\varphi_1\) are empirical parameters. We follow Goudriaan\(^3\) to have:

\[
G(\mu) = \varphi_1 + \varphi_2 \mu
\]
\[
\varphi_2 = \varphi_0 (1 - 2 \varphi_1)
\]

Our main goal is to search for the best set of parameters \(C'_{j,\delta,\eta,\lambda}, C'_{j,\mu,\lambda}, \alpha_{0g,\eta,\lambda}, \alpha_{c,\eta,\lambda}, \Lambda_{\eta,\lambda}, \) and \(\varphi_j\) that most realistically capture the predictable dynamic variations of snow-free land surface albedo inherent in the MODIS data. These parameters also vary with LCC types (except \(C'\)) but are not a direct function of locations. Many other factors, however, are currently not measurable and nor predictable. We therefore introduce a soil albedo localization factor (SALF) to depict the static portion of albedo that is geographically dependent:

\[
\alpha_{\eta,\lambda} = \alpha_{v,\eta,\lambda} f_v + \alpha_{g,\eta,\lambda} (1 - f_v)
\]
\[
\alpha'_{\eta,\lambda} = \gamma_{\eta,\lambda} \alpha_{\eta,\lambda}
\]

where \(f_v = \text{FVC}\) and \(\gamma_{\eta,\lambda} = \text{SALF}\) vary with geographic locations. The \(\alpha_{\eta,\lambda}\) is the dynamic component of the new parameterization that represents the predictable albedo dependences on solar zenith angle, surface soil moisture, land cover category, fractional vegetation cover, and leaf plus stem area index. The final albedo \(\alpha'_{\eta,\lambda}\) incorporates a statistic correction for static effect specific of local surface characteristics.

3.2 Solving the nonlinear constrained optimization problem

The new conceptual model, as described in Eqs (2-7), requires specification for six groups of parameters \((C'_{j,\delta,\eta,\lambda}, C'_{j,\mu,\lambda}, \alpha_{0g,\eta,\lambda}, \alpha_{c,\eta,\lambda}, \Lambda_{\eta,\lambda}, \) and \(\varphi_j\)) to define the dynamic component of albedo temporal and spatial variations, which is corrected by local \(\gamma_{\eta,\lambda}\) to account for other unresolved effects that are specific to each geographic location. It is impossible for any optimization solver to estimate all these unknowns at once. Our strategy is to use a subset of the data that pertain to the physical regime dominating a specific group of parameters and solve the optimization problem group by group in a pre-sorted sequential order. The optimization solver used in this study is the FORTRAN Feasible Sequential Quadratic Programming (FFSQP)\(^{12}\). Most of the parameters to be estimated have distinct physical meanings and thus must be objectively constrained. The FFSQP solver finds the shortest path in the multi-parameter space. This path is only one of many numerical solutions satisfying the specified functions and preserves no physical meaning of the parameters. As such careful pre-thinking of the physical representation of each parameter must be taken and conceptualized into the mathematical constraints.

4. PRELIMINARY RESULT

A summary of the preliminary result for direct visible and near-infrared radiation components for 16 land use categories is shown in Fig. 1. This compares correlation coefficients and biases between calculated and MODIS values for the old\(^5\) and new parameterizations. For direct visible radiation, the correlation coefficients between MODIS and old parameterization values are generally in the range of 0.2-0.4 while relative biases range between 20-100%. The results for the new parameterization are much improved with correlation coefficients uniformly high in the range of 0.75-0.9 and biases in the range of 15-45%. The improvement for direct near-infrared radiation is even more pronounced. In this case, the old parameterization produces very poor results. For most land use categories, correlation coefficients are near zero or even negative; the best correlation values are only around 0.3. The biases are generally in the range of 20-50%,
with a couple of higher values near 80%. By comparison, the new parameterization produces correlation coefficients in the range of 0.7-0.9, similar to the results for direct visible radiation. Also, the biases are quite small, less than 20% in all cases.

A similar summary for diffuse radiation components is shown in Fig. 2. For diffuse visible radiation, correlation coefficients using the old parameterization are mostly in the range of 0.3-0.5 with a couple of lower values. Biases range between 25-100%. As was the case for the direct visible component, the new parameterization results in markedly improved results. Correlation coefficients are in the range of 0.75-0.9 and biases in the range of 10-40%. For diffuse infrared radiation, the correlation coefficients for the old parameterization are mostly near zero with biases covering a wide range of 20-100%. Again, marked improvement is noted in the results for the new parameterization. Correlation coefficients range between 0.5-0.9 while biases are uniformly less than 20%.

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REFERENCE

Fig. 1. Correlation coefficients and biases for direct visible and near-infrared radiation components for 16 land use categories.

Fig. 2. Correlation coefficients and biases for diffuse visible and near-infrared radiation components for 16 land use categories.