An Improved Aerosol Optical Depth Retrieval Algorithm for Multiangle Directional Polarimetric Camera (DPC)

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S1.MODIS products

1. MYD09

   MODIS surface reflectance (MYD09) products have been corrected for the effects of atmospheric gases and aerosols under cloud-free conditions and were stored in a 5-min swath. A global validation shows that most surface reflectance (SR) products are within theoretical one-sigma error $(\pm0.005 + 5\%)$. In this paper, three years (2016–2018) MYD09 Scientific Data Set (SDS) data: 1km Atmospheric Optical Depth Band 3, 1km Reflectance Data State QA and 1km Surface Reflectance band1, band2, band9, band10 were used to analyze and construct the constraints of DPC SRRs. In addition, corresponding MYD03 products (1km) were used to provide solar, satellite zenith and azimuth angles, and land/sea masks.

2. MCD43D

   MCD43D is retrieved separately from the MCD43A1, but the daily product is at a global scale, and the spatial resolution is 30 arc-second (about 1 km). Because of the large size, each RossThick-LiSparseReciprocal (RTLSR) BRDF model kernel coefficients product for all seven bands is stored in a separate MCD43D file. In this study, b7, three kernel coefficient products: isotropic (MCD43D19), volume (MCD43D20), and geometry (MCD43D21), were used to construct the BRDF shape.

3. MYD08_D

   MODIS gridded atmosphere daily global joint products (MYD08_D3) contain daily 1×1 degree grid average values of atmospheric parameters. In this study, the total ozone burden and atmospheric water vapor of MYD08_D3 were used to correct the influences of the gaseous absorption.

4. MCD12Q1

   MCD12Q1 IGBP classification product mentioned in Section 2.1 was used to determine surface types.

5. Aerosol products

   MYD04_L2 (10 km) is the aerosol products that are retrieved from DT and DB operational algorithms. In addition, DT also provides 3km aerosol products (MYD04_3k) to monitor aerosol parameters at small or local scales [1]. In this study, the MYD04_L2 (C6.1) SDS: Image_Optical_Depth_Land_And_Ocean (MYD04_L2_DT), Deep_Blue_Aerosol_Optical_Depth_550_Land (MYD04_L2_DB), and Image_Optical_Depth_Land_And_Ocean (MYD04_3k_DT) from MYD04_3k (C6.1) were used to compare with DPC aerosol products.

S2. K_{443_670} and K_{490_670} **varies with** *NDVI* **and** *SCA* **over different surface types**

Table S1. K_{443_670} and K_{490_670} varies with *NDVI* and *SCA* over (1) Evergreen Needleleaf Forests

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.43	0.60	0.45	0.55	0.45	0.55	0.45	0.58	0.48	0.53
(0.2, 0.4]	0.44	0.64	0.43	0.53	0.47	0.56	0.51	0.60	0.51	0.60
(0.4, 0.6]	0.56	0.71	0.46	0.59	0.47	0.58	0.52	0.62	0.56	0.63
(0.6, 0.8]	0.60	0.84	0.51	0.64	0.50	0.62	0.53	0.61	0.57	0.62
(0.8, 1.0]	0.62	0.71	0.62	0.71	0.60	0.68	0.67	0.69	0.65	0.66

Table S2. Same as Table S1, but for (2) Evergreen Broadleaf Forests

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.43	0.57	0.43	0.58	0.58	0.67	0.66	0.70	0.63	0.65
(0.2, 0.4]	0.41	0.63	0.50	0.63	0.57	0.65	0.63	0.68	0.62	0.68
(0.4, 0.6]	0.52	0.64	0.50	0.60	0.56	0.64	0.63	0.68	0.66	0.71
(0.6, 0.8]	0.64	0.71	0.56	0.64	0.58	0.65	0.63	0.68	0.66	0.70
(0.8, 1.0]	0.62	0.73	0.62	0.73	0.63	0.69	0.68	0.70	0.79	0.76

Table S3. Same as Table S1, but for (3) Deciduous Needleleaf Forests

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.42	0.49	0.42	0.49	0.41	0.49	0.42	0.48	0.45	0.43
(0.2, 0.4]	0.40	0.58	0.39	0.46	0.42	0.50	0.44	0.50	0.45	0.49
(0.4, 0.6]	0.44	0.56	0.37	0.47	0.41	0.50	0.45	0.52	0.48	0.54
(0.6, 0.8]	0.44	0.58	0.44	0.58	0.44	0.56	0.47	0.55	0.49	0.56
(0.8, 1.0]	0.54	0.66	0.54	0.66	0.55	0.66	0.56	0.60	0.56	0.60

Table S4. Same as Table S1, but for (4) Deciduous Broadleaf Forests

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.66	0.71	0.48	0.64	0.46	0.58	0.52	0.56	0.53	0.56
(0.2, 0.4]	0.48	0.60	0.51	0.65	0.48	0.60	0.52	0.58	0.54	0.58
(0.4, 0.6]	0.43	0.62	0.51	0.66	0.49	0.60	0.52	0.59	0.55	0.60
(0.6, 0.8]	0.41	0.64	0.50	0.64	0.50	0.60	0.52	0.59	0.56	0.61
(0.8, 1.0]	0.52	0.62	0.52	0.62	0.56	0.64	0.56	0.60	0.57	0.59

Table S5. Same as Table S1, but for (6) Closed Shrublands

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.53	0.70	0.52	0.66	0.50	0.62	0.53	0.59	0.50	0.55
(0.2, 0.4]	0.49	0.65	0.52	0.66	0.52	0.61	0.53	0.59	0.55	0.60
(0.4, 0.6]	0.61	0.73	0.52	0.67	0.48	0.58	0.47	0.56	0.54	0.60
(0.6, 0.8]	0.55	0.67	0.55	0.67	0.55	0.65	0.53	0.61	0.55	0.59
(0.8, 1.0]	0.52	0.62	0.52	0.62	0.52	0.62	0.58	0.64	0.68	0.70

Table S6. Same as Table S1, but for (7) Open Shrublands

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.45	0.57	0.45	0.56	0.45	0.56	0.46	0.56	0.50	0.52
(0.2, 0.4]	0.44	0.57	0.44	0.56	0.45	0.58	0.46	0.57	0.46	0.55
(0.4, 0.6]	0.45	0.58	0.44	0.57	0.44	0.58	0.47	0.59	0.50	0.58
(0.6, 0.8]	0.46	0.59	0.45	0.59	0.46	0.60	0.48	0.59	0.53	0.59
(0.8, 1.0]	0.46	0.59	0.44	0.58	0.44	0.58	0.44	0.58	0.44	0.58

Table S7. Same as Table S1, but for (8) Woody Savannas

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.43	0.60	0.43	0.52	0.42	0.52	0.46	0.55	0.54	0.56
(0.2, 0.4]	0.48	0.61	0.42	0.52	0.44	0.54	0.48	0.55	0.50	0.55
(0.4, 0.6]	0.45	0.62	0.41	0.52	0.44	0.54	0.49	0.57	0.53	0.59
(0.6, 0.8]	0.54	0.64	0.47	0.61	0.48	0.60	0.50	0.58	0.53	0.59
(0.8, 1.0]	0.63	0.73	0.53	0.64	0.59	0.66	0.63	0.67	0.61	0.64

Table S8. Same as Table S1, but for (9) Savannas

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.43	0.60	0.43	0.52	0.42	0.52	0.46	0.55	0.54	0.56
(0.2, 0.4]	0.48	0.61	0.42	0.52	0.44	0.54	0.48	0.55	0.50	0.55
(0.4, 0.6]	0.45	0.62	0.41	0.52	0.44	0.54	0.49	0.57	0.53	0.59
(0.6, 0.8]	0.54	0.64	0.47	0.61	0.48	0.60	0.50	0.58	0.53	0.59
(0.8, 1.0]	0.63	0.73	0.53	0.64	0.59	0.66	0.63	0.67	0.61	0.64

Table S9. Same as Table S1, but for (11) Permanent Wetlands

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.46	0.58	0.46	0.59	0.48	0.59	0.49	0.56	0.51	0.53
(0.2, 0.4]	0.47	0.59	0.48	0.61	0.49	0.60	0.49	0.57	0.49	0.55
(0.4, 0.6]	0.46	0.60	0.47	0.62	0.49	0.62	0.49	0.59	0.51	0.57
(0.6, 0.8]	0.48	0.61	0.49	0.63	0.50	0.62	0.50	0.60	0.52	0.59
(0.8, 1.0]	0.46	0.60	0.47	0.61	0.53	0.63	0.51	0.59	0.45	0.52

Table S10. Same as Table S1, but for (14) Cropland/Natural Vegetation Mosaics

NDVI/SCA	(60, 100]		(100,120]		(120,140]		(140,160]		(160,180]	
	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}	K_{443_670}	K_{490_670}
[0.0, 0.2]	0.51	0.63	0.50	0.63	0.51	0.62	0.53	0.60	0.52	0.57
(0.2, 0.4]	0.51	0.63	0.51	0.63	0.52	0.63	0.53	0.61	0.53	0.58
(0.4, 0.6]	0.50	0.64	0.49	0.65	0.51	0.63	0.53	0.62	0.53	0.59
(0.6, 0.8]	0.53	0.64	0.52	0.66	0.52	0.65	0.53	0.63	0.55	0.61
(0.8, 1.0]	0.56	0.67	0.53	0.66	0.55	0.66	0.58	0.65	0.57	0.6

S3. Atmospheric correction method considering the non-Lambertian effect

This paper adopted a linear semi-empirical kernel-driven RossThick LiSparseReciprocal (RTLSR) BRDF model to describe the anisotropic surface reflectance (SR) [2,3]. The equation of the RTLSR model is as follows:

$$R_{SR}(\lambda, \theta_s, \theta_v, \emptyset) = f_{iso}(\lambda)\, K_{iso}(\theta_s, \theta_v, \emptyset) + f_{vol}(\lambda)\, K_{vol}(\theta_s, \theta_v, \emptyset) \qquad (S1)$$
$$+ f_{geo}(\lambda)\, K_{geo}(\theta_s, \theta_v, \emptyset)$$

where λ is the wavelength, $\theta_s, \theta_v, \emptyset$ are solar zenith angle and sensor zenith angle and relative azimuth angle, respectively. R_{SR} represents the surface directional reflectance, K_{iso}, K_{vol} and K_{geo} represent the isotropic, volumetric and geometric kernels, respectively, where $K_{iso} = 1$, expression of K_{vol} and K_{geo} can be found in Wanner, *et al.* [4], which are fixed functions and only dependent on the solar and viewing geometry. $f_{iso}(\lambda)$, $f_{geo}(\lambda)$ and $f_{vol}(\lambda)$ are the coefficients of the three kernels, and varied with wavelength and surface characteristics. Besides, Equation (1) can be separated into two terms:

$$R_{SR}(\lambda, \theta_s, \theta_v, \emptyset) = \rho(\lambda)[1 + \alpha_1(\lambda)\, K_{vol}(\theta_s, \theta_v, \emptyset) + \alpha_2(\lambda)\, K_{geo}(\theta_s, \theta_v, \emptyset)] \qquad (S2)$$

where $\rho(\lambda) = f_{iso}(\lambda)$ means the "reflectance magnitude," which is governed by surface type microphysical properties and changes rapidly with wavelength and time. α_1, α_2 represent the geometric factor and volumetric factor, respectively, and $\alpha_1(\lambda) = \frac{f_{vol}(\lambda)}{f_{iso}(\lambda)}$,

$\alpha_2(\lambda) = \frac{f_{geo}(\lambda)}{f_{iso}(\lambda)}$. The part in the square bracket is the BRDF shape ($BRDF_s$) function (Equation (S3)), which is driven by the macroscopic structure of surface types and remains nearly independent of wavelength, and changes slowly in a short time [5]:

$$BRDF_s = 1 + \alpha_1(\lambda)\, K_{vol}(\theta_s, \theta_v, \emptyset) + \alpha_2(\lambda)\, K_{geo}(\theta_s, \theta_v, \emptyset) \qquad (S3)$$

Overlying the Lambertian homogeneous surface and under a cloud-free, plane-parallel atmosphere condition, the satellite sensor received reflectance (R_{TOA}) at the top of atmosphere (TOA) can be written as:

$$R_{TOA}(\lambda, \tau, \theta_s, \theta_v, \emptyset) = T_g\left(R_{atm}(\lambda, \tau, \theta_s, \theta_v, \emptyset) + \frac{T^{\downarrow}(\theta_s) R_{SR} T^{\uparrow}(\theta_v)}{1 - R_{SR}S}\right) \qquad (S4)$$

where τ is the optical depth, T_g means the gaseous transmission caused by gases, R_{atm} refers to the aerosol and molecular intrinsic reflectance, The $T^{\downarrow}$ and $T^{\uparrow}$ are transmission, S is the spherical albedo of the atmosphere, R_{SR} is the angular SR.

In this study, a fast, accurate non-Lambertian atmospheric radiative transfer function considering the anisotropy of surface-based on four-stream theory was adopted, which has high precision with mean relative differences in spectral (range from UV to NIR) TOA simulation less than 0.7% for different surface types [6]. This forward model has been widely used for aerosol and surface parameters retrieval [7-9], and the equation can be expressed as:

$$R_{TOA}(\lambda, \tau, \theta_s, \theta_v, \emptyset) \tag{S5}$$
$$= T_g(R_{atm}(\lambda, \tau, \theta_s, \theta_v, \emptyset)$$
$$+ \frac{\vec{T}(\theta_s)^T \, \textbf{\textit{R}} \, \vec{T}(\theta_v) - e^{-\tau/\theta_s}|\textbf{\textit{R}}|e^{-\tau/\theta_v}S}{1 - R_{BHR}S})$$

where $\vec{T}(\theta_s) = [e^{-\tau/\theta_s}, t_s(\theta_s)]^T$ and $\vec{T}(\theta_v) = [e^{-\tau/\theta_v}, t_s(\theta_v)]^T$ and $t_s(\theta_{s/v})$ refers to the diffuse transmission, $\textbf{\textit{R}}$ is the reflectance matrix, $|\textbf{\textit{R}}|$ is the determinant of $\textbf{\textit{R}}$:

$$\textbf{\textit{R}} = \begin{bmatrix} R_{SR} & R_{DHR} \\ R_{HDR} & R_{BHR} \end{bmatrix} \tag{S6}$$
$$|\textbf{\textit{R}}| = (R_{SR}R_{BHR} - R_{DHR}R_{HDR}) \tag{S7}$$

where R_{DHR} represents the directional–hemispherical reflectance (DHR), i.e., black-sky albedo (R_{bs}), which describes the diffuse reflection of the incoming direct beam over the hemisphere. R_{HDR} refers to the hemispherical–directional reflectance (HDR), which describes the direct reflection of the incoming diffuse radiation from the whole hemisphere. R_{BHR} is bi-hemispherical reflectance (BHR), i.e., white-sky albedo. R_{DHR}, R_{HDR} and R_{BHR} can be computed using the following Equations (S8)–(S11) [9]:

$$R_{DHR}(\lambda, \theta_s) = f_{iso}(\lambda)h_{iso}(\theta_s) + f_{vol}(\lambda)h_{vol}(\theta_s) + f_{geo}(\lambda)h_{geo}(\theta_s) \tag{S8}$$
$$R_{HDR}(\lambda, \theta_v) = f_{iso}(\lambda)h_{iso}(\theta_v) + f_{vol}(\lambda)h_{vol}(\theta_v) + f_{geo}(\lambda)h_{geo}(\theta_v) \tag{S9}$$
$$R_{BHR}(\lambda) = f_{iso}(\lambda)H_{iso} + f_{vol}(\lambda)H_{vol} + f_{geo}(\lambda)H_{geo} \tag{S10}$$
$$h_k(\theta_s) = g_{0k} + g_{1k}\theta_s + g_{2k}\theta_s^2 + g_{3k}\theta_s^3 \tag{S11}$$

where H_k and g_{ik} (i = 0, 1, 2, 3; k = iso, vol, geo) are the regression coefficients listed in Table S3.

Considering the non-Lambertian characteristics of the surface, the atmospheric correction (AC) was implemented to get accurate directional surface reflectance $R_{SR}(\lambda)$. The detailed formula derivation process is as follows:

(1) The gas absorption correction is performed for all the input measured reflectance $R_{TOA}^{Meas}(\lambda)$ using the Equation (S12), then get the gas corrected reflectance ($R_{TOA}^{Meas\_gasc}(\lambda)$);

$$R_{TOA}^{Meas\_gasc}(\lambda) = R_{TOA}^{Meas}(\lambda)/T_g(\lambda) \tag{S12}$$

(2) Extracting the $f_{iso}(\lambda)$ parameter of the Equation (S8)–(S10), we can get the remaining parts and name them $R'_{DHR}(\lambda, \theta_s)$, $R'_{HDR}(\lambda, \theta_v)$ and $R'_{BHR}(\lambda)$, respectively, as shown in the Equation (S13)–(S15);

$$R'_{DHR}(\lambda, \theta_s) = 1 + \alpha_1(\lambda)h_{vol}(\theta_s) + \alpha_2(\lambda)h_{geo}(\theta_s) \tag{S13}$$
$$R'_{HDR}(\lambda, \theta_v) = 1 + \alpha_1(\lambda)h_{vol}(\theta_v) + \alpha_2(\lambda)h_{geo}(\theta_v) \tag{S14}$$
$$R'_{BHR}(\lambda) = 1 + \alpha_1(\lambda)H_{vol} + \alpha_2(\lambda)H_{geo} \tag{S15}$$

(3) Expand the reflectance matrix $\textbf{\textit{R}}$ and determinant $|\textbf{\textit{R}}|$ with other parameters of Equation (S6), the expanded equation can be divided into the following four parts (F_1, F_2,

F_3 and F_4) as shown in the Equation (S16)–(S19). Meanwhile, we define the part in the square bracket of Equation (S17)–(S19) as F'_2, F'_3 and F'_4;

$$F_1(\lambda, \tau, \theta_s, \theta_v, \emptyset) = R_{TOA}^{Meas\_gasc}(\lambda, \tau, \theta_s, \theta_v, \emptyset) - R_{atm}(\lambda, \tau, \theta_s, \theta_v, \emptyset) \tag{S16}$$

$$F_2(f_{iso}, \lambda, \tau, \theta_s, \theta_v) = f_{iso}(\lambda)[e^{-\tau/\theta_s}BRDF_s e^{-\tau/\theta_v} + t_s(\theta_s)R'_{HDR}e^{-\tau/\theta_v}) \tag{S17}$$
$$+ e^{-\tau/\theta_s}R'_{DHR}t_s(\theta_s) + t_s(\theta_v)R'_{BHR}t_s(\theta_v)]$$

$$F_3(f_{iso}, \lambda, \tau, \theta_s, \theta_v) = f_{iso}(\lambda)\left[e^{-\tau/\theta_s}(R'_{DHR}R'_{HDR} - BRDF_s R'_{BHR})e^{-\tau/\theta_v}S\right] \tag{S18}$$

$$F_4(f_{iso}, \lambda, \tau) = f_{iso}(\lambda)[R'_{BHR}S] \tag{S19}$$

(4) Combine the Equation (S16)–(S19) and Equation (S5), we can simplify Equation (S5) to the following form:

$$F_1 = \frac{f_{iso}(\lambda)(F'_2 - F'_3)}{1 - f_{iso}(\lambda)F'_4} \tag{S20}$$

Then, three kernel coefficients $f_{iso}(\lambda)$, $f_{geo}(\lambda)$ and $f_{vol}(\lambda)$ of the RTLSR BRDF model and the directional surface reflectance $R_{SR}(\lambda)$ can be obtained as follows:

$$f_{iso}(\lambda) = F_1/(F'_2 + F'_3 + F'_4 * F_1) \tag{S21}$$
$$f_{vol}(\lambda) = f_{iso}(\lambda)\alpha_1 \tag{S22}$$
$$f_{geo}(\lambda) = f_{iso}(\lambda)\alpha_2 \tag{S23}$$
$$R_{SR}(\lambda) = f_{iso}(\lambda)BRDF_s \tag{S24}$$

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