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Simultaneous retrieval of aerosol properties and clear-sky direct radiative effect over the global ocean from MODIS

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HIGHLIGHTS

- Clear-sky direct radiative effects (DREAs) of different aerosol types are quantified from satellite data.
- Unified algorithm is developed to simultaneously retrieve aerosol properties and DREA.
- New DREA values of different aerosol types provide valuable dataset for model comparisons.

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ABSTRACT

A unified satellite algorithm is presented to simultaneously retrieve aerosol properties (aerosol optical depth; AOD and aerosol type) and clear-sky shortwave direct radiative effect (hereafter, DREA) over ocean. The algorithm is applied to Moderate Resolution Imaging spectroradiometer (MODIS) observations for a period from 2003 to 2010 to assess the DREA over the global ocean. The simultaneous retrieval utilizes lookup table (LUT) containing both spectral reflectances and solar irradiances calculated using a single radiative transfer model with the same aerosol input data. This study finds that aerosols cool the top-of-atmosphere (TOA) and bottom-of-atmosphere (BOA) by 5.2 ± 0.5 W/m² and 8.3 W/m², respectively, and correspondingly warm the atmosphere (hereafter, ATM) by 3.1 W/m². These quantities, solely based on the MODIS observations, are consistent with those of previous studies incorporating chemical transport model simulations and satellite observations. However, the DREAs at BOA and ATM are expected to be less accurate compared to that of TOA due to low sensitivity in retrieving aerosol type information, which is related with the atmospheric heating by aerosols, particularly in low AOD conditions; consequently, the uncertainties could not be quantified. Despite the issue in the aerosol type information, the present method allows us to confine the DREA attributed only to fine-mode dominant aerosols, which are expected to be mostly anthropogenic origin, in the range from -1.1 W/m² to -1.3 W/m² at TOA. Improvements in size-resolved AOD and SSA retrievals from current and upcoming satellite instruments are suggested to better assess the DREA, particularly at BOA and ATM, where aerosol absorptivity induces substantial uncertainty.

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1. Introduction

Accurate quantification of radiative forcing of aerosols is a key parameter in assessing global climate change due to their strong impacts on the Earth's radiation budget. Aerosols perturb the radiation budget directly by scattering and absorbing radiation and

indirectly by modifying microphysics of clouds (IPCC, 2007). Among the various effects of aerosols, direct radiative effect of aerosol (hereafter, DREA), defined as the difference in the net fluxes (downward irradiance–upward irradiance) between aerosol-laden and aerosol-free conditions, has been quantified as a course to assess the direct radiative forcing (Loeb and Kato, 2002).

In quantifying the DREA, recent studies have favorably utilized satellite observations and/or chemical transport model (CTM) simulations because of their global coverage (Yu et al., 2006 and references therein). The two approaches are complementary;

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satellite observations provide validation data to the CTM simulations, such as aerosol optical depth (AOD) and radiation field at TOA, while CTM provides data on chemical compositions of the aerosols, which are not readily available from satellite observations. The chemical composition can be used to derive aerosol absorptivity, i.e., the single scattering albedo (SSA), which is a critical parameter in quantifying the atmospheric heating by aerosols and thus better assessing the surface cooling.

One of the advantages of satellite remote sensing is that the DREA at TOA can be directly quantified due to the observation characteristic measuring the radiation field from space. However, problems remain in deriving the DREA at the atmosphere (hereafter, ATM) and bottom-of-atmosphere (BOA), where aerosol absorptivity induces substantial uncertainty, and thus, accurate retrieval of aerosol type information is of importance. In addition, partitioning the anthropogenic contribution from the total effect and extending the coverage to cloudy conditions have been of interest since those quantities are not immediately available from satellite observations (Chung et al., 2005; Kaufman et al., 2005b; Choi et al., 2009; Chen et al., 2011; Oh et al., 2013).

Recent satellite instruments designed to observe aerosol properties and radiation budget, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Clouds and the Earth's Radiant Energy System (CERES), and appropriate analysis tools have significantly extended our understanding of DREA. Deriving DREA from narrowband instruments (e.g., MODIS) require both spectral and angular conversions to calculate the irradiance field (Chou et al., 2002; Remer and Kaufman, 2006). On the other hand, broadband instruments (e.g., CERES) require only angular conversion using scene-dependent angular distribution models (Christopher and Zhang, 2002, 2004; Loeb and Kato, 2002). However, the broadband instruments, due to their low spatial resolution, require high spatial-resolution information about aerosols and clouds from other data sources to understand and minimize the cloud contamination issue.

In this study, we present a methodology for simultaneously retrieving aerosol properties (AOD and aerosol type) and DREA over clear-sky ocean from MODIS. Since the present method is solely based on the MODIS observations, data can be processed in the near real-time without additional information from other data sources. We present the data record for a long-term period from 2003 to 2010. An anthropogenic component in the total DREA is confined based on the aerosol type retrievals, and discussions on the DREA at BOA is provided.

2. Method

2.1. Retrieving aerosol properties and DREA from MODIS

Deriving DREA at a given atmospheric level requires, by definition, the corresponding irradiance fields between aerosol-laden and aerosol-free conditions. Therefore, considering radiance (or reflectance) observations from MODIS instrument, a method to convert the spectral reflectances to the broadband irradiance field must be provided, and the conversion can be done by radiative transfer model (RTM) calculations with appropriate aerosol input data.

Remer and Kaufman (2006) proposed a method to derive DREA over clear-sky ocean using aerosol optical properties retrieved and derived from MODIS (spectral AOD, SSA, and asymmetry parameter; ASP) and offline irradiance calculations using an independent RTM (Chou, 1992). The MODIS aerosol algorithm retrieves AODs in each one of fine- and coarse-mode aerosol type at each pixel, out of four fine-mode and five coarse-mode aerosol types, of which combination minimizes the difference between the observed and calculated

spectral reflectances (0.55 μm –2.12 μm) and makes the difference to within 3% (Remer et al., 2005; Kim et al., 2007; Lee et al., 2012). Therefore, the set of inherently consistent aerosol optical properties with the observed spectral reflectances can generate more accurate irradiance field when fed into a RTM compared to only using AOD (and assumed spectral SSA and ASP) because the irradiance field not only depends on AOD but SSA and ASP.

Here, we expand the previous study and propose a method for simultaneous retrievals of aerosol properties and DREA over clear-sky ocean from MODIS/Aqua. To this end, we created lookup table (LUT) containing both spectral reflectances at MODIS channels for aerosol retrievals and solar irradiances using a single RTM (Nakajima and Tanaka, 1986) with the same aerosol input data for both quantities. The dimensions of the LUT are shown in Table 1.

Five aerosol types extracted from the work of Dubovik et al. (2002) are assumed in creating LUT, which represent marine, dust, and three fine-mode dominant aerosol types categorized by SSA. Each aerosol type is classified further into three different types having different size distributions. The volume size distributions of the aerosol types to be fed into RTM are represented by bimodal lognormal distributions as follows:

$$\frac{dV(r)}{d\ln r} = \sum_{i=1}^2 p_i \exp \left[-\frac{(\ln r - \ln r_{vi})^2}{2s_i^2} \right], \quad (1)$$

where p_i is relative peak of each lognormal distribution, r_{vi} is mode radius, and s_i is geometric standard deviation. Given peak ratio, p_1/p_2 , for each aerosol type, the volume concentration of each lognormal distribution is automatically scaled with respect to the input AOD in the RTM. The optical and physical properties of the 15 aerosol types are shown in Table 2.

For the surface reflectance, we assumed a bidirectional reflectance distribution function (BRDF) of ocean surfaces determined as the Fresnel reflection weighted by the wave slope probability (Cox and Munk, 1954) with mean wind speed of 7 m/s (Monahan, 2006). The solar irradiances are calculated at both TOA and BOA given aerosol properties and solar angles at high spectral-resolution (100 spectral bands in the range of 0.2–5.0 μm).

The MODIS Level 2 reflectance data (*Mean_Reflectance_Ocean* in *MYD04* products) for the period from 2003 to 2010 are processed to retrieve AOD and aerosol type out of the 15 types at each pixel using the same inversion technique as used in the MODIS operational algorithm. The AOD is at 550 nm unless otherwise stated and is scaled for different wavelengths when calculating DREA. Then, the DREA can be derived at both TOA and BOA using the irradiance values corresponding to the retrieved AOD and aerosol type. We only show the DREA at TOA due to accuracy issue in deriving the

Table 1

LUT dimensions for the MODIS retrievals. Descriptions in the parentheses are for the solar irradiance calculations. Dimensions between radiance and irradiance are the same unless otherwise stated.

Variable	No. of entries	Entries
Wavelength (λ)	7 (1)	470, 555, 650, 860, 1240, 1630, 2120 nm (0.2 μm –5.0 μm for solar irradiance)
SZA (θ_s)	8	0, 10, ..., 70°
VZA (θ_v)	8 (0)	0, 10, ..., 70° (N/A for solar irradiance)
RAA (ϕ)	19 (0)	0, 10, ..., 180° (N/A for solar irradiance)
AOD (τ)	9	0.0, 0.1, 0.3, 0.6, 1.0, 1.5, 2.1, 2.8, 3.6
Aerosol type	15	Three size distributions for each marine, dust, highly-absorbing, moderately-absorbing, and non-absorbing fine-dominated aerosols, extracted from Dubovik et al. (2002).

SZA: solar zenith angle, VZA: viewing zenith angle, RAA: relative azimuth angle.

Table 2

Optical and physical properties of the 15 aerosol types used in calculating the LUT. The effective SSA and ASP are mean values in the wavelength range from 0.3 to 5.0 μm weighted by spectral AOD.

Aerosol type	$r_{v1}; r_{v2}^a$	$s_1; s_2^a$	p_1/p_2	AE (440/860)	Effective SSA	Effective ASP
HA	$0.12 + 0.04\tau$	0.43; 0.63	5/1	2.23	0.85	0.60
	(0.44);		3/1	2.11	0.85	0.62
	$2.72 + 0.60\tau$		1/1	1.68	0.85	0.68
MA	$0.11 + 0.13\tau$	0.43; 0.79	5/1	2.14	0.87	0.63
	(0.44);		3/1	1.93	0.88	0.66
	$2.76 + 0.48\tau$		1/1	1.30	0.89	0.72
NA	$0.12 + 0.11\tau$	0.38; 0.75	5/1	2.27	0.95	0.63
	$3.03 + 0.49\tau$		3/1	2.06	0.95	0.66
	(0.44)		1/1	1.43	0.96	0.71
Dust	0.12; 1.90	$0.49 + 0.10\tau$	1/3	0.86	0.98	0.68
		(0.44);	1/5	0.58	(0.94 ^b)	0.69
		$0.63 - 0.10\tau$			(0.94 ^b)	
		(0.44)	1/7	0.42	0.98	0.69
Marine	0.16; 2.70	0.48; 0.68	1/1	1.44	0.98	0.73
			1/2	1.07	0.98	0.75
			1/3	0.84	0.98	0.76

^a Abstracted from Dubovik et al. (2002).

^b Effective SSA in visible range.

value at BOA, and discussions are provided for DREA at BOA. Linear interpolation is used for searching the LUT. It should be noted that only three marine aerosol types are used for $\text{AOD} \leq 0.15$ due to low sensitivity in retrieving aerosol types in low AOD conditions, and 12 other models are used when the AOD retrieved using the marine aerosol types is higher than 0.15. In addition, the threshold of 0.15 results in mean AOD of marine aerosol types consistent with a previous study (Kaufman et al., 2001). Further information on this will be provided in Section 3.

Because the DREAs derived from the present method represent instantaneous values, it should be converted into 24-h mean values. To this end, the conversion factor, F , is calculated for the retrieved AOD and aerosol type at each pixel considering daytime length and time-dependent SZA, so that the 24-h mean DREA can be derived as follows:

$$\text{DREA}(24 \text{ h}) = \text{DREA}(\text{instantaneous}) \times F, \quad (2)$$

where F is defined as:

$$\frac{\text{mean}(\text{DREA}[\text{AOD}, \text{aerosol type}, \text{SZA}(t)])}{\text{DREA}(\text{instantaneous})} \times \frac{\text{daytime length}}{24}. \quad (3)$$

The time-dependent DREA is calculated every 1° latitude daily given AOD and aerosol type at each pixel. The 24-h mean DREA values are then averaged in $1^\circ \times 1^\circ$ (longitude $\times$ latitude) grid boxes on a daily basis and weighted by the number of observation pixels and the cosine of the latitudes to account for the observation coverage and surface area change with respect to latitude. The results shown in this article are monthly mean values calculated from the daily averages, and annual mean values calculated using the monthly mean values are used for multi-year averaging.

2.2. Simulated DREA of each aerosol type

Fig. 1 shows sensitivities of DREAs to AOD and aerosol type to understand radiative characteristics of aerosol types used in the present method. The DREAs show consistently negative values

Fig. 1. Simulated DREAs of the 15 aerosol types used in the MODIS algorithm as a function of AOD at 550 nm. The results are calculated at (a) TOA, (b) ATM, and (c) BOA, assuming ocean surface and an SZA of 0° . Three different lines with the same color represent results from the different size distributions, showing increasing effective radius in order of circle, square, and triangle. SSAs of the fine-dominated aerosols decrease in order of non-absorbing (NA), moderately-absorbing (MA), and highly-absorbing (HA). Note the inverted numerical scale of the y-axis in the result for ATM.

representing cooling effects at TOA and BOA and positive values representing warming effects at ATM. The ocean surface is dark enough for any aerosol types considered in this study to enhance the upward irradiance at TOA due to backscattering of solar radiation by aerosols. The increasing AOD enhances the radiative effect as expected. However, the detailed feature becomes complex and differs from one aerosol type to another. For a given AOD of 1.0, the DREA at TOA is highest for dust and generally decreases in the order of marine, non-absorbing fine-dominated (hereafter, NA), highly-absorbing fine-dominated (hereafter, HA), and moderately-absorbing fine-dominated (hereafter, MA) types. The features also change with respect to AOD and size distribution of each aerosol type.

The DREA at ATM represents atmospheric heating by spectral absorption-AOD in the solar wavelength range, which is defined by $\text{AOD} \times (1 - \text{SSA})$. Thus, it always shows a positive value unless aerosol is completely scattering. From the calculation result, the DREAs of NA, marine, and dust show weaker warming effects than MA and HA, mainly due to differences in SSA. By definition, low SSA corresponds to strong atmospheric warming. The dust known as absorbing aerosol shows weak warming effects because dust absorbs radiation in ultraviolet (UV) and shorter visible wavelengths only in wavelengths ranging from UV to near-infrared, where a large proportion of solar energy is contained, while the anthropogenic aerosols absorb radiation in a wider wavelength range (Dubovik et al., 2002). At BOA, the DREA represents the combined effects of those at ATM and TOA, $\text{DREA}_{\text{BOA}} = \text{DREA}_{\text{TOA}} - \text{DREA}_{\text{ATM}}$, so that the radiative effects are stronger in the negative direction than those at TOA and ATM. At AOD of 1.0, the value generally increases in the negative direction in the order of NA, marine, MA, dust, and HA, and the detailed features are functions of AOD and size distribution.

3. Retrieved aerosol properties from MODIS

The characteristics of the retrieved aerosol properties from the present method are investigated. The global distribution of the mean AOD shown in Fig. 2 reflects strong spatial variability of aerosols and enhanced aerosol signals caused by dust from the Sahara Desert and Arabian Desert, biomass burning from Southern Africa, and anthropogenic aerosols from Asia, America, and Europe. The global mean AOD was 0.138 for the period considered.

Fig. 3 shows AOD proportions of each aerosol type to the total AOD in each regional section defined in Fig. 2. Before interpreting

Fig. 2. Global distribution of mean AOD retrieved from the present method from 2003 to 2010. Results are averaged using monthly mean data only at pixels with more than 18 data points (about 20% of the total). The 13 regional sections used in Yu et al. (2006) are also shown for further analyses.

Fig. 3. Ratios of AOD of each aerosol type to the total AOD in each regional section defined in Fig. 2, calculated using the Level 2 aerosol products (AOD, aerosol type) retrieved from 2003 to 2010.

the data, we investigated the validity of the assumption of using only three marine aerosol types for $\text{AOD} \leq 0.15$ and the other 12 models for $\text{AOD} > 0.15$. To this end, we calculated the contribution of marine aerosol types to the global mean AOD for the whole period. We derived the mean marine AOD of 0.054, and it was consistent with the work of Kaufman et al. (2001), which derived the median baseline AOD at 500 nm of 0.052 over the Pacific Ocean.

However, one should consider the regional differences in AOD distribution when interpreting the data in the regional sections. For strong wind conditions that can enhance the marine AOD greater than 0.15, dust instead of marine aerosol types can be detected due to the similar size distribution. On the other hand, for calm conditions with $\text{AOD} \leq 0.15$, the marine AOD can be overestimated when mixed with other aerosol types. The dust proportions in sections 9 (South Pacific) and 13 (Southern Ocean) where dust transport from the source regions is expected to be negligible seem to be due to the former feature.

Keeping in mind the characteristics of the retrieval algorithm, marine aerosol types are found to be the most dominant aerosol type except for section 4 (Asian Pacific), where NA is the most dominant, and sections 6 (Saharan Atlantic) and 7 (northern Indian Ocean), where dust is the most dominant. The sum of the DREA of all fine-mode dominant aerosol types (NA, MA, HA) shows dominant effect in sections 3 (Mediterranean Sea), 4 (Asian Pacific), 7 (northern Indian Ocean), and 8 (South China Sea).

An evaluation of the retrieved AOD is conducted compared with the Aerosol Robotic Network (AERONET) sun/sky radiometer observations (Holben et al., 1998) in Fig. 4. The collocation criteria of ± 30 min in time and 25 km in space were used for collocations. The performance of the developed algorithm is revealed to be comparable to the MODIS Collection 5 algorithm, showing a Pearson coefficient of 0.92 and a root mean squared error of 0.06. The results from the present method show slight improvements in mean bias and slope of the regression equation compared to the MODIS algorithm. As a result, one can conclude that the retrieval results reasonably reflect the aerosol properties in reality. In particular, despite qualitative information, the aerosol type retrievals allow us to confine DREA of each aerosol type.

4. Derived DREA from MODIS

4.1. Global distribution

The 24-h mean DREA at TOA for the period from 2003 to 2010 is shown in Fig. 5. Strong radiative effects are derived over the areas with high AOD, generally representing the effects of natural aerosols over the Saharan Atlantic (dust), Arabian Sea (dust), and Southern Ocean (sea salt, DMS) and the effects of anthropogenic aerosols over Asian coasts, the northern Pacific and Atlantic, and

Fig. 4. Comparison of AOD between AERONET and MODIS collection 5 algorithm (left) and the developed algorithm (right) over the global ocean from 2003 to 2010. The collocation criteria of ± 30 min and 25 km were used. Data are sorted in 20 equal-number-of-data bins, and mean AODs $\pm$ standard deviation are presented. Dotted and dashed lines represent the one-to-one line and the MODIS expected error line ($\pm[0.03 + 0.05 \times \text{AOD}]$), respectively. Each statistic represents the number of data (N), Pearson coefficient (R), root mean squared error (RMSE), and mean bias (MB).

Southern African coast. The global mean DREA is found to be -5.9 W/m^2 , and the value becomes -5.2 W/m^2 when considering the cloud-contaminated AOD of 0.015–0.020 (Kaufman et al., 2005a).

Although the sum of the fine-mode dominant aerosol types does not exactly represent the anthropogenic component, the DREA of the fine components of -1.3 W/m^2 seems reasonable compared to the work of Kaufman et al. (2005b), which derived the DREA of anthropogenic aerosols of $-1.4 \pm 0.4 \text{ W/m}^2$ using MODIS data. Assuming a uniform cloud contamination regardless of aerosol type and region, the value is reduced to -1.1 W/m^2 . Table 3 summarizes the seasonal and annual statistics of the DREA.

Despite the low sensitivity of aerosol type retrievals particularly in low AOD conditions, the DREA efficiency (which is defined by the DREA per unit AOD) at ATM shows characteristic features with regard to the aerosol type information. In Fig. 6, it is clear that the aerosol absorptivity is weaker over remote ocean areas and the Saharan Atlantic, where marine or dust aerosols are dominant compared to those over downwind areas of Asia, Southern Africa, and Central America, where absorbing anthropogenic aerosols are abundant. This can be explained by the relatively low absorption efficiencies of marine and dust aerosols compared to those of MA and HA aerosols. Note that the strong DREA efficiencies observed

over the high latitudes are due to the long daytime length (i.e., the polar day) when data are available.

The seasonal mean DREA at TOA (Fig. 7) generally shows the maximum cooling effect of anthropogenic aerosols over the northern hemisphere in MAM and a decreasing tendency in the order of JJA, DJF, and SON, while the effect of biomass burning aerosols from Southern Africa shows the maximum in JJA and is maintained through SON. In the case of natural sources, the DREA of Saharan dust shows the maximum cooling effect in JJA and tends to decrease in the order of MAM, DJF, and SON.

As shown in Fig. 8, AODs (and thus DREAs) over the Northern Hemisphere have maximum values in MAM except for sections 6 (Saharan Atlantic) and 7 (Arabian Sea), while the values reach a maximum in DJF or SON in the Southern Hemisphere due to the combined effect of higher aerosol loading and longer daytime length. The strongest radiative effect throughout the year occurs in section 7 due to persistent dust aerosols over the Arabian Sea and anthropogenic aerosols over the northern Indian Ocean, followed by the Asian Pacific region, where both anthropogenic and natural aerosols are abundant.

4.2. Time series

Fig. 9 shows the time series of the monthly mean AOD and DREA of the total and each aerosol type (dust, marine, and fine-mode sum). For the global ocean, the AOD generally varies in the range from 0.12 to 0.16, with a mean value of 0.138 for the whole period. Correspondingly, the DREA changes in the range from -5.0 W/m^2 to -7.0 W/m^2 with a mean value of -5.9 W/m^2 . For the eight-year record, the monthly mean DREA shows the maximum cooling effect in March for five years and during MAM for seven years.

The DREA of each aerosol component shows that the radiative cooling of anthropogenic aerosols is the maximum in April or May, while the effect of dust generally reaches the maximum in July. While sea salt AOD over the Southern Ocean reaches the maximum

Fig. 5. Global distribution of mean DREA at TOA derived from the present method from 2003 to 2010. The results are averaged using monthly mean data, and only pixels with more than 18 data points (about 20% of the total) are shown.

Table 3

Global mean DREA at TOA from 2003 to 2010. The cloud-corrected values are shown in the parentheses. The mean AOD was 0.138 for the period considered.

Aerosol type	DJF	MAM	JJA	SON	Annual
Total	−5.7	−6.3	−6.1	−5.8	−5.9 (−5.2)
Fine-Mode	−1.0	−1.5	−1.1	−1.3	−1.3
Dust	−2.0	−2.4	−2.5	−1.8	−2.2
Marine	−2.6	−2.4	−2.4	−2.7	−2.5

Fig. 6. Global distribution of mean DREA efficiency at ATM derived from the present method from 2003 to 2010. The results are averaged using monthly mean data, and only pixels with more than 18 data points (about 20% of the total) are shown.

in DJF, the time series of marine aerosol reaches the maximum radiative effect in SON, followed by DJF due to the larger area of low AODs in SON than in DJF. Although strong radiative effects are observed where dust and/or anthropogenic aerosols are abundant, marine aerosol is the greatest contributor to the global radiative effect due to its persistent presence over the ocean.

The DREAs in different areas show characteristic features according to the aerosol amount and sources. The Asian Pacific area (section 4) generally shows AOD in the range from 0.15 to 0.5. Because of the high AOD, the DREAs are also much higher than

Fig. 8. Seasonal mean AOD (top) and DREA at TOA (bottom) in each regional section. Four numbers in each box correspond to months in upper-left corner of the map.

Fig. 7. Global distribution of mean DREA derived from the present method at TOA in (a) December–January–February (DJF), (b) March–April–May (MAM), (c) June–July–August (JJA), and (d) September–October–November (SON) from 2003 to 2010. The results are averaged using monthly mean data, and only pixels with more than four data points (about 20% of the total) are shown.

Fig. 9. Time series of monthly mean AOD (left column), total DREA (center column), and DREA of each aerosol type (dust, marine, and fine-dominated sum) (right column) from 2003 to 2010. The DREAs are at TOA. The results are calculated using the global data (first row), section 4 (second row), section 6 (third row), and section 9 (fourth row). The fine-dominated sum represents the sum of DREA due to HA, MA, and NA.

those of the global average, ranging from -5.0 W/m^2 to -20 W/m^2 . The most dominant contributors to the radiative effect in this area are anthropogenic aerosols followed by dust. On the other hand, the Saharan Atlantic (section 6) is another area strongly influenced by aerosol due to the prevailing influence of dust, showing AOD ranging from 0.1 to 0.3 and DREA from -5.0 W/m^2 to -15 W/m^2 . In the South Pacific (Section 9), the DREA is generally attributed to marine aerosols, showing a radiative effect weaker than -5.0 W/m^2 due to persistently low AOD.

5. Uncertainty

Remer and Kaufman (2006) derived an unbiased uncertainty of 11% for the DREA at TOA from MODIS aerosol data in terms of a root square error and a biased uncertainty due to cloud-contaminated AOD of 0.015–0.020 (Kaufman et al., 2005a). The sources of the unbiased uncertainty included instrument calibration status, matching of spectral reflectance between measurements and simulations, assumed input parameters for independent RTM

calculation, conversion of the instantaneous DREA to the 24-h mean value, and correction of the cloud contamination (Table 2 in Remer and Kaufman, 2006). Because the present method is a revised version of the work of Remer and Kaufman (2006), most of the derived uncertainties can be applied to the results in this study. Among the sources of uncertainty, we improved the ocean albedo, conversion factor, and spectral resolution in calculating DREA. As a result, we estimate the unbiased uncertainty for the cloud-corrected results in the range of 7–9% by assuming that we completely corrected all the errors caused by the improvements made (7%) and reduced half of the errors (9%). When adopting the maximum value, the uncertainty at TOA becomes 0.5 W/m^2 ; thus the final result becomes $-5.2 \pm 0.5 \text{ W/m}^2$.

6. Summary and discussions

A method is proposed to simultaneously retrieve aerosol properties and DREA over the clear-sky global ocean from MODIS, and the results are analyzed for the period from 2003 to 2010. With the advantage of the aerosol type retrievals, the DREA of each aerosol component as well as the total value were confined. The results showed that aerosols cool the TOA by $5.2 \pm 0.5 \text{ W/m}^2$ with the contribution of fine-dominated aerosols in the range from -1.1 W/m^2 to -1.3 W/m^2 . It should be noted that the total DREA derived from narrowband observations from MODIS is remarkably consistent with those of CERES observations combined with MODIS, which showed values in the range from -5.3 to -5.5 W/m^2 (Loeb and Manalo-Smith, 2005; Zhang et al., 2005). The fine-mode component is also well within the error range of a previous study ($-1.4 \pm 0.4 \text{ W/m}^2$; Kaufman et al., 2005b). It was found that the marine aerosols are the most dominant contributor to the global mean DREA at TOA (despite the low AOD) due to their persistent presence over the ocean, while anthropogenic aerosols and/or dust influence strongly over some areas.

Although not shown in the analyses due to the accuracy issue, the present method can technically derive DREA at BOA as well since irradiance fields at both levels can be calculated by RTM. However, it should be noted that the DREA at BOA strongly depends on the aerosol type information, of which accuracy cannot be quantified at the moment. Thus, cautions should be made when interpreting the data. The results showed that aerosols cool the BOA by 8.3 W/m^2 due to the TOA cooling of 5.2 W/m^2 and atmospheric heating by aerosols of 3.1 W/m^2 . Despite the accuracy issue, the value at BOA show reasonable consistency with the previous studies using the combinations of satellites and chemical transport model (CTM) simulations. Yu et al. (2006) and many references therein derived the DREA ranging from -3.8 W/m^2 to -6.5 W/m^2 at TOA and from -7.7 W/m^2 to -11.1 W/m^2 at BOA. The median values were -5.5 W/m^2 and -8.8 W/m^2 at TOA and BOA, respectively. The consistency supports, at some degree, the validity of the aerosol type retrievals from the developed algorithm. To better assess DREAs of total aerosols and each component and at both TOA and BOA from satellite observations, improvements in size-resolved AOD and SSA retrievals from current and upcoming satellite instruments are suggested.

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