Sample Bias Estimation for Cloud-Free Aerosol Effects Over Global Oceans

Sundar A. Christopher and Thomas A. Jones

***Abstract*—Satellite-based methods for estimating the top-of-atmosphere shortwave direct radiative effect (SWRE) either use the spatial distribution of aerosol optical thickness (AOT) coupled with radiative transfer calculations or combine the AOT with broadband radiative energy data sets such as the Clouds and the Earth's Radiant Energy System (CERES). The first approach typically utilizes the AOT at a spatial resolution of $10 \times 10\ \mathrm{km}^2$ from the Moderate Resolution Imaging Spectroradiometer (MODIS), and the second method relies on the same AOT, but it is convolved within the CERES footprint and has spatial resolutions that are greater than $20 \times 20\ \mathrm{km}^2$. Therefore, the SWRE may vary as a result of this difference in spatial resolution that we call sample bias. We correct for this sample bias using the AOT reported at the MODIS and the CERES product levels coupled with the radiative efficiency (SWRE per-unit optical depth) for 13 regions over the ocean as a function of season between December 2003 and November 2004 and demonstrate that the sample biases are seasonally and spatially dependent. Overall, nearly 75% of the pixels over the global oceans require a sample bias adjustment of some form. However, the adjustment is large ($\mathrm{MODIS\ AOT} - \mathrm{CERES\ AOT} > 0.1$), which is less than 7% of the time, primarily during the spring and summer months, in association with large dust aerosol concentrations with large optical depth gradients. If sample biases are not accounted for, they will globally reduce the SWRE by an average of 30% (-4.1 versus $-5.3\ \mathrm{W \cdot m^{-2}}$), although regionally, the adjustment could be larger ($> 40\%$). We argue that these bias corrections are robust and simpler to use when compared with methods that employ narrow- to broadband relationships.**

***Index Terms*—Aerosols.**

I. INTRODUCTION

THE ROLE of aerosols on climate, air quality, precipitation, and hydrological cycle on a global scale is well established. Significant progress has been made over the last five years largely due to well-calibrated high-quality satellite data sets, advances in numerical modeling, and carefully designed strategies for *in situ* measurements through field campaigns and ground-based networks (see [1]–[3] and references therein). It is now generally recognized that an optimum strategy for assessing aerosol climate impacts is to use *in situ* measurements for validating and refining algorithms, satellite measurements for capturing the spatial distribution of aerosols and constraining modeling calculations, and, finally, numerical simulations for prediction purposes [1].

Recent comprehensive reports, as part of the Climate Change Science Panel, showed remarkable consistency among nearly a dozen satellite-based methods for calculating the cloud-free shortwave direct radiative effect (SWRE) of all aerosols over the global oceans [3]. Over oceans, in cloud-free regions, near daily satellite retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) have provided seven years of columnar aerosol optical thickness (AOT; at 0.55 μm) values at a spatial resolution of 10×10 km^2 (at nadir) that have been used in numerous studies [3]. There are two primary methods for calculating the SWRE using the MODIS AOT (MAOT). The first method, which we call MOD, uses the MAOT values and radiative transfer calculations [4] to calculate the top-of-atmosphere (TOA) reflected shortwave radiation without (F_{clr}) and with (F_{aer}) the presence of aerosols [5]. The second method, which we call CER, utilizes the MAOT coupled with broadband measurements from the Clouds and the Earth's Radiant Energy System (CERES) to obtain the SWRE without the use of radiative transfer calculations [6]. In this paper, we are primarily concerned with the TOA SWRE of all aerosols, and no distinction is made between natural and anthropogenic aerosols.

The MOD and CER methods each have their own advantages and disadvantages. One of the major advantages of the MOD approach is that the SWRE can be calculated at a spatial resolution of 10×10 km^2. Over oceans, the MODIS uses four hundred 500-m pixels coupled with multispectral and spatial methods to identify clouds, aerosols, and other features and then retrieves the mean AOT for the 10×10 km^2 grid using lookup table approaches [7]. However, in the MOD method, several assumptions are necessary to determine wavelength-dependent aerosol models for the entire shortwave spectrum [5]. In MOD, the clear sky fluxes are calculated from a radiative transfer model by assuming that $\mathrm{AOT} = 0$, and aerosol-sky fluxes are calculated for each MODIS pixel that has a reported AOT value. The CER method, on the other hand, utilizes well-calibrated broadband radiance measurements and specific angular models for aerosols [8], which are used to obtain shortwave fluxes at the CERES pixel level of 20×20 km^2 (at nadir). However, the CERES instrument has a limited number of broadband channels that cannot be used to identify aerosols. Therefore, the MAOT pixels are collocated within the CERES footprint to form a merged single-satellite footprint product. Considering that the CERES pixel size is larger than that of MODIS, even if one MAOT pixel within the CERES footprint is cloud contaminated, this CERES pixel is discarded, thereby

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TABLE I
SAMPLE BIAS STATISTICS FOR EACH REGION WHERE MAOT IS THE MONTHLY MEAN MAOT, CAOT IS THE POINT-SPREAD FUNCTION WEIGHTED CAOT FOOTPRINT, ISWRE IS THE INSTANTANEOUS TOA SWRE, DSWRE IS THE DIURNALLY AVERAGED SWRE, AND BSWRE IS THE SAMPLE BIAS ADJUSTED SWRE. BADJ IS THE BIAS ADJUSTMENT (IN PERCENTAGE) BETWEEN THE DSWRE AND BSWRE

Region	Latitude	Longitude	MAOT	CAOT	ISWRE	DSWRE	BSWRE	BADJ (%)
1	30-60N	180-90W	0.16	0.14	-8.6	-4.2	-5.5	33
2	30-60N	90-0W	0.15	0.15	-10.0	-5.0	-6.2	23
3	30-60N	0-90E	0.19	0.16	-12.2	-6.0	-7.4	24
4	30-60N	90-180E	0.22	0.18	-12.8	-6.1	-8.1	32
5	0-30N	180-90W	0.12	0.09	-6.2	-2.8	-4.0	42
6	0-30N	90-0W	0.23	0.17	-11.2	-5.2	-7.3	41
7	0-30N	0-90E	0.31	0.20	-13.2	-6.0	-8.4	39
8	0-30N	90-180E	0.16	0.16	-10.1	-4.6	-5.6	22
9	0-30N	180-90W	0.10	0.08	-5.4	-2.5	-3.4	35
10	30S-60S	90-0W	0.13	0.12	-8.1	-3.8	-4.8	26
11	30S-60S	0-90E	0.14	0.13	-8.0	-3.8	-4.8	27
12	30S-60S	90-180E	0.13	0.11	-7.1	-3.4	-4.4	30
13	30S-60S	180W-180E	0.13	0.12	-7.9	-3.9	-4.8	23

creating a sample bias [9]. Therefore, to compare CER- and MOD-derived SWREs, a sample bias adjustment must be applied to values derived from the CER method to account for this bias.

Another method that has been employed to account for sample bias is to use narrow- to broadband regressions [10]. This method is much more complicated than the sample bias adjustment used in this paper. In the narrow- to broadband method, the cloud-free CERES shortwave radiances (0.4–4.5 μm) are related to the MODIS cloud-free narrowband radiances at 0.64, 0.58, and 1.632 μm in specific solar zenith, observation zenith, and relative azimuth angle bins, respectively. Therefore, for each 10×10 km^2 MAOT value, a broadband shortwave radiance can be obtained based on this relationship. The overarching assumption in this method is that the narrowband radiances well represent the broadband radiances. Once the MODIS-level radiances are obtained, these values are converted to fluxes based on theoretical anisotropic factors derived from radiance-to-flux tables built as a function of AOT and wind speed over ocean using only the maritime tropical model with a single scattering albedo of 0.998 at 0.55 μm [10]. Therefore, there could be significant differences, regionally and globally, due to the assumptions in aerosol models [8]. A thorough uncertainty assessment in the CER method is presented by Zhang *et al.* [9].

II. DATA AND METHODS

We use data from December 2003 to November 2004 of the merged CERES single-satellite footprint product (FM1, Edition 2B) containing MODIS aerosols (collection 4) and CERES radiances to calculate the SWRE. The AOT is sampled at a 10×10 km^2 resolution in the level-2 aerosol products, which is then convolved into the larger ($\sim 20 \times 20$ km^2) CERES footprint using the CERES pixel point-spread function. The CERES radiances are converted to fluxes using angular models developed by Zhang *et al.* [8], which are a function of AOT, fine-mode fraction that is an index of particle size, and near-surface ocean wind speed. To eliminate the effect of clouds, we only use cloud-free pixels, where the CERES clear sky fraction is greater than 99%, with the separately measured MODIS cloud fraction $\leq 1\%$ for viewing, and the zenith solar angles are less than 60°. Clear sky (defined as cloud- and aerosol-free) flux values are calculated on a CERES pixel-by-pixel basis by assuming that a linear relationship exists between the cloud-free AOT and TOA shortwave flux for AOT values less than 0.4 [11]. For every 6° solar zenith angle bin, the regression coefficient and intercept between the AOT and shortwave flux values are computed. The clear sky flux value is derived by subtracting the AOT times the slope values from the CERES fluxes [9].

Thirteen regions over the global oceans are identified, which are similar to the ones used by Yu *et al.* [3] (Table I). The methods are shown in the form of a flow chart in Fig. 1. In CER (and MOD), the SWRE is also defined as the difference between clear and aerosol sky fluxes ($F_{\rm aer}$). For cloud-free pixels, $F_{\rm aer}$ is simply the TOA shortwave flux values for CERES pixels that have a MODIS-reported AOT. The SWRE at the time of the satellite overpass is called instantaneous SWRE, and it ranges from -5 to -13 W $\cdot$ m^{-2}, with an excellent linear correlation between the MAOT and the CERES shortwave fluxes, which is similar to the one shown in Zhang *et al.* [9]. Diurnal mean SWRE values can be obtained by assuming that the AOT remains constant during the day and

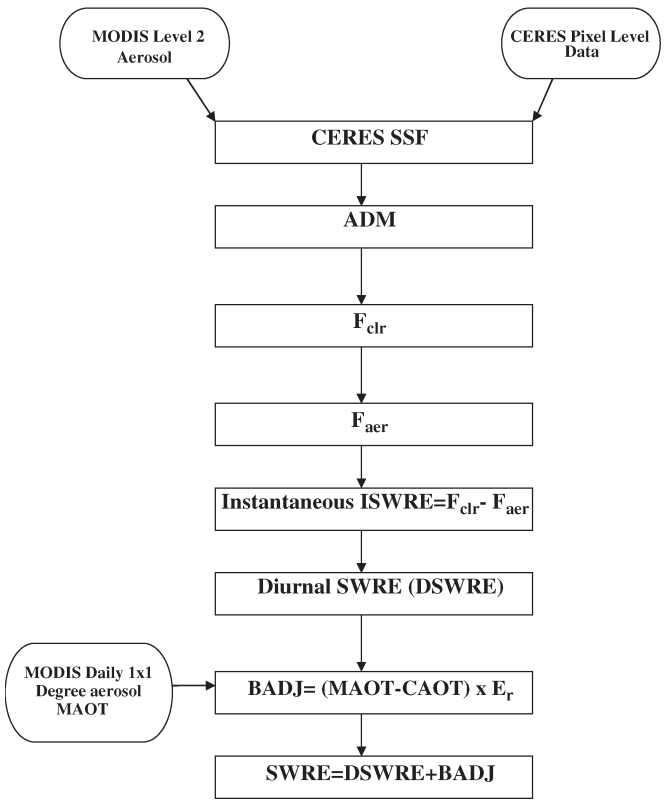

Fig. 1. Flow chart of how sample bias adjustment is calculated. See text for further details and for explanations of acronyms.

by scaling for solar zenith angles [9]. Both the CER and MOD approaches apply diurnal corrections in a similar fashion. We can then calculate the radiative efficiency (E_τ) as the slope of the diurnal SWRE to the AOT, which is a commonly used parameter to assess various methods [1], which is a function of aerosol type, surface, and atmospheric conditions. This diurnal value still contains sample biases that must be corrected.

For the MOD method used by Remer and Kaufman [5], MAOT values are obtained from the monthly mean aerosol product and placed on a $2^\circ \times 2^\circ$ grid. Similarly, in the CER method, the MAOT within the CERES (CAOT) product can be gridded to $2^\circ \times 2^\circ$ bins. Note that the CERES does not retrieve the AOT values but uses the level-2 MAOT and convolves it within the CERES footprint using point-spread functions. Even for completely overcast aerosol fields of view, due to the larger CERES footprint, the energy weighting resulting from the point-spread function will render a CAOT that is different from the MAOT. The CAOT could also be smaller than the MAOT due to the removal of cloud-contaminated pixels, as explained earlier. To account for this sample bias, we must first calculate the difference between MAOT and CAOT. This is the portion of the AOT that was "missed" by the CER method when calculating the instantaneous SWRE. For each region and season, the radiative efficiency value is first obtained and multiplied with the difference between MAOT and CAOT. The result is defined as the bias adjustment, which is then added to the diurnal SWRE on a grid-cell-by-grid-cell basis to obtain the bias-adjusted SWRE. When applying this correction, we assume that the radiative efficiency of the aerosol pixels near clouds is approximately the same as the radiative efficiency of aerosols near clear sky regions. Although this may not be a robust assumption [12], it is beyond the scope of this paper to verify how aerosols change in the vicinity of clouds. As Koren *et al.* [12] argue, the use of satellite data to assess the change in radiance values in the transition zone between aerosol and cloudy regions has several uncertainties.

III. Results

Zhang *et al.* [9] multiplied the global mean MAOT minus the CAOT by a global radiative efficiency value to adjust for the sample bias. However, this value is space- and time-dependent, as shown by Christopher and Jones [11] who analyzed dust aerosols over the Atlantic during Northern Hemisphere summer months. In this paper, we use one year of MODIS and CERES data over the global oceans to examine sample biases as a function of region and season. Fig. 2 shows the bias adjustment $[(\mathrm{MAOT} - \mathrm{CAOT}) \cdot \mathrm{E}_\tau]$ in terms of watts per square meter for four seasons, including the following: 1) December–February (DJF) [Fig. 2(a)]; 2) March–May (MAM) [Fig. 2(b)]; 3) June–August (JJA) [Fig. 2(c)]; and 4) September–November (SON) [Fig. 2(d)]. Note that, although the MAOT minus the CAOT is a first-order estimate of the bias adjustment, this value must be multiplied by the appropriate radiative efficiency value to obtain the correct bias adjustment, to make it more meaningful because different aerosol types in different regions could have different optical properties. We do not attempt to separate various aerosol types but simply constrain the bias adjustment by regionally and seasonally dependent values.

Fig. 2 shows several interesting features, and the relevant statistics for each region are summarized in Table I. MAOT is greater than the CERES AOT for 75% of all $2^\circ \times 2^\circ$ grid cells, with the difference being small or even slightly negative, where AOT values are low and/or change little as a function of time (e.g., in the South Pacific). Regions colored in blue are areas where the bias adjustment is less than 1 $\mathrm{W} \cdot \mathrm{m}^{-2}$ and correspond to regions with low AOT and nonchanging AOT. The highest sample bias corrections are during MAM and JJA in the Atlantic when substantial dust concentrations are present, indicating that CERES pixels with a mix of aerosols and clouds may be responsible. The misclassification of dust as cloudy pixels does not appear to be a significant issue because cloud-free data availability is actually greater in high-dust-concentration regions such as off the West African coast [13]. In general, sample biases are higher in regions that have a mixture of aerosols and clouds in a CERES footprint, particularly where AOTs are high. Note that sample bias adjustments exist even when the mean MAOT is equal to the CERES AOT, considering that the distribution of AOTs is different for each region but the mean values are similar. Atmospheric moisture content is generally greater in the vicinity of clouds, which, if high enough, could also affect the observed characteristic aerosols in the same region. It is possible that a portion of the higher AOTs observed in the MODIS data is a result of sampling aerosols in more moist environments. Unfortunately, limitations in the available data make it very difficult to quantify this effect, if indeed it occurs. During MAM, high sample bias adjustments

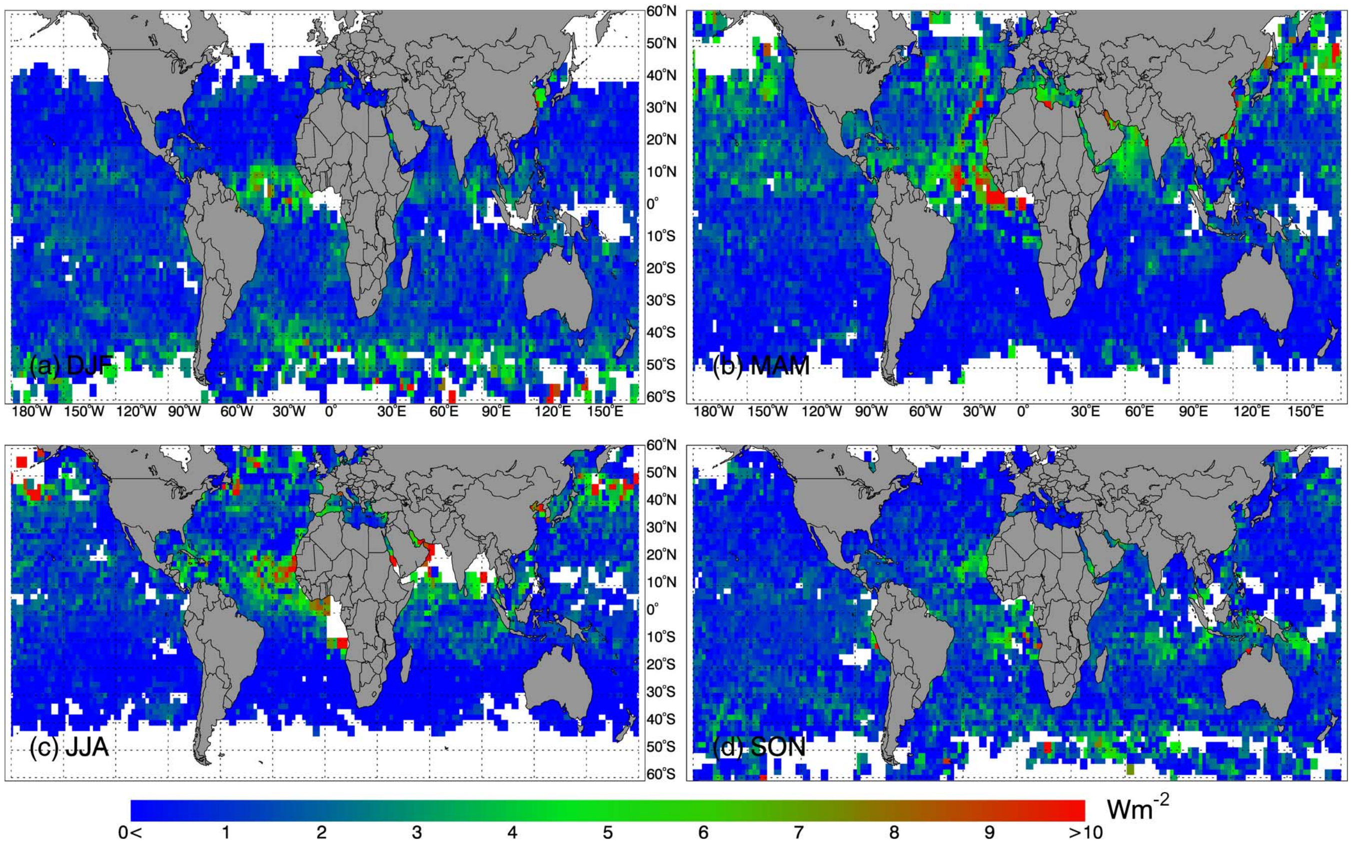

Fig. 2. Sample bias adjustment for 2° × 2° grids over the global oceans (60° N–60° S) in watts per square meter for four seasons: (a) DJF, (b) MAM, (c) JJA, and (d) SON for 2003–2004.

of 4–6 W $\cdot$ m^{-2} are also possible. The global diurnally averaged SWRE between December 2003 and November 2004 was -4.1 W $\cdot$ m^{-2}, with a corresponding efficiency of -31.8 W $\cdot$ m$^{-2} \cdot \tau^{-1}$. Applying the bias adjustment results in a globally averaged SWRE of -5.3 W $\cdot$ m^{-2}, which is a 30% increase in (absolute) SWRE. The adjustment is largest ($\sim$40%) in regions that contain a large proportion of dust aerosols, particularly in the North Atlantic Ocean (Table I).

IV. Conclusion

Multisensor approaches represent an independent method to assess the effects of aerosols on climate. However, the spatial resolution and the methods used can substantially vary. One such issue is the sample bias that is created when coarse-resolution instruments, such as the CERES, are compared to higher resolution instruments such as the MODIS. In this paper, we examine a simple method for adjusting the SWRE computed from the CERES using AOT and radiative efficiencies. One of our key assumptions is that the aerosols in the vicinity of clouds have a similar radiative efficiency value when compared with those in cloud-free regions, which may require further investigation [12]. Our analysis for December 2003–November 2004 indicates that the bias adjustment is seasonally and regionally dependent and could be greater than 40%, depending upon the region and season. We argue that our method for adjusting for sample bias is simpler than other methods and could be applied to CERES data, provided that the analysis is done regionally and seasonally. Studies that use CERES and MODIS must first obtain the instantaneous shortwave radiative using appropriate angular models. Then, after diurnal adjustments are applied, a spatiotemporal correction must be estimated to correct the diurnal values for sample bias to be able to compare with other methods that do not have sample biases. Without the use of sample bias, the global SWRE will be less by nearly 30% (considering that the AOT pixels have been discarded), and therefore, studies using CERES data for aerosol research must estimate and correct for these effects.

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References

[1] T. L. Anderson *et al.*, "An A-train strategy for quantifying direct climate forcing by anthropogenic aerosols," *Bull. Amer. Meteorol. Soc.*, vol. 86, no. 12, pp. 1795–1809, Dec. 2005.

[2] T. S. Bates *et al.*, "Aerosol direct radiative effects over the northwest Atlantic, northwest Pacific, and North Indian Oceans: Estimates based on *in-situ* chemical and optical measurements and chemical transport modeling," *Atmos. Chem. Phys. Discuss.*, vol. 6, no. 1, pp. 175–362, 2006.

[3] H. Yu *et al.*, "A review of measurement-based assessment of aerosol direct radiative effect and forcing," *Atmos. Chem. Phys. Discuss.*, vol. 5, no. 4, pp. 7647–7768, 2005.

[4] M.-D. Chou, "A solar radiation model for use in climate studies," *J. Atmos. Sci.*, vol. 50, no. 5, pp. 673–690, 1992.
[5] L. A. Remer and Y. J. Kaufman, "Aerosol effect on the distribution of solar radiation over the clear-sky global oceans derived from four years of MODIS retrievals," *Atmos. Chem. Phys. Discuss.*, vol. 5, no. 4, pp. 5007–5038, 2005.
[6] S. A. Christopher and J. Zhang, "Cloud-free shortwave aerosol radiative effect over oceans: Strategies for identifying anthropogenic forcing from Terra satellite measurements," *Geophys. Res. Lett.*, vol. 31, no. 18, p. L18101, 2004. DOI:1029/2004GL020510.
[7] L. A. Remer, Y. J. Kaufman, D. Tanré, S. Mattoo, D. A. Chu, J. V. Martins, R.-R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, and B. N. Holben, "The MODIS aerosol algorithm, products, and validation," *J. Atmos. Sci.*, vol. 62, no. 4, pp. 947–973, Apr. 2005.
[8] J. Zhang, S. A. Christopher, L. A. Remer, and Y. J. Kaufman, "Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 1. Angular models for aerosols," *J. Geophys. Res.*, vol. 110, no. D10, p. D10S23, 2005. DOI: 10.1029/2004JD005008.
[9] J. Zhang, S. A. Christopher, L. A. Remer, and Y. J. Kaufman, "Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 2. Seasonal and global distributions," *J. Geophys. Res.*, vol. 110, no. D10, p. D10S24, 2005. DOI: 10.1029/2004JD005009.
[10] N. G. Loeb and N. Manalo-Smith, "Top-of-atmosphere direct radiative effect of aerosols over global oceans from merged CERES and MODIS observations," *J. Climate*, vol. 18, no. 17, pp. 3506–3526, 2005.
[11] S. A. Christopher and T. A. Jones, "Net radiative effect of dust aerosols over global oceans from MODIS and CERES," *IEEE Geosci. Remote Sens. Lett.*, vol. 5, no. 1, pp. 74–77, Jan. 2008.
[12] I. Koren, L. A. Remer, Y. J. Kaufman, Y. Rudich, and J. V. Martins, "On the twilight zone between clouds and aerosols," *Geophys. Res. Lett.*, vol. 34, no. 8, p. L08805, Apr. 2007. DOI:10.1029/2007GL029253.
[13] J. M. Prospero, P. Ginoux, O. Torres, and S. Nicholson, "Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS-7 TOMS absorbing aerosol product," *Rev. Geophys.*, vol. 40, no. 1, p. 1002, 2002. DOI:1029/2000RG000095.

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