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Short-wave aerosol radiative efficiency over the global oceans derived from satellite data

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ABSTRACT

Using 5 yr (December 2000–November 2005) of satellite data from the clouds and the earths radiant energy system (CERES) and moderate resolution imaging spectroradiometer (MODIS), we examine the instantaneous short-wave radiative efficiency (E_τ) of aerosols during the morning Terra satellite overpass time over the global oceans (60°N–60°S). We calculate E_τ using two commonly used methods. The first method uses the MODIS aerosol optical thickness (AOT) at 0.55 μm with radiative transfer calculations, whereas the second method utilizes the same AOT values along with a new generation of aerosol angular distribution models to convert the CERES-measured broad-band radiances to fluxes. Over the 5 yr, the global mean instantaneous E_τ between the methods is remarkably consistent and within 5 W m^{-2} τ^{-1} with a mean value of –70 W m^{-2} τ^{-1}. The largest differences between the methods occur in high-latitude regions, primarily in the Southern Hemisphere, where AOT is low. In dust dominated regions, there is an excellent agreement between the methods with differences of <3 W m$^{-2}\tau^{-1}$. These differences are largely due to assumptions in aerosol models and definition of clear sky backgrounds. Independent assessments of aerosol radiative effects from different satellite sensors and methods are extremely valuable and should be used to verify numerical modelling simulations.

1. Introduction

Aerosols significantly perturb the radiative balance of the earth–atmosphere system. Although they are short lived in the atmosphere, with lifetimes of 1–2 weeks depending on aerosol type, several hundred teragrams of aerosols are emitted annually from both natural and anthropogenic sources, creating strong gradients in surface and atmospheric radiative fluxes. They not only affect the radiative balance but also have important implications for health, climate, hydrology and other environmental factors. Although numerical modelling simulations indicate that greenhouse gas emissions warm the surface temperature (Hansen et al., 2005), the effect of aerosols on surface temperatures is uncertain due to the complexities in determining aerosol types, their interaction with clouds, the effect of meteorology and other physical, dynamic, chemical and radiative factors. However, recent research suggests that overall, aerosols act to cool the atmosphere, though substantial variability exists, depending on aerosol species and distributions (Yu et al., 2006).

Short-wave radiative efficiency (E_τ) is the efficiency of aerosols in perturbing the net flux of solar radiation at the top of atmosphere, which is expressed in W m^{-2} per unit aerosol optical thickness (τ^{-1}) and is the ratio of the short-wave radiative effect (SWRE) and AOT. SWRE is defined as the difference at clear sky (F_{clr}) and aerosol sky (F_{aer}) regions, both representing cloud free regions. In this study, the slope of the AOT and SWRE regression line is defined as the radiative efficiency (E_τ), which is a more robust measure of E_τ than a simple ratio. The goal of this study is to examine the efficiency (E_τ) by which aerosols perturb the short-wave radiation at the top of atmosphere. This is a key parameter for studying the effect of aerosols on climate, since if aerosol optical thickness (AOT, a measure of aerosol concentration) is known, then the product of AOT and E_τ can provide an estimate of climate forcing of aerosols (Anderson et al., 2005). E_τ can also be used as a parameter to evaluate model performance since it removes the geographical dependence of AOT. We define AOT as the MODIS AOT at 0.55 μm unless otherwise noted. The term, climate forcing of aerosols is applied while studying anthropogenic aerosols such as those from incomplete fossil fuel combustion, anthropogenic biomass burning, industrial emission and other human activities. However, it is a non-trivial task to separate anthropogenic sources from natural ones, although surrogates using the fine mode fraction of aerosols have been developed using satellite data (Kaufman et al., 2005).

In this study, we do not separate natural from anthropogenic aerosols; we only calculate the E_τ of 'all' aerosols in an atmospheric column. We further examine the E_τ over 13 regions over

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the global oceans (60°N–60°S), primarily with two commonly used methods. The first method utilizes the MODIS AOT and internally consistent aerosol properties in a radiative transfer model (MOD) that was developed by Remer and Kaufman (2005). The second method (CER) utilizes the same MODIS AOT but a new generation of angular models derived from Terra, to convert the broad-band clouds and the earth's energy radiant energy system (CERES) radiances to fluxes (Zhang et al., 2005).

2. Data and methods

We use 5 yr (2000–2005) of the merged MODIS (collection 4) and CERES data over the global oceans contained within the pixel-level CERES single scanner footprint (SSF) FM-1, Edition 2B product. Although collection 5 MODIS aerosol properties are now available, the current CERES SSF product does not contain collection 5 MODIS data as of this writing. The point spread function weighted MODIS AOT is reported for each CERES footprint (20 km at nadir). The TOA fluxes in the CERES SSF product are derived as a function of near-surface wind speed, but aerosol fluxes are built from theoretical radiative transfer calculations by assuming a single maritime tropical aerosol model with a single scattering albedo of 1.0 at 0.5 μm. Since aerosol properties vary globally and the Terra-MODIS samples the entire globe on a near daily basis (as opposed to the limited TRMM latitudinal sampling), a new generation of angular distribution models (ADM) were built as a function of wind speed, AOT and fine mode fraction (an index of particle size) by Zhang et al. (2005). We use these ADMs to convert the CERES-measured radiances to fluxes.

In contrast, Remer and Kaufman (2005) used monthly mean $1^\circ \times 1^\circ$ AOT data (MOD08 product) over the global oceans and a radiative transfer model (Chou et al., 2002) to calculate E_τ, which we label the 'MOD' method. This model requires wavelength-dependent surface and aerosol properties over the full spectrum (0.175–10 μm), in addition to vertical profiles of water vapour, temperature and trace gases. Remer and Kaufman (2005) use a mid-latitude temperature and humidity profile for all model runs. The sea surface is set to a constant albedo of 0.07 and the $\underline{F}_{\mathrm{clr}}$ background is obtained by running the model for AOT = 0. To calculate F_{aer}, the MODIS aerosol retrievals of single scattering albedo, AOT and asymmetry parameters from seven wavelengths bands between 0.47 and 2.13 μm over the ocean are used as inputs to the model. Since the model requires wavelength dependent properties over the full solar spectrum in eleven spectral bands, interpolations and extrapolations are necessary to match the MODIS values to the RT model requirements. Remer and Kaufman (2005) provide full details of this method.

In MODIS aerosol retrievals, nine aerosol models are used: four representing fine mode aerosols and five representing coarse mode aerosols (Remer and Kaufman, 2005). Based on aerosol optical properties of each one of the nine aerosol modes in the RT model, the TOA short-wave (SW) flux for aerosols is calculated for nine solar zenith angle (SZA) bins for a range of AOT values. Since the MODIS data product also provides the AOT attributed to each mode, the fluxes are calculated by combining the distribution of aerosol models from the MODIS retrieval. Using these instantaneous retrievals of SWRE, the 24-h averages are then estimated by assuming that the aerosol AOT and properties do not vary during the day. To avoid uncertainties in estimating the diurnal values due to various assumptions (Anderson et al., 2005), we examine only the instantaneous values during the time of the Terra overpass (~10:30 a.m. local time) for both the MOD and CER methods.

For the CER method, F_{clr} is estimated by regressing the MODIS (level 2, collection 4) 10×10 km^2 AOT to CERES fluxes for a series of solar zenith angle and surface wind speed bins and assuming that F_{clr} is equal to the regression constant where AOT = 0 (Zhang et al., 2005). Therefore, F_{clr} between MOD and CER methods may differ. F_{aer} is obtained for each CERES pixel that is at least 99% non-cloud contaminated for which MODIS identifies aerosols. Angular models developed by Zhang et al., (2005) are then applied to the CERES measured radiances for these pixels to produce TOA SW fluxes.

3. Results and discussion

Fig. 1 shows the mean E_τ for 13 regions over the global oceans in 2005 for the CER and MOD methods, with different colours indicating various seasons (other years are similar). The mean AOT for each year and for the 13 regions from the level 2 MODIS aerosol product are given in Table 1(a). The E_τ from the CER and MOD methods (in parenthesis) is given in Table 1(b). There is a remarkable linear relationship (Fig. 1) between the MODIS AOT and the CERES SWRE, for all seasons, from two different sensors as indicated by linear correlation coefficients generally in excess of 0.85. This indicates the strengths of using multiple sensors to study aerosol climate effects. The AOT over the global oceans is relatively constant on a year-by-year basis, but shows substantial seasonal variability, especially in regions 7 (primarily dust) and 11 (primarily anthropogenic aerosols) (Fig. 2a and Table 1). Aerosol concentrations in region 7 vary due to increasing dust transport from the Saharan Desert into the Arabian Sea during the summer months as a result of the onset of the Indian Monsoon. Region 11 (R11) is associated with large aerosol concentrations produced from seasonal biomass burning in southern Africa. Another high aerosol concentration exists in the Northwestern Pacific (R4) due to a combination of dust, biomass burning and pollution aerosols.

As with AOT, E_τ for the CER and MOD method shows only small variations as a function of year, but larger seasonal variations in some regions corresponding to variations in AOT and aerosol type. Table 1 shows that over the global oceans (averaged over all 13 regions), the instantaneous E_τ from the CER method ranges from –66 to –68 W m^{-2} τ^{-1}, with a mean value

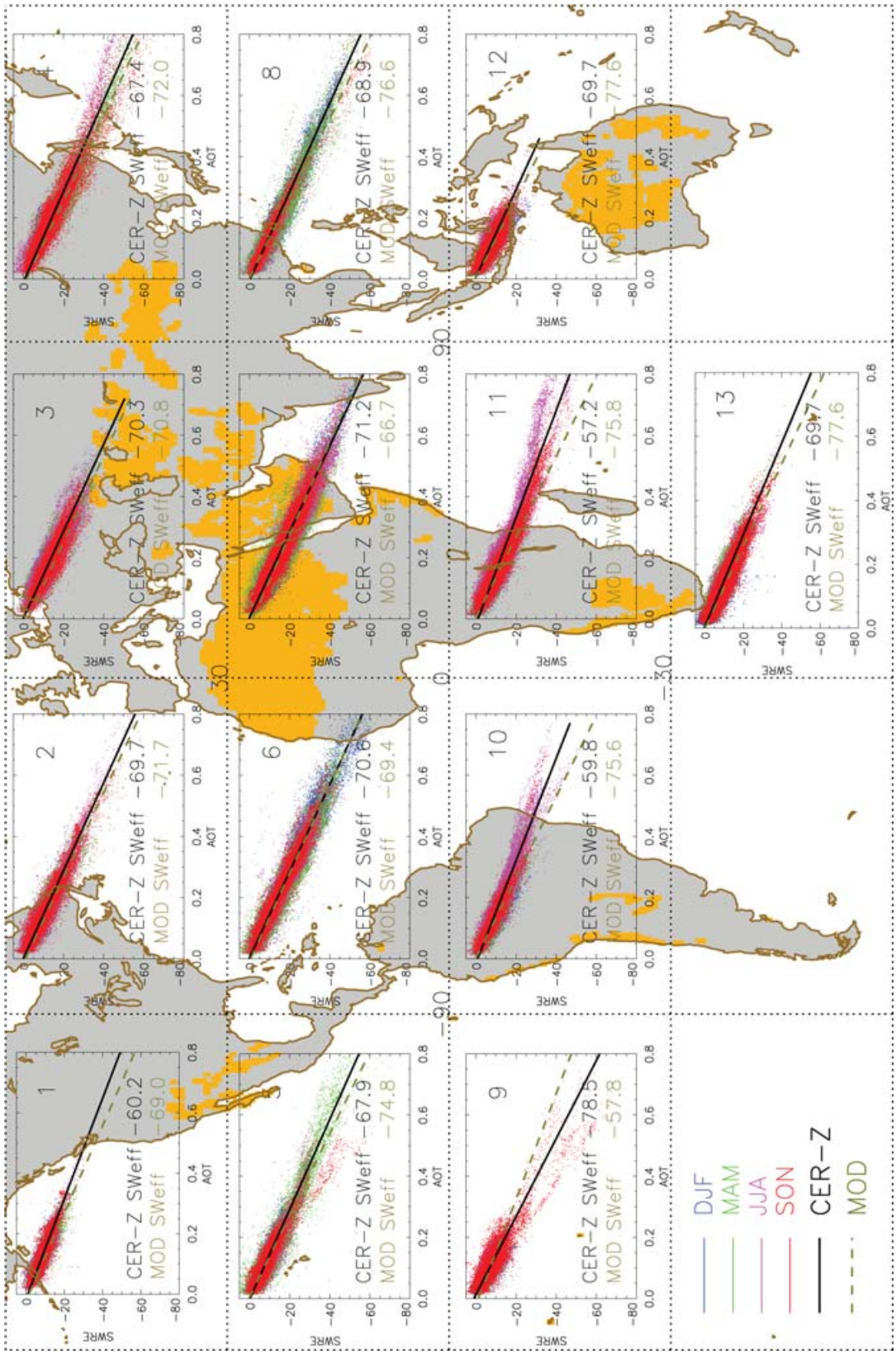

Fig. 1. The relationship between MODIS Level 2 AOT and short-wave radiative effect (SWRE) for MOD and CER-Z methods for 13 regions over the cloud-free oceans for 2005. The first method uses the SWRE from the CERES fluxes and the data points for four seasons are shown in different colours. The annual mean linear fit from the CER methods is shown by the solid black line. The MOD method utilizes the MODIS AOT and radiative transfer calculations as outlined in Remer and Kaufman (2005). The dashed line indicates the linear fit from this method. All these values are instantaneous and no diurnal averaging has been performed. The yellow shading over the continents denotes major desert ecosystems.

Table 1. Ocean-only global (60°S–60°N) values for 13 regions during the time of Terra overpass

(a) AOT

Region	Latitude (degrees)	Longitude (degrees)	2001	2002	2003	2004	2005	Mean
1	30–60N	180–90W	0.161	0.150	0.169	0.159	0.144	0.157
2	30–60N	90–0W	0.148	0.158	0.160	0.153	0.148	0.153
3	30–60N	0–90E	0.191	0.199	0.201	0.187	0.188	0.193
4	30–60N	90–180E	0.261	0.246	0.283	0.222	0.248	0.252
5	0–30N	180–90W	0.127	0.126	0.129	0.120	0.133	0.127
6	0–30N	90–0W	0.232	0.229	0.238	0.227	0.235	0.232
7	0–30N	0–90E	0.300	0.291	0.318	0.314	0.310	0.307
8	0–30N	90–180E	0.142	0.157	0.148	0.163	0.171	0.156
9	0–30N	180–90W	0.099	0.099	0.099	0.099	0.105	0.100
10	30S-60S	90–0W	0.123	0.127	0.129	0.132	0.141	0.130
11	30S-60S	0–90E	0.137	0.135	0.139	0.14	0.146	0.139
12	30S-60S	90–180E	0.119	0.126	0.12	0.127	0.123	0.123
13	30S-60S	180W-180E	0.128	0.130	0.133	0.129	0.132	0.130
Yearly mean			0.167	0.167	0.174	0.167	0.171	0.169

(b) Radiative Efficiency E_τ for CERES and MODIS method (in parenthesis)

Region	2001	2002	2003	2004	2005	Mean
1	−69 (−67)	−69 (−71)	−69 (−71)	−70 (−72)	−60 (−69)	−67 (−70)
2	−72 (−75)	−69 (−76)	−69 (−81)	−69 (−75)	−70 (−72)	−70 (−76)
3	−67 (−68)	−70 (−71)	−66 (−71)	−70 (−71)	−70 (−71)	−69 (−70)
4	−70 (−71)	−68 (−74)	−63 (−76)	−69 (−76)	−67 (−72)	−67 (−74)
5	−68 (−74)	−67 (−73)	−65 (−74)	−71 (−67)	−68 (−75)	−67 (−73)
6	−69 (−71)	−70 (−69)	−68 (−67)	−71 (−69)	−70 (−69)	−69 (−69)
7	−69 (−64)	−71 (−66)	−71 (−65)	−72 (−67)	−71 (−67)	−70 (−66)
8	−68 (−77)	−66 (−77)	−67 (−77)	−63 (−77)	−69 (−77)	−66 (−77)
9	−66 (−56)	−69 (−59)	−65 (−61)	−68 (−57)	−79 (−58)	−69 (−58)
10	−66 (−73)	−62 (−75)	−66 (−75)	−64 (−74)	−60 (−76)	−63 (−75)
11	−62 (−72)	−59 (−74)	−59 (−74)	−59 (−74)	−57 (−76)	−59 (−74)
12	−67 (−74)	−64 (−76)	−67 (−76)	−63 (−74)	−70 (−78)	−65 (−76)
13	−69 (−78)	−67 (−79)	−65 (−80)	−69 (−79)	−70 (−78)	−68 (−79)
Mean	−68 (−71)	− 67 (−72)	−66 (−73)	−67 (−72)	−69 (−72)	−67 (−72)

of –67 W m^{-2} τ^{-1} and is remarkably uniform over all 5 yr. Where high concentrations of aerosols from biomass burning exist, E_τ is between 5 and 10 W m^{-2} τ^{-1} less negative when compared with regions with mostly naturally occurring (sea-salt) or pollution based (sulphate) aerosols. This difference is a result of the absorbing characteristics of black carbon aerosols, which are a by-product of biomass burning. Still, these differences are relatively small when averaged globally, and it should be noted that for all regions, nearly 50% of all aerosols are considered to be coarse-mode, sea-salt types by the MODIS retrievals.

The corresponding MOD values for E_τ range between –71 and –73 W m^{-2} τ^{-1}, with a mean value of –72 W m^{-2} τ^{-1}. Large differences in E_τ of 15 W m^{-2} τ^{-1} between the two methods occur when AOT is low (region 9, where AOT = 0.1), and assessing E_τ in these low AOT regions may not be meaningful. With the exception of region 9, where the linear regression fits are poorest, E_τ from CER is generally equal or less negative than MOD. The reasons CER is less negative than MOD are primarily darker aerosol-free background (F_{clr}) and assumptions in converting the MODIS AOT to fluxes in the radiative transfer model. The best agreement occurs where AOT values are high (such as regions 2–4, 6 and 7) where the differences are less than 5 W m^{-2} τ^{-1}. These differences can be easily accounted for by reducing the clear-sky background SW fluxes by about 5% in the MOD method. Recall that the MOD method calculates clear sky (F_{clr}) background conditions by assuming that AOT = 0 and may be too small in some areas. When this is subtracted from F_{aer}, the resulting SWRE and E_τ values will become more negative.

To assess the differences between methods, we compare the difference between the CER method using new aerosol ADMs (Zhang et al., 2005), which we call CER-Z, and MOD method as a function of 13 regions (Fig. 2b). We also assess the difference between the SW fluxes derived from CER-Z and the values derived from the ADMs, developed by Loeb and Kato (2002), CER-T, which is shown in Fig. 2b. Using CER-T, E_τ becomes less negative, with a 5 YR average of only –63.5 W m^{-2} τ^{-1},

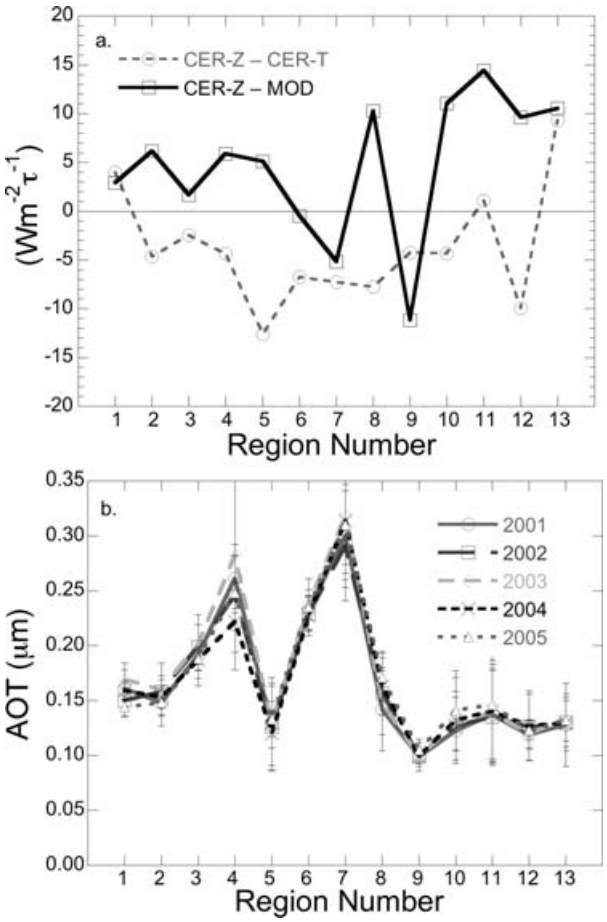

Fig. 2. Yearly averaged (a) MODIS AOT with seasonal variability denoted by error bars and (b) Difference in SWRE between CERES and MOD methods as a function of region.

though the overall correlation remains greater than 0.85. The differences between CER-T and CER-Z can be explained by analysing the SW flux as a function of ADMs that were used to convert the CERES-measured radiances to fluxes. Recall that the CER-Z has a much improved aerosol characterization than the CER-T ADMs. CER-T SW flux values are often 10% greater than corresponding values derived from CER-T ADMs when AOT is less than 0.4. Given the differences observed in E_τ between ADMs, it is necessary to use AODs that are function of not only wind speed but also AOT and particle size, to obtain the most realistic estimate of E_τ (Zhang et al., 2005).

4. Summary and conclusions

Radiative efficiency, $E_\tau = (F_{\text{clr}} - F_{\text{aer}})/\text{AOT}$, is a useful parameter that can be derived from satellite observations and retrievals that can be used as a benchmark for validating numerical models. In this paper, we calculate E_τ using two commonly used observational methods over the global oceans for 5 yr (2001–2005). We further calculated E_τ as a function of 13 regions and seasons at the time of the satellite overpass. We deliberately did not calculate diurnal values since there are various assumptions involved in that process, which are identical for both methods. For each year, E_τ is remarkably consistent between the two methods (MOD and CER) with a difference of only 5 W m^{-2} τ^{-1} with a mean value of about –70 W m^{-2} τ^{-1}. Although theoretical calculations (Remer and Kaufman, 2005) and empirical approaches (Zhang et al., 2005) show that E_τ is different for different aerosol species, which is a function of aerosol properties such as single scattering albedo, the maritime aerosol background smears these differences and produces an almost uniform E_τ for each region. Finally, we recommend that ADMs, sensitive to aerosol properties such as those developed by Zhang et al. (2005), must be used for studies that convert the CERES measured radiances to fluxes to ensure a bias does not exist in global estimates of SWRE.

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