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Satellite-based assessment of top of atmosphere anthropogenic aerosol radiative forcing over cloud-free oceans

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[1] Most assessments of the direct climate forcing (DCF) of anthropogenic aerosols are from numerical simulations. However, recent advances in remote sensing techniques allow the separation of fine mode aerosols (anthropogenic aerosol is mostly fine aerosol) from coarse mode aerosols (largely marine and dust, which are mostly natural) from satellite data such as the Moderate Resolution Imaging SpectroRadiometer (MODIS). Here, by combining MODIS narrowband measurements with broadband radiative flux data sets from the Clouds and the Earth's Radiant Energy System (CERES), we provide a measurement-based assessment of the global direct climate forcing (DCF) of anthropogenic aerosols at the top of atmosphere (TOA) only for cloud free oceans. The mean TOA DCF of anthropogenic aerosols over *cloud-free oceans* [60N–60S] is -1.4 ± 0.9 Wm^{-2}, which is in excellent agreement (mean value of -1.4 Wm^{-2}) with a recent observational study by Kaufman et al. [2005]. **Citation:** Christopher, S. A., J. Zhang, Y. J. Kaufman, and L. A. Remer (2006), Satellite-based assessment of top of atmosphere anthropogenic aerosol radiative forcing over cloud-free oceans, *Geophys. Res. Lett.*, *33*, L15816, doi:10.1029/2005GL025535.

1. Introduction

[2] The earth's climate is governed by the balance between the solar energy absorbed by the earth and the longwave energy radiated back to space. Since greenhouse gases absorb the earth-emitted longwave energy, and reemit part of it back toward the earth's surface, the amount of radiation at the top of atmosphere (TOA) is reduced. The warming of the earth's surface due to this radiation imbalance and the resulting TOA radiative forcing of 2.4 Wm^{-2} has been attributed to increase in anthropogenic greenhouse gases. Tropospheric aerosols on the other hand are another key component of the climate system, acting opposite to the greenhouse gas warming by reducing the amount of solar radiation reaching the surface, and therefore cooling the earth's surface. Aerosols are often classified into natural (largely dust and sea salt) and anthropogenic (pollution and smoke aerosol) components. The change in net radiation at the TOA due to the reflection and absorption of incoming solar radiation by *anthropogenic aerosols* is called as the direct climate forcing (DCF) which is the focus of this paper.

[3] Although aerosols have short lifetimes of about a week, they are critical components of the climate system since they affect not only the radiative but the hydrological budget of the earth-atmosphere system. Global estimates of all sky DCF of anthropogenic aerosols including land and oceans, primarily derived from model simulations, indicate a large range of values between -0.1 to -1.0 Wm^{-2} [*Intergovernmental Panel on Climate Change*, 2001]. There are several approaches for examining the DCF, ranging from use of simple radiative transfer approximations [*Penner et al.*, 1994] to more complex global models [*Takemura et al.*, 2005]. However, numerical simulations of aerosols often require detailed information on the spatial distribution and radiative properties of aerosols that are often not readily available at suitable spatial and temporal scales. However, a major advantage of global models is the ability to separate the effect of anthropogenic from natural aerosols. Alternatively, observational methods use narrowband satellite measurements coupled with radiative transfer equations [e.g., *Bellouin et al.*, 2005] or by combining narrowband and broadband satellite data sets [e.g., *Zhang et al.*, 2005b] to estimate the combined direct radiative effect (DRE) of both the anthropogenic and natural aerosols. A review of the radiative effect of aerosols from both satellite-based methods and global models are provided by *Yu et al.* [2005].

[4] Along with global satellite retrievals of total column aerosol optical thickness (AOT), recent advances in retrieval techniques also provide the fraction of the AOT contributed by fine aerosol (effective radius 0.1–0.25 μm) called the fine mode fraction (FMF) [*Kaufman et al.*, 2005]. Since satellite measurements do not measure the chemical composition directly from space, the FMF has been used as a surrogate for anthropogenic aerosols and the reported uncertainty of FMF of anthropogenic aerosols over ocean is ±30% [*Kaufman et al.*, 2005]. Satellite retrieval of FMF from the MODIS has recently facilitated the calculation of DCF of anthropogenic aerosols over oceans. *Bellouin et al.* [2005] used the MODIS AOT and MODIS FMF (over ocean), MODIS AOT and FMF from chemistry transport models (over land) and reported the *cloud-free* TOA DCF over *both land and ocean* to be -1.9 ± 0.3 Wm^{-2}. *Chung et al.* [2005] used the Aerosol Robotic Network (AERONET) sun photometers, chemistry transport model results (for estimating anthropogenic fractions), MODIS AOT, and radiative transfer modeling and reported the *cloud-free* DCF over *both land and ocean* to be -1.08 Wm^{-2}. The differences between these studies are possibly due to several reasons, including the different methods used and the

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uncertainties in aerosol models in the calculations. *Kaufman et al.* [2005] describe the technique to separate the anthropogenic AOT from total column MODIS measurements and using the ratio of anthropogenic to total forcing efficiency from the MODIS aerosol models, they report a global mean DCF over *cloud-free oceans* to be -1.4 ± 0.4 Wm^{-2}. In this paper we take a different approach for estimating DCF over the global oceans. We use collocated MODIS and broadband earth radiation budget measurements from the Clouds and the Earth's Radiant Energy System (CERES) to estimate DCF of anthropogenic aerosols thereby avoiding radiative transfer calculations to calculate TOA fluxes from MODIS AOT values [*Christopher and Zhang*, 2004]. We use the same MODIS FMF data product used by *Kaufman et al.* [2005] and *Bellouin et al.* [2005] and calculate the difference between clear and aerosol regions from the CERES to report DCF of anthropogenic aerosols. We use nearly a years worth (November 2000–August 2001) of collocated MODIS and CERES data from the Terra satellite to examine the DCF of anthropogenic aerosols over the cloud-free global oceans. To maintain consistency, we use the same data set that was used to develop angular models for aerosols [*Zhang et al.*, 2005a]; calculate total radiative effect over global oceans for all aerosols [*Zhang et al.*, 2005b]; and for outlining strategies for separating the anthropogenic forcing from combined CERES and MODIS measurements [*Christopher and Zhang*, 2004].

2. Methods and Results

[5] The anthropogenic AOT is calculated based on the technique outlined by *Kaufman et al.* [2005] and only a brief description is included here for sake of completeness. The MODIS retrieved column AOT at 550 nm (τ_{550}) is the sum of maritime (τ_m), dust (τ_d), and anthropogenic (τ_a) components. The fraction of τ_{550} contributed by fine mode aerosol (f_{550}) is also reported from the MODIS retrievals. *Kaufman et al.* [2005] used the MODIS aerosol measurements separately in regions with high concentrations of dust, smoke, and largely maritime aerosol to determine the fraction of fine aerosol for each one of these aerosol types. Based on this analysis, $f_{an} = 0.92 \pm 0.03$ for anthropogenic aerosols, $f_{du} = 0.51 \pm 0.03$ for dust aerosols, and $f_{ma} = 0.32 \pm 0.1$ for maritime aerosols.

[6] In this study, we first estimate the background marine aerosol optical thickness (τ_m) as $0.007 \times w$ [where w is the Special Sensor Microwave Imager (SSM/I) near surface wind speed] [*Zhang et al.*, 2005b] and no additional term is added to fit the base line τ of 0.06 [*Kaufman et al.*, 2005]. After the background component is estimated and removed from the MODIS AOT, the anthropogenic component is estimated using τ_{550} and f_{550} for each pixel as

$$\tau_a = [(f_{550} - f_{du})\tau_{550} - (f_{ma} - f_{du})\tau_m]/(f_{an} - f_{du})$$

[7] The same fraction between dust and anthropogenic components from MODIS data is then applied to the CERES cloud-free footprints. We note that *Kaufman et al.* [2005] used the 0.55 μm channel to estimate the FMF, while we apply this to CERES data in the total shortwave spectrum between 0.2–4.5 μm. This approximation is valid to within 8–10% (instantaneous and ~4–5% for diurnally averaged values) by examining the near-linear relationship between CERES SW flux for aerosols and MODIS AOT for the range of aerosol optical thickness under consideration from our current analysis. To determine clear sky fluxes (F_{clr}), we first select the CERES footprints that have no cloud contamination based on the MODIS data. For 2 × 2 latitude-longitude regions, for each month, we then determine F_{clr} for pixels with $\tau_{0.55} \leq 0.007 \times w$. We then subtract each instantaneous CERES measurement from F_{clr} [*Zhang et al.*, 2005b]. These pixels now contain the portion of the shortwave flux due to the combined anthropogenic and dust components. If the fraction f_{550} within the CERES footprint is greater than f_{an}, then the shortwave flux is assigned entirely to the anthropogenic component. If f_{550} is between f_{du} and f_{an}, we scale the shortwave flux for the dust and anthropogenic components according to τ_d and τ_a, to estimate the anthropogenic aerosol component.

[8] We further correct for the sample biases between the CERES and MODIS data and correct for diurnal effects based on *Zhang et al.* [2005a] using forcing efficiency for anthropogenic aerosols derived from our data set. We examined the relationship between the MODIS τ_{550} and CERES flux using observations for $f_{550} > 0.9$, to estimate anthropogenic aerosol forcing efficiency. For $\tau_{550} < 0.4$, we obtained a diurnally averaged anthropogenic forcing efficiency (E_a) of -32 Wm^{-2}. *Yu et al.* [2005] report a mean E_a value of -37 Wm^{-2} with a relative uncertainty of 19%. Furthermore, we also account for a 10% overestimation of MODIS AOT due to cloud artifacts [*Zhang et al.*, 2005c]. As discussed in *Kaufman et al.* [2005], 20% of total smoke aerosols are from natural sources and we also accounted for that in our global mean calculations.

[9] Figure 1 shows the global cloud-free DCF for anthropogenic aerosols. Also superimposed in the figure, is the zonal and meridional distribution of SWARF indicating the large regional effects of aerosols. Figure 1 shows the DCF due to both pollution and vegetation fires. Large DCF values due to anthropogenic pollution are seen off the coast of North America, East Asia, and India. The anthropogenic forcing also has a distinct seasonal cycle with maximum values during the Northern Hemisphere fall and winter months when winds are off shore bringing pollution from the Indian subcontinent into the Indian Ocean and Bay of Bengal. Off the coast of West Africa, South America and Central America, the large DCF values are primarily due to vegetation fires in the dry season comprising off submicron particles. The largest DCF values are off the Indian continent and East Asia and such gradients in radiative fluxes at the TOA have implications for hydrological processes and regional climate. Due to the scattering and absorbing properties of these aerosols, less solar insolation is available below the aerosol layers while absorption due to these aerosols in the atmosphere could also change atmospheric circulation patterns.

[10] The satellite analysis also clearly indicates that the DCF due to anthropogenic aerosols is nearly three times higher over the Northern hemisphere (2.3 Wm^{-2}) when compared to the Southern hemisphere (0.8 Wm^{-2}). The meridional distribution indicates that the pollution effects from the Indian subcontinent have large DCF values when

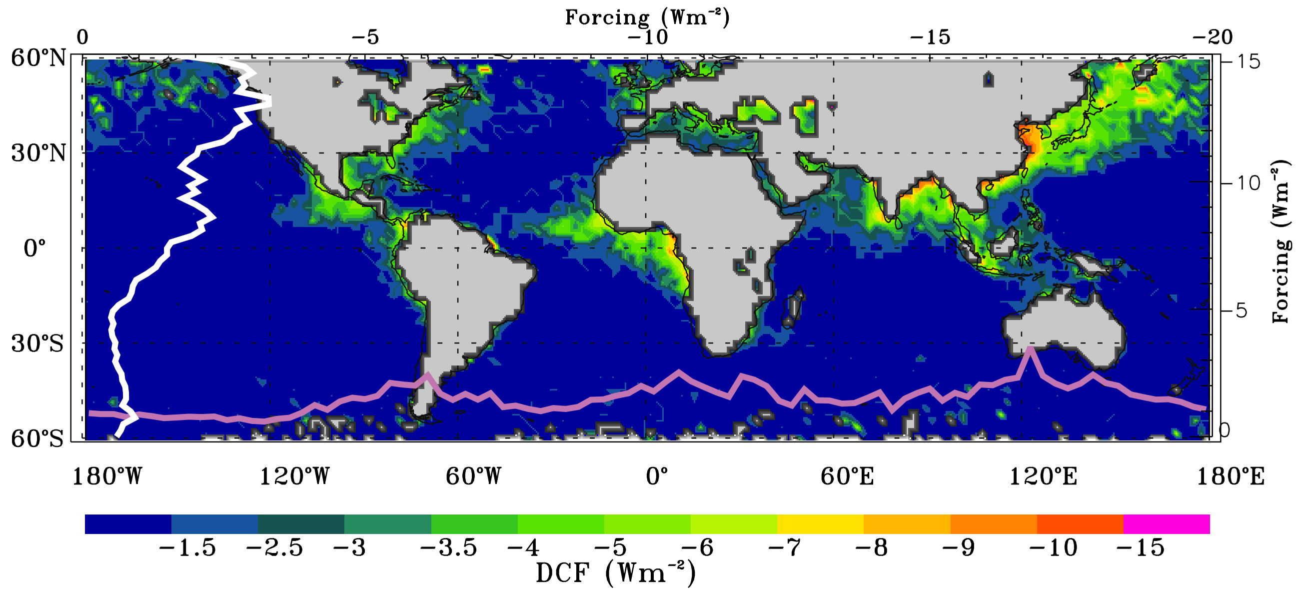

Figure 1. Spatial distribution of the ten month mean (Nov 2000–Aug 2001) Direct Climate Forcing (DCF) of anthropogenic aerosols for cloud-free conditions. Superimposed is the zonal (in white, with corresponding axis on top) and meridional distribution (in pink with corresponding axis on the right) of DCF in Wm^{-2}.

compared with relatively clean conditions off the Eastern Pacific Ocean and other regions. The largest values are in the northern hemisphere spring ($-1.7\ Wm^{-2}$) and lower values during winter ($-1.4\ Wm^{-2}$) and summer ($-1.2\ Wm^{-2}$). The global mean DCF due to anthropogenic aerosols for cloud-free conditions is $-1.4\ Wm^{-2}$ that is in excellent agreement with mean values ($-1.4\ Wm^{-2}$) reported by *Kaufman et al.* [2005].

[11] While this measurement-based approach is a direct method for evaluating the aerosol effects on climate, there are several sources of uncertainty including instrument calibration ($\sim$0.8Wm^{-2}), conversion of filtered to unfiltered radiances ($\sim$0.8Wm^{-2}), angular dependence models ($\sim$0.25 Wm^{-2}), cloud contamination ($\sim$10%, or 0.3 Wm^{-2}), MODIS anthropogenic AOT ($\sim$33%), and aerosol forcing efficiency (10%). Therefore total uncertainties can be estimated using equation 1 [*Zhang et al.*, 2005b].

$$U_t = \exp\left[\sum(\log U_i)^2\right]^{1/2} \qquad (1)$$

Where U_i is the uncertainty factor from each individual source of uncertainty and U_t is the total uncertainty factor. After accounting for diurnal averages, the uncertainty in diurnally averaged DCF of anthropogenic aerosols is 0.9 Wm^{-2}.

3. Summary

[12] Using combined MODIS and CERES data sets from the Terra satellite we have reported the cloud-free DCF of anthropogenic aerosols to be $-1.4 \pm 0.9\ Wm^{-2}$ over the global oceans. This study was possible because angular models specifically constructed for fine mode aerosols were used in the analysis. The uncertainties in these estimates will continue to reduce as satellite algorithms coupled with other measurements continue to mature. Future studies must address observational strategies to calculate DCF over both land and ocean over clear and all sky conditions.

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References

Bellouin, N., O. Boucher, J. Haywood, and M. S. Reddy (2005), Global estimate of aerosol direct radiative forcing from satellite measurements, *Nature*, *438*, 1138–1141, doi:10.1038/nature04348.

Christopher, S. A., and J. Zhang (2004), Cloud-free shortwave aerosol radiative effect over oceans: Strategies for identifying anthropogenic forcing from Terra satellite measurements, *Geophys. Res. Lett.*, *31*, L18101, doi:10.1029/2004GL020510.

Chung, C. E., V. Ramanathan, D. Kim, and I. A. Podgorny (2005), Global anthropogenic aerosol direct forcing derived from satellite and ground-based observations, *J. Geophys. Res.*, *110*, D24207, doi:10.1029/2005JD006356.

Intergovernmental Panel on Climate Change (2001), *Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., 881 pp., Cambridge Univ. Press, New York.

Kaufman, Y. J., O. Boucher, D. Tanré, M. Chin, L. A. Remer, and T. Takemura (2005), Aerosol anthropogenic component estimated from satellite data, *Geophys. Res. Lett.*, *32*, L17804, doi:10.1029/2005GL023125.

Penner, J. E., et al. (1994), Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols, *Bull. Am. Meteorol. Soc.*, *75*, 375–400.

Takemura, T., T. Nozawa, S. Emori, T. Y. Nakajima, and T. Nakajima (2005), Simulation of climate response to aerosol direct and indirect effects with aerosol transport-radiation model, *J. Geophys. Res.*, *110*, D02202, doi:10.1029/2004JD005029.

Yu, H., et al. (2005), A review of measurement-based assessment of aerosol direct radiative effect and forcing, *Atmos. Chem. Phys. Disc.*, *5*, 7647–7768.

Zhang, J., S. A. Christopher, L. A. Remer, and Y. J. Kaufman (2005a), Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 1. Angular models for aerosols, *J. Geophys. Res.*, *110*, D10S23, doi:10.1029/2004JD005008.

Zhang, J., S. A. Christopher, L. A. Remer, and Y. J. Kaufman (2005b), Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 2. Seasonal and global distributions, *J. Geophys. Res.*, *110*, D10S24, doi:10.1029/2004JD005009.

Zhang, J., J. S. Reid, and B. N. Holben (2005c), An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products, *Geophys. Res. Lett.*, *32*, L15803, doi:10.1029/2005GL023254.

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