Direct Aerosol Radiative Forcing Uncertainty Based on a Radiative Perturbation Analysis

NORMAN G. LOEB
NASA Langley Research Center, Hampton, Virginia

WENYING SU
SSAI, Hampton, Virginia

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ABSTRACT

To provide a lower bound for the uncertainty in measurement-based clear- and all-sky direct aerosol radiative forcing (DARF), a radiative perturbation analysis is performed for the ideal case in which the perturbations in global mean aerosol properties are given by published values of systematic uncertainty in Aerosol Robotic Network (AERONET) aerosol measurements. DARF calculations for base-state climatological cloud and aerosol properties over ocean and land are performed, and then repeated after perturbing individual aerosol optical properties (aerosol optical depth, single-scattering albedo, asymmetry parameter, scale height, and anthropogenic fraction) from their base values, keeping all other parameters fixed. The total DARF uncertainty from all aerosol parameters combined is 0.5–1.0 W m^{-2}, a factor of 2–4 greater than the value cited in the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report. Most of the total DARF uncertainty in this analysis is associated with single-scattering albedo uncertainty. Owing to the greater sensitivity to single-scattering albedo in cloudy columns, DARF uncertainty in all-sky conditions is greater than in clear-sky conditions, even though the global mean clear-sky DARF is more than twice as large as the all-sky DARF.

1. Introduction

Radiative forcing by aerosols is identified as the largest uncertainty in anthropogenic radiative forcing of climate. Aerosols influence the radiation budget of the earth directly by scattering and absorbing solar radiation (direct radiative forcing) and indirectly by modifying the microphysical characteristics and lifetimes of clouds (indirect forcing). Recently, Forster et al. (2007) provided a review of several model- and observation-based estimates of clear-sky and all-sky direct aerosol radiative forcing (DARF) at the top of atmosphere (TOA) and surface since the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report (TAR; Penner et al. 2001). DARF is defined as the mean radiative flux perturbation due to the anthropogenic component of present-day aerosols relative to the start of the industrial era (about 1750). Based upon a synthesis of model and satellite results, Forster et al. (2007) conclude that the all-sky DARF is -0.5 W m^{-2}, with an uncertainty of 0.4 W m^{-2} at the 90% confidence level. This represents significant progress in reducing the uncertainty of the anthropogenic direct radiative forcing relative to IPCC TAR (Solomon et al. 2007; Haywood and Schulz 2007) and leads to a medium-low level of scientific understanding in the current (fourth) IPCC assessment report. Largely owing to the reduced uncertainty in DARF, Forster et al. (2007) assessed the total anthropogenic forcing as ''virtually certainly positive, and conversely exceptionally unlikely negative.'' More recently, Myhre (2009) combined results from a global aerosol model and satellite observations to obtain a DARF estimate of -0.3 W m^{-2}, with an uncertainty of ± 0.2 W m^{-2}—half the uncertainty cited in Forster et al. (2007). Note that the low ''uncertainty'' in Myhre (2009) is based upon the consistency between model-based DARF and a combined model–observation-based DARF that are not independent of one another.

The DARF uncertainty estimates in Forster et al. (2007) and Myhre (2009) stand in marked contrast to recent assessments of the current state of the art in

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Corresponding author address: Dr. Norman G. Loeb, NASA Langley Research Center, Mail Stop 420, Hampton, VA 23681-2199.
E-mail: norman.g.loeb@nasa.gov

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Table 1. TOA clear-sky and all-sky DARF from recent publications.

	Coverage	DARF (W m^{-2})	Reference	Comment
Clear sky	Ocean	-1.4 ± 0.4	Kaufman et al. (2005)	Satellite
	Global	-1.3 ± 0.3	Bellouin et al. (2008)	Satellite
	Global	-1.3 ± 0.8	Yu et al. (2006)	Satellite and model
	Global	-0.68 ± 0.24	Schulz et al. (2006)	Model
All sky	Global	-0.35 ± 0.25	Chung et al. (2005)	Satellite and ground
	Global	-0.65 ± 0.10	Bellouin et al. (2008)	Satellite
	Global	-0.5 ± 0.33	Yu et al. (2006)	Satellite and model
	Global	-0.22 ± 0.16	Schulz et al. (2006)	Model
	Global	-0.5 ± 0.40	Forster et al. (2007)	Satellite and model

satellite-based aerosol remote sensing. In the recent U.S. Climate Change Science Program (CCSP) assessment of aerosols (Remer et al. 2009), the satellite-based cloud-free anthropogenic direct radiative forcing at the TOA is estimated to be -1.1 ± 0.4 W m^{-2} over the global ocean, where the ± 0.4 W m^{-2} uncertainty corresponds to one standard deviation. Table 1 provides recently published observation-based estimates of clear- and all-sky TOA DARF. Several of these results were used in Forster et al. (2007) to derive the DARF uncertainty in the fourth IPCC assessment report. Overall, these results suggest that all-sky DARF is a factor of 2–3 smaller than clear-sky DARF, and, curiously, the uncertainty in all-sky DARF is a factor of 2 smaller than that in clear-sky DARF, despite the increased uncertainty associated with aerosol direct radiative effects in cloudy columns.

The objective of this study is to provide an independent estimate of DARF uncertainty for the ideal case in which the current ground-based capability of the Aerosol Robotic Network (AERONET; Holben et al. 1998) to retrieve aerosol properties is applicable globally. A radiative perturbation analysis is used whereby DARF calculations for a base state of climatological cloud and aerosol properties is performed and then repeated after perturbing individual aerosol optical properties from their base values, keeping all other parameters fixed. The focus here is on the aerosol optical depth (AOD), single-scattering albedo (SSA), asymmetry parameter, aerosol scale height, and anthropogenic fraction. This analysis represents a best-case scenario since we assume all of the uncertainty resides in present-day aerosol properties and ignore any uncertainty associated with preindustrial aerosols, cloud, and surface properties. Furthermore, the use of AERONET uncertainties to determine the perturbed aerosol parameters in the analysis is highly optimistic since AERONET aerosol properties (e.g., aerosol optical depth) are nearly 3–5 times more accurate than current satellite aerosol retrievals (Remer et al. 2009). The DARF uncertainty is assumed to originate entirely from observational uncertainty and is derived independently of any model constraints. Only systematic (nonrandom) uncertainties that persist after averaging a large ensemble (e.g., years) of data are considered. Comparing the DARF uncertainty derived in this manner with those cited in Forster et al. (2007) and Myhre (2009) serves to place the latter in perspective, and hopefully will shed some light on the apparent discrepancy between the magnitude of the uncertainties between satellite-based assessments and Forster et al. (2007).

2. Methodology

DARF is determined from the difference between the global mean TOA radiative flux for preindustrial and present-day aerosols. Radiative fluxes are computed using the base-state mean aerosol, surface, and cloud properties defined separately for ocean and land (Tables 2 and 3). Because there is no community-accepted mean-state aerosol "climatology" available, we have used values based upon various sources in the literature. The sensitivity in the DARF uncertainty to the assumed base-state aerosol conditions is evaluated using two sets of mean aerosol optical depth, single-scattering albedo, and asymmetry parameter values (Table 2). Aerosol optical depths in the first base state are from Yu et al. (2006), and the single-scattering albedo and asymmetry parameter are adapted from the Optical Properties of Aerosols and Clouds (OPAC) database (Hess et al. 1998). In the second base state, the aerosol optical depth and single-scattering albedo are adapted from Chung et al. (2005), and the asymmetry parameter is from OPAC. The overall aerosol properties (aerosol optical depth, single-scattering albedo, and asymmetry parameter) are determined assuming the aerosol components are externally mixed. The aerosol scale height for both base states is 1 km. The anthropogenic fraction, defined as the difference between the present-day and preindustrial aerosol optical depth divided by the present-day aerosol optical depth (Schulz et al. 2006; Myhre 2009), is 0.29 for the first base state and 0.40 for the second base state. Table 3 summarizes the global mean cloud and surface properties for land and ocean assumed in the DARF calculations.

TABLE 2. Aerosol properties used to define base states. PreInd refers to pre-industrial aerosol; PresDay refers to present-day aerosol.

	Base state 1 aerosol properties											
	Aerosol optical depth				Single-scattering albedo				Asymmetry parameter			
	Ocean		Land		Ocean		Land		Ocean		Land	
	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy
Water soluble	0.036	0.063	0.072	0.141	0.991	0.991	0.988	0.988	0.739	0.739	0.724	0.724
Sea salt	0.073	0.073			1.0	1.0			0.803	0.803		
Dust			0.060	0.063			0.960	0.960			0.670	0.670
Soot		0.004		0.016		0.21		0.21		0.388		0.388
Total	0.109	0.140	0.132	0.220	0.997	0.975	0.970	0.925	0.782	0.770	0.703	0.700

	Base state 2 aerosol properties											
	Aerosol optical depth				Single-scattering albedo				Asymmetry parameter			
	Ocean		Land		Ocean		Land		Ocean		Land	
	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy	PreInd	PresDy
Water soluble	0.039	0.0665	0.078	0.147	0.991	0.991	0.988	0.988	0.739	0.739	0.724	0.724
Sea salt	0.032	0.032			1.0	1.0			0.803	0.803		
Dust			0.010	0.023			0.960	0.960			0.670	0.670
Soot		0.0055		0.013		0.21		0.21		0.338		0.388
Total	0.071	0.104	0.088	0.183	0.995	0.952	0.985	0.928	0.768	0.755	0.717	0.710

The global mean aerosol and cloud properties listed in Tables 2 and 3 are input into a plane-parallel radiative transfer code (Fu and Liou 1992, 1993) to calculate the DARF. This code has been highly modified and is now dubbed the Langley Fu–Liou code, which includes 25 aerosol types. The baseline and perturbed values of each parameter are used to calculate TOA fluxes over ocean and land for solar zenith angles corresponding to 24-h periods at hourly time steps for 15 January, 15 April, 15 July, and 15 October for 13 latitudes from 90°S to 90°N at 15° intervals. Global mean fluxes are obtained by area weighting fluxes over ocean and land. The computed present-day global annual average TOA flux for each base state $\overline{F}_{\mathrm{PresDy}}$ is then normalized to be consistent with the global annual mean TOA flux from the Clouds and the Earth's Radiant Energy System (CERES) $\overline{F}_{\mathrm{CERES}}$ (Loeb et al. 2009). The preindustrial and perturbed global annual average TOA fluxes are then adjusted by the ratio of $\overline{F}_{\mathrm{CERES}}$ to $\overline{F}_{\mathrm{PresDy}}$.

The perturbed values of present-day aerosol optical depth, single-scattering albedo and asymmetry parameter values are inferred from AERONET systematic (nonrandom) uncertainties (Dubovik et al. 2000). The aerosol optical depth is perturbed by ±0.01, the asymmetry parameter is perturbed by ±0.02, and the single-scattering albedo is perturbed by ±0.06 over ocean and ±0.03 over land. The single-scattering albedo perturbations are based upon Table 4 in Dubovik et al. (2000), where the uncertainty for aerosol optical depths <0.2 is between 0.05 and 0.07, and that for aerosol optical depths >0.2 is 0.03. This level of uncertainty in single-scattering albedo is comparable to that cited in other

TABLE 3. Climatological cloud properties for ocean and land used in radiative perturbation analysis.

Variable	Ocean	Land	Reference
Surface albedo	0.07	0.24	Jin et al. (2004); D. R. Doelling (2009, personal communication)
Emissivity	0.924	0.971	Zhang et al. (2007)
High cloud fraction	0.26	0.27	Stubenrauch et al. (2009)
Low cloud fraction	0.47	0.32	Stubenrauch et al. (2009)
High cloud optical depth	1.39	1.78	Rossow and Schiffer (1999)
Low cloud optical depth	2.51	2.12	Rossow and Schiffer (1999)
High cloud-top pressure (hPa)	511	443	Wang et al. (2000)
High cloud-base pressure (hPa)	625	576	Wang et al. (2000)
Low cloud-top pressure (hPa)	866	811	Wang et al. (2000)
Low cloud-base pressure (hPa)	951	899	Wang et al. (2000)
High cloud effective ice crystal diameter (μm)	50	45	Stubenrauch et al. (2009)
Low cloud water droplet radius (μm)	15	13	Stubenrauch et al. (2009)

TABLE 4. DARF (W m^{-2}) values for the two base-state climatologies, aerosol parameter perturbations used in the radiative perturbation analysis, and corresponding DARF uncertainties expressed as $\Delta^+|\Delta^-$, where Δ^- is associated with negative and Δ^+ is associated with positive aerosol parameter perturbations.

		Clear sky		All sky	
Parameter	Perturbation	Base state 1	Base state 2	Base state 1	Base state 2
DARF		−0.78	−1.06	−0.37	−0.54
Aerosol optical depth	0.01|−0.01	−0.30|0.30	−0.30|0.30	−0.24|0.24	−0.22|0.22
Asymmetry parameter	0.02|−0.02	0.01|−0.02	0.03|−0.10	0.01|−0.02	0.01|−0.06
Single-scattering albedo	0.06−0.06 ocean; 0.03|−0.03 land	−0.55|0.86	−0.59|0.69	−0.67|1.11	−0.73|0.87
Scale height (km)	0.8	0.05	0.05	0.15	0.16
Anthropogenic fraction	0.05|−0.05	−0.26|0.26	−0.20|0.20	−0.22|0.22	−0.16|0.16
Total ($\rho = 0$)		0.68|0.95	0.70|0.78	0.76|1.17	0.79|0.92
Total ($\rho = -1$)		0.36|0.63	0.37|0.45	0.51|0.92	0.56|0.69

recent studies from both ground and airborne measurements (Russell et al. 2002; Chowdhary et al. 2005; Waquet et al. 2009). The AERONET inversion algorithm (Dubovik and King 2000) retrieves single-scattering albedo from sun and sky radiances using input of aerosol optical depth derived from sun-photometer measurements. At the present time, no quantitative assessment is available regarding the correlation between the uncertainties of the aerosol optical depth and single-scattering albedo. However, simulations in Dubovik et al. (2000) do suggest that SSA tends to be biased low when AOD is biased high. Therefore, we provide two total DARF uncertainties: one calculated assuming that the AOD and SSA are independent (which corresponds to the upper bound of the DARF uncertainty) and the other is assuming AOD and SSA are perfectly anticorrelated (which corresponds to the lower bound of the DARF uncertainty). To include the effect of these uncertainties in the vertical distribution of aerosols, the aerosol scale height is perturbed from 1 to 1.8 km (Waquet et al. 2009). The anthropogenic fraction is perturbed by ±0.05 (Kaufman et al. 2005), by adjusting the preindustrial aerosol optical depth while holding the preindustrial single-scattering albedo and asymmetry parameter constant. Note that the uncertainty of 0.05 (corresponding to 17% and 12% changes in the anthropogenic fractions for the two cases) that we used for the anthropogenic fraction is optimistic. Yu et al. (2009) assessed that the uncertainty factor of the anthropogenic aerosol optical depth is 1.5 over ocean, which corresponds to a 50% uncertainty in the anthropogenic fraction.

3. Results and conclusions

Table 4 (first row of values) shows the global mean DARF for the clear-sky and all-sky conditions corresponding to the two base states used in the perturbation analysis. These values fall well within the range of other studies (Table 1), indicating that aerosols have a net cooling effect on climate, at least globally. The second through sixth rows of values provide DARF uncertainties for the positive and negative perturbations from the base-state conditions of each of the aerosol parameters considered, and the last two rows show the total DARF uncertainties corresponding to the case where AOD and SSA are assumed to be independent ($\rho = 0$), and where AOD and SSA are anticorrelated ($\rho = -1$). The lower and upper bounds for the total DARF uncertainty are determined from the sum of the squares of the negative or positive uncertainties associated with the individual parameter perturbations. Results are also plotted in Figs. 1a and 1b, together with the IPCC DARF uncertainty (dashed line). In all cases, DARF uncertainties correspond to one standard deviation (1σ). Uncertainties associated with single-scattering albedo perturbations dominate the DARF uncertainty in both clear- and all-sky conditions, with values ranging between −0.55 and 1.11 W m^{-2}. This alone exceeds the IPCC 1σ uncertainty of 0.24 W m^{-2} by a factor of 2–4. Note that the DARF uncertainties are not symmetric about zero, but rather they tend to be greater for the negative parameter perturbations. Perturbations in other parameters, such as anthropogenic fraction, aerosol optical depth, asymmetry parameter, and scale height, result in DARF uncertainties <0.3 W m^{-2}. Assuming the individual uncertainties are independent ($\rho = 0$), the total all-sky DARF uncertainty ranges from 0.76 to 1.17 W m^{-2}, and ranges from 0.51 to 0.92 W m^{-2} for $\rho = -1$. To examine the influences of different climatological cloud and surface properties on the results in Table 4, the radiative perturbation analysis was repeated after increasing the surface albedos, cloud fractions, and cloud optical depths in Table 3 by 5%. While the DARF is found to be sensitive to these changes (especially the all-sky DARF), the uncertainties show little change.

Table 4 also shows that while the DARF uncertainty is up to ≈30% larger for clear-sky than all-sky conditions

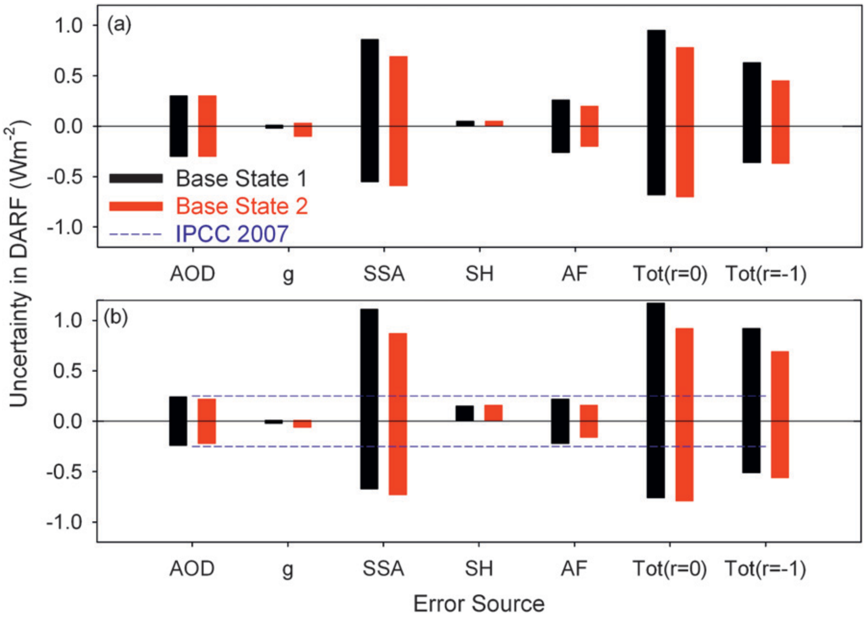

FIG. 1. DARF uncertainty associated with different aerosol parameters for (a) clear- and (b) all-sky conditions. The dashed line corresponds to the DARF uncertainty in Solomon et al. (2007).

when the aerosol optical depth is perturbed, the all-sky DARF uncertainty is ≈20% larger when the single-scattering albedo is perturbed. Because of the relatively larger albedo of clouds, perturbing the aerosol absorption in a cloudy column has a much greater effect on DARF than it does in a clear column. Since DARF uncertainty due to single-scattering albedo is the dominant error source, the overall all-sky DARF uncertainty exceeds the clear-sky DARF uncertainty, despite the factor of 2 larger global mean DARF for clear-sky compared to all-sky conditions. Hence, the common practice of scaling clear-sky DARF uncertainty by a clear area fraction leads to a significant underestimation of the all-sky DARF uncertainty.

A reasonable question to ask is whether the uncertainty in DARF associated with the single-scattering albedo uncertainty in the observations can be reduced by constraining the measurements with model-based information on aerosol absorption. Unfortunately, the emission inventories of carbonaceous aerosols are highly uncertain (Bond et al. 2004) and the amounts of black carbon in current climatologies produced by tracer transport models must be increased by a factor of 2–4 to yield the best agreement with AERONET when black carbon is assumed to be externally mixed with other aerosols (Sato et al. 2003). Further, the AODs of black carbon differ markedly among the Aerosol Comparisons between Observations and Models (AeroCom) models (Kinne et al. 2006). Consequently, given the large differences among the models, it is unlikely that model constraints on the AERONET single-scattering albedo retrievals would reduce the overall DARF uncertainty.

Given that this analysis is highly optimistic since it assumes uncertainties from AERONET, which are only available over land and are 3–5 times more accurate than current global satellite retrievals, our results cast serious doubt on the Solomon et al. (2007) DARF uncertainty and the conclusion in Forster et al. (2007) that total anthropogenic radiative forcing is ‘‘virtually certainty positive, and conversely exceptionally unlikely negative.’’ Part of the reason for the discrepancy may be that the uncertainty in Solomon et al. (2007) is largely derived from differences in DARF among various climate models. While interesting, this cannot be claimed to give the uncertainty in DARF, but rather the diversity based upon prescribed emission scenarios. Another factor may be that the observation-based uncertainties cited in Solomon et al. (2007) either ignored uncertainties in key parameters such as single-scattering albedo (Chung et al. 2005) or simply scaled the clear-sky DARF uncertainty by the clear-area fraction to determine the all-sky DARF uncertainty, thereby ignoring uncertainties associated with aerosols in the cloudy column. The large sensitivity of DARF to small perturbations in single-scattering albedo clearly points to a need for accurate global measurements of absorption by aerosols, both in cloud-free columns and above clouds.

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