Global, Multi-Year Analysis of Clouds and Earth's Radiant Energy System Terra Observations and Radiative Transfer Calculations

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Introduction

An extended record of the Terra Surface and Atmosphere Radiation Budget (SARB) computed by CERES (Clouds and Earth's Radiant Energy System) is produced in gridded form, facilitating an investigation of global scale direct aerosol forcing. The new gridded version (dubbed FSW) has a spacing of 1° at the Equator. A companion document (Rutan et al. 2005) focuses on advances to (and validation of) the ungridded, footprint scale calculations (dubbed CRS), primarily in clear-sky conditions. While mainly intended to provide observations of fluxes at the top of atmosphere (TOA), CERES (Wielicki et al. 1996) includes a program to also compute the fluxes at TOA, within the atmosphere and at the surface, and also to validate the results with independent ground based measurements (Charlock and Alberta 1996). ARM surface data has been a focus for this component of CERES. To permit the user to infer cloud forcing and direct aerosol forcing with the computed SARB, CERES includes surface and TOA fluxes that have been computed for cloud-free (clear) and aerosol-free (pristine) footprints; this accounts for aerosol effects (SW scattering and absorption, and LW scattering, absorption and emission) to both clear and cloudy skies.

Computation of Fluxes

The major inputs to the flux calculation are retrievals of cloud area, height, optical depth, particle size and phase from small (<1 km) MODIS pixels (Minnis et al. 2002); TOA fluxes from the CERES instrument in large (~20 km) footprints; gridded temperature, humidity, surface wind (GEOS4); and ozone from National Centers for Environmental Prediction (Yang et al. 2000). Aerosol information is taken from moderate-resolution imaging spectroradiometer (MODIS) and the National Center for Atmospheric Research (NCAR) Model for Atmospheric Transport and Chemistry (MATCH), an assimilation that incorporates aerosols from MODIS (Fillmore et al. 2005). The record has “tuned” flux profiles calculated by algorithms that partially constrain to CERES TOA observations (Rose et al. 1997); and “untuned” fluxes calculated by the original inputs. Aerosol forcings based on the untuned and tuned records hardly differ (see right columns of Table 1).

Table 1. Comparison of observed fluxes with SARB footprint scale (Terra CRS Edition 2B) calculations, and computed direct aerosol forcings, over ARM SGP sites for 2002.

	Observed	**Sample**	**(Untuned - Observed)**	**Aerosol Forcing**	
				Untuned	**Tuned**
	Wm^{-2}	**N**	**Wm^{-2}**	**Wm^{-2}**	**Wm^{-2}**
All sky					
Surface LW down	327.6	8749	-10.4	0.7	0.7
Surface SW down	583.5	4392	10.3	-15.6	-15.9
TOA LW up (OLR)	239.2	9449	2.1	-0.3	-0.3
TOA SW up	285.1	4717	2.1	4.6	4.9
Clear sky as per MODIS					
Surface SW down	723.1	1329	3.3	-14.0	-14.0
TOA SW up	169.3	1404	-0.9	5.0	4.9

The CERES SARB uses a correlated-k radiative transfer code (Fu and Liou 1993; Fu et al. 1999; Rose and Charlock 2002) which is available “point and click” at http://www-cave.larc.nasa.gov/cave/. Constituents for the thermal infrared include H_2O, CO_2, O_3, CH_4 and N_2O and CFCs. The CERES 8.0-12.0 µm window is computed (Kratz and Rose 1999) with Clough CKD 2.4 version of the H_2O continuum. We employed the HITRAN2000 data base to determine correlated k’s in the SW (Kato et al. 1999). We estimate the effects of inhomogeneous cloud optical thickness in the SW with the gamma weighted two stream approximation of Kato et al. (2004). An external mixture of aerosols, clouds, and gases is assumed. All-sky aerosol forcing is determined from compute flux with clouds (if present), gases and aerosols, subtracting the flux from a run with no aerosols. The theoretical clear-sky aerosol forcing is the difference of the cloud-free flux with aerosols minus the cloud-free flux with no aerosols.

Land surface albedo is explicitly retrieved for clear footprints using a quick table look-up (Rutan and Charlock 1999) to the Langley Fu-Liou code that relates observed CERES TOA albedo, surface albedo, solar zenith angle (SZA), precipitable water, and aerosol optical thickness (AOT). The spectral shape of the surface albedo is assumed as per the International Geophysical Biospherical Project (IGBP) land type. When cloudy, the land surface albedo is taken from a gridded record of clear-sky retrievals during the same month; it is adjusted to account for an effective diffuse SZA beneath clouds. Ocean spectral albedo is obtained using a look up table (LUT) based on discrete ordinate calculations with a sophisticated coupled ocean atmosphere radiative transfer code (Jin et al. 2004). Inputs for ocean spectral albedo include SZA, wind speed, chlorophyll concentration, and optical depth of clouds and aerosols.

AOT is taken from MODIS (MOD04 described by Kaufman et al. 1997) when available. Over the ocean, MOD04 is used for 7 wavelengths; the AOT is interpolated to the remainder of the spectrum using the selected aerosol type, as specified below. Over the land, MOD04 provides AOT at 3 wavelengths, and the MOD04 Angstrom exponent is used to guide the extension over the spectrum. If the MOD04 instantaneous AOT is not available (i.e., footprint is overcast), we temporally interpolate from a file of the MODIS Daily Gridded Aerosol. When cloudiness in the footprint exceeds 50%, or when there is no MODIS AOT, we use AOT from the NCAR MATCH. MATCH AOT is apportioned to 7 types (small dust, large dust, soot, soluble organic, insoluble organic, sulfate, and sea salt) on a daily basis over the globe for all sky condition. This includes explicit height profiles for the 7 types that vary for each gridbox, each day. When in the same vertical column, the relative heights of absorbing aerosols and clouds can strongly influence direct aerosol forcing at TOA. Aerosol type is always taken from MATCH; this guides the selection of the asymmetry factory (g) and the single scattering albedo (SSA). Asymmetry factors and SSA are assumed from OPACS-GADS (Hess et al. 1998) for all aerosols excepting desert dust. Optical properties for dust have been supplied by Dr. Andrew Lacis at National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (personal communication, 2004).

Table 1 compares untuned calculations for the ungridded SARB (Terra CRS Edition 2B) with observations at the Southern Great Plains (SGP) for several thousand matchups during 2002. LW parameters are compared for day and night. SW parameters are compared only for the ~1030 LST overpass of Terra. TOA observations are based on the CERES instrument. Surface observations are from ground based radiometers. No ground-based radiometric data are used for input to the calculations or for tuning. The bias (untuned calculation minus observation as 3.3 Wm^{-2} in Table 1) for surface insolation (723.1 Wm^{-2}) in clear sky is well below 1% (and much smaller than the corresponding value of –14.0 Wm^{-2} for aerosol forcing). The biases for all-sky SW insolation and for downward longwave (LW) at the surface are larger.

Global Aerosol Forcing

Aerosol forcings on the global seasonal and interannual scales are best diagnosed with a gridded form of the CERES SARB. The form now available (FSW) simply places the ungridded footprints (CRS) in the nearest hourly slot. A typical gridbox then has data for two slots a day per satellite: the Terra (or Aqua) daytime ~1030 (or 1330) LST and nightime ~2230 (or 0130) LST overpasses. The FSW fluxes and forcings do not represent true diurnal means. In the grid-based FSW results in Figures 1 and 2 and Table 2, both shortwave (SW) and LW parameters have been averaged for day and night. This contrasts with the footprint-based CRS results shown previously in Table 1, for which SW parameters were averaged over daylight passes only. The global annual mean all-sky aerosol forcing to surface insolation in Table 2 (gridded FSW) is –6.2 Wm^{-2} as a day plus night value; this contrasts with the SGP annual mean all-sky aerosol forcing to surface insolation in Table 1 (ungridded CRS) of –15.9 Wm^{-2}, which is a daytime only value. There is another difference, in that aerosol forcings in Table 2 and Figures 1 and 2 correspond to net fluxes. Net SW flux at TOA is downwelling SW flux at TOA minus upwelling SW flux at TOA; the corresponding aerosol forcing is then net SW flux at TOA with aerosols minus net SW flux at TOA without aerosols. For the gridded (FSW) fields in this section, we report theoretical “clear sky” forcing, which is computed regardless of the presence of clouds in a gridbox. For the previous ungridded (CRS), we reported in Table 1 “clear sky” parameters using only those footprints screened by MODIS as cloud free.

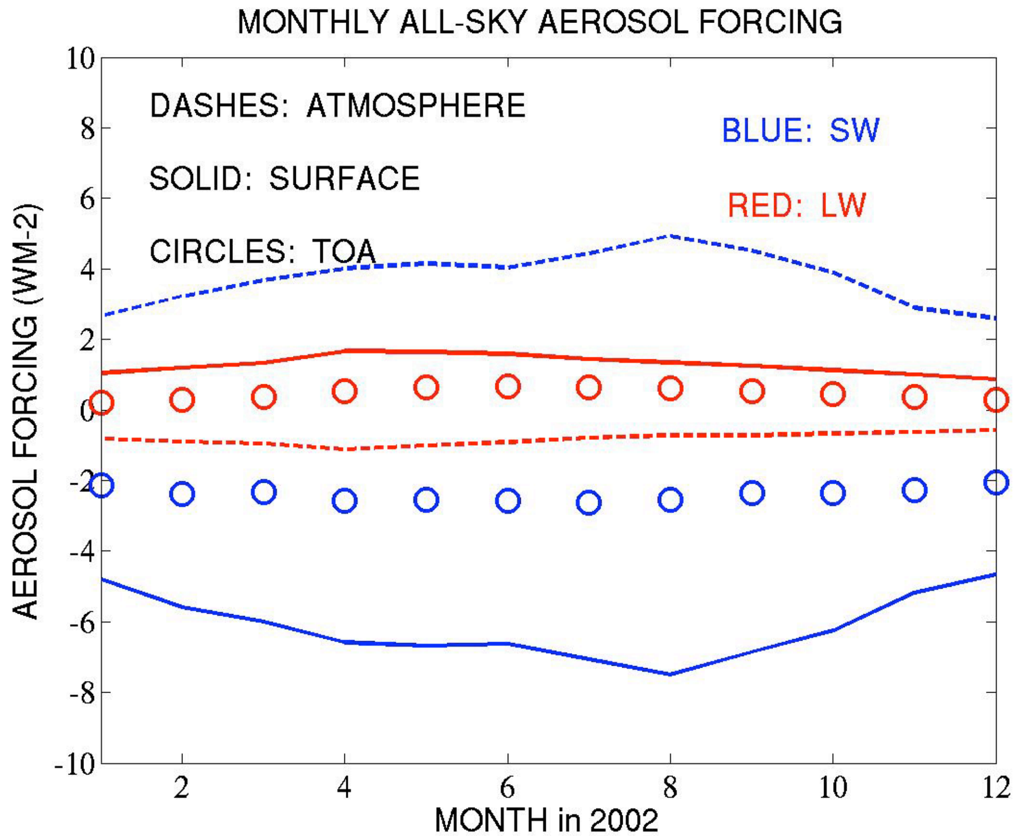

Figure 1. Monthly all-sky direct aerosol forcing for atmosphere, surface, and TOA (from global means of day and night CERES Terra CRS Edition 2B during 2002).

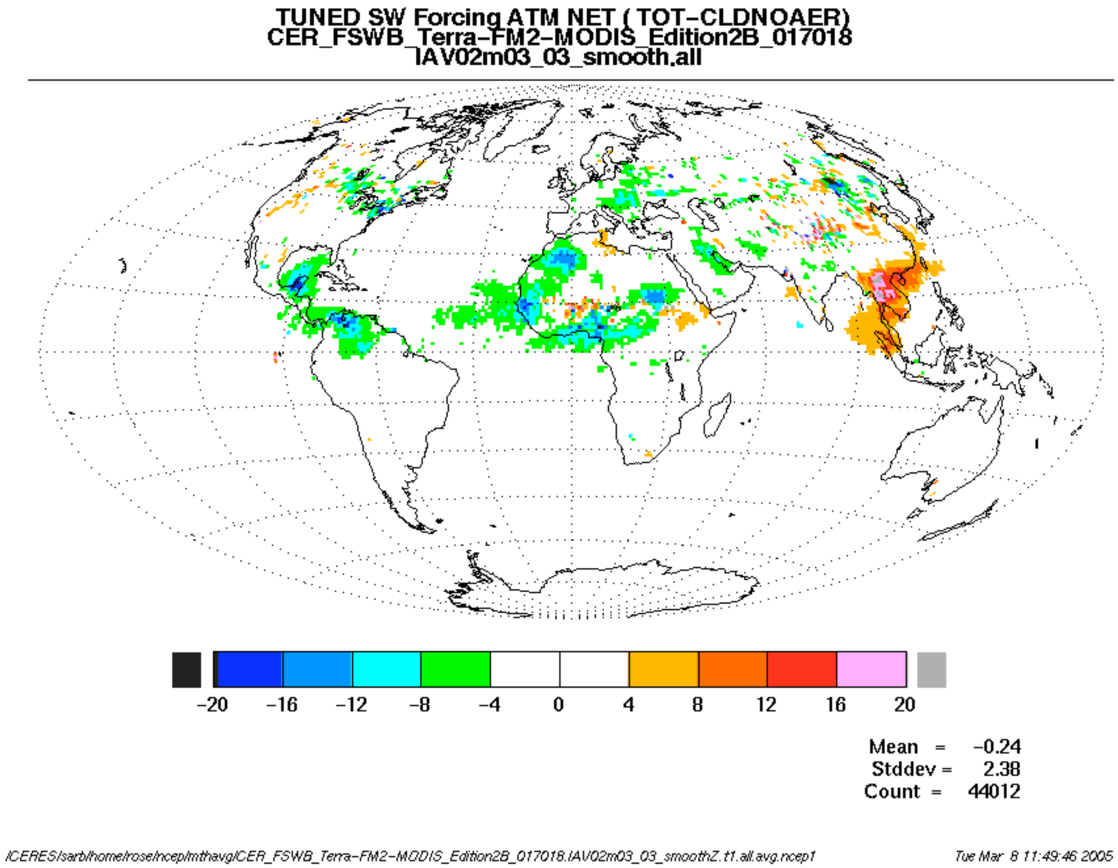

Figure 2. Change in all-sky aerosol SW heating of atmosphere (March 2003 – March 2002).

Table 2. Aerosol Forcing at Time of Terra Overpass during 2002 (from 12 monthly global means of day and night views).

	All sky SW	All sky LW	All sky SW+LW	Clear sky SW
TOA	-2.4 Wm^{-2}	0.5 Wm^{-2}	-1.9 Wm^{-2}	-4.0 Wm^{-2}
Atmosphere	3.8 Wm-^{2}	-0.8 Wm^{-2}	2.9 Wm^{-2}	3.9 Wm^{-2}
Surface	-6.2 Wm^{-2}	1.3 Wm^{-2}	-4.9 Wm^{-2}	-7.9 Wm^{-2}

Note that while aerosol forcings to LW have smaller magnitudes than those to SW, the LW effects are quite significant (Table 2). The all-sky SW forcing of aerosols tends to cool the globe at TOA (-2.4 Wm^{-2}), but the all-sky LW forcing at TOA (0.5 Wm^{-2}) offsets this with slight heating. On a global scale, clouds substantially reduce aerosol SW forcing at both TOA and at the surface. But aerosol induced SW heating of the global atmosphere for all-sky (3.8 Wm^{-2}) is almost the same as for the theoretically clear sky (3.9 Wm^{-2}) in Table 2; this is mostly due to the large amount of heating by dust aerosols over clear desert regions.

Figure 1 shows the seasonal cycle of the same gridded, day plus night aerosol forcings during 2002. Aerosol forcing to SW heating of the atmosphere displays a pronounced annual cycle; it peaks during August. The combined all-sky SW plus LW forcing of aerosol to atmospheric heating (not shown) has a minimum of 1.8 Wm^{-2} in January and a maximum of 4.2 Wm^{-2} in August. Relative to this atmospheric forcing, the seasonal variations of aerosol forcings at TOA (which are more commonly evaluated with satellite data) are weak.

Figure 2 provides a glimpse of year to year changes in aerosol forcing to SW heating of the atmosphere, in this case March 2003 minus March 2002. The global mean difference is only –0.24 Wm^{-2}. But the interannual forcing is regional, ranging from less than –10 Wm^{-2} over Central America and North Africa to over 10 Wm^{-2} over Southeast Asia; it is coherent at the hemispheric and continental scales (i.e., like the Walker and Hadley cells). Aerosol heating of the atmosphere has a direct impact on the hydrological cycle (i.e., Liepert et al. 2004). Our assessment of in-atmosphere heating by aerosols is especially contingent on the assumption for single scattering albedo, which is uncertain. The earlier Terra CRS Edition 2A had a smaller single scattering albedo for dust and consequently more aerosol forcing to SW heating of the atmosphere (Charlock et al. 2005). More in depth validation of this product is needed.

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